Technical Summaries

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Plasmonics for improved photovoltaics

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

Solar energy is currently enjoying substantial growth and investment, owing to worldwide sensitivity to energy security and climate change. In this talk I will describe approaches to control of light-matter interactions leading to enhanced absorption in solar photovoltaic structures. Conventionally, photovoltaic cells have a physical thickness comparable to their 'optical thickness' for full light absorption and photocarrier current collection. Solar cell design and material synthesis considerations are strongly dictated by this simple optical thickness requirement. Dramatically reducing the absorber layer thickness or volume confers several fundamental and practical benefits, including increased open circuit voltage and conversion efficiency, and also expansion of the scope and quality of absorber materials that are suitable for photovoltaics. Plasmonics and metamaterials design can also be exploited advantageously in photovoltaics. I will describe design approaches using metallic nanostructures to excite localized and propagating surface plasmons which can enhance overall photoabsorption in plasmonic solar cells relative to conventional light-trapping structures. Future metamaterial optical design directions for dramatic reduction of solar cell active volume will also be outlined.

Quantum wells in multiple junction photovoltaics

T. N. D. Tibbits, M. P. Lumb, QuantaSol Ltd. (United Kingdom)

Triple-junction (3J) solar cells are the world’s most efficient photovoltaic conversion devices, hero cells operating >41% under concentration between 300 and 500 suns. The typical 3J approach has a bandgap combination that limits the cell efficiency at approximately 49%. Different combinations of bandgaps can increase the theoretical efficiency to closer to 60%, and use of metamorphic materials has attempted to demonstrate still higher efficiencies. Multiple quantum wells (MQW) can also be used to fabricate materials with different effective bandgaps from the host semiconductor, and can do so without the attendant lattice constant change and dislocations associated with metamorphics. We show that sufficiently high absorption in MQWs increases the efficiency of 3J solar cells without incorporating defects during epitaxy, both in simulations and in practice.

Hot carrier solar cells: the ultimate photovoltaic conversion in practice

J. F. Guilleminoles, Institut de Recherche et Développement sur l’Energie Photovoltaïque (France)

Hot carrier solar cells (HCSC) provide an attractive solution to overtake the intrinsic efficiency limit for solar cells. By converting with improved efficiency the high energy range of the solar spectrum into electric power, they may allow conversion efficiencies above 50%, exceeding the single junction limit. Models have been proposed for ideal cells, where all losses are neglected. Here we develop a model for a more realistic device including carrier extraction, carrier thermalization and absorptivity losses. We then compare the model to experimental data obtained on test epitaxial structures and discuss the path to the realisation of such devices.
Hybrid organic/inorganic optical cavities: weak and strong-coupled structures

D. G. Lidzey, The Univ. of Sheffield (United Kingdom)

No abstract available

Optical injection of quantum-dash semiconductor lasers at 1550 nm for tunable photonic oscillators

M. C. Pochet, N. A. Naderi, The Univ. of New Mexico (United States); V. I. Kovanis, Air Force Research Lab. (United States); L. F. Lester, The Univ. of New Mexico (United States)

In this talk, we will theoretically compute and experimentally investigate the dynamics of an optically injected nanostructure laser as a function of the injection strength and the optical detuning frequency. A unique optical injection model is derived that accounts for the large nonlinear gain component associated with nanostructure lasers through the gain coefficient’s derivative with respect to perturbations in the carrier and photon density. The nonlinear gain (carrier) relaxation rate and gain compression coefficient account for the perturbation in photon density, and are theoretically shown to have a strong impact on the level of stability exhibited by the optically-injected laser. The theoretical model is experimentally verified through the optical-injection of a quantum-dash Fabry-Perot laser at an operating wavelength of 1560 nm. The quantum-dash laser’s large damping rate and potential for a small linewidth enhancement factor are observed to inhibit period-doubling and chaotic operation under zero frequency-detuning conditions. Additionally, the optically injected quantum-dash laser exhibits a large period-one operational state as the injection strength and/or the detuning frequency are varied, resulting in a highly tunable microwave frequency in the coupled system’s equilibrium state. The enhanced and undamped relaxation oscillations of the period-one state are discussed as a building block for tunable photonic oscillators in various RF photonics applications. Finally a path towards realizing an optically-injected diode laser with a THz resonance frequency will be reviewed.

Polarization-resolved nonlinear dynamics in long-wavelength single-mode VCSELS subject to orthogonal optical injection

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

Vertical-Cavity Surface-Emitting Lasers (VCSELS) emitting at the telecom wavelength of 1550 nm are very promising devices due to their inherent advantages in comparison with edge-emitting devices. Optical injection is a method that can induce a rich variety of nonlinear dynamics in the light emitted by the VCSEL. Nonlinear dynamics in VCSELS subject to orthogonal optical injection has been recently studied in short and long-wavelength devices. In this configuration linearly polarized light from a tunable laser is injected orthogonally to the linear polarization of a free-running VCSEL.

In this work we perform an experimental study of the polarization-resolved nonlinear dynamics of a 1550 nm wavelength single-mode VCSEL when subject to orthogonal optical injection. The RF and optical spectrum of both polarizations are measured for different frequency detuning and injected power values. We consider a frequency detuning given by the frequency difference between the injected signal and the subsidiary orthogonal polarization mode of the VCSEL. An stability map identifying the boundaries between regions of different dynamical behavior is obtained for a bias current given by five times the threshold value. Dynamical regimes including periodic, period doubling and irregular and possibly chaotic dynamics are observed for both polarizations when the frequency detuning is negative. For positive frequency detuning periodic dynamical behaviors are observed only for the orthogonal polarization. The nonlinear dynamics of the system will be also studied by analyzing the temporal series of the polarized and total emitted powers.

Properties of a single-mode quantum-dash semiconductor laser emitting at 1.55 µm submitted to optical injection

Z. Hao, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France); P. Besnard, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France) and Univ. Européenne de Bretagne, Enssat (France); F. LeLarge, G. Duan, Alcatel-Thales III-V Lab. (France); J. Hayau, Institut de Physique de Rennes (France); A. Accard, Alcatel-Thales III-V Lab. (France)

We describe, to our knowledge, for the first time, the properties of a single frequency quantum-dash semiconductor laser emitting at 1.55 µm that is submitted to optical injection. Previous results were dedicated to conventional laser (bulk, quantum wells) [1], multi-frequency lasers [2] or quantum-dot lasers emitting at 1.3 µm [3]. We show that the dynamics is strongly affected by the strong damping of such structure.


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

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

We propose a novel injection locking scheme, involving distributed Bragg reflector (DBR) master lasers monolithically integrated with microring lasers. Semiconductor ring lasers are ideal for this particular application, as they can be designed for minimal back reflections (eliminating the need for optical isolators protecting the master laser from optical feedback), while simultaneously allowing for complete coupling of the DBR laser output into the ring, supporting the favored propagation direction. By the very nature of the ring laser, low reflectivity for incident light does not at all compromise the quality of the ring cavity, and does not affect the threshold condition for the wave propagating in the favored direction. This makes ring lasers free from the design constraints that edge-emitting lasers and VCSELS suffer from.

The dynamics of an optically injection-locked microring laser monolithically integrated with single-mode master DBR laser was modeled by a system of the first-order rate equations written in terms of the photon numbers, phases, and total carrier numbers in the
master DBR and microring lasers. Parameters used for simulation were calculated assuming that both 1-mm long master DBR laser and 20-mm-diameter ring laser are based on an InGaAs/AlInGaAs/InP MQW ridge waveguide laser structure optimized for single mode operation. The power reflectivity of the back DBR mirror was assumed to be 100%, whereas that of the front injecting DBR mirror was calculated at 1.55 mm wavelength to be ~41% for the front mirror consisting of only one quarter-wave layer of BCB separating the identical ridge waveguide structures of the master laser and the injecting waveguide. Improved high-speed performance of the proposed injection-locking scheme was confirmed in numerical modeling.

7933-13, Session 3

**Influence of the linewidth enhancement factor on the modulation response of a quantum nanostructure based semiconductor laser operating under external optical feedback**

F. Grillot, Institut National des Sciences Appliquées de Rennes (France) and Ecole Nationale Supérieure des Télécommunications (France); N. Dubey, Indian Institute of Technology Guwahati (India)

The dramatic variation in the linewidth enhancement factor (H-factor) that has been reported for quantum dot (QD) lasers makes them an interesting subject for optical feedback studies. A low H-factor combined with a high damping factor is especially interesting because it should increase the tolerance to optical feedback in these devices and may offer potential advantages for direct modulation. In the particular case of QD lasers, the carrier density is not clearly clamped at threshold. The lasing wavelength can switch from the ground state (GS) to the excited state (ES) as the current injection increases meaning that a carrier accumulation occurs in the ES even though lasing in the GS is still occurring. The filling of the ES inevitably enhances the above threshold GS H-factor and after balooning the H-factor can even plummet to negative values. The purpose of the paper is to show that the exploitation of the nonlinear properties arising from nanostructure based semiconductor lasers operating under external optical feedback can lead under specific conditions to a bifurcation of the modulation properties. Starting from the generalized rate equations, the laser’s modulation response is determined. Under a short external cavity, calculations show that large variations of the H-factor contribute to improve the dynamical properties such as the relaxation frequency as well as the laser’s bandwidth. On the contrary, assuming a long external cavity, numerical results show that even small reflections in the percent range when combined to significant variations of the H-factor alter the laser's modulation response.

7933-14, Session 4

**Epitaxial III-V photovoltaics on flexible low cost metal substrates**

A. Freundlich, A. Mehrotra, M. Wu, A. Alemu, Univ. of Houston (United States); S. N. Sambandam, SuperPower, Inc. (United States); V. Selvamanickam, Univ. of Houston (United States)

Combining the unsurpassed performance of GaAs based multi-junction technologies with a conventional reel to reel processing standards of thin film industry could lead to paradigm-shifting reduction of the cost of solar electricity and increase of specific efficiencies.

Here we report on the fabrication of single crystalline GaAs-based epilayers and solar cells on thin (50microns) flexible polycrystalline Ni-based hastelloy 276 metallic substrates. A rapid (1 meter/hour) roll to roll ion beam assisted deposition is used to deposit oxide based adaptation buffers on the metal substrates followed by a growth of highly textured thin Ge films and the subsequent growth of Ge and (Al,In) GaAs epilayers by molecular beam epitaxy. RHEED, X-ray diffraction and transmission electron microscopy analysis confirm the (001) orientation and the single crystalline nature of the GaAs films. The fabricated samples exhibit strong photoluminescence response and analysis of near band edge excitons confirms minimal (or no) thermoelastic/lattice mismatch strain in GaAs epilayer.

Finally a GaAs-based single junction p/n diode design, geared toward minimizing the effect of treading dislocations (estimated to <18 cm-2 based on TEM analysis), is developed and devices are processed in an all front electrode configuration using multilevel lift-off and mesa-etch lithography. Dark and illuminated I-V characteristics as well as quantum efficiency measurements under short circuit conditions and as a function of applied external bias are implemented to demonstrate the suitability of the approach for the development of high efficiency, lightweight and potentially low-cost Photovoltaics.

7933-15, Session 4

**Dilute nitride multi-quantum well multi-junction design: a route to ultra-efficient photovoltaic devices**

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

Over the past decade an important effort has been dedicated to the development of 1-1.1 eV devices using dilute nitrogen III-V alloys (i.e InGaAsN) to enable ultra-efficient tandems, but thus far the success of the approach with bulk dilute nitride solar cells has been hindered by poor minority carrier properties, Leading to degraded IV characteristics. Previously we have reported an attractive alternative with III-V-N multi-quantum wells (MQW) solar cells showing significant photo-conversion without catastrophic voltage degradation [1].

In this work, we evaluate the potential of such MQW device in triple and quadruple junction configuration. The evolution of electron and hole fundamental and excited confined states are calculated within the framework of 8 band p-k formalism that account for strain-induced deformations and anti-crossing of N-localized states and host conduction band. The absorption properties of well and barriers are modeled by taking into account the increase of electron effective masses and excitonic contributions. The external quantum efficiency and I-V characteristics are calculated using standard carrier drift-diffusion model and a thermo-tunneling-assisted carrier extraction from wells. The modeling parameters are adjusted to account for existing experimental results. We show that by carefully adjusting the QW design parameters significant below-GaAs bandgap current outputs are achievable (>18mA/cm-2 under 1sun AM0 illumination). Finally, the integration of these MQWs in quadruple junction designs is predicted to offer practical conversion efficiency in excess of 40% and ~50% under 1 sun and 500 sun concentration respectively.


7933-16, Session 4

**Carrier dynamics in MOVPE-grown bulk dilute nitride materials for multi-junction solar cells**

Y. Sin, S. La Lumondiere, The Aerospace Corp. (United States); T. Garrod, L. J. Mawst, Univ. of Wisconsin-Madison (United States); S. C. Moss, The Aerospace Corp. (United States)

Dilute nitride materials with a 1eV band-gap lattice matched to GaAs substrates are attractive for high-efficiency multi-junction solar cells, where carrier lifetime measurements are crucial in optimizing material growth and p-i-n field-aided carrier-extraction-device design. A few research groups have reported carrier lifetimes of MBE-grown bulk InGaAsN/Sb materials, but there has been no report of carrier lifetime measurements from bulk InGaAsN/Sb grown by MOVPE. In this study, we report the first carrier lifetime measurement from MOVPE-grown bulk dilute nitride materials.
InGaNAsSb materials with \( E_g = 1.0 - 1.2 \text{ eV} \) at 300K. We studied carrier dynamics in MOVPE-grown bulk dilute nitride materials nominally lattice matched to GaAs (100) substrates: 1\textmu m thick In\textsubscript{0.025GaN\textsubscript{0.975}}As \((E_g=1.0 \text{ eV} \) at 300K) and ~0.2\textmu m thick GaN\textsubscript{0.01-0.02}AsSb\textsubscript{(0.02-0.06)} layers \((E_g=1.2 \text{ eV} \) at 300K). Both structures are fully strained. No other groups have successfully demonstrated bulk InGaNAsSb by MOVPE. The incorporation of N in InGaNAs leads to degradation in photoluminescence efficiency, but prior studies indicate the addition of Sb in MBE-grown InGaNAsSb improved the PL efficiency. Two-step post-growth thermal annealing processes were optimized to obtain maximum PL efficiencies that yielded a typical blue shift of 50 and 30meV for InGaNAs and InGaNAsSb, respectively. We employed a streak camera to measure carrier lifetimes from both as-grown and thermally annealed samples. Carrier lifetimes of <30ps were obtained from as-grown InGaNAs sample, whereas carrier lifetimes of ~60ps were obtained from as-grown InGaNAsSb sample. Post-growth annealing yielded longer carrier lifetimes of ~40 and ~70ps in InGaNAs and InGaNAsSb samples, respectively. We will discuss possible reasons for short carrier lifetimes in MOVPE-grown InGaNAsSb.

7933-17, Session 4

**Up-conversion luminescence enhancement in erbium-doped porous silicon photonic crystals for photovoltaics**

C. M. Johnson, P. J. Reece, G. J. Conibeer, The Univ. of New South Wales (Australia)

Silicon solar cell efficiency can be vastly increased by adding a rear layer that captures unabsorbed low-energy photons and combines their energy to emit higher-energy photons. This “up-conversion” concept has previously been demonstrated for silicon solar cells using rare-earth-doped phosphors. Here we investigate the possibility of enhancing up-conversion processes by using photonic crystal structures.

We designed one-dimensional photonic crystals made of erbium-doped porous silica as an alternative to phosphors for up-conversion layers for solar cells. In photonic crystals such as Bragg reflectors, periodic variation of the refractive index results in “photonic band gaps” in which optical modes cannot propagate. For modes near the edges of these bands, group velocity is suppressed, resulting in high internal energy densities. These “slow-light modes” have been shown to enhance processes such as UC which demonstrate nonlinear power dependence.

We fabricated the Bragg reflectors by periodically varying the etching current and time for a silicon anodization process in ethanolic hydrofluoric acid. The resulting multilayer porous silicon films were then doped with erbium by electroplating followed by oxidation and diffusion anneals. The design parameters for the Bragg reflectors were iteratively determined so that the short-wavelength edge of the photonic band gap was located near 1550nm after processing.

When these structures are illuminated with a 1550nm laser, we can detect strong room-temperature luminescence corresponding to known transitions in optically-activated erbium. Luminescent intensity is enhanced fourfold when the band edge is well-matched to the incident wavelength. We associate this increase with suppressed group velocities at this point.

7933-19, Session 5

**Broadband all-dielectric nanophotonic light trapping for thin active layers in organic solar cells**

A. P. Raman, Z. Yu, S. Fan, Stanford Univ. (United States)

Organic solar cells (OPV) are an active contemporary area of research due to the promise they hold of greatly reducing the cost of photovoltaics. However, bulk heterojunction organic solar cells present a mismatch between their photon absorption length scales (~100s nm) and exciton diffusion scales (~10s nm), rendering device active layers sub-optimally absorbing, and limiting OPV efficiency. Light trapping is a solution to this challenge, but one that requires novel nanophotonic approaches for the sub-100nm thick active layers used in OPV cells. In our work, we specifically consider the heretofore-overlooked problem of broadband light trapping for a reasonably well-absorbing 60-100nm thick active layer.

This is motivated by the parameters and behavior of recently developed record-efficiency organic solar cells. In particular, they present absorption behavior different from traditional light trapping regimes in crystalline silicon (where the absorber is ultra-weak). In fact they absorb light reasonably well, approximately 25-30% single-pass absorption over most of the relevant spectrum for an active layer thickness of 80nm. However, with nearly optimal internal quantum efficiencies, their 50-60% device absorptivity is one of their key weaknesses and sources for substantial device efficiency improvement.

We show that non-metallic wavelength-scale grating structures for an 80nm-absorbing layer can couple strongly into Fabry-Perot resonances, creating multiple low-Q broadband (100nm-wide) resonances where absorption approaches unity. As such, only a few resonances are needed to cover the entire spectrum for OPV cells. We numerically demonstrate a scheme based on the polymer PBDBTTT’s absorption characteristics with ~36% absorption enhancement over its entire spectrum. Moreover, we highlight general device design guidelines to substantially improve absorption in a broadband way for this class of bulk heterojunction-based organic solar cells.
7933-20, Session 5

Numerical study on the optical properties of vertically-aligned silicon nanowire and nanohole arrays for photovoltaic applications
C. Lin, M. L. Povinelli, The Univ. of Southern California (United States)

We simulate the optical properties of vertically-aligned silicon nanowire and nanohole arrays using the transfer matrix method. We find that the optical absorption in both silicon nanowire and nanohole arrays increases with increasing lattice constant up to 600nm - 700nm. We attribute the observed optical absorption enhancement effect to an increase in the field concentration inside the active silicon region as well as the excitation of guided resonance modes. For optimized parameters, both structures can be more absorptive than an equally-thick silicon solid film with an optimal single layer silicon nitride anti-reflection coating. This conclusion holds true for both optically thin (±33nm) and optically thick (100μm) structures. We also compare the absorption of our optimal structures to the maximum achievable absorbance in an equally-thick silicon solid film under the conventional light trapping limit. For optically thin structures, the enhancement in the optimal nanohole array exceeds the conventional light trapping limit. For optically thick structures, the enhancement in both optimal nanohole and nanowire arrays exceeds the light trapping limit. In addition, we show that the overall absorption efficiencies for hexagonal and square lattices of nanowires are very similar. Furthermore, we used the finite-difference time domain method to study whether metallic caps can provide plasmonic enhancement of optical absorption in the silicon nanowire arrays grown by the vapor-liquid-solid method. We found that gold, copper, and silver caps do not increase integrated optical absorption across the solar spectrum. Lastly, we look at the effect of aperiodicity on the optical absorption in silicon nanowire arrays.

7933-21, Session 5

Rigorous optical simulation of light management in thin film polycrystalline silicon solar cells with textured interfaces
D. Lockau, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); S. Burger, L. W. Zschiedrich, F. Schmidt, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); F. Ruske, B. Rech, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

In most of the solar spectrum relevant to photovoltaics crystalline silicon is an indirect semiconductor with a relatively poor absorption. Absorption management therefore is a critical issue for thin film polycrystalline silicon photovoltaic devices. To gain optimum efficiency this device class demands a specific absorption management. A full theoretical understanding of near field effects of scattering from textured interfaces is difficult but simulations open up a good way of estimating and optimizing the efficiency of light management textures. We investigate poly-silicon thin film solar cells with ZnO front and ZnO/Silver back contacts and periodic patterns as well as rough textures for light management.

In our simulation approach we employ the finite element method to obtain rigorous solutions of Maxwell’s equations for scattering problems in 3D. A requirement that has to be met in geometric representation of thin film solar cells is a computationally cheap incorporation of very thin layers. The use of unstructured grids which are well adapted to this layered media structure makes is possible for us to simulate sufficiently large device volumes. Complete cell simulations including the thick glass substrate are carried out using a domain decomposition algorithm. The simulations of devices with rough interfaces further require a Monte Carlo sampling over a set of surface representations.

7933-22, Session 5

High efficiency triple-junction solar cells employing biomimetic antireflective structures
M. Chiù, C. Chang, F. Chang, P. Yu, National Chiao Tung Univ. (Taiwan)

In this work, we demonstrate a thorough device design, fabrication, characterization, and analysis of sub-wavelength structures (SWSs) for a Ga0.5In0.5P/GaAs/Ge triple-junction solar cell using the polystyrene (PS) colloidal lithography. The SWSs are fabricated on SiNx employing PS nano-spheres with a monolayer and hexagonal arrangement as the sacrificial masks and followed by the reactive ion etching. The sidewall profiles of SWSs can be controlled by adjusting anisotropic etching parameters to mimic moth-eye structures. Compared to a conventional single-layer anti-reflective coating (SL ARC), the SWS ARC shows a broadband spectral response of reflection characteristics, particularly in the ultraviolet and near-infrared wavelength range. The AM1.5G-weighted reflectance of SWSs is approximately 7.28% for the wavelength range of 300 nm to 1700 nm, which is ~3.04% lower than that of the SL ARC, ~10.32%. Based on the angle-resolved reflectance spectroscopy measured by an integrating sphere, we found the spectral response of SWS is much broadband and less sensitive to the angle of incidence than SL ARC. The conversion efficiency of a GaInP/ GaAs/Ge triple-junction solar cell with implemented SWSs is enhanced by 26.74% and 3.48% compared to cells without an ARC and with a SL ARC, respectively. The external quantum efficiency measurement further confirms the efficiency enhancement by the improved absorption and current-matching between the top and middle sub-cells. Moreover, a rigorous coupled-wave analysis (RCWA) method is employed to verify the broadband antireflection characteristics of SWSs and served as an optimization tool for the implementation of sub-wavelength antireflective structures in multi-junction solar cells.

7933-23, Session 5

Luminescence coupling effects on spectral photocurrent response of multi-junction solar cells
S. H. Lim, J. Li, D. Ding, M. DiNezza, H. Detlaff, Y. Zhang, Arizona State Univ. (United States)

Radiative recombination in solar cells is a loss mechanism and influences the behavior and performance of such devices. In multi-junction solar cells, this can lead to a phenomenon known as luminescence coupling whereby an emitted photon from a subcell with a high bandgap is reabsorbed by a subsequent subcell with a lower bandgap. Such effects have recently been shown to be related to certain measurement artifacts in the quantum efficiency (QE) response of the Germanium subcell in a high efficiency InGaP/InGaAs/Ge solar cell. In this study we test the QE and electrical properties of many MJ cells and thoroughly analyze the effect of luminescence coupling on the electrical response of the solar cell to external optical stimuli. An optical-electrical feedback mechanism is revealed and shown to be key to understanding the artifact features in the spectral QE measurements, specifically the observation of a higher than expected QE outside the Ge absorption wavelength range and a lower than expected QE within the Ge absorption range. Experimental QE and electroluminescence spectrums as functions of light bias intensity are presented to demonstrate such effects. Our method offers a quantitative way to obtain correct QE for all the subcells. With improving material quality and device design, luminescence coupling effects will become increasingly important. A thorough understanding of such effects would be critical to experimentalists and could also lead to some interesting device applications.
Modeling of radiation induced defects in space solar cells
R. J. Walters, S. R. Messenger, C. D. Cress, U.S. Naval Research Lab. (United States); M. Gonzalez, S. I. Maximenko, Global Defense Technology & Systems, Inc. (United States)

This talk will discuss how to model the effect of radiation induced defects on the performance of solar cells in space. The talk will begin with a description of the space radiation environment, identifying the major constituents of the environment and showing how the radiation particles interact with the devices. The primary degradation mechanism for optoelectronic devices is displacement damage, and the talk will describe how displacements form and present a methodology for modeling the radiation induced displacement damage. The displacement damage will be correlated to device performance degradation using solar cells as an example device. A full analysis of the response of a solar cell in a space radiation environment will be presented and compared to on orbit data.

Advanced concept solar cells using hybrid approaches
C. B. Honsberg, Arizona State Univ. (United States)

In the last decade, multiple advanced concept approaches have been investigated to exceed the Schottky-Queisser efficiency limit. All of these have theoretical efficiencies which approach the thermoelectric efficiency limit of an infinite stack of solar cells under maximum concentration. However, each approach varies widely in their response due to the impact of “non-idealities” such as spectral sensitivity, and to concentration. Although there has been substantial investigation into different advanced concept approaches, there has been relatively little attention to “hybrid” approaches, consisting of combinations of conventional and new approaches or of two new approaches. The paper analyzes three different hybrid concepts: (1) A conventional cell coupled to new concepts; (2) A hybrid of multiple exciton and intermediate band; and (3) a hybrid between a “thermal” and a quantum converter. In this case, the term “thermal” refers to a conversion process in which the energy of the incident photon is transferred to a “pool” of carriers or energy, and the converter may draw an arbitrary amount of energy from this pool. A thermophotovoltaic device is a quantum converter, and a hot carrier device is a thermal converter. By contrast, a quantum converter is one in which the incident energy is transferred to another particle, and the energy is either used by that particle or dissipated as heat. While all the different classes of hybrids have advantages, hybrid thermal-quantum converters uniquely have higher efficiency than either quantum or thermal devices by themselves, reaching an thermodynamic efficiency of nearly 70% under one sun.

Modeling and analysis of multijunction solar cells incorporating quantum wells
N. J. Ekins-Daukes, J. Adams, P. N. Stavrinou, Imperial College London (United Kingdom); R. J. Walters, U.S. Naval Research Lab. (United States); M. Gonzalez, Global Defense Technology & Systems, Inc. (United States); C. D. Cress, P. R. Jenkins, U.S. Naval Research Lab. (United States)

Multijunction solar cells incorporate semiconductor junctions of different band gaps that are chosen to provide maximum absorption of the broad solar spectrum of light. Maximum photon to electricity conversion efficiency is attained when the various bandgaps in the multijunction solar cell are well matched to the incident spectrum much like the case of a multicolor photodetector. The challenge in multijunction solar cell design is attaining the optimum bandgaps in materials that can be grown with high quality, in particular finding materials that can be grown lattice matched to available growth substrates like GaAs or Ge. To achieve band gaps beyond those of bulk, lattice matched materials, multiple quantum wells can be added to one of more of the junctions in the multijunction stack. Significant progress has been made high efficiency multijunction solar cells with and without quantum wells with world record efficiencies of nearly 42% being attained under concentration. A significant gap in this technological development, however, is modeling. Imperial College London has developed a modeling routine that accurately describes a single junction solar cell with multiple quantum wells, and in a collaborative effort with the US Naval Research Laboratory, are working to extend this capability to describe multijunction solar cells incorporating quantum wells. This paper will describe the methodology of this model and present latest results.

Resonant thermo-tunneling design for ultra-efficient nanostructured solar cells
A. Alemu, A. Freundlich, Univ. of Houston (United States)

Nanostructured solar cells are touted to lead to super high photo-conversion efficiencies. Nevertheless the inclusion of potential energy fluctuations associated with those structures hinders the smooth vertical transport of photo-generated carriers. We present an innovative energy level engineering design that significantly facilitates the collection of all photo-generated carriers. Using dilute nitride III-V semiconductor quantum wells embedded in a conventional III-V GaAs host, we demonstrate the possibility of achieving a quasi-flat valence band that will ease the smooth transport of holes. The conduction band confinement energies are designed in a way that promotes thermotunneling electrons from their potential wells to the conduction band continuum. Energy levels were calculated by including strain and spin-orbit interaction. The calculation of confinement energies was also undertaken. Once confinement energies and potential barrier heights were determined we complemented the theoretical evaluation by calculating carrier escape times via thermionic and tunneling routes at 300 K. Here we demonstrate that an optimized resonant thermotunneling design leads to ultra rapid escape. The suggested approach is thus expected to circumvent recombination losses and lead to a substantial carrier collection and efficiency improvements.

FEM solver for 3D numerical simulations of integrated optical devices
S. Burger, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); J. Pomplun, L. Zschiedrich, F. Schmidt, JCMwave GmbH (Germany)

For an efficient design of integrated photonic components 3D simulations of Maxwell’s equations are needed. Sizes of typical computational domains are tens of microns in two dimensions with a layered structure in the third dimension. Often, the simulation problems have some multi-scale nature, i.e., the functionality of the component may critically depend on certain geometrical parameters on a nanometer scale while the total computational domain may be on a micron scale. 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 [1]. The method allows to accurately simulate the performance of integrated photonic devices. As 3D application examples we present simulations for the design of add/drop filters, of grating couplers and of resonators for optical switching.
We demonstrate convergence of the respective numerical results to high levels of accuracy.


7933-29, Session 7
Design of complex large-scale photonic integrated circuits (PICs) based on ring-resonator structures

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The number of components in Photonic Integrated Circuits (PICs) is growing exponentially, similar to Moore’s law of electronic ICs. The number of elements in most advanced PICs reaches a few hundred already now. This leads to the necessity of photonic design tools with systems-level abstraction for complex large-scale PICs. Traditional tools based on FDTD and BPM solvers are widely used for modeling small-scale PICs. However, they are not appropriate for modeling large-scale PICs because they are too slow and their layout editors are inconvenient for defining large-scale structures. Ring-resonators and derived structures represent one example for large scale photonics integration. They find a growing number of applications in modulation/demodulation, switches, delay lines and other signal processing applications.

In this work, we present how distributed or lumped optical waveguide models are used as functional elements of ring-resonator structures for transporting signals between different PICs components within a sophisticated design environment. The propagation of signals along the photonic waveguides is described by a two-component sampled signal representing the two orthogonally polarized guided modes. TE and TM mode are characterized by their own effective and group mode indices, attenuation and insertion losses, or alternatively, by delay time and optical losses. The model works in time domain, accurately dealing with delay times. So it can be combined with other systems-level models, based on the Transmission-Line Laser-Model, for instance. In the final paper, we present representative examples demonstrating how systematic variation of volatile parameters allows a comfortable design and analysis of complex integrated structures.

7933-30, Session 7
Ultra wideband integrated polarization splitter/combiner using electro-optic effect in GaAs

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We propose a novel design of integrated polarization splitter/combiner with ultra wide bandwidth. The proposed design utilizes the electro-optic (Pockels) effect in GaAs for splitting the polarizations. It also exploits the self imaging phenomenon in MMI couplers with a parabolic index distribution in the vertical direction to significantly increase the bandwidth. A stair case index approximation of this index profile is utilized to facilitate the fabrication process. The fabrication of this profile is feasible through the current technology using multiple etching. Our proposed design maintains a variation of less than 0.5 dB in the power coupling over a bandwidth of 400 nm. We also propose a novel approach for design optimization of the proposed structure. This approach is capable of extracting the propagation constants and their gradient with respect to all the design parameters. This allows for using gradient-based optimization [1]. The computational time of this optimization procedure is only a fraction of that for other recently proposed approaches.


7933-31, Session 7
The performance of all-optical switching based on fiber Bragg grating

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In this Letter, the nonlinear response of all-optical switching in Yb3+-doped fiber Bragg grating was investigated and a numerical analysis of the switching property based on FSG is presented. Since the wavelength characteristics of the grating depend on the effective refractive index of the fiber, Kerr-like nonlinearity can alter the wavelength response of the grating. We found that different detuning and coupling coefficient can affect the threshold power and extinction ratio.

The experimental setup of all-optical switching under cross-phase modulation is shown in Figure 1. The wavelength different between the pump and the probe light is sufficiently large that there is no parametric amplification of the probe beam. Second, the CW probe beam is sufficiently weak that by itself do not experience any nonlinear effects. In our model, the transfer matrix method was used to analyse the characteristic of nonlinear optical switching and give the switching power for pump light in various conditions. Figure 2 shows the switching characteristics curve of the transmitted and reflected light, for different values of the frequency detuning from the Bragg resonance under the condition of $L=8$.

In Figure 2 (a) the detuning $\alpha = 41.60 \text{cm}^{-1}$, which corresponds to the wavelength of the probe light is 1.1 nm lower than the Bragg wavelength, which is at the left side of the photonic bandgap of the grating. By increasing the pump power the stop band shifts to higher wavelengths, but only obtains a slow variation transition about 80%–100%, there is no evident switching phenomenon. In Figure 2 (b) the detuning $\alpha = 10.67 \text{cm}^{-1}$, which corresponds to the wavelength of the probe light is in the photonic bandgap of the grating. As can be seen, at low pump power, the reflectivity attains its maximum value R=1. The R is initially nearly constant, and then it shows a sudden drop to R=0, when the pump power reaches the switching value P≈11mW. It also can be seen, for P>11 the reflectivity R oscillates while it increases slowly. May be the oscillations are due to the strong reshaping of the fields inside the grating. In Figure 2 (c), the detuning $\alpha = -22.72 \text{cm}^{-1}$, which corresponds to the wavelength of the probe light is 0.6nm longer than the Bragg wavelength. Figure 2 (d) is obtained with $\alpha = -30.19 \text{cm}^{-1}$, it is obviously that the reflectivity initially increases with the pump power until it reaches a value about P=20mW and then R tends to drop slowly and oscillate with P. In Figure 3, numerical result about the extinction ratio versus the pump power P for the fiber grating is “weak” and “strong” is given. Under the same magnitude of pump power P, for a certain wavelength light, when large, it will obtain large extinction ratio. In conclusion, the detuning and coupling are the important factor which determine the performance of the switching. By optimizing the detuning and coupling, we found that optimal switching conditions may be achieved.

7933-32, Session 7
Analysis of thermoelectric properties of AlInN semiconductor alloys

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The thermoelectric applications of III-Nitride semiconductor alloys have drawn lots of attentions in recent years. The experimental thermoelectric characterization results of InGaN, AlInN, as well as the potential of direct integration with nitride-based devices widely used in high power, high temperature situations have shown the III-Nitride alloys as promising material for solid state cooling, also possibly for thermoelectric power generation.

In this work, we investigate the thermoelectric properties of n-type wurtzite Al1-xInxN alloys by analyzing the electron and phonon transport equation considering all major electron scattering mechanisms,
including charged dislocation scattering, ionized and non-ionized impurity scattering, acoustic phonon scattering by deformation potential and piezoelectric field, polar and non-polar optical phonon scattering. The lattice thermal conductivity is calculated by considering phonon scatterings including impurity and alloy scattering, Umklapp scattering, boundary scattering and electron-phonon scattering. The power factor and thermoelectric figure of merit (Z′T) of Al1-xSnx with different alloy compositions are also obtained. The simulation results show that at room temperature, with electron density of Al0.83In0.17N changes from 5x10^17/cm^3 to 3.5x10^18/cm^3, the Seebeck coefficient changes from -4.55x10^-4 V/K to -2.84x10^-4 V/K, and the electrical conductivity changes from 1800/(Ω.m) to 11800/(Ω.m), result in a power factor from 3.8x10^-4/(mK^2) to 9.5x10^-4/(mK^2). With a thermal conductivity from 3.60 W/(mK) to 3.66 W/(mK), the obtained value of Z′T ranges from 0.031 to 0.078 at 300K, which agree with the experiment data. The simulation provides useful guideline in material optimization for thermoelectricity.

7933-33, Session 8
Quantum optics with semiconductor quantum dots in microcavities
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Theoretical results for the emission properties of single quantum-dot lasers are compared to recent experiments. Stimulated emission in the weak and strong coupling regime is analyzed and modifications of the photon statistics due to the interplay of light-matter interaction, multi-exciton contributions and dissipation are discussed. With a single quantum dot emitter in a high-quality cavity, the ultimate limit of miniaturization for a semiconductor laser is reached [1]. The system shows interesting similarities but also important differences in comparison to current experiments on quantum optics with trapped atoms. Recent experiments on single QD lasers exhibit for the input-output curve an s-shaped behavior known from multi-emitter lasers [1]. Quantum mechanical models based on two or four-level single-emitter systems do not reproduce this observation. Furthermore, measurements of the second-order photon correlation function reveal a transition from antibunching to bunching in the laser threshold region before coherent emission is reached. The appearance of photon bunching is surprising for a single-emitter source. We propose a new model and explain the input-output curve as well as the transition from antibunching to bunching in terms of competing contributions from various possible excited transitions of the single QD [2]. We also study stimulated emission in the presence of strong coupling and identify signatures from higher rungs of the Jaynes-Cummings ladder in the emission spectrum of a single quantum dot laser.


7933-34, Session 8
Impact of temperature and excited states on quantum dot laser dynamics
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Self-organized semiconductor quantum-dot (QD) lasers, which are promising candidates for high-speed data communication applications, are modelled using a microscopically based rate equation approach containing Auger type scattering processes between the carrier reservoir and confined QD levels. The Auger scattering rates into the ground and excited state of the QD are calculated using a density matrix approach. During laser operation the electrons are electrically injected into the 2D carrier reservoir (QW) before Coulomb interaction between QW carriers leads to the population of the confined QD levels. As a result of the microscopic approach electron and hole scattering rates differ which leads to desynchronized internal dynamics of electrons and holes. We are able to quantitatively model the small-signal response and turn-on dynamics of the QD laser without assuming fit parameters for the carrier lifetimes. In fact the nonlinear dependence of the microscopically obtained carrier lifetimes on the carrier density in the QW allows to model in detail, e.g., the effect of doping on the device performance. Here we find that p-doping leads to increasing damping of the relaxation oscillations while n-doping does the opposite. By furthermore including a dynamic device temperature in our simulations we are able to quantitatively model the large signal response of the QD laser. A detailed analysis of the influence of temperature effects on the dynamics of the device is performed showing excellent agreement with experimental results.

7933-35, Session 8
Dynamical properties of semiconductor quantum dot based nanocavity devices
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Semiconductor lasers are central components of current optical technologies such as optical data storage and optical communications. To meet the continuously increasing need for progressively higher data transmission rates, a high modulation bandwidth of the underlying semiconductor device is required. In recent years semiconductor quantum dots (QDs) have emerged as new active materials for optoelectronic devices, already used in LED’s, lasers, or optical amplifiers. The combination of QDs with high-quality cavities, e.g. realized by photonic crystals, opens a multitude of possibilities for guiding and modifying the emission properties of QD-based devices via the Purcell effect.

We apply a microscopic theory to study dynamical properties of QD based nanocavity devices. Application relevant quantities such as the modulation bandwidth as well as fundamental properties such as the laser linewidth and switch-on behavior are determined consistently from a microscopic semiconductor approach. Our theory predicts a reduction of the modulation bandwidth at high scattering rate allowing for optimization of QD based nanocavity devices. This behavior arises from a delicate balancing of the emission time and the photon lifetime in the cavity, as both the relaxation oscillation frequency and the damping of the relaxation oscillations grow with faster scattering. This phenomenon, that is observed only in nanocavity devices with substantial Purcell enhancement can be analyzed using a simplified model where the modulation bandwidth as well as its maximum can be given analytically as a function of beta-factor, photon lifetime, and emission time.

7933-36, Session 8
Modeling and simulation of nanocrystal solids with rate equations
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Colloidal semiconductor nanocrystals and their solid films created a promising field of research during the last decade. They offer the advantage of optical and electrical tunability and ease of large area processing. Solar cell devices, optical sensors and transistors are among promising applications of these artificial atom solids. When carrier tunneling and trapping mechanisms are considered, carrier transport in quantum dot solids is similar to vertical carrier transport in epitaxial multi-quantum wells, self-assembled quantum dots, and superlattices where carrier transport is in the layer growth direction. We present a rate
equation model to simulate unipolar electron transport in DC-biased one-dimensional chain of PbSe nanocrystals. Tunneling, cooling, trapping and heating of electrons are modeled with transition rates and parameters. Each nanocrystal site creates a quantum dot with quantized energy states. Organic ligands are the energy barriers between the nanocrystals. Three lowest orbitals in each quantum dot are taken into account to simulate unipolar transport through nanocrystal solids. Transitions between the orbitals and neighbor quantum dots are modeled using experimental reports in the literature. Numerical solutions of the rate equations for each state results in a balance between all states in the device. Effect of carrier generation rate, trapping rate and temperature on the simulated current density is investigated for photodetector, solar cell and transistor applications. Shell filling of quantum dots and their dependence on carrier generation rate is estimated. The proposed model can be extended into more detailed rate equations and ensemble particle simulators in the future.

7933-37, Session 8

Modeling the impact of temperature on the performance of monolithic passively mode-locked quantum dot lasers

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Quantum dot (QD) mode-locked lasers (MLLs) possess several unique features which enable the formation of short pulses with minimal timing jitter and precise repetition rates. It is highly desirable to engineer these devices to allow for uncooled operation. In this paper, we model the temperature performance of quantum dot MLLs based on an 8-band k.p formalism and an analytic net-gain modulation phasor approach. The latter allows us to determine the stability of ML operation based on knowledge of the measured gain and absorption as a function of temperature and current density. We confirm the validity of this approach to study the stability of an InAs/GaAs QD MLL over a broad temperature range. Robust mode-locking at 20°C for absorber reverse bias values of 5-6 V, a striking degradation in performance at 60°C, and the failure to mode lock at 70°C are correctly predicted by the model. Based on our model and measurements, we find that the behavior of the differential gain plays a critical role in the stability of mode-locking in QD devices. To add to our predictive capabilities we use the k.p analysis to generate temperature dependent gain and absorption spectra and to then assist a comparison to the measured gain and absorption of the nanostructures. This ability is critical to determining the impact of temperature on the performance of these devices in a predictive manner. This model will be useful in guiding the design of next generation uncooled QD MLLs capable of stable operation up to 100°C.

7933-38, Session 8

Modeling spectral responsivity of InAs QD-embedded GaAs solar cells

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InAs/GaAs quantum dot (QD) embedded solar cells have the unique ability to absorb light otherwise unavailable to the GaAs host, via sub-GaAs-bandgap InAs QD state absorption. In this work, this mechanism is investigated using spectral responsivity measurements of various multi-layer QD solar cells. Previous investigations have shown that the integrated responsivity of the sub-GaAs-bandgap absorption spectrum correlates to an increase of 0.025mA/cm² per QD layer. The modeling of the wavelength dependent absorption coefficient of these nanostructures is performed here to corroborate the experimental results. This mechanism is more complex than bulk semiconductor absorption. Increased oscillation strength and discrete-like states produce sharply peaked absorption spectra. The non-homogeneity of the discontinuous island-like media inherent in QD layers allow for a density-dependent photon capture cross-section influence the intensity, and both the size distribution and thermal effects broaden the full width at half maximum. The absorption coefficient of these nanostructures is calculated using an effective mass envelope function. This calculation is then converted to a spectral responsivity value (amperes/watt) and is used to fit to the experimental responsivity data. Conclusions regarding the per-QD absorption as well as other fitting parameters will be discussed. The modeling results provide options for improving InAs QD-enhanced GaAs solar cell design and will be highlighted.

7933-39, Session 9

Position controlled GaN nanorods: growth mechanisms and optical properties

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Position controlled GaN nanorods (NRs) containing quantum discs or core shell heterostructures are promising to improve light emitting devices in the future. High aspect ratios allow for a significant reduction of defects by bending of threading dislocations to the NR sidewall surface. Dimensions of the order of the emission wavelength result in unique optical and electronic properties of individual NRs and of periodic arrays of those. Theoretical investigations and numerical simulations are performed to determine the optical properties of NRs. These reveal that optical resonances lead to an enhancement in spontaneous emission, an improved extraction of light and the possibility to shape the emission far field. In periodic arrays of NRs, both vertical waveguiding within individual NRs as well as resonant scattering on neighbouring NRs is present. A thorough mode design is used to identify optimal geometries for the design of masking layers and the growth conditions of NRs. Nanorod arrays are fabricated either by bottom-up position controlled MOVPE growth or by a top-down approach, etching nanostructures into a conventional 2D film. In both cases, nanoimprint lithography is used to define dense patterns for NRs with diameters down to 200nm. Doped NRs (using Silicon and Magnesium) as well as InGaN/GaN heterostructures are fabricated. While top-down NRs represent idealized quantum disc structures, bottom-up NRs (grown on c-plane sapphire substrates or GaN templates on sapphire) form core shell structures with active layers on the m-planes (sidewalls) and strong lateral overgrowth of p-GaN.

Transmission electron microscopy and cathodoluminescence measurements reveal different growth rates and emission energies on distinct crystal planes. Optical characterization and identification of the optical resonances is performed by photoluminescence and angle-resolved spectroscopic reflectometry.

7933-40, Session 9

Photon transport and recycling in high efficiency LED structures

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The emission and reabsorption of photons, i.e. the photon recycling enhances the light extraction from optically confining semiconductor structures. In addition, it provides a mechanism for the radiative transport of energy within the light emitting structure. We discuss general models...
for describing the light propagation and radiative transport of energy in III-V light-emitting diodes (LEDs). In particular, we employ the radiative transport equation for modeling the interaction of a quantum well with the optical field in a cavity formed by semiconductor slab. The model is used for numerical simulations that self-consistently account for the photon emission, transmission and absorption and the diffusive transport of charge carriers within the quantum well. We compare the carrier diffusion problem with photons traveling as means of transporting energy within the active region of a light-emitting diode and discuss applications for LED structures with a high recycling factor and high efficiency.

7933-41, Session 9

An investigation into LED multiplexing and homogenisation

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Currently the market for white LED light is dominated by the use of blue/UV pump LEDs and a photoluminesant materials which combine to make a white light. An alternative approach is multiplexing where different coloured LEDs (usually red, blue and green) are mixed to produce white light. The advantages of this approach are there is no longer a dependency of the photoluminesant material, the brightness and efficiency is now only subject to how well the LEDs and optical system work. There is also the advantage of being able with the correct combination of wavelengths to reach almost all parts of the CIE chromaticity diagram which would allow a multitude of correlated colour temperature (CCT). This paper will investigate the use of Zemax optical modeling software to create a model of the patent pending NeoLite LED Multiplexer, which is designed for LED multiplexing through the use of dichroics. An optical model will be developed to look at the properties of the light exiting the system including a measure of the total luminous flux, the angular distribution, uniformity of the illuminance and colour mixing at the exit aperture. Optimisation is then carried out to find the CCT of the D65 CIE standard illuminant and analysis carried out to determine the changes that creates. The luminous flux value and CCT is then verified with the use of an integrating sphere and spectrometer.

7933-42, Session 9

Numerical study on efficiency droop of blue InGaN light-emitting diodes

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The InGaN-based light-emitting diodes (LEDs) have attracted much attention in backlighting, general illumination, and many other applications. Because of the huge commercial demands, it is highly desirable for these LEDs to emit a high power luminescence at high current densities. Unfortunately, an adverse phenomenon: the reduction in efficiency when the current is increased, which is well-known as "efficiency droop", is a serious restriction for high-power applications. Although many efforts have been made to improve the efficiency droop, there is no effective method to completely solve this problem. In this paper, some specific designs on band structure near the active region, including the modifications of barrier material or thickness, the redesigns of electron blocking layer (EBL), etc., in the InGaN blue LEDs are investigated numerically by using the APSYS (Advanced Physical Model of Semiconductor Devices) simulation program in order to overcome the problem. Specifically, the energy band diagrams, radiative and SRH recombination rates, distribution of electrons and holes in the active region, and electron overflow are studied. Simulation results show that, with appropriate designs, the efficiency droop may be effectively reduced due to the increase of hole injection efficiency, the enhancement of blocking capability for electrons, or the more uniform carrier distribution of carriers in the active region. The methods proposed in this paper are of advantages especially for the situation of relatively high current injection.

7933-43, Session 10

FDTD simulation of metal-embedded semiconductor single quantum dot and improved photon extraction with corn structure

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We have proposed a metal-embedded semiconductor pillar and demonstrated highly pure single-photon emission with very low second-order photon correlation function g(2) = 0 [H. Nakajima et al, this conference]. In this work, metal-embedded semiconductor structures are simulated with the FDTD method. It is demonstrated that the modification of a cylindrical semiconductor pillar into a corn structure drastically improves the photon extraction efficiency. Semiconductor corn structures close to the simulated structures were prepared with InP-based InAs quantum dots (QDs) and bright luminescence from single QDs embedded in Au could be observed. In the FDTD simulation a QD was replaced with a tiny current source flowing CW in the cross-sectional plane of a 300-nm long InP pillar embedded in silver. The excitation wavelength was assumed to be 1550 nm. The bottom pillar surface facing the silver metal was assumed to have a diameter of 200 nm. The photon extraction out of the InP pillar was limited to ~45% with 2-D simulation and to the lower value of ~14% with a more realistic 3-D simulation. The coupling efficiency to a lens with a numerical aperture (NA) of 0.4 was limited to just 4.4%. The situation is much improved with the inclusion of taper toward the air-semiconductor interface. The coupling efficiency to the lens with an NA of 0.4 improved to 56% for a corn angle of 30°, in which only 13% is due to absorption of silver. The remaining part of 31% depends on the emitted far-field pattern and the lens NA. InGaAsP coms on InP substrates were fabricated with reactive ion etching with a corn angle of ~30° and preliminary observation of single QD luminescence was possible from Au-embedded structures.

7933-44, Session 10

The limit of light trapping in grating structures

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We use a rigorous electromagnetic approach to analyze the fundamental limit of light-trapping enhancement in grating structures. This limit can exceed the bulk limit of 4n^2, but has significant angular dependency. We explicitly show that 2D gratings provide more enhancement than 1D gratings. We also show the effects of the grating profile's symmetry on the absorption enhancement limit. Numerical simulations are applied to support the theory. Our findings provide general guidance for the design of grating structures for light-trapping solar cells.

7933-45, Session 10

Composite-mode theory for coupled semiconductor lasers and external cavities

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High-speed semiconductor lasers are essential components in many optoelectronic applications. To achieve high modulation speed, optical injection locking has been widely used over a variety of experimental configurations. In traditional optical injection locking set-ups, an optical isolator is put between the master and slave lasers to prevent feedback from the slave laser into the master laser. However, in practical monolithic implementations, it is highly desirable to simplify the set-up by removing
The pole condition as transparent boundary condition for resonance problems: detection of spurious modes

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For designing functional nano-structures, resonance problems turned out to be of outstanding importance. Resonance problems are eigenvalue problems posed on spatially unbounded domains where one seeks a resonance mode (eigenvector) that has the correct radiation property at “infinity”. Compared to standard eigenvalue problems the situation is more involved as the sought eigenvector enters the radiation condition.

Many implementations of transparent boundary conditions introduce spurious modes which are hard to distinguish from the physical solutions of the problem without a priori knowledge of the solutions of the system. Our implementation of transparent boundary conditions relies on the pole condition [1,2] and leads to a sparse eigenvalue problem which is linear in the eigenvalue. This method is able to treat waveguide-type inhomogeneities in the domain with non-compact support. Also, it has a complex parameter that can act as tuning parameter. Our investigations have shown that the physical solutions of the resonance problem are invariant under parameter-change while the spurious solutions are sensitive to the change of this parameter. This opens the path for several ways of distinguishing between physical and spurious solutions of the problem. We will present a sensitivity analysis of the eigenvalues with respect to the parameter of the pole condition. As a real-life example we will present calculations of a surface plasmon polariton microdisc resonator [3].


7933-47, Session 10

Similar structures, different characteristics: optical performances of circular polarizers with single- and multi-helical metamaterials

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Recently, it was demonstrated by J.K. Gansel et al. that three-dimensional single-helical metamaterials can serve as broadband circular polarizers in the infrared range. In this study, we proposed new structured metamaterials with multi-helical nanowires to construct circular polarizers with boarder operation bands and higher signal-to-noise (S/N) ratios. Using the finite difference time domain (FDTD) method, we systematically studied the optical performances of single-, double-, triple-, and quadra-helices. The simulation results show that the influence laws of the structure parameters are quite distinct between the single- and multi-helix. The results also confirmed that the circular polarizers with the multi-helical structures have two orders higher S/N ratios and 50% broader operation regions than those of the single-helical devices.

7933-48, Session 11

Analogue modulation performance of 20 GHz vertical cavity surface emitting lasers for radio over fiber applications

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850 nm VCSELs are the dominant light sources for short reach optical networks operating at bit rates to 10 Gbps and beyond. Alongside recent improvements in digital transmission data rates, there is also current research interest in devices with high bandwidth and linearity which will be required to support advanced modulation formats and for next generation Radio-over-Fibre (RoF) applications.

This paper will describe the use of oxide confined GaAs/InGaAs VCSELs designed for high-speed modulation at low current densities. The microcavity active region is comprised of strained InGaAs quantum wells which exhibit superior high-speed modulation properties, surrounded by AlGaAs barrier layers and AlGaAs distributed Bragg reflectors in a novel heat-dissipating top emitting device geometry, with an oxide aperture of 9µm and a mesa diameter of 28µm. The VCSELs have a threshold current of 0.6 mA at 25°C and 1 mA at 70°C.

This paper will describe how these VCSELs exhibit excellent linear performance over the frequency range of 1 to 19 GHz, with SFDR values consistently above 85 dB.Hz/2 and peak values as high 100 dB.Hz/2 for temperatures up to 70°C. This is further demonstrated through the successful transmission of IEEE 802.11g 54 Mbps 64-QAM OFDM signals over optical links consisting of 100m of OM3 multimode fiber for carrier frequencies up to 20 GHz and with received EVM values <5.6%. This demonstrates the suitability of the VCSELs for use in next generation RoF applications.

7933-49, Session 11

Novel mode hop free chirped laser

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Chirped or tunable lasers are a key requirement in a number of applications from spectroscopy, environmental sensors, WDM transmitters to Fourier transform spectrometers. In many of these applications maintaining mode hop free behavior while frequency tuning is critical but difficult to achieve especially when based around laser
diodes. Here we describe a novel and potentially cheap way of achieving this. The key in mode hop free tuning is to effectively change the optical cavity length so as to maintain resonance while the frequency of the laser is being chirped. Here our frequency tuning element, an etalon, has substrates either side of its cavity which are wedged such that if these substrates were to be placed together they would create a parallel sided optical window or shear plate. The wedge angle of these substrates has been chosen so as to effectively create an appropriate angle of incidence on the effective shear plate such that on frequency tuning ie etalon rotation, the optical cavity length tracks so as to inhibit mode hops. Using this novel concept we can demonstrate how mode hop free frequency chirps can be achieved over at least 500GHz or more.

7933-50, Session 11
Performance of vertical-external-cavity surface-emitting lasers in the multi-10W regime
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Over the last years, Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) have moved into the research focus due to their highly desirable combination of high output power, good efficiency, and good beam quality out of a small package. We experimentally investigate the emission characteristics of a model high-power device under extreme pumping conditions. A 1040nm VECSEL is realized using the semiconductor chip and a spherical output coupler in a linear cavity design. The chip is bonded to a diamond heat spreader which in return is mounted on a thermoelectrically cooled copper heat sink able to dissipate up to 200 W of power. We monitor the laser’s performance by measuring both the input-output power characteristics as well as the laser emission spectrum. Additionally, the sample photoluminescence background emission during and without laser operation are imaged out of the cavity and detected both spatially and spectrally resolved. This spatially-resolved photoluminescence data allows for the reconstruction of the thermal profile within the active medium. Different pump spot sizes and pumping conditions are investigated and the implications for power scaling in the extreme pumping regime are discussed.

7933-51, Session 11
Giant lasing effect in magnetic nanoconductors and its detection by DC electrical measurements
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We propose a new principle for a compact solid-state laser in 1-100 THz regime based on a new mechanism for creating spin-flip processes in ferromagnetic conductors. The mechanism is due to a coupling of light to the exchange interaction in the magnetically ordered conductors via the dependence of the conduction electron spin - magnetic moment exchange interaction on the conduction electron momentum. The interaction strength is proportional to the large exchange energy and exceeds the Zeeman interaction by orders of magnitude. On the base of this interaction, a giant lasing effect is predicted in a system where a population inversion has been created by injection of spin-polarized electrons from one ferromagnetic conductor to another - the magnetization of the two ferromagnets having different orientations.

The optical gain is estimated to exceed the optical gain of conventional semiconductor lasers by 4 or 5 orders of magnitude. This effect may also be detected by electrical measurements. We have shown that the relative change of the resistance of a ferromagnetic point contact under an electromagnetic irradiation has a narrow peak at the irradiation frequency equal to the exchange splitting in the conduction electron spectrum, the height of the peak being direct proportional to the power of the stimulated emission of photons from the ferromagnetic point contact. Analytical calculations and numerical estimations show that the experimental implementation of the new principle for a solid-state lasers is quite feasible.

7933-97, Session 11
Optimization of current injection area for low threshold operation of 3D lasers
A. V. Maslov, M. Miyawaki, Canon U.S.A., Inc. (United States)
Low threshold current is one of the desired characteristics of lasers. In general, the threshold current depends on such basic laser properties as gain in the active region, the profile and lifetime of the optical mode, and the geometry of current injection. Among these properties, the geometry of current injection seems to be the easiest candidate for optimization using, for example, current apertures. In this work, we analyze the reduction of threshold current by optimizing the area of the active layer into which the carriers are injected. In order to understand basic directions for reducing threshold current, we consider a simple model for the operation of a general 3D laser. In our model, we assume that the current is injected uniformly into some area of the active layer. The active layer is located inside a laser cavity operating at a single mode. The area subjected to the current injection overlaps with the optical mode and, therefore, provides some optical gain. The area of the active layer not subjected to the current is treated as either with or without free-carrier absorption. These two cases give different recipes for optimization.

We show that the optimal area depends not only on the size of the optical mode but also on the cavity lifetime and the nonlinearity of the gain dependence on the current density in the active layer. In all regimes, the threshold current density lies in the region where the gain versus current density becomes nonlinear. This implies that the minimization of the threshold current by optimizing the injection area requires an accurate knowledge of the gain dependence on the current density for the active layer, in addition to the knowledge of the optical mode distribution.

7933-68, Poster Session
Top transmission grating GaN LED simulations for light extraction improvement
S. Trieu, X. Jin, California Polytechnic State Univ., San Luis Obispo (United States); B. Zhang, X. Kang, G. Zhang, C. Xiong, W. Wei, Y. Sun, X. Fu, Peking Univ. (China)
We present the top transmission grating’s improvement on GaN LED light extraction efficiency. We use the finite difference time domain (FDTD) method, a computational electromagnetic solution to Maxwell’s equations, to measure light extraction efficiency improvements of the various grating structures. Also, since FDTD can freely define materials for any layer or shape, we choose three particular materials to represent our transmission grating: 1) non-lossy p-GaN, 2) lossy indium tin oxide (ITO), and 3) non-lossy ITO ( = 0). The p-GaN material encounters no loss because the loss factor, , is zero at the wavelength of 460 nm. We define a regular spacing between unit cells in a crystal lattice arrangement by employing the following three parameters: grating cell period ( ), grating cell height (d), and grating cell width (w). The conical grating model and the cylindrical grating model are studied. We also directly compare the study’s results with reflection grating results. Both studies show that the top grating has better performance, improving light extraction efficiency by 165%, compared to that of the bottom reflection grating (112%).
and top-bottom grating (42%). We also find that when grating cells closely pack together, a transmission grating maximizes light extraction efficiency. This points our research towards a more closely packed structure, such as a 3-fold symmetric photonic crystal structure with triangular symmetry and also smaller feature sizes in the nano-scale, such as the wavelength of light at 460 nm, half-wavelengths, quarter wavelengths, etc.

7933-69, Poster Session

Influence of pressure on optical absorption of triglycine selenium single crystals
J. A. Owisk, Military Univ. of Technology (Poland); K. Ozga, I. V. Kityk, Czestochowa Univ. of Technology (Poland); J. Berdowski, J. Dlugosz Univ. de Czestochowa (Poland); Z. Tylcynzynski, Adam Mickiewicz Univ. (Poland); A. Wojciechowski, A. Slezak, Czestochowa Univ. of Technology (Poland); A. Z. Rembielki&324;ka, LOT Polish Airlines (Poland) For the first time we have shown that increasing uniaxial pressure on the triglycine selenium single crystals leads to occurrence of several spectral maxima below the energy gap. It is principal that after interruption of the applied uniaxial pressure there is observed the remarkable spectral shifts up to 20 nm of the principal spectral maxima at 280 nm and 340 nm. The effect is caused by the changes of inter-molecular interactions of van der Waals type in the such kinds of the crystals and occurrence of and elastic interactions. The effects has irreversible character and after the several applying of uniaxial pressure we see that there occur several strains which may be considered like the remaining inter-molecular stresses. The observed phenomenon may be used for creation of the optoelectronic sensors of the pressure with the forces up to 4 K. The performed investigations have shown that the spectral broadening is not sensitive to the pressure, however their spectral shift are substantially sensitive to the applied pressure. The observed effect possess a long time reversibility (up to one month). Additional studies of photooptical effects has shown its sensitivity to the external cw green laser light at power 300 mW. Using the thermoluminescence we have established that the crystals are very sensitive to the number of trapping levels within the energy gap. Additionally there were performed studies of electrooptical effects for the pulsed 10 ns Nd-YAG laser. We have found that the electrooptical coefficients of the samples under the pressure are substantially higher with respect to the free samples.

7933-70, Poster Session

Design and theoretical characteristics of directional coupler-type optical polarization splitters using dielectric periodic multilayers
K. Baba, T. Nakai, Sendai National College of Technology (Japan)
A periodic dielectric multiplier is one of artificial anisotropic media and exhibits large birefringence. In this work, we have designed a novel directional coupler-type optical polarization splitter using the dielectric periodic multilayer for glass integrated optics. The optical polarization splitter consists of the directional coupler in which two cores with same refractive index and diameter are very close to each other. The periodic dielectric multiplier with large birefringence is loaded on one core (core 1) of the directional coupler as outer cladding layer. On another core (core 2), a conventional glass layer with no birefringence is loaded as outer cladding layer. The periodic dielectric multiplier is designed as the effective refractive index for the TM polarization becomes equal to that of the conventional glass layer loaded as the outer cladding layer. In this optical polarization splitter, a guiding wave in the core 1 transfers to the core 2 because of the mode coupling for the TM polarization. On the other hand, for the TE polarization, a guiding wave in the core 1 does not transfer to the core 2 because of no mode coupling as the effective refractive indices of two waveguides are different from each other. In addition, we used a phase-front accelerator proposed by Shinya, et al.

7933-71, Poster Session

Modeling of energy band diagram of asymmetric variable-gap multilayer structures
B. S. Sokolovsky, Ivan Franko National Univ. of Lviv (Ukraine) The report presents results of analytical and numerical calculations of energy band diagram of homogeneously doped asymmetric variable-gap multilayer structures consisting of periodically arranged semiconductor layers in which coordinate dependences of energy band gap and electron affinity have a piecewise linear form with the slopes being different in the adjacent layers. The extrema of the band gap diagram of the structures under consideration are shown to be located within the layers while in the symmetric structures they are located at the interfaces. It has been found that the shape of energy band diagram of such structures changes under variation of the structure’s period with the largest transformation of the energy band diagram occurring when the layer thickness is of the order of the Debye screening length. For the case of large period of the structures the band gap diagram has linear form in the most part of the layer volume and the edge of major carrier band practically does not depend on the coordinate. At small values of the structure’s period the band gap diagram has noticeably nonlinear character and edges of both conduction and valence band undergo coordinate variation irrespective of the type and level of doping. Numerical calculations have been carried out for the case of HgCdTe solid solution of spatially variable composition.

7933-72, Poster Session

Demonstration of arbitrary channel selection utilizing a pulse-injected double phase-locked semiconductor laser with optical injection
Y. Juan, F. Lin, National Tsing Hua Univ. (Taiwan) We demonstrate and characterize arbitrary channel selection utilizing both the double phase-locked and optical injection schemes experimentally. The double phase-locked scheme is realized by both optical injection and electrical modulation to the slave laser (SL) from a pulsed laser. The pulsed laser is generated by the semiconductor laser under optoelectronic feedback, which outputs repetitive pulse train with the repetition frequency controlled by the feedback delay time and feedback strength. When the SL subject to only the optical pulse injection from the pulsed laser, a broadband microwave frequency comb with amplitude variation ±5 dB in a 20 GHz range is generated. By further applying an electrical modulation to form a double phase-locked condition, a main channel can be selected accordingly. The advantages of large channel suppression ratio, system stabilization, and spurious noise reduction are obtained by using the double phase-locked technique. Moreover, by further applying an optical cw injection from a tunable laser, we demonstrate the selection of a secondary channel. A selection range of about 7.2 GHz is achieved by adjusting the SL subject to only the optical injection and electrical modulation to the slave laser (SL) from a tunable laser. We demonstrate the selection of a secondary channel. A selection range of about 7.2 GHz is achieved by adjusting the SL subject to only the optical injection and electrical modulation to the slave laser (SL) from a tunable laser.
Energy enhancement in mode-locked lasers using sinusoidal transmission functions for saturable absorption

E. Ding, E. Shilizerman, J. N. Kutz, Univ. of Washington (United States)

The master mode-locking equation, which is essentially the cubic-quintic Ginzburg-Landau equation, describes the averaged mode-locking dynamics in a ring cavity laser mode-locked with a combination of waveplates and a passive polarizer. The equation is obtained by distributing the sinusoidal transmission function of the mode-locking elements over the entire laser cavity and expanding the result as a power series in the pulse intensity. The parameters in this model are explicitly related to the orientations of the mode-locking elements. In this work we generalize the master mode-locking model by retaining the full transmission function instead of performing the series expansion, and the resulting equation is referred to as the sinusoidal Ginzburg-Landau equation (SGLE). The SGLE improves on the master mode-locking model and is a qualitatively accurate model in characterizing the stability of the mode-locking process and operating regimes of the laser cavity. It is found that the single mode-locked pulse of the SGLE splits into two through a short periodic transition as recently confirmed in theory. This multi-pulsing instability is often undesirable for many applications where high-energy pulses are required. By modifying the transmission function, which can be done by orienting the waveplates judiciously, it is found that the laser cavity can achieve a high-energy mode-locked state without going through the multi-pulsing instability. Our work thus provides practical guidelines for significantly enhancing the performance of the laser. Specifically, full advantage is taken of the hitherto ignored sinusoidal transmission function provided by the waveplates and polarizer.

Simulation of hot electron quantum well AlGaAs/GaAs photovoltaics

H. Z. Fardi, Univ. of Colorado Denver (United States)

The effects of carrier escape from quantum well (QW) and the interaction of hot electrons with crystal lattice are of importance to the physical understanding of QW hot carrier solar cells where the cooling dynamics in photo-excitied structures affect the cell efficiency. The absorption of high-energy photons produces electron hole pairs with excess kinetic energy, which are dissipated to the lattice thru phonon scattering. Quantum wells were proposed as one approach in utilizing these carriers with excess kinetic energy. These hot electrons, so called hot carriers, alter the conversion efficiency in photovoltaic silicon cells.

The energy balance equations coupled with non-isothermal drift diffusion transport equations are solved in single quantum well hot electron solar cell. The size quantization and the two-dimensional (2D) density of states are applied in the quantum wells. Energy transfer among the charge carriers and crystal lattice is modeled by an energy relaxation lifetime. Multi quantum well structures can slow down the cooling process by reducing the phonon scattering effects. The rate at which the carriers are lost to the lattice is slowed. As a result, quantum well can enhance solar cell efficiency in devices by reducing the non-radiative recombination effect.

We have studied an AlxGa1-xAs / GaAs structure with several quantum wells placed in the intrinsic region. Our results show that hot electron effects lead to an increase in short circuit current. The increase in short circuit current is due to hot carriers escaping from the wells without any significant SRH recombination, which may lead to higher cell efficiency. These results support the experimental data recently published by others.

Bias-dependent measurement of quantum efficiency in GaAs-based multi-junction solar cells

D. Kim, H. Ryu, Inha Univ. (Korea, Republic of)

Quantum efficiency (QE) of GaAs-based single and multi-junction solar cells is investigated. We consider three kind of solar cells, a GaAs single junction, an InGaP/GaAs dual junction, and an InGaP/GaAs/Ge triple junction cell. The QE spectra for each sub-cell of the multi-junction solar cell are measured and compared with simulation results obtained by the APSYS software. Good agreements between measurements and simulations are found for well chosen material parameters such as carrier lifetime and surface recombination velocity. By integrating the QE with solar spectral irradiance at zero bias, short-circuit current in each cell is determined, which can be used for the optimization of the solar cell structure. When the QE is measured with increasing forward bias of the solar cell, the QE begins to decrease rapidly as the bias voltage approaches the voltage at the maximum efficiency. The bias-dependent QE spectra can be used to determine a current-voltage (I-V) curve and cell efficiency for arbitrary solar spectra. The I-V curve is obtained from the photo-current at each bias voltage, where the photo-current approaches the voltage at the maximum efficiency. The bias-dependent QE spectra can be used to determine a current-voltage (I-V) curve and cell efficiency for arbitrary solar spectra. The I-V curve is obtained from the photo-current at each bias voltage, where the photo-current approaches the voltage at the maximum efficiency. The bias-dependent QE spectra can be used to determine a current-voltage (I-V) curve and cell efficiency for arbitrary solar spectra. The I-V curve is obtained from the photo-current at each bias voltage, where the photo-current approaches the voltage at the maximum efficiency.
Rapidly optimizing optoelectronic devices using full wave 3D simulation software.

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Fabricating optoelectronic devices can be extremely costly due to the need for using high end fabrication methods such as photo lithography. Therefore, the importance of being able to accurately and rapidly prototype an optoelectronic device cannot be overstated. By using commercially available full wave 3D simulation software (FW3D), rapid prototyping can be achieved. A complete rapid prototyping process would require a discussion on simulation as well as fabrication work, however for this paper we will only focus on the simulation aspect which is rapid optimization. The bulk of our work will be to model and rapidly optimize an optoelectronic device which is currently of interest to many optoelectronic researchers. This structure is labeled as a frequency selective surface. By using two widely known numerical methods, we will demonstrate the modeling and simulation aspects needed for achieving rapid optimization and fully characterizing the optoelectronic performance of this device.

In addition to rapidly optimizing a device to perform optimally, full wave 3D software also provides multiple boundary conditions and excitation in order to accurately model a device for real world behavior. Important boundary conditions such as periodicity which is important for photonic crystals and surface plasmons behavior are accurately modeled and also visualized in full 3D. In addition to boundary conditions, perturbation effects can be easily modeled to observe trends in behavior of optoelectronic devices. Another important factor to accurately model an optoelectronic device is having the correct excitation. Full wave 3D software has a broad range of excitations ranging from plane waves to transverse modes in waveguides which have applications in nano and micro cavity optoelectronic devices.

Efficiency enhancement of organic solar cells using plasmonic silver nanowire electrodes

T. Xu, M. Kang, H. Park, L. J. Guo, Univ. of Michigan (United States)

Organic solar cells (OSCs) offer a promising alternative to inorganic solar cells due to their low cost, easy fabrication, and compatibility with flexible substrates over a large area. However, further enhancement of the power conversion efficiency (PCE) is still required for practical applications. Considering the thickness of the organic semiconductors in OSCs is about several tens of nanometer, which coincides with the field decay length of surface plasmons in typical dielectric layer, surface plasmon resonance (SPR) enhancement is naturally suited to increase the optical absorption of the organic semiconductors. In this work, we demonstrated surface plasmon enhanced photo-current and PCE of organic solar cells using periodic silver nanowires as transparent electrodes as compared to the device with conventional indium tin oxide (ITO) electrodes. The specially designed OSC using silver electrodes that can enhance the absorption by the organic semiconductors for both TE and TM polarized light. The organic materials in our OSCs consist of PEDOT:PSS, copper phthalocyanine (CuPc), buckminsterfullerene (C60), and bathocuproine (BCP), which are used as hole transporting layer; electron donor and acceptor layer; exciton blocking layer, respectively. External quantum efficiencies are broadly enhanced across the visible band, resulting in about 2.5 fold increase around the peak solar spectrum wavelength of 568nm, and a 35 % overall increase in power conversion efficiency than the ITO control device under normal unpolarized light. Besides the efficiency enhancement, the plasmonic transparent silver nanowire electrodes offer improved mechanical durability than the conventional ITO electrodes for future high performance, large-area, and flexible applications.

Plasmonics-based nonmagnetic optical polarization rotators for optical isolation

H. S. Kim, T. Lee, G. Oh, Y. Choi, Chung-Ang Univ. (Korea, Republic of)

Recently, many methods have been proposed to meet the demand for an optical isolation in a photonic integrated circuit (PIC). The optical isolators in which light can propagate only one-direction play a crucial role in PIC, because reflection from nearby structures of emitted light can make the operation of laser diodes unstable. Most isolators are based on the Faraday effect and external magnetic fields. However, many problems exist in these methods such as difficult fabrications, expensive materials, and so on. In this paper, we propose a plasmonics-based optical polarization rotator for an optical isolation. The proposed structure consists of a slotted or a slanted waveguide and a metal film. Optical polarization rotators have been designed theoretically in slotted and slanted waveguides using skewing phenomena of propagation waves. We have been analyzed various structures such as slanted waveguides with metal film, semi-slanted waveguides with metal film, and slotted waveguides with metal film. A metal film on the waveguide acts to rapidly rotate the optical polarization, because it has characteristics of negative Goos-Hänchen shift as negative index materials. Therefore, a ultra-small sized perfectly polarization rotator can be realized by the plasmonics-based asymmetric cross sections of waveguides. The proposed devices would be useful for the construction of optical isolators and future Si-based optical integrated circuits.
Effect of polarization state on characteristics of InGaN/GaN multiple quantum well solar cells

J. Chang, Y. Kuo, National Chianghua 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 advantages, the realization of high crystalline quality InGaN films is highly challenging to achieving efficient PV devices, especially for high indium composition. One of the problems is attributed to the large lattice mismatch between InN and GaN, which results in misfit dislocations and phase separation within the InGaN layers. It was shown that strain could suppress phase separation in InGaN layers and thus the solar cells with InGaN/GaN multiple quantum wells (MQWs) had been reported (Appl. Phys. Lett. 94, 063505, 2009) with the attempt to alleviate the phase separation issue. The polarization induced surface charge densities in InGaN/(In)GaN MQW light-emitting diodes (LEDs) is an important issue influencing the device performance. Hence, it is supposed that this issue might also play a key role for the InGaN/GaN MQW solar cells. The main factor responsible for this phenomenon is presumably the ability of carrier transportation across the QW region. In this paper, the effect of polarization state in InGaN/GaN MQW solar cells is investigated numerically by using the APSYS (Advanced Physical Model of Semiconductor Devices) simulation program. The effect of polarization on the electrical properties of the InGaN/GaN MQW solar cells will be explored in detail.

2×2 Photonic crystal fiber splitter for 800 nm spectral domain optical coherence tomography

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We report on the fabrication and performance of 2×2 Photonic crystal fiber (PCF) splitter which was designed as single mode splitter at 800 nm optical band. PCF splitter has been made by PCF-to-PLC connections. PCF array blocks were lithographically fabricated to have fiber V grooves and used to firmly hold PCFs. PLC chip was also fabricated to have single mode property at 800 nm wavelength. The core size of splitter chip was about 5 µm × 5 µm and the core-cladding index difference was about 0.15%. With the implemented PCF PLC splitter, we obtained a low excess loss of 1.2 dB at 850 nm, a low polarization-dependent loss of 0.19 dB. With the proposed 2×2 Photonic crystal fiber (PCF) splitter, OCT images of an in vitro biological sample were successfully obtained.

Efficient couplers for spoof surface plasmon polaritons

W. Zhao, Z. Lu, Rochester Institute of Technology (United States)

Spoof surface plasmon polaritons (SPPs), by tailoring the topography of a perfect electrical conductor (PEC), provide a new method to achieve surface waves at longer wavelengths. Here we demonstrate that by careful designing the parameters of surface groove arrays, a textured metal slab at terahertz frequencies can function as a coupler attracting light from free space to its surface efficiently. For simplicity, we used the PEC model instead of real metal in the numerical simulations, since at THz frequency regime, metal can be roughly treated as perfect conductor. The coupler is constructed by micromachining uniform groove arrays (for the one dimensional grooves, width w=5 µm, height h=5.08 µm, period d=12.7 µm) on the surfaces of the PEC slab. The input beam is two periods away from one end of the coupler. We investigated the conditions when the source is incident on the coupler with the grooves only on top surface and the grooves on both top and bottom surfaces, respectively. From the field intensity and power distributions, it is clearly seen that EM waves are strongly confined to the surface of the coupler after some propagation distance. The coupling efficiencies are measured after light propagates about 800 µm on the coupler. For both conditions the results are similar, around 90% coupling efficiencies are achieved. The proposed structure is easy for fabrication, which needs only one lithography process for the uniform grooves since they have identical heights.

Effect of rapid thermal annealing on optical and photovoltaic properties of dilute nitride bulk and quantum well materials

M. Wu, A. Mehrrota, G. K. Vijaya, A. Freundlich, Univ. of Houston (United States)

The dilute nitride bulk and quantum well semiconductor has attracted increasing attention since the incorporation of small amounts of N in GaAs leads to a large band-gap reduction which holds a great potential for its application in optoelectronic and photovoltaic devices. However, a severe degradation of minority carrier properties at the presence of nitrogen in these alloys has been a major impediment toward the success development of efficient devices. Post growth rapid thermal annealing has been shown to be effective in improving optical properties of dilute nitrides; however, the success of the conventional technique has been limited for alloys with N composition >2 %. In this work we have systematically studied the effect of RTA on structural and luminescence properties of dilute nitride bulk and quantum well materials grown by chemical beam epitaxy (CBE) on GaAs (100) substrates. The effect of RTA on of substitutional nitrogen composition is investigated by high resolution x-ray diffraction (HRXRD), whereas the evolution of surface morphology is characterized by atomic force microscopy and scanning electron microscopy. It is shown that a careful optimization of RTA parameters could result in a significant improvement of luminescence properties. Here, we show that even for alloys with nitrogen content in excess of 3%, the near-band edge photoluminescence signal could be improved by three orders of magnitude. The resulting PL intensities are shown to be comparable to those recorded from high quality reference GaAs films. The presentation will also report the evolution of the optical properties as a function of the temperature and discuss the suitability of the approach toward the development of 0.9-1.1 eV photonic and photovoltaic devices.
Super fast physical-random number generation using laser diode frequency noises

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Pseudo-random numbers’ periodicity renders them inappropriate for use in cryptographic applications, but, naturally-generated, physical-random numbers have no calculable periodicity, thereby making them ideally-suited to the task.

Diode lasers naturally produce wideband “noise” signals that are believed to have tremendous capacity and great promise, for the rapid generation of physical-random numbers, for use in cryptographic applications. Researchers use diode laser’s intensity noises to generate physical-random numbers, at speeds exceeding 100Gbps, and optical feedback, to create chaotic oscillation.

A diode laser’s frequency noise spectrum depends on its bias current, and is capable of spreading beyond 10GHz, so we tried to- in a sense, turn the tables 180 degrees-, and use the frequency noises, to generate the super fast physical-random numbers. We worked to identify the frequency noises by observing the transmitted light intensity at a fast photo detector through the frequency reference, and generated the physical-random numbers using a fast analog-digital (A/D) converter at 10GSps. We completed the process, using the original parallel binary random number generating system and multiplied the speed at which physical-random numbers could be generated. We then identified and evaluated the binary-number-line’s statistical properties. Our results showed that fast (up to 40Gbps) physical-random number generation, was achieved, and that it could be increased to some hundreds of Gbps, using the diode laser’s frequency noise characteristic.

Modeling and optimal designs for dislocation and radiation tolerant single and multijunction solar cells

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

Crystalline defects (e.g. dislocations or grain boundaries) as well as electron and proton induced defects cause reduction of minority carrier diffusion length which in turn results in degradation of efficiency of solar cells. Hetro-epitaxial or metamorphic III-V devices with low dislocation density have high BOL efficiencies but electron-proton radiation causes degradation in EOL efficiencies. By optimizing the device design (emitter-base thickness, doping) we can obtain highly dislocated metamorphic devices that are radiation resistant. Here we have modeled III-V single and multi junction solar cells using drift and diffusion equations considering experimental III-V material parameters, dislocation density, 1 Mev equivalent electron radiation doses, thicknesses and doping concentration. Thinner device thickness leads to increment in EOL efficiency of high dislocation density solar cells. By optimizing device design we can obtain nearly same EOL efficiencies from high dislocation solar cells than from defect free III-V multijunction solar cells. As example defect free GaAs solar cell after optimization gives 15.6% EOL efficiency (under typical 2x1E15cm-2 1 MeV electron fluence) while a GaAs solar cell with high dislocation density (108 cm-2) after optimization gives 15.2% EOL efficiency. The approach provides an additional degree of freedom in the design of high efficiency space cells and could in turn be used to relax the need for thick defect filtering buffer in metamorphic devices.

Charge density waves in superconductors

N. P. Netesova, Lomonosov Moscow State Univ. (Russian Federation)

Superconducting phase separation at temperatures above the phase transition by numerous experimental methods was revealed. Phase are formed, rich media-CDW and depleted electrons - the dielectric, where electron Wigner crystals may form. CDW and the electromagnetic wave in the dielectric phase run with the same velocity in phase. A graph of superconducting phase separation by the Hubbard model can get. Fundamental principle of superconducting phase separation proposed earlier us - it is necessary to satisfy condition 11 = -12, where 12 is interaction energy in an initial phase, 11 is interaction energy in the local again formed phase.

Each electron in a crystal experiences the effect of an oscillating potential V(t)=Vo cos(Ωt), where Vo - a function of the wave vector k, Q - wave vector of the charge density wave. Electron charge density Ne oscillates in the space Ne=No[1+ cos(Ωt)], where No - the average electron charge density, the wave vector Q and the amplitude of -1 < Ωt < +1 according to the condition of - the free energy is minimal. CDW cause periodic shifts in the crystalline positive background U=B sin(Ωt). The local positive charge density is determined by the N+=-No (-1+div U), =BQ. In the electronic spectrum E(k) energy gaps are manifested, the Fermi level EF is located in the gap, Q=2kF. Electronic excitations play a dominant role in the superconducting phase transition origin. From the plasma mechanism of superconductivity follows superconducting crystals exist at room temperature. There are superconductors with temperatures of phase transition above a room temperature.

Revisit of transmission spectrum through a single nano slit in metallic thick film: a universal phase shift effect in the slit interface

S. G. Chang, Y. Su, National Cheng Kung Univ. (Taiwan)

In this paper, we revisit the resonant transmission behavior of transverse magnetic wave through a single sub-wavelength slit in metal film. While the film is thick enough so that Fabry-Perot(FP) resonance occurs, it is observed that the resonant peak wavelength shifts as the gap size changes. We show that this resonant wavelength shift is due to a universal phase shift of the transmission/reflection coefficient in the interface independent of the film material. The surface plasmon ploaritons in the gold or silver film play only minimal role to affect the dispersion. This distinct phase shift depends only on the wave k vector and gap size. We further adopt a simple transmission line theory to explain the phase shift in the semi-infinite slit interface. An analytical form of this phase shift was presented. This phase shift leads to the impedance mismatch in the interface to constitute the two reflecting mirrors in the FP resonator. Furthermore, we use such complex-number impedances to derive the single nanoslit Fabry-Perot resonant spectrum with normal incident and multiple reflections. The result agrees extremely well with full wave FDTD simulation. Our result shows that by conformal mapping of wavelength by surface plasmon dispersion relation, we obtain identical transmission spectrum through a single slit in thick metal film independent of the film material such as gold or perfect electric conductor. In conclusion, the seemly complex diffraction problem of transmission through a single slit in thick metal film with surface plasmon polaritons effect can be treated as a simple Fabry-Perot resonator. The universal phase shift due to the geometry structure in the slit interface accounts for the diffraction effect for EM field with the same wave k vector. The surface plasmon polaritons coupling in the slit channel only play a role to determine the effective wave k vector. The slit can be treated as a Fabry-Parot cavity with two complex reflecting mirrors. Consequently, we can perfectly predict the transmission peaks of a single sub-wavelength slit in metal films.
7933-92, Poster Session

1550 nm DFB semiconductor laser with high power and low noise

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1550 nm single mode semiconductor lasers with high power, low noise and narrow linewidth have important applications in RF over fiber systems. The Distributed-Feedback (DFB) lasers with output power over 500 mW have already been demonstrated. However, the lasers have large related intensity noise (RIN) measuring -90 dB/Hz at the laser relaxation oscillation frequency [1]. To increase the relaxation oscillation frequency or decrease the laser RIN, some research groups have used the injection-lock technology, or used the effect of fiber dispersion on the propagation of the laser noise. Since the former needs two lasers, and the latter needs a very long fiber, which will increase the system volume and complexity.

We have studied laser structure and injected current dependence of laser relaxation oscillations and RIN spectra. Our results show that a DFB laser can be designed with peak relaxation oscillations shifted above 20GHz. Using commercially available software PICS3D we have simulated the laser performance and determined that the laser structure can deliver output power over 200 mW with side-mode suppression ratio over 50 dB and RIN less than -165 dB/Hz in the frequency range 1 - 20GHz. Fabrication of the laser structure is under way and results will be presented.


7933-93, Poster Session

Modeling and design particularities for distributed feedback lasers with laterally-coupled surface gratings

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The paper presents the modeling, simulation and design guidelines for laterally-coupled distributed feedback (LC-DFB) lasers. The LC-DFB lasers are based on surface gratings resulted from lateral corrugations of the ridge waveguide. Unlike the conventional buried-gratings, the LC-DFB surface gratings can be fabricated in a single growth and processing sweep, which avoids epitaxial overgrowth, simplifies the device fabrication and reduces the device cost. The device fabrication cost is further reduced in our approach by using a highly-productive and cost-effective UV-nanoimprint lithography technique.

The LC-DFB lasers have multiple particularities: the grating interaction with the optical field; the grating coupling coefficient calculation; the effect of grating geometry, including the limitations imposed by the fabrication technology, on the coupling coefficient, on the single transverse mode operation and on device characteristics. These particularities are analyzed in the paper, in conjunction with the device fabrication experiments and device characterization feedback. Characteristics such as threshold current, output power, side-mode-suppression-ratio, spectral linewidth and 3-dB modulation bandwidth are considered in the paper. The uncontrollable facet reflection phase, which depends on the position of the cleaved facet relative to the grating corrugation, is included in the simulations, together with the facet reflection magnitude, and the corresponding statistical variations of device characteristics with facet reflections are presented for lasers with different lengths and grating coupling coefficients.

The device development work presented in the paper targets two main applications: 894 nm narrow linewidth LC-DFB lasers suitable for Cesium atomic clocks and 1310 nm high-speed LC-DFB lasers for optical communications.

7933-94, Poster Session

Theoretical and experimental investigation of excitability in semiconductor microring lasers

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Semiconductor Micro Ring Lasers (MRLs) are a class of semiconductor lasers whose active cavity is characterized by a circular geometry. They have attracted attention due to the possibility of monolithic integration of thousands of them in a cheap and reliable way on a single chip. SRLs are interesting for applications that rely on the presence of two counterpropagating modes inside the optical cavity. For instance, fully symmetric coupled MRLs have been proposed as candidates for the realization of small and fast all-optical memories.

At the same time, a wealth of nonlinear and stochastic dynamics have been predicted and observed in symmetric MRLs which is a consequence of the underlying Z2-symmetry of the device.

However, unavoidable fabrication defects, material roughness and chip-cleaving break the device symmetry in an uncontrolled way, which may result in a deterioration of the device’s performance. Despite their importance, the effects of symmetry breaking in MRLs remain unaddressed.

In this contribution we investigate theoretically and experimentally the dynamics of MRLs with weakly broken Z2-symmetry. For a not-too-weak symmetry breaking, we reveal that MRLs become excitable and therefore can emit large, deterministic power bursts as a response to stochastic fluctuations.

The origin of excitability is explained by investigating the topology of the invariant manifolds of an asymptotic two-dimensional phase space model. In particular, these manifolds define the excitability in MRLs, and we demonstrate how it can be crossed by optically injecting a pulse into the semiconductor ring laser.

The results of the experiments confirm the prediction of the theory.

7933-95, Poster Session

Enhanced near-infrared light harvesting using micro- and nano-scale surface textures in crystalline silicon photovoltaics

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As current crystalline silicon photovoltaics evolves towards thin-wafer technologies (<100 μm), optical absorption becomes challenging, where that of the near infrared is particularly worse than the ultraviolet and visible. In this work, we employs combined micro- and nano-scale surface textures to increase light harvesting in the near infrared for crystalline silicon photovoltaics, and discuss the associated antireflection and scattering mechanisms. The combined surface textures are achieved by uniformly depositing a layer of indium-tin-oxide nanowhiskers on passivated, micro-grooved silicon solar cells using electron-beam evaporation. The nanowhiskers facilitate optical transmission in the near-infrared, which is optically equivalent to a stack of two dielectric thin-films with step- and graded- refractive index profiles. The corresponding reflectance spectrum is significantly reduced (R<5%) in the wavelength range of 350-1100nm. Compared to a conventional Si solar cell, the combined surface texture solar cell shows much improved external quantum efficiency (EQE) for 700-1100nm wavelengths. As a result, the ITO nano-whisker coated Si solar cell further enhances the power conversion efficiency from 16.08% to 17.18%. Finally, we show that the nanowhiskers also provide strong forward scattering for the ultraviolet and visible light, favorable in thin-wafer silicon photovoltaics to increase the optical absorption path.
Design of simultaneous bidirectional CMOS transceiver with a resistor-transconductor hybrid for optical chip-to-chip interconnects

I. A. Ukaegbu, J. Sangirov, T. Ngo, T. Lee, H. Park, KAIST (Korea, Republic of)

A simultaneous bidirectional CMOS transceiver (SBI-TRx) has been proposed for full duplex chip-to-chip optical interconnects. The transceiver utilizes a resistor-transconductor hybrid. The SBI-TRx offers a solution to achieving bidirectionality especially for transmissions between CPU and memory. The SBI-TRx is made up of a receiver, a transmitter, and a hybrid circuit. Signals from the optical link are converted into electrical signals at the receiver circuit which moves through a voltage divider in the hybrid circuit onto a balanced line. In this work, the input signals of the hybrid are the voltage of the transmitting end and the current sensing voltage from the voltage divider. The hybrid finally extracts inbound signals from these signals and passes the resulting signal to the transmitter end, where the signals are converted and sent down the optical link. The SBI-TRx is designed in 0.18 μm Si-CMOS technology, with power dissipation less than 60 mW and 70 mW for the transmitter and receiver, respectively. It achieves a 3-dB bandwidth of 4 GHz and 3 GHz in transmitter and receiver modes respectively.

Modulation effects in multi-section semiconductor lasers

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Experimental measurements performed by modulating the applied current in multi-section quantum-dot lasers will be presented. In contrast with conventional modulations studies, these measurements involve modulation frequencies well beyond the laser’s free spectral range. As a consequence, resonant peaks in the modulation response are created. Although this scenario has been investigated in the past in external cavity lasers, this work focuses on monolithic devices for what we believe to be the first time. Moreover, a new analytical model, which predicts these effects with an algebraic modulation function, will be described. To verify the algebraic model and compare with the experimental results, numerical simulations using a simplified traveling-wave equation will be presented. This tool will be used to predict the results expected under a variety of cavity configurations. Finally, the role played by the linewidth-enhancement factor on devices operating in this regime will be addressed with the numerical model.

Mode-locking theory for ultra-short few-femtosecond laser pulses

J. N. Kutz, Univ. of Washington (United States); E. D. Farnum, Kean Univ. (United States)

Recently achieved short pulse durations and broad spectral content has opened up vast new possibilities for exploring the fundamental nature of atomic and molecular physics at the fastest time-scales, including molecular vibrations, chemical reactions, and light-matter interactions. Indeed, even single electron transition events can now be captured and an absolute measure of time potentially established. Towards this end, we develop a generic mode-locked laser theory for femtosecond and sub-femtosecond pulse formation in analogy with the master mode-locking equation that has dominated mode-locking theory for nearly two decades. Given the lack of attosecond laser theory, the aim of the manuscript is to provide a beginning theoretical treatment for a more precise and quantitative understanding of the pulse-formation, dynamics, and interactions at the attosecond timescale. We have proposed a new model for quantifying the mode-locking dynamics in laser cavities in the few femtosecond and sub-femtosecond pulse regime. This model is analogous to the master mode-locking equation and is valid well beyond the breakdown of the master mode-locking center-frequency expansion. Given the lack of theoretical models describing few cycle and attosecond pulses, the current theory provides the first theoretical platform for a more precise and quantitative understanding of the pulse-formation, dynamics, and interactions at the few femtoseconds and hundreds of attoseconds timescale. The model exhibits all the hallmark features of mode-locking and provides excellent platform for performing theoretical studies of laser cavity performance as well as giving fundamental insight into sub-femtosecond pulse generation and dynamics.

Four-wave mixing analysis of quantum dot and quantum well lasers

H. Lin, F. Lin, National Tsing Hua Univ. (Taiwan)

The four-wave mixing analysis has been used to measure quantum well semiconductor lasers. In this paper, we characterize and compare a quantum dot and a quantum well lasers with the similar technique. The optical and power spectra of the four-wave mixing state in the quantum dot laser are studied both numerically. The tendency of the amplitude versus detuning in the quantum dot laser is very similar with those in the quantum well laser. The four-wave mixing spectra and the power spectra from both lasers are symmetric, while asymmetry in the regenerated signal is found. Compared to the quantum well lasers, the high resonance peak of the regenerated signal of the quantum dot lasers appears on the opposite side of the detuning in the optical spectra. The intrinsic parameters of the lasers are also obtained by fitting the optical spectrum and power spectrum obtained experimentally with those derived directly from the rate equations.

Characterizing and suppressing multi-pulsing instabilities in mode-locked lasers

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Multi-pulsing instabilities are pernicious in laser cavities due to their imposed limitations on mode-locked pulse energies. The method of proper orthogonal decomposition (POD) is applied to the governing equations of various mode-locked laser systems and allows one to obtain a reduced model that accurately captures the laser cavity dynamics. In this work we apply the POD method to governing equations of two different mode-locking systems - a ring cavity laser and a fiber laser mode-locked with waveguide arrays. For a ring cavity laser, the governing equation is the cubic-quintic Ginzburg-Landau equation that describes the averaged mode-locking dynamics where the mode-locking process is controlled by a combination of waveplates and a passive polarizer. The waveguide array mode-locking model combines the nonlinear mode-coupling of waveguide arrays with the saturating and bandwidth limited gain of erbium doped fiber. For each system, the dynamics of the POD model agrees well with the full governing equations. In particular, each model accurately describe the multi-pulse transition in which a single mode-locked pulse is transformed into a double-pulse when cavity gain is increased. Such instabilities are observed in experiments and are undesirable for the performance of the system. Dynamical systems analysis identifies the mechanisms that are responsible for these instabilities and thus provides the range of parameters to obtain stable operation. Moreover, the model reveals simple parameter relations that allow for optimizing the energy output as a function of the cavity parameters.
Noise suppression in chaotic lidars under different synchronization schemes

Y. Liao, W. T. Wu, F. Lin, National Tsing Hua Univ. (Taiwan)

We study the noise suppression in chaotic lidars under different synchronization schemes numerically using the coupled rate equations. The channel noise considered includes two parts: (1) amplitude noise described as a white Gaussian noise and (2) phase noise randomly distributed between $-\pi/4$ and $\pi/4$. The ability of noise suppression is quantified by the correlation coefficients as a function of the signal-to-noise ratio (SNR). The simulation results show that, in the low noise region (SNR $> 15$ dB), the direct correlation (conventional) scheme has the best correlation performance. When the noise increases to $-20$ dB $< $ SNR $< 15$ dB, both optical and optoelectronic feedback synchronization schemes show better ability of noise suppression than the conventional scheme. After the noise increases to SNR $< -20$ dB, the synchronization conditions are broken and hence the effect of noise suppression disappears. Compared with the optoelectronic feedback scheme, a suitable optical coupling strength ($\text{kasi} \approx 0.3$) must be chosen in the optical feedback scheme under the generalized synchronization condition to achieve high correlation coefficient. We also find that the generalized synchronization scheme has better noise suppression performance than the completed ones.

The dynamics of optoelectronic oscillators

T. Erneux, Univ. Libre de Bruxelles (Belgium); L. Larger, Univ. de Franche-Comté (France)

In recent years, compact optoelectronic oscillators (OEOs) have been developed that rival the best RF oscillators over broad offset frequencies. They incorporate an electro-optic modulator, an optical-fiber delay line, and optical detection in a closed-loop resonating configuration. This hybrid source simultaneously generates, within the same optoelectronic cavity, an ultra-low-jitter stream of short optical pulses with high repetition-rate capabilities [1].

OEOs can be modeled mathematically by a simple nonlinear delay differential equation. Combined experimental and theoretical studies have shown that it accurately describes a large variety of oscillatory outputs [2]. Today, OEOs have attracted the attention of several laboratories with quite different objectives. They range from fundamental questions (the synchronization properties of two coupled OEOs [3] or new forms of chaos [4]) to applied projects (chaotic encryption for secure communication [5]). In this presentation, we highlight some of these problems. In addition to numerical simulations, we extract analytical approximations of physical significance by using asymptotic techniques appropriate for delay differential equations.


Oscillation frequency shifts observed in vertical cavity surface emitting lasers exposed to magnetic fields

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Much attention has been focused on diode lasers’ oscillation wavelengths’ susceptibility to fluctuations in injection current and temperature, among other things. As long as ago as the 1960’s, scientists were testing to see what, if any, changes might be brought about, by exposing them to magnetic fields of varying strengths. At that time, they revealed their findings, indicating that oscillation wavelengths shifted to the shorter (high frequency) side, at extremely low temperatures (<80K) and strong magnetic fields (<4T). While we were fully aware of their work, our experience differed in that, when we exposed Fabry-Perot type diode lasers oscillating at 780nm to weak magnetic fields (<1.4T), at room temperature (300K), we observed that the oscillation wavelength shifted to the low frequency side. This result is explained by temperature rises in the active region, and this means that this effect is too slow for applications.

In this work, we applied a magnetic field to the Vertical Cavity Surface Emitting Laser (VCSEL), because when the magnetic field applied to the direction of its current flow, carrier density increased in the active region, thereby causing a rapid shift to the shorter wavelength side; results that differed markedly from those obtained using a Fabry/Perot-type laser.

New modeling of laterally coupled diode lasers: analysis and comparison with experimental results

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The dynamics and static behavior of lateral coupled diode laser arrays has been a subject of interest in past years. These studies have focused mainly on devices as suitable sources for high power low divergence lasers (multi-array) (D. Botez, “Diode laser arrays”, 1994) and as a way to increase the modulation bandwidth beyond the intrinsic relaxation oscillation frequency of a single laser diode proposed theoretically, by using two laterally coupled diode lasers (LCLD) (G. A.Wilson, R. K. Defrez, and H. G. Winful, JQE, 27, 1991) and experimentally demonstrated by means of locking the two lateral modes of these LCLD (H. Lamela, B. Roycroft, et al, Opt. Let, 27, 2002). More recently an experimental study showed that the relaxation oscillation frequency of each laser waveguide is strongly influenced by the coupling between the two lasers (G. Carpintero, R. Santos, and H. Lamela, Opt. Lett, 34, 2009). As pointed out by the review made by Glova (A. F. Glova, Quantum Electronics, 33, 2003) on phase locking of coupled lasers, little experimental work has been done on the dynamics and on the complete characterization of the emission spectrum of the LCLDs.

In this work, the authors’ goal is to carry out a new dynamic modeling of laterally coupled diode lasers based on the model locked behavior exhibited in semiconductor lasers. While the steady state theory of LCLDs explains very well the LCDL mode-locked behavior, it can not explain the modulation response, which is a transient behavior (W. Yang, JSTQE, 13, 2007). The modulation response, on the other hand, also exhibits characteristically different properties than its normal single diode laser. It shows additional resonance that is beyond the normal relaxation oscillation resonance frequency. This novel modulation property is particularly interesting since it promises high frequency, high speed direct modulation that exceeds the conventional relaxation oscillation resonance limits. This additional resonance is attributed to the coupling effect between different diode lasers (H. Lamela, M.Leonés, et al, JSTQE, 7, 2001). Finally, we present results obtained with this new model and we compare them with previous experimental result (R Acedo, H. Lamela, et
Influence of the alfa factor in a nonlinear semiconductor optical amplifier loop mirror performance for pulse shaping of Gain switching diode lasers

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Generation of high quality ultrashort optical pulses find a wide range of applications from high data bit rate optical communications to measurement of fast physical phenomena or its use in biomedical imaging systems [1]. Gain-Switching is a direct and straightforward technique developed to obtain picoseconds pulses that can be applied to Commercial Off The Shelf (COST) diode lasers, which are compact, cost effective and highly efficient light sources. However, the power at hand is small (mean power of mW’s) with long pulse duration and the shape of the pulses is not symmetric and presents wide pedestals. The improvement of the performances of these pulses has attracted a lot of interest in the past few years. Nonlinear Optical Loop Mirrors (NOLM) are able to offer nonlinear compression and pulse shape improvement [2-3].

In this work we report a NOLM configuration based on a Semiconductor Optical Amplifier (SOA) and a highly nonlinear Microstructured Optical Fiber (MOF) that offers a stable compression ratio and reshaping capabilities for pulses obtained from Gain Switching sources [4]. The device is perfectly adapted to the particularities of such sources, namely their low power, their asymmetric nature and the presence of wide pedestals, without the need of intermediate stages to pre-process the pulses.

Experimental and numerical studies are presented where the influence and importance of the dynamic of the Semiconductor Amplifier on the overall pulse compression performance of the NOLM is explored. Results show that the saturation and gain compression are important to understand the system behavior. Along with these effects, the influence of the alfa factor [5] and its dependence on the carrier density under high input conditions is evaluated. Numerical and experimental results show relevant agreement, what sheds light on the device behavior and helps understand the influence of the several physical effects behind it.

References:

Laser power converters for space based power transfer applications

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Conversion of laser light into electrical power opens-up numerous applications such as optical fiber power delivery, remote powering of subcutaneous electrical devices for medical diagnostics and line-of-sight wireless powering of electronic equipment. However, of most interest to this work is the controlled delivery of solar radiation to Earth via conversion to laser power on-board a geo-stationary satellite and subsequent transmission to earth. This requires a high efficiency...
A light emitting diode for entangled photons

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Existing sources of entangled photons require a laser excitation, imposing a practical limit on their potential for large-scale quantum information applications [1]. For the widely used parametric down-conversion sources, zero or multiple photon-pairs are usually emitted due to the probabilistic nature of the non-linear process. This presents an additional fundamental limitation in the form of efficiency and errors. Here we demonstrate the first electrically driven entangled light source, based on a layer of InAs quantum dots embedded in a p-i-n light emitting diode structure, with potential to operate ‘on-demand’ [2].

A quantum dot can emit a pair of photons by the radiative decay of the biexciton state to the ground state to produce the entangled Bell state |ψ+⟩. The biexciton state is formed by carrier capture from current passing through the diode. Polarization dependent cross-correlation measurements between biexciton and exciton photons were performed at ~5K with a dc injection current of 31nAµm-2. The fidelity of the measured photon pairs to the expected Bell state |ψ+⟩ reaches a maximum of 0.71±0.02 for photon pairs emitted simultaneously, which is comparable to similar optically driven sources. Furthermore the device can be operated in ac mode with measured fidelity up to 0.83±0.03.

The detected photon pairs are shown to violate Bell's inequality, indicating the quality of entangled light is sufficient for applications such as quantum key distribution [5]. The fidelity may be increased further by increasing the speed of the device to minimize re-excitation during pulsing, and by reduction of background light.

Electrically-pumped photonic nanowire single-photon source with an efficiency of 89%

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The single-photon source (SPS) is a central device in quantum cryptography and in linear optics quantum information processing. A key figure of merit is the efficiency, defined as the number of photons per trigger detected by the collection optics. Achieving a high efficiency requires careful tailoring of the photonic environment, traditionally performed by placing a quantum dot (QD) inside a high-quality micro-cavity. However, strong sensitivity to surface roughness has limited the efficiency of this approach to 44%.

Recently, a new SPS design based on a QD embedded in a photonic nanowire was proposed. Here, a geometrical effect ensures good coupling between the QD and the optical mode, and a regular tapering section is employed to control the far field emission profile. Unlike cavity-based approaches, the photonic nanowire SPS features broadband spontaneous emission control and high tolerance towards surface roughness. This has lead to a record-high measured efficiency of 72% for an optically pumped device. However, for practical applications electrical pumping is desired. Since metal contacts strongly absorb and scatter light, the implementation of electrical contacts without compromising the efficiency poses a challenge.

In this work we propose a new electrically-pumped photonic nanowire SPS design. For realistic parameters, the design features an efficiency of 89% predicted by numerical simulations. The new design includes an inverted tapering section, in which the optical mode is adiabatically expanded inside the nanowire to ensure a low-divergence output beam while minimizing the relative modal overlap with the metal contacts.
Nanocrystals.

When 0.1 mol.% of YF₃ was substituted by ErF₃, an emission at 980 nm with clear Stark splitting was observed by 800 nm excitation of glass-ceramic revealed that precipitated crystalline phase was solely YLF. The precursor glass was heat-treated at 550 °C for 2 h in order to obtain the glass-ceramic. X-ray diffraction powder pattern of the crystallized glass and demonstration of light controlling with the electro-optic (EO) effect based on second-order optical nonlinearity for the future optical communication will be presented. Research collaboration with the Asahi Glass Co. has been performed to achieve “active” fiber devices such as variable optical attenuator and polarization controller involved in the glass fiber networks with huge number of access lines. We have succeeded in developments of novel glass ceramics with large second-order optical nonlinearity, new processing for space-selective laser-crystallization, and advanced fiber-type devices with the glass-crystal hybrid structure. The active fiber-type devices have exhibited the electro-optically modulations of intensity and phase in light propagation. In addition, the most impressive property from this device is the ultra-low electrical power dissipation, nano-wattage (nW), for EO operations. This is an important requirement for the future optical communication system in the world, since the “nano-watt devices” will save the energy crisis caused by the millions of usage in active optical components.

Synthesis of novel transparent glass ceramics containing rare earth ion-doped YLF nanocrystals for fiber amplifiers and fiber lasers

In recent years, rare earth ion-doped glasses have attracted a great interest due to their applications on solid state lasers, fiber lasers and fiber amplifiers. Among them, the oxide fluoride glass ceramics have been paid much attention due to their combined advantages of oxide glasses and fluoride crystals: high chemical and mechanical stabilities and low phonon energy. YLF₄ (YLF) is one of the most common rare earth-doped laser materials, with the largest number of laser lines from the UV to mid-IR range among fluoride crystals. In this paper, we report synthesis of electronically doped glass-ceramics containing YLF nanocrystals by conventional melt quenching of glass followed by controlled heat treatment of the precursor glass.

The mixture of LiF-YF₃-Al₂O₃-SiO₂ powder was melted at 1450 °C for 1 h then poured on to a steel plate pre-heated at the glass transition temperature. The precursor glass was heat-treated at 550 °C for 2 h in order to obtain the glass-ceramic. X-ray diffraction powder pattern of the glass-ceramic revealed that precipitated crystalline phase was solely YLF. The averaged diameter of primary crystallitles was roughly about 8 nm, which was small enough to keep transparency after crystallization of YLF.

When 0.1 mol.% of YF₃ was substituted by ErF₃, an emission at 980 nm with clear Stark splitting was observed by 800 nm excitation of glass ceramic though no emission was observed at the wavelength for the precursor glass. This indicates that Er³⁺ could be incorporated into YLF nanocrystals.

Fabrication and scintillation characteristic of Pr:LuAG transparent ceramics

Pr-doped Lu₃Al₅O₁₂ (Pr:LuAG) transparent ceramics were fabricated by solid state reaction and vacuum sintering. We prepared 0.3at% Pr:LuAG and 0.5at%Pr:LuAG, together with pure LuAG transparent ceramics. The thickness of each sample is 1mm. The transmittance of the ceramics beyond 310 nm reaches to around 75%. The microstructure of mirror-polished and thermal-etched surfaces of the samples was also performed by EPMA method. No pores or impurities in or between the grains were detected from one can see. The grain boundary was clean and no secondary phase was detected at the grain boundary. Furthermore, the emission and excitation spectrum of Pr:LuAG ceramics was investigated, and an obvious emission at 310nm was observed due to the radiative transition of 5d⁻4f of Pr³⁺, which is in agreement with Pr:LuAG single crystals. Radioluminescence spectra and photoluminescence decay of Pr:LuAG was measured and compared to the standard BGO single crystal sample. Light yield of Pr:LuAG was nearly two times higher than BGO. Scintillation decay of Pr:LuAG was measured and a dominant decay time of about 20 ns was detected. For the Pr:LuAG ceramics, the sintering temperature is much lower than single crystals, which may be a potential advantage. More importantly, it could be a very potential candidate for medical imaging that requires high stopping power, high light yield, fast decay and high spatial resolution.

Transparent Ce³⁺:GdYAG ceramic phosphors for white LED

The commercial white LED consist of blue LED-chip and Ce: YAG (Ce³⁺:Y₃Al₅O₁₂) powder phosphor packed with organic resins. However, these LEDs have poor heat-resisting properties.

We have proposed a white LED using rare earth ion doped transparent YAG ceramic phosphors because they have excellent formability and heat resist ance property. In addition, the emission band can be shifted from 530 nm to 575 nm by substituting the Y³⁺ sites with Gd³⁺ ion. Since the combination of the blue light and the yellow emission of Ce³⁺-YAG is cool white light, the red-shift gives warmer white light which is suitable for general illumination.

In this study, transparent Ce³⁺:(Gd, Y)AG (Ce³⁺:Y₃Al₅O₁₂ (x=0, 0.25, 0.5, 0.75)) ceramic phosphors were investigated. They were synthesized from Ce³⁺:(Gd, Y)AG nanosized powder which was obtained by the co-precipitation method with hydroxide. The Ce³⁺:(Gd, Y)AG ceramic phosphor had a broad emission band peaked at 530 nm – 560 nm due to the 5d 4f transition of Ce³⁺. With increasing Gd concentration, the redshift of emission peak wavelength occurred and the color coordinates under 465 nm LED excitation shifted to closer to the Planckian locus for the blackbody radiation in the CIE chromaticity diagram. This is related to the increase of the 5d orbital splitting of Ce³⁺ ion due to Gd³⁺ substitution at the Y³⁺ sites. The color coordinates also changed between the blue and yellow region by sample thickness. We believe that the transparent Ce³⁺:(Gd, Y)AG ceramic phosphors can improve luminescence properties of YAG-based white LED.

Fabrication of newly developed fiber-type devices with hybrid structure of crystallized glass and demonstration of light controlling with the electro-optic (EO) effect based on second-order optical nonlinearity for the future optical communication will be presented. Research collaboration with the Asahi Glass Co. has been performed to achieve “active” fiber devices such as variable optical attenuator and polarization controller involved in the glass fiber networks with huge number of access lines. We have succeeded in developments of novel glass ceramics with large second-order optical nonlinearity, new processing for space-selective laser-crystallization, and advanced fiber-type devices with the glass-crystal hybrid structure. The active fiber-type devices have exhibited the electro-optically modulations of intensity and phase in light propagation. In addition, the most impressive property from this device is the ultra-low electrical power dissipation, nano-wattage (nW), for EO operations. This is an important requirement for the future optical communication system in the world, since the “nano-watt devices” will save the energy crisis caused by the millions of usage in active optical components.
What Er3+-doped laser materials can do for you
M. Dubinski, U.S. Army Research Lab. (United States)

This presentation provides a brief overview of the very recent and the most promising laser results obtained with Er3+-doped bulk crystalline as well as silica-based fiber laser materials. It indicates that Er3+ ion has a great potential as a dopant for eye-safe lasers in the ∼1.6-um wavelength domain as well as in the 3-um wavelength domain if significant power scaling is a goal.

Results to mention are:
- Optical-to-optical efficiency close to its quantum defect limited value has been achieved with resonantly-pumped SM Yb-free Er-doped laser, which exhibited ~85%-efficient operation,
- Ultra-low quantum defect (a QD of only 1.5%) and efficient laser operation has been demonstrated for Er3+:Sc2O3 laser - the lowest QD laser operation among all known eye-safe lasers,
- Optical-to-optical efficiency close to its quantum defect limited value has been demonstrated for Er3+:Y2O3 laser pumped into upper laser level (at 974 nm) and operating at ~2.7 m,
- Over 100 W of CW power was obtained from resonantly cladding-pumped Yb-free Er-doped LMA fiber with ~69% optical to optical efficiency, to name just a few.

The results above will be presented and analyzed along with other results of similar importance for laser power scaling.

Lifetime and energy-transfer in rare-earth highly-doped glasses for 2 micron lasers
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Highly-doped glasses will be extremely useful for compact 2-micron lasers, in particular fiber lasers. In order to evaluate laser performances we made a set of tellurite glasses with Tm concentration ranging from 0.3%wt% to 10%wt% (2.2 10E21 ion/cm3). We measured the lifetime of energy level involved in the pumping and lasing processes and we inferred the energy-transfer parameters.

In addition we made a second set of Yb codoped glasses and we evaluated the energy-transfer between Yb and Tm ions (Yb doping at to 4wt%).

Lifetime measure and energy transfer were also investigated by looking at the pump-spontaneous emission transfer function.

From results we find out a fitting trend able to predict the parameters for other doping values within the investigate concentration interval.

The results are extremely useful for laser modelling since they allow to simulate lasers by using the proper parameters as the doping level is changed. To our knowledge, is the first time this investigation is made using a set of samples covering such a large doping interval.

We also assessed the impact of radiation self-trapping on lifetime and emission spectra measurement. We measured emission at several position within bulk sample. We found that impact of self-trapping, using an optimized optical system to collect fluorescence, is minimal on lifetime while more significative distortion appear on recorded emission spectra.

Nd3+ sensitized upconversion luminescence of Nd3+/Pr3+ codoped KPb2Cl5 low phonon crystal
R. Balda, M. Al-Saleh, J. Fernandez, Univ. del Pais Vasco (Spain)

Frequency upconversion of infrared (IR) into visible (VIS) light in rare-earth (RE) doped solids has been intensively investigated due to the possibility of infrared-pumped visible lasers and their potential applications such as color display, optical storage, and medical applications. In order to investigate new upconversion materials with high luminescence efficiency, hosts with low phonon energies are required. The advantage of sulphide and halide (chloride, bromide..) based hosts over the most extensively studied fluoride compounds is the lower phonon energy which leads to a significant reduction of the multiphonon relaxation rates. Unfortunately, one drawback of chloride systems is that these materials usually present poor mechanical properties, moisture sensitivity, and are difficult to synthesize. Potassium lead chloride, KPb2Cl5, has been studied as a promising host for RE ions because it is non-hydroscopic and readily incorporates rare-earth ions. The crystal is biaxial, crystallizes in the monoclinic system (space group P21/c) and it is transparent in the 0.3 to 20 m spectral region. According to Raman-scattering measurements the maximum phonon energy of optical phonons for this crystal is 203 cm⁻¹.

In this work, we report the upconversion emission from Pr3+ and Nd3+ ions in potassium lead chloride crystal after excitation in the 4F5/2, 3/2 levels of Nd3+ ions. We have observed violet, blue, green, orange, and red emissions at room temperature. Blue emission from Pr3+ ions is induced by near infrared laser excitation of Nd3+ through energy transfer from Nd3+ to Pr3+ ions. The mechanisms leading to the visible emissions have been investigated by studying the dependence of the upconversion luminescence on the wavelength and intensity of the IR pump light as well as their temporal behaviour.
Ultra-compact reconfigurable integrated silicon photonic structures

A. Adibi, Georgia Institute of Technology (United States)

No abstract available

Si-based 1D and 2D slot waveguides for magneto-optics

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Recently, new schemes using slot geometries have been proposed for various applications in integrated optics [1]. In particular, they can be useful for integrating non-Si materials into silicon based waveguides for overcoming limitations of silicon (inert band gap, small electro-optic effect etc.) [2]. Authors have earlier presented theoretical studies of 2D slot waveguide and asymmetric-1D slot waveguide geometries and their applications [3-5].

In this paper we focus on different magneto-optic effects in 2D and asymmetric-1D slot waveguides. In 2D slot waveguides non-reciprocal TE/TM mode conversion, and in asymmetric-1D slot waveguides non-reciprocal phase shift, respectively, are studied. Special polymers to enable such effects in slot waveguide geometries are also analyzed.

References:

Erbium-doped metaphosphate glasses for temperature sensing

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Frequency upconversion emission (UC) in visible region from Er\textsuperscript{3+}-doped materials have been intensively investigated in the last decades and employed in the development of photonic devices such as temperature sensors [1-3]. Among the multitude of potential hosts, phosphate glasses are promising materials for this purpose due to their physical properties such as large thermal expansion coefficient, low melting temperatures, high transparency in the UV range and efficient infrared-to-visible UC [4]. In this work, we investigate the use of Er\textsuperscript{3+}-doped tungsten-lead and sodium-lead-metaphosphate glasses as temperature sensors, based on the frequency upconversion property of Er\textsuperscript{3+} ions. Using a Ti:Sapphire laser tuned at 810 nm as excitation source and a compact CCD spectrometer, the fluorescence intensity ratio technique [1] was utilized for this purpose, and the spectral responses of gratings subjected to varying degrees of tension have been measured at a variety of temperatures, enabling us to report the differential wavelength shifts of each cladding mode’s response to tensile strain and thermal load.

References:

Phase response characterization of semiconductor saturable absorber for applications in nonlinear optical signal processing and phase-modulated signals regeneration

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The phase response of a commercial saturable absorber based on semiconductor quantum wells embedded in an asymmetric Fabry-Perot cavity operating in reflection is extensively investigated under different conditions of incident power and detuning from cavity resonant wavelength. First, the nonlinear spectral absorption is measured in order to extract information on the carrier density variation as a function of incident power, by means of numerical fitting with the results provided
by a nonlinear model. In a second set of measurements, the complex reflected field from the nonlinear cavity is measured by means of an optical complex spectrum analyzer (OCSA), and the phase change induced by the device on an incident short pulse is evaluated for different levels of saturated absorption. By relating the two sets of measurements, the linewidth enhancement factor of the device is then calculated. The chirp induced on the reflected field is also measured with the OCSA. Results are carried out using short optical pulses at 2.5 Gb/s.

The numerical model is also exploited to investigate the effect of the various cavity parameters on the phase change induced by the saturable absorber under different operating conditions. It turns out that the cavity design strongly affects the nonlinear amplitude and phase characteristic of the device, thus allowing the realization of application-tailored devices. The results from this experimental characterization and the numerical analysis show the potential of the device for practical applications like dynamic dispersion compensation, nonlinear signal processing and all-optical regeneration for phase-modulated optical signals.

7934-15, Session 4

Organic-inorganic hybrid films highly doped with functional centers for advanced photonics applications

M. Takahashi, Osaka Prefecture Univ. (Japan); H. Kakiuchida, National Institute of Advanced Industrial Science and Technology (Japan)

A new family of organic-inorganic hybrid materials will be introduced as one of candidate materials for advanced photonics applications. Alternating oxo copolymers modified with organic functional groups were prepared with solventless and catalyst free process for the first time [1]. A variety of optical functional centers such as rare earth ions, dyes and metal/semiconductor nano particles can be doped into the new materials with a high dispersivity to attain efficient optical activities [2]. The cheap fabrication of micro structures is possible by soft-lithographic or self-organized bottom-up processes because the new hybrid can be prepared through all liquid phase chemical processes. Some representative recent achievements of the new hybrid materials will be introduced in this lecture. Reversible photorefractive effect was observed for Nd ion or organic dye-doped hybrid thin films [3]. Photo-thermal processing was used to attain such a reversible effect in combination with the slow dynamics of glassy nature of the photorefractive material. Rewritable holographic memory with a novel operating mechanism was demonstrated with the material [4]. A silica glass micro spheres coated with a thin layer (< 200 nm) of Er-doped hybrid materials exhibited a low lasing threshold with a large spontaneous emission coupling factor[5].


7934-16, Session 4

Hybrid polymer optical materials and devices: the best of both worlds

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We will discuss our development of both hybrid polymer optical devices, such as high performance hybrid electro-optic polymer/sol-gel/ ion exchange waveguide modulators, and hybrid polymer optical materials, such as inorganic nanoparticle/polymer nanocomposites for integrated optical isolators and all-optical switching. Both the devices and materials have demonstrated performances beyond those of monolithic systems, while preserving many of the fabrication benefits that ordinarily accompany polymer technology.
Development of ultrahigh-speed CCD with maximum frame rate of 2 million frames per second

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We developed an ultrahigh-speed CCD with a maximum frame rate of 2 million frames per second. The shooting speed of the CCD was made possible by directly connecting CCD memories, which record video images, to the photodiodes of individual pixels. The simultaneous parallel recording operation of all pixels results in the ultimate frame rate. We analyzed the equivalent circuit model of the ultrahigh-speed CCD by using SPICE simulator to estimate the maximum frame rate. The pixel area was constructed of 410 pixels in vertical and 720 pixels in horizontal and divided into 8 blocks for parallel driving. An equivalent circuit of one block was constructed from an RC circuit with 410×90 pixels. The voltage wave pattern at the final stage was calculated when a square wave pulse was input. Results showed that the square wave pulse became blunt when the driving speed was increased. After estimation, we designed the layout of the ultrahigh-speed CCD and fabricated the device. Results of a driving evaluation experiment indicated a saturation signal level of 100% that was maintained up to 300,000 frames per second. A saturation signal level of 50% was observed in 1,000,000 frames per second and of 13% in 2,000,000 frames per second. We clarified that the maximum frame rate is dependent on a drop of the saturation signal level resulting from becoming blunt of driving voltage.

Ultra-high sensitivity photodetector arrays with integrated amplification and passivation nano-layers

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We report a hetero-junction phototransistor (HPT) array enabled by two nano-layers in its HPT pixels. The HPT base amplification layer delivers high sensitivity photon detection by 1.000x signal amplification at zero avalanche excess noise and minimal 1/f flicker noise. The passivation layer on the mesa sidewall maintains high S/N ratio for micron-size pixels, thus allowing the large-scale integration of millions of pixels into one millimeter-size small chip. The enhanced performance and reduced size, weight and cost readily translates into the same features in the resulting low-light-level focal plane array and overall spectroscopy system.

We fabricated and characterized the HPT detector pixels complete with both nano-layers - one nano-layer for low-noise high-gain amplification and the other for trench isolation, surface passivation and large-scale integration. The amplification nano-layer is the 80 nm of high-mobility HPT base layer grown epitaxially on InP substrate; and the passivation nano-layer is typically 20 nm of alumina (Al2O3) deposited by Atomic Layer Deposition (ALD) using the Savannah 100 system from Cambridge Nano Tech on the mesa device. The passivation nano-layer readily resulted in trench isolated mesa pixels.

The fabricated and measured nano-passivated HPT pixels clearly show high electrical gain, which is higher than InGaAs/InP avalanche photodiode (APD) arrays, the commercially available semiconductor photodetector array of the highest sensitivity based on our experience with Raman spectrometers. With further surface passivation to suppress dark current to pico-Amperes, the nano-passivated HPT will readily detect sub-pico-Watts of optical signal.
Recently, to further improve the nonlinear coefficient for FWM applications, much attention has been paid to non-silica fibers (e.g., SF6, Bi2O3-based, chalcogenide fibers) with higher nonlinear refractive indices. These have many advantages over silica fibers, such as low threshold to initiate the nonlinear processes, short length to generate various efficient nonlinear phenomena, and a potential for generating mid-infrared supercontinuum (SC) light. Tellurite fibers, as one type of highly nonlinear optical fiber, have a wider mid-infrared transmission window compared to SF6 and Bi2O3-based fibers, and a lower toxicity, better chemical, and thermal stability compared to chalcogenide fibers. Therefore, tellurite fibers are one of the most promising candidates for infrared nonlinear applications. However, broadband wavelength conversion based on FWM has not been reported in tellurite microstructured fibers, though a FWM demonstration has been reported in a 10 m long Er3++-doped tellurite microstructured fiber. This is mainly because the dispersion control of tellurite fibers is much more difficult in comparison to silica fibers, due to their large material dispersion in the telecom window. Tellurite microstructured fibers which have chromatic dispersion applicable to broadband wavelength conversion have not yet realized. We have successfully fabricated tellurite microstructured fibers which are adequate for broadband wavelength conversion. In this presentation, we report broadband wavelength conversion based on FWM and flattened supercontinuum generation spanning from 900 to 2800 nm in a 36-cm long tellurite microstructured fiber with a high nonlinearity.

7934-24, Session 6

Structured material combined HMO-silica fibers: preparation, optical and mechanical behaviour

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We report about preparation technique and characterization of structured fibers composed of glasses with very different thermochemical and optical properties: silica and HMO glasses. Two processes are developed, one based on glasses prepared by melting and precipitation-sintering method, the other using the powder way. Finally the fiber is manufactured following the stack-and-draw process. The HMO glasses are high lanthanum containing silicate glasses with a high nonlinearity, suitable for nonlinear applications (e.g. supercontinuum sources). The partial substitution of lanthanum by rare earth (e.g. Ytterbium) allows the preparation of effective short length laser fibers with extremely high rare earth concentration up to 5 mol%. The concentration of alumina in the HMO glasses as “solubilizer” for lanthanide was adjusted to about 20 mol%. So we overcame the concentration limits of rare earth doping of MCVD (maximum ca. 2 mol% RE2O3). Nevertheless, the investigated HMO glasses show their limits by integration in structured silica based fibers: Optical losses are typically higher than in MCVD based lanthanide containing fibers with sub-mol% concentrations of rare earth but are compensated by the high non-linear coefficient of the material and rare earth doping with higher concentration. The mechanical stability of fibers is decreased by mechanical strain caused by the high thermal expansion (3-6 ppm/K~1~) and the lower network bonding stability of the HMO glasses. We report about experimental results: tensile strength, transmission loss, bending loss, numerical aperture, mode field investigation, splicing with silica fibers.

7934-26, Session 6

Transmission characteristics of a modal interferometer based on a polarization-maintaining photonic crystal fiber depending on input polarization states

Y. Han, H. Kim, Hanyang Univ. (Korea, Republic of)

Optical fiber interferometers have attracted much attention in fiber-optic sensors because of their many advantages, such as easy manufacture, flexibility and high sensitivity to external perturbation change. To realize high quality of optical devices and fiber-optic sensors, optical interferometers based on polarization maintaining fiber have been widely investigated due to their properties of birefringence and polarization stability. The polarization-maintaining fiber-based interferometers have a drawback of temperature instability because the thermal effect considerably changes the birefringence. To stabilize their temperature sensitivity, photonic crystal fiber based-interferometers were proposed. However, the effect of the polarization states on the performance of the PM-PCF-based interferometer is not fully investigated. In addition, it is not reported that interference corresponding to two orthogonal polarization states are distinct. In this letter, a modal interferometer based on a polarization-maintaining photonic crystal fiber depending on two orthogonal input polarization states is investigated. The different wavelength spacing of the modal interferometer is observed by changing input polarization states. The proposed interferometer differently responds to temperature and ambient index change as the input polarization states are changed.

7934-25, Session 6

Guiding and confining light in low-index circularly symmetric waveguides

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Guiding light in low-index materials such as air is demonstrated in both planar and circularly waveguides by external reflections from multiple dielectric layers or photonic crystals. In addition, planar slot waveguides also can confine light in low index materials by the large discontinuity of the electric field at high-index-contrast interfaces. In this paper, we demonstrate that light can be guided in low-index materials by large discontinuity of the electric field, just like the slot waveguide and different from the hollow Bragg fiber and photonic crystal fiber, in circularly symmetric waveguides. The core region of the circular waveguides proposed here has a structure with high, low and high index from center to outside and the cladding is low index material. The modes of the waveguide are calculated by a full-vector finite-difference complex mode solver for optical waveguides of circular symmetry. The results show that the TM01 mode of the proposed circular waveguide is suitable for applications of concentrating the light in the low index region for it has radial electric field line. The optical field confinement factor, defined as the fraction of power confined and guided in the low index region, is thoroughly studied by changing the structure parameters (such as index difference and width of low index material, etc.). It is shown that the circular structure is able to concentrate the optical field in nanometer-thin low-index ring region with very high optical mode confinement density. The field confinement factors can be larger than 15% in Silica-air wire and larger than 60% in Silicon-air wire. The circular waveguides have at least the same efficiency comparing with the planar slot waveguides. Besides, the excitation of the TM01 mode is discussed. The waveguide structure has many potential applications in different fields such as such as optical communications, optical measurements and sensors.

7934-27, Session 6

Hexagonal photonic crystal waveguide based on barium titanate thin films

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There is interest in the development of ultra-wide bandwidth devices that operate at frequencies of 100GHz and above for future telecommunication applications. Ferroelectric barium titanate (BTO) has one of the highest electro-optic coefficients, making it a potential candidate for high frequency electro-optic (EO) modulators. One approach is to utilize a 2-D photonic crystal (PhC) with epitaxial BTO as the active layer. We have previously reported that the PhC superlattice structure has significant advantages over conventional devices, including both a much reduced size and large tunability of the bandgap. In this study we fabricated PhCs with hexagonal symmetry using focused ion beam (FIB) milling for the Si3N4/BTO/MgO thin film waveguide structure for operation at 1550 nm. The band structure and transmission spectra were simulated by two-dimensional finite-difference time-domain (FDTD) calculations. The hexagonal symmetry PhC has a 6-8 THz wide bandgap centered at a wavelength of 1550 nm. Simulations indicate a complete bandgap is present for a hexagonal PhC for a 30-micron long active region. Addition of a single line defect in the PhCs will generate a transmission window at a wavelength of 1550nm inside the gap. Experimental optical transmission measurements on these PhC waveguides over the wavelength range from 1456 to 1584nm indicate the presence of a bandgap. PhCs based on Si3N4/BTO/MgO multilayer thin films also show the potential of a large tunability of the bandgap. The bandgap tunability of the hexagonal PhC structures was simulated and measured.

7934-28, Session 7
A novel fabrication technique of long-period fiber gratings based on periodic ridge structures in the cladding of a single-mode fiber
Y. Han, O. Kwon, S. Park, Hanyang Univ. (Korea, Republic of)

Long-period fiber gratings (LPFGs) have attracted much attention in optical communication optical systems and sensors because of their many advantages, such as low cost, ease fabrication, and electromagnetic immunity. To fabricate LPFGs with UV laser, photosensitive fibers are necessary. However, it is not easy to fabricate LPFGs with special fibers, such as photosensitive fiber, photonic bandgap fiber, and silica fiber without photosensitivity. Recently new fabrication methods of LPFGs by using CO2 laser or electric arc discharge were reported. However, the additional loss can be induced and it is not easy to control the quality of the LPFG. In this paper, a novel fabrication method of long-period fiber gratings (CLPFG) based on periodic ridge structures in the cladding of a single-mode fiber is proposed and experimentally demonstrated for mass production. The proposed fabrication technique of LPFGs is based on double layers of polymer coatings surrounding a single-mode fiber. The corrugated LPFG was previously proposed. To induce the periodic groove structures in the cladding layer, a dispersion-shifted fiber was implemented and the thin metal layers were deposited on the surface of the DSF for etching protection by using an evaporation system. However, it is not easy to symmetrically coat the surface of the DSF because of the cylindrical shape of the fiber. The metal coating can be readily removed by a hydrofluoric acid (HF) because of the low adhesion force in the silica surface with a cylindrical shape in the optical fiber. Therefore, it is not easy to induce grating structures in the fiber surface. In the proposed technique, however, the polymer was utilized instead of the thin metal layer. By using double coating processes, the polymer-based segmented ring patterns were periodically coated in the surface of a single-mode fiber. The polymer (PCA-3000PM) with a thickness of 150 m was coated on the substrate by using a spin coater. After positioning a single-mode fiber on the surface of the polymer surface, the same polymer was covered the optical fiber by using a spin coater again. The solvent included in the polymer was removed by using a hot plate. The doubly coated single-mode fiber was periodically exposed to an UV lamp through a shadow mask and the UV cured polymer regions were removed by using a developer (P-7G). The grating period and the length of the shadow mask were 550 m and 20 mm, respectively. The periodic grating patterns on the surface of a single-mode fiber were for HF production. The periodically polymer-prepatterned single-mode fiber was soaked in the HF solution and the periodic ridges in the surface of the fiber were created by etching the silica cladding. The remained periodic polymer structures were removed by using acetate solution. Consequently the LPFG with periodic ridge structures in the cladding region was realized. A high quality of the transmission with a high extinction ratio of 15 dB was obtained. The peak depth was controlled by changing the applied tensile strain without center wavelength shift.

7934-29, Session 7
Wavelength tunable long period gratings based on silica waveguide geometric modulation
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This paper presents long period grating (LPG) devices based on a periodic thickness variation in the waveguide structure, fabricated by etching into the lower cladding layer prior to definition of the waveguide core. This periodic geometric change results in a stable grating structure and a permanent refractive index modulation of 10-4 or higher, which is comparable to the index modulation in Ge-doped silica material induced by photo irradiation that has been widely used in grating fabrications. This grating produces a strong resonance at a particular wavelength in the transmission spectrum, demonstrating broad applications ranging from wavelength filter to signal distribution in the communication area. In this work, a polymer and silica hybrid architecture has been implemented in order to achieve wavelength tunability. Using a thermal oxide layer as a lower cladding, a Ge-doped silica ridge is patterned using conventional photolithography and reactive ion etching to form the waveguide core, which is then covered with a low index fluorinated polymer cladding. While the silica waveguides offer a lower propagation loss and an easy processability, the top polymer allows the device to be thermally tuned over a wide wavelength range by exploiting the large thermo-optic coefficient of the fluorinated polymer and the high sensitivity of the underlying LPG to the refractive index of the cladding layer. Strong rejection bands have been demonstrated in the C+L band, in a good agreement with theoretical calculations. Corrugated structures have been defined across an extended area under multiple waveguides resulting in coupling of light from the core propagation mode into cladding modes and back into the neighboring waveguides located far from the evanescent coupling distance. This kind of coupler can facilitate devices that require extraction and control of a particular waveguide mode for applications such as multiple channel signal distribution and temporal pulse shaping. Implementation of LPFGs for these applications will be discussed.

7934-30, Session 7
Subwavelength metallic gratings as an integrated device: polarized color filter
H. N. Nguyen, Y. Lo, Y. Chen, T. Yang, National Cheng Kung Univ. (Taiwan)

Subwavelength metallic gratings were proposed as integrated polarized-RGB (red, green, and blue) color filters here and their performance was further numerically optimized with the rigorous coupled-wave analysis (RCWA) method and the genetic algorithm (GA). Grating types include the single-layer type and the double-layer one while parameters to be optimized are the period, filling factor, and thickness of each layer. The ideal performance is defined both by the large extinction ratio over the visible range and by the high transmittance aiming at wavelengths of 700 nm (R), 546.1 nm (G), and 435.8 nm (B). Results showed that a double-layer grating achieves about 50% transmission efficiency and a large extinction ratio (60dB), which are better than those in previous studies. If the proposed design can integrate with popular liquid crystal display panels, a promising way can be paved to reduce the volume and cost of display electronics.
7934-31, Session 7

Polarization-insensitive stacked liquid crystal polarization grating bandpass filters

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We introduce a polarization-insensitive optical filter that has high throughput for unpolarized and/or arbitrary input polarization. This configuration has the potential for compact and low cost applications in spectroscopy, remote sensing, and beyond. Similar to Lyot and Solc filters (but without polarizers), this design is based on a stacked configuration of polymer polarization gratings (PGs) and either fixed or tunable wave plates. PGs are anisotropic diffraction gratings, which exhibit unique properties including zero-order transmittance that is independent of incident polarization. PGs can be configured to operate at visible and infrared wavelengths, and practically all diffracted light appears (in experiment and theory) within the zero- and first-diffraction orders with efficiency in the range of nearly 100% to 0%. This filter concept comprises several broadband PGs along with conventional wave plates stacked in various configurations to function as polarization-independent fixed or tunable bandpass filters with minimum loss: high peak transmittance (~ 90%) is achievable, which is nearly impossible with polarization-based technologies. In this work we explore a variety of filter stack configurations and analyze them theoretically using Jones Calculus and Poincare Sphere reasoning. Both fixed and tunable filter configurations are presented and analyzed in terms of finesse, full width at half maximum, free spectral range, and tuning range. We then present preliminary experimental data for a three stage fixed bandpass filter. We will also evaluate the most likely practical limitations imposed by material properties and fabrication.

7934-32, Poster Session

Research on testing instrument and method for correction of the uniformity of image intensifier fluorescence screen brightness

Y. Qiu, Nanjing Univ. of Science & Technology (China)

To test the parameters of image intensifier screen is the precondition for researching and developing the third generation image intensifier. When testing the uniformity of image intensifier fluorescence screen brightness, although the uniformity of electron source meets American Army Standard, the power and density of edge electrons still weaker than that of the middle by about 5%. The picture of brightness uniformity of tested fluorescence screen shows bright in middle and dark at edge, It is not so direct to evaluate the performance of fluorescence screen. We analyze the energy and density distribution of the electrons. We correct the measured value with correction formula for correction principle. After correction, the image in computer is very uniform. So the uniformity of fluorescence screen brightness can be judged directly. It also shows the correction method is reasonable and close to ideal image.

When the uniformity of image intensifier fluorescence screen brightness is corrected, the testing instrument is developed. In a vacuum environment of better than 1×10^-4Pa, area source electron gun emits electrons. Going through the electric field to be accelerated, the high speed electrons bombard the screen and the screen luminize. By using testing equipment such as imaging luminance meter, fast storage photometer, optical power meter, current meter and photosensitive detectors, the screen brightness, the uniformity, light-emitting efficiency and afterglow can be tested respectively. System performance are explained. Testing method is established; Test results are given.

7934-06, Poster Session

Emission from a bismuth doped chalcogenide glass spanning from 1 μm to 2.7 μm

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In this paper we report emission form Bi doped gallium lanthanum sulphide (Bi:GLS) glass with a full width at half maximum (FWHM) of 600 nm which is flattened and covers the entire telecommunications window. The excitation wavelength of this emission was 1020 nm, the quantum efficiency (QE) was 17%, the lifetime was 160 μs and product of the emission cross section and lifetime (em) was 2x10^-25 cm2s. The maximum room temperature QE was 32% at 900 nm excitation. At cryogenic temperatures the FWHM reached 850 nm with 974 nm excitation and we observed two new bismuth emission bands at 2000 and 2600 nm. The QE reached 40% for both 974 and 808 nm excitation at cryogenic temperatures. Emission spectra, normalized to the excitation power, taken with excitation wavelengths of 480-1300 nm, revealed 4 absorption bands at 680, 850, 1020 and 1180 nm. The 1180 nm absorption band was previously unobserved. Deconvolution of the emission spectra into Gaussians indicated 5 distinct emission bands over the entire excitation range. The maximum room and cryogenic temperature lifetimes were 175 and 280 μs, respectively. Their respective emission and excitation wavelengths were ~1500 and 974 nm; and ~1600 and 808 nm. By examining previously published models of Bi emission in glasses to see if they could account for the 2000 and 2600 nm emission bands, and reviewing other previously published evidence, we propose that the origin of the emission in Bi:GLS is Bi2 (2-) dimers.

7934-33, Poster Session

Novel method for fabrication of metal- or oxide-nanoparticle doped silica-based specialty optical fibers

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Nanoparticle-doped optical fibers are causing significant scientific interest in different application fields. Doping of silica glass layers during optical fiber preform fabrication was so far reported by sol-gel and solution doping processes, by flame hydrolysis spraying and by pulling hollow cylinders from nanoparticle suspensions. All these methods have shown deficiencies for fabrication of high quality fibers, therefore a novel method is suggested.

Proposed method is based on “flash vaporization” deposition process, previously reported as method to fabricate rare earth- and metal ion-doped specialty optical fibers. “Flash vaporization” method allows vapor-phase doping of silica layers by impulse evaporation of finely distributed aerosols, produced from solutions or suspensions of organometallic precursors with organic solvents. Experiments were made where SiO2 layers were deposited using “flash vaporization”-equipped MCVD system while doping was achieved by injecting vapors containing metal and oxide nanoparticles (Cu or mixture of Er2O3 / Au2O3) into deposition zone.

Analysis of produced preforms confirms presence of nanoparticles in deposited layers, albeit with low deposition rate due to weak thermophoretic forces acting on very small particles or agglomerations. Based on results, a number of improvements were suggested and implemented in fabrication process, device design and choice of precursor materials.

It has been demonstrated that “Flash vaporization” method allows deposition of nanoparticles in silica layers and that it provides advantages over other deposition technologies - it permits in-situ fabrication of complete preforms, it provides easy upgrade path for existing MCVD and OVD deposition systems and allows co-doping by a wide range of other co-dopants.
Measurement of a single polarization state and transmission characteristics of a Sagnac loop interferometer based on a single polarization fiber

Y. Han, O. Kwon, Hanyang Univ. (Korea, Republic of)

The optical fiber sensors have been of interest in mechanical and chemical sensing applications because of many virtues, such as ease fabrication, low insertion loss, and electromagnetic immunity. The polarization state of light is importantly considered to realize the high quality of the fiber-optic interferometric sensors and devices. The birefringence components, such as a polarization maintaining fibers and photonic crystal fibers, are important to induce the interference pattern. Recently single polarization fiber (SPF) was developed and applied to many research areas, such as fiber lasers, fiber-gyroscopes, and fiber sensors. If the modal interferometer is configured by using a SPF, it is very useful for fabrication of versatile devices and sensors. However, modal interference properties based on a SPF were not fully investigated yet. In this paper, we investigate the interference characteristics of a SPF-based Sagnac loop mirror. Since the SPF has two cutoff wavelengths (cutoff-1 and cutoff-2) corresponding to two orthogonal input polarization states, a single polarization mode is only propagated in a specific wavelength range, which induces peculiar interference patterns. Two polarization lights can be interacted at the wavelength range under the cutoff-1 because two polarization modes can be propagated. However, there are no interference patterns if the wavelength is ranged in a single polarization region (between cutoff-1 and cutoff-2). By using a unique interference pattern of the SPF, the cutoff wavelengths for each polarization state can be readily determined. Many devices and equipments to measure two cutoff wavelengths of the SPF are required and the input polarization state should be precisely controlled. However, it is easy to obtain the optical properties of the SPF, such as birefringence and two cutoff wavelengths by using the SPF-based Sagnac interferometer. We also measure the transmission characteristics of the SPF-based Sagnac interferometer as the applied temperature and strain are changed. Since the SPF has an elliptic core surrounded by two air holes, peak wavelengths shift to the longer wavelength.

Fabrication of long-period fiber grating based on a periodic micro-tapering technique

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Technical progress of optical fiber gratings has got great impact on development in telecommunications and optical sensing. Fiber gratings are important devices to control properties of optical signals and they are utilized for applications to spectral filters, dispersion compensating components in wavelength division multiplexing systems, and fiber sensing elements. The operating principle of a fiber grating is based on periodic perturbation of a refractive index, which induces the coupling of the fundamental mode to the other mode, such as backward propagating core mode or forward propagating cladding modes. In a long-period fiber grating (LPFG), the mode coupling between the core and cladding modes generates the attenuation band in the transmission spectrum. Many techniques to fabricate LPFGs in single mode fibers and other special fibers were proposed. The common techniques are the use of ultraviolet (UV) irradiation, CO2 laser irradiation, and corrugation method. In the case of UV irradiation and CO2 laser irradiation, however, high cost special fiber or complex fabrication equipments are necessary. The process of corrugation method is very complicated. Therefore, it is important to investigate a novel fabrication method of fiber gratings. In this paper, a novel fabrication technique of the LPFG based on a micro tapering method is presented. The micro tapering method is composed of two simultaneous processes. One is a heating process and the other is an elongation process by using a pulling device. Control the elongation speed of pulling device and the temperature of heating process can change the structure of fiber without unwanted defect. The micro tapering method does not need high cost equipment, such as CO2 laser, hydrogen loaded fiber and amplitude mask. Process of micro tapering method is simple. And parameters of LPFG are easily adjustable. Therefore, the micro tapering method is very useful for fabrication of fiber gratings.

Study on photodoping properties for the multilayered films GeS2/Ag/GeS2 and Ag/GeS2/Ag


Photodoping phenomenon found by Kostyniuk in Russia is observed when a double-layer consisting of amorphous chalcogenide film and metal films is exposed to the light. Among light-induced phenomena in amorphous chalcogenide films, the photodoping phenomenon has been investigated by many researchers according to not only an expectation for useful applications but also the interest in abnormal diffusion mechanism. It is well-known that the chalcogenide glasses (As2S3, As2Se3, Ge2S6, GeSe2 etc.) change their physical, chemical and mechanical properties remarkably by photodoping of metal (Ag, Cu etc.). Among these chalcogenides, it is known Ge2S6 exhibits small lateral diffusion, which is good for fine processing. The application to high-speed light switches that change electrical resistance on light irradiation, waveguides formed by the doped regions, and high density memories using holographic recording are thought as potential applications of the photodoping phenomenon. In this report, the photodoping characteristics of multilayer film systems, Ge2S6/Ag/Ge2S6 and Ag/Ge2S6/Ag, were analyzed and compared with the conventional double layer film system Ag/Ge2S6. Multi layered films were fabricated to examine the optical application for higher doping rate of Ag adaptable to high-speed systems. The photodoping phenomena were observed by using the lasers with three different wavelengths. Moreover, the difference of the photodoping phenomena was observed by using...
different type of multi layered films. The feasibility to apply three layered films to optical memories and waveguides were discussed.

7934-38, Poster Session

Soliton self-frequency shift in tellurite microstructured fiber
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Soliton self-frequency shift (SSFS) is a well-understood phenomenon in fiber-optic communications. SSFS has been investigated in various silica fibers over the past decade to fabricate fiber-delivered, widely frequency-tunable and femtosecond pulse sources. TeO2-B2O3-ZrO2-Na2O (TBZN) tellurite fibers with large usable Raman shift and about 20 times higher Raman gain coefficient than that of silica have been developed. In this paper, we have used TBZN tellurite fiber as the Raman gain medium for SSFS. We report broad near-infrared soliton source generation in a TBZN tellurite microstructured optical fiber (MOF) pumped by a 1557 nm femtosecond fiber laser. A continuous soliton wavelength shift from 1582 nm to 1851 nm was realized through a tellurite MOF as short as 6.5 cm. In order to simulate SSFS in tellurite MOF, it is necessary to model the Raman response of tellurite glass for numerical simulations. An analytical description of the Raman response function of tellurite glass is provided, and a Raman contribution factor of 0.51 is obtained from the actual Raman gain spectrum. The intermediate-broadening model can provide an accurate quantitative description of Raman response of TBZN tellurite fiber. Experimental results are in good agreement with the numerical simulations using a generalized nonlinear Schrödinger equation. We also give the comparison of SSFS in silica and TBZN tellurite fiber. The frequency shift amount of TBZN tellurite fiber is much larger than that of silica fiber. These results show that the TBZN tellurite glass is a promising material for SSFS.

7934-39, Poster Session

Dispersion controlled tellurite air-clad fibers for supercontinuum generations pumped by picosecond and femtosecond fiber lasers respectively
M. Liao, X. Yan, G. Qin, C. B. Chaudhari, T. Suzuki, Y. Ohishi, Toyota Technological Institute (Japan)

Supercontinuum (SC) generation has the important applications such as broadband light source, Optical coherence tomography, ultra-short pulse compression, and optical frequency metrology, etc. Tellurite glass is transparent in the mid-infrared range, and has a higher n2 than silica glass by at least one order of magnitude. In this research, we have fabricated the hexagonally shaped tellurite air-clad fiber with a core diameter of around 1 μm through controlling the temperature field exactly in the process of fiber-drawing. Since the SC generation strongly depends on the chromatic dispersion, which is determined by the microstructure of fiber, it is interesting to investigate and demonstrate such dependence for such a small core fiber in detail. In this work by pumping a positive pressure of nitrogen gas into the holes of preform, we obtained 1 μm core fibers with diameter ratio of holey region to core (DRHC) varied from 3.5 to 20. The dispersion was tailored effectively by the variation of DRHC. Dependences of SC on the microstructure and dispersion were demonstrated. The pump lasers were picosecond and femtosecond fiber lasers, respectively. One octave flattened SC generation was obtained for the fibers pumped by 1064 nm picosecond fiber laser with the pulse energy of several hundred pJ. Intense second and third harmonic generations were obtained under the pump of 1557 nm femtosecond fiber laser. The correlation of dispersion and SC spectra was analyzed. Such tellurite microstructured fibers, with high nonlinearity and controlled dispersion are significant in nonlinear applications.

7934-40, Poster Session

Polarization hologram with a low aspect ratio
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The interaction of light with a sub-wavelength periodic grating can be approximated by a uniform medium with an effective index. The effective index is a function of the grating structure, the indices of its composite materials and the polarization of light. A polarization hologram is designed which makes the light in certain linear polarized mode diffract and the perpendicular linearly polarized mode transmit based upon this principle. In the hologram, an area with a sub-wavelength gratings and another area with a flat surface are placed periodically and a high index film is deposited on both areas. The structure of the sub-wavelength gratings and thickness of the film are adjusted that the phase shifts of the light generated in both areas balance each other out, and a design with a low aspect ratio below 1.0 is achieved. This low aspect ratio is an advantage in production. Also fabrication and testing the hologram is performed.

In addition, in the case of light in different wavelength and each with the perpendicular polarization the hologram acts as a wavelength selective optical element.

7934-41, Poster Session

Ion beam figuring of silicon aspheres
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Silicon lenses are widely used for infrared applications. Especially for portable devices the size and weight of the optical system are very important factors. The use of spherical lenses instead of spherical silicon lenses results a significant reduction of weight and size. The manufacturing of silicon lenses is challenging compared with the manufacturing of standard glass lenses. Typically conventional methods like diamond turning, grinding and polishing are used. Due to the high hardness of silicon diamond turning is very difficult and need a lot of experience. To achieve surfaces of high quality a polishing step is mandatory. The required surface form accuracy cannot be achieved by using conventional polishing methods because of unpredictable behaviour of polishing tools which results in an unstable removal rate. To overcome these disadvantages a method called Ion Beam Figuring can be used to manufacture silicon lenses with high surface form accuracies. The general advantages of the Ion Beam Figuring technology are the contactless polishing without aging effects of the tool. Due to this an excellent stability of the removal rate without any mechanical surface damage are achieved. The related physical process called sputtering is observed on any material and is therefore appropriated for materials of high hardness like Silicon (SiC, WC) as well. The process is realized on the commercially available ion beam figuring system IonScan 3D. During the process, the substrate is moved in front of a focussed broad ion beam. The local milling rate is controlled upon a modulated velocity profile which is calculated specifically for each substrate in order to mill the material at the associated positions to the target geometry. The authors will present aspherical silicon lenses with very high surface form accuracies compared with conventional manufactured lenses.

7934-42, Poster Session

Global characterization of an advanced prototype of a multi-channel acousto-optical spectrometer for the Mexican Large Millimeter Telescope
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Both ground-based and satellite applications have demonstrated that acoustooptical spectrometers of radio-signals represent really reliable signal-processing technique for sub-millimeter and millimeter radio-astronomy due to these devices exhibit rather well efficiency as well as present sufficiently high frequency resolution in reasonably large frequency bandwidth. The key component of spectrometer is the acoustooptical cell, which dictates the basic parameters of signal processing. Its operation is based on the ability of cell to produce a large amount of independent from one another dynamic acoustic diffractive gratings, so that each of them reproduces the amplitude and frequency of only one spectral component from the incoming radio-signal. A multi-pixel COG linear array detects and digitizes the obtained responses in the Fourier plane of a large-aperture integrating lens. The main peculiarity of this prototype lies in exploiting a large-aperture tellurium dioxide crystalline acoustooptical cell, oriented along the [001]- and [110]-axes, in the regime of anomalous light scattering by extremely slow acoustic waves providing the improved frequency resolution. This circumstance determines the majority of technical requirements to the framing sub-systems and performances of prototype as a whole. Due to an extremely high anisotropy of this crystal, the efficiency of light scattering depends essentially on the ellipticity of the incident light polarization, so that high-efficient operation needs the eigen-state elliptic polarization, which is determined by the incidence angle, light wavelength, and accuracy of the cell's crystallographic orientation. The first trial experiments have shown frequency resolution of about 20 KHz within operating up to 3000 parallel frequency channels in real time scale.

7934-43, Poster Session

Furnace chemical vapor deposition (FCVD) method for special optical fibers fabrication

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The quality of an optical fiber directly depends on the quality of the initial preform. To date there is a lot of technological processes for optical fiber preform manufacturing: OVD, VAD, APVD, MCVD, FCVD and PCVD. The latter three methods are very similar. Our work is devoted to the Furnace Chemical Vapor Deposition (FCVD) method. In spite of the fact that the FCVD method has certain advantages and was used, in particular, by firms Draka and Alcatel, there are few publications on this method and references in the majority of cases have an indirect character.

The features of the Furnace Chemical Vapor Deposition (FCVD) method of manufacturing preforms for special optical fibers are considered. It is shown that misalignment of substrate silica tube and furnace hole axes has a negative effect on the quality of fabricated preforms, leading to angular and radial asymmetry of the refractive index profile. Ways of getting rid of this and other disadvantages of the FCVD method are described. A comparison of the FCVD and MCVD methods is carried out. It was demonstrated that the FCVD method, despite some drawbacks, allows you to manufacture high-quality fiber preforms with good symmetry of the refractive index profile, and thus it is promising for fabrication of special-purpose optical fibers. Research has shown that FCVD method is especially attractive for dispersion, dispersion varying and active fibers manufacturing. Optical fibers made from such preforms have good characteristics and, hence, may find wide application in various fields of fiber optics.

7934-44, Poster Session

Optical absorption spectra of GaMnN films

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Room temperature ferromagnetism of GaMnN thin films with different Mn concentrations were grown on c-sapphire substrates by metal organic chemical vapor deposition (MOCVD). Compared with GaN, the results of optical absorption spectra for the GaMnN samples were shown that a peak of absorption can be observed near 1.44 eV, and the absorption coefficient increased with the increase of the Mn content. In addition, electronic structure and optical properties for several Mn concentrations doping GaN were calculated using density functional theory. The theoretical data were in excellent agreement with the experimental results. Associated with theoretical data, the peak of absorption near 1.44 eV is assigned to ST2 5E internal transition between the e state and the t2 state of Mn3+ ion.

7934-45, Poster Session

Photocurrent spectrum measurements of doped black silicon

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Black silicon has realized full wavelength absorption from ultraviolet to infrared and opens new ways to produce low-cost and high-efficiency photodetectors, light emitters and solar cells as well. The advantages for the industry include reduction of cost, an increase in conversion efficiencies and improvements in manufacturing yields. In any optoelectronic applications, photocurrent measurement is one of the key characterizations. In this work, a simple method is provided to characterize photoelectrical properties of doped black silicon materials. Current-voltage curves and photocurrent spectra of three black silicon samples that were annealed at different temperatures were measured. The measured photocurrent spectra were found to depend on spacing between electrodes. Hall measurements show high concentration but low mobility of electrons in these samples. The experiments results show that doped black silicon is suitable for photoconductors. But due to its low mobility, its response speed will be low. Pressure on electrodes also affects measurements of photocurrent spectra.

7934-46, Poster Session

Comparison of spectroscopic properties of neodymium-doped aluminium garnet (Nd:YAG) ceramics obtained by reactive sintering of Al2O3, Y2O3 and Nd2O3 and by synthesis of nanocrystalline Nd:YAG powders

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Ceramic materials are interesting alternative to single crystals for various optoelectronic applications including high-power lasers and photodetectors. Main advantages of ceramics compared to their single crystal counterparts are lower costs of production, ability to incorporate higher dopant concentrations and possibility to manufacture larger elements. In the present work, the spectroscopic properties of ceramics obtained by two different methods are compared. First method relies on solid-state reaction of nanometric oxide powders, i.e. Al2O3, Y2O3 and Nd2O3. The oxides with addition of tetraethyl orthosilicate were sintered under vacuum and annealed. Second method is the synthesis of neodymium-doped aluminium garnet (Nd:YAG) nanocrystalline powders prepared by coprecipitation technique. The powders were calcined and vacuum-sintered in optimized process conditions.

For all ceramic samples absorption, fluorescence and decay data is.
presented. In the part devoted to the Nd:YAG nanocrystalline powders and synthesized from them ceramics, the spectroscopic properties for both powders and ceramics are analyzed. It was found that the decay times of the Nd3+ luminescence were significantly longer for nanocrystalline powders than for sintered ceramics. The discussion of effects leading to the life-time shortening in ceramics is given.

Presented results indicate that the ceramic samples obtained by reactive sintering method have superior spectroscopic properties compared to the samples synthesized from Nd:YAG nanocrystalline powders. The optimization of manufacturing process allowed to demonstrate ceramics having the properties comparable to single crystal counterparts. Optical quality and luminescent properties make the ceramics manufactured at the Institute of Electronic Materials Technology an interesting candidate for laser applications.

7934-47, Poster Session

**Toward single-material multilayer interference mid-infrared filters with sub-wavelength structures for cryogenic infrared astronomical missions**

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We are developing high performance mid-infrared (especially 30-40µm wavelength regions) multilayer interference filters with mechanical strength and robustness for thermal cycling toward cryogenic infrared astronomical missions.

In mid- and far-infrared (MIR/FIR) regions, there are a few optical materials so that we can only use limited refractive index values to design filters, which makes difficult to realize high performance filters.

It is also difficult to deposit thick layers required for MIR/FIR multilayer filters.

Furthermore, deposition of two materials, which have different coefficients of thermal expansion, makes filters fragile for thermal cycling.

To clear these problems, we introduce sub-wavelength structures (SWS) for controlling the refractive index.

Then, only one material is necessary for fabricating filters, which enables us to fabricate filters with mechanical strength and robustness for thermal cycling.

According to the effective medium approximation (EMA) theory, the refractive index of randomly mixing materials in sub-wavelength scale is controllable by changing the ratio of mixing materials.

However, it is not clear that EMA can be applied to such simple SWS, periodic cylindrical holes on a bulk material, which is easily fabricated by photolithography.

In order to verify the controllability of refractive index by simple SWS, we have fabricated simple SWS on a silicon substrate and measured its transmittance.

Comparing measured transmittance with theoretical transmittance calculated by EMA, we confirm that EMA can be applied to simple SWS fabricated by photolithography.

Also we confirm that measured transmittance agrees with the result of rigorous coupled wave analysis (RCWA) simulation.

7934-48, Poster Session

**Spectroscopic properties of Nd Er codoped glasses for solar-pumped fiber lasers**

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In this study, the absorption and fluorescence characteristics of Nd, Er codoped fluoride glasses were investigated under simulated sunlight or laser beam illumination to show their solar energy application potential. The simulated sunlight was composed of a Xe lamp with a built-in air mass (AM) 1.5 filter which cut the wavelengths above about 800 nm. Er was assumed to enable the energy transfer in Nd doped fluoride glasses to enhance their NIR emission due to additional light absorption in the ultraviolet and visible regions. It is because Er, Nd codoped fluoride glasses have the overlaps of the absorption peaks at the wavelengths of 800 and 530 nm whose peaks are might be a pass for the energy transfer from Er to Nd. Er-doped fluoride glasses showed four emission peaks at the wavelengths of 550, 848, 977, and 1533 nm attributed to the electronic transitions of Er3+ ions under simulated sunlight illumination. Nd, Er codoped fluoride glasses showed the same emission peaks but comprised also emission peaks attributed to 4F3/2 - 4I9/2, 4F3/2 - 4I11/2, and 4F3/2 - 4I13/2 transitions of Nd3+ ions. The energy transfer from Er to Nd was studied by 404 nm laser light illumination which is absorbed by Er3+ ions only. Strong contribution of Er absorption to 1.05 µm emission was observed in Nd, Er codoped fluoride glasses proposing them for use in solar energy applications.

7934-49, Poster Session

**Fabrication and performance characterization of 1550nm hetero-multiplication avalanche photodiodes for single photon detection**

W. Ho, J. Liu, S. Ou, C. Chen, H. Tang, National Taipei Univ. of Technology (Taiwan)

We report the fabrication and performance characterization of 1550 nm separate absorption, grading, charge, and InP/InAlAs hetero-multiplication avalanche photodiodes (SAGCHMs) for single photon detection applications. The linear mode performance of the fabricated APDs are firstly characterized that the dark current at 95% of the breakdown voltage was 30 pA and 15 nA at 200K and 300K, respectively. The gain-bandwidth product of 62 GHz was obtained at room temperature. For single photons detection characterization, however, our APD was operated in the gated passive quenching mode, at lower temperature and incorporated with an optimizing spike-cancellation self-differencing circuit. Under the temperature of -50°C and the gate repetition frequency of 100 KHz with pulse width of 2 ns, the lowest dark count probability (Pdc) of 1.2 x 10-5, the highest single-photon detection efficiency (det) of 22.5%, and the lowest noise equivalent power (NEP) of 1.5 x 10-15 W/(Hz)1/2 were obtained, respectively. Moreover, we demonstrated the transmission distance as a function of quantum bit error rate (QBER) based on the obtained performance parameters. The maximum transmission distance, at QBER = 15%, of 43 km was achieved.

7934-50, Poster Session

**Characterization of a generalized elliptical phase plate by using equivalent theorem of a linear phase retarder and a polarization rotator**

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An equivalence theory based on a unitary optical system of a generalized elliptically birefringent phase plate is proposed and derived. The elliptical phase plate can be treated equivalently as the combination of a linear phase plate and a polarization rotator. Three fundamental parameters, including the elliptical phase retardation, the azimuth angle, and the ellipticity angle, of the fast elliptical eigenstate are derived. All elliptical parameters of a generalized elliptical phase plate are applicable in terms of the equivalent parameters of the equivalently optical components.
Characterizing the polarization features of a multi-prism fused-silica beam expander for a wide-aperture acousto-optic applications

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Practical applications confirm that acousto-optical spectrometers of optical and radio signals provide efficient, reliable, and accurate processing of data in real time scale. The key component of similar spectrometers is the acousto-optical cell, which dictates performances of spectrum analysis. Within non-collinear arrangement of spectrometer, cell determines the groove density and the aperture of dynamic diffractive grating, i.e. spectrum resolution of the system. The most efficient and wide-band regimes of operation can be realized via exploiting crystalline cells. However, desirable crystals have a high optical anisotropy and optical activity, so that their efficiency depends essentially on the incident light polarization. Therefore, a high-efficient and wide-band operation of crystalline cells requires the eigen-states of elliptic polarization conditioned by the incidence angle, light wavelength, and the cell’s crystallographic orientation. The most compact and simplest scheme of really wide-aperture expander appears with the even numbers of prisms. Similar arrangement does not deflect light beam, provides high transmission, and needs less alignment precision than one made from a telescope. We consider the expander consisting of four BK7-glass Litrow-prisms (30°-60-90 triangles). With linear polarization oriented in the plane of expanding, more than 40-time magnification and 70%-transmission are achieved at a distance of 10 cm. Within elliptical polarization, this expander exhibits properties of an amplitude filter being very sensitive to the angle of beam incidence due to varying the transmittance ratio. In a view of obtaining the needed eigen-states of elliptical polarization at the output of expander, the detailed analysis of polarization features is performed, numerically estimated, and selectively compared with experimental data.
7934-55, Poster Session

**Broadband source for sensor characterization**

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Continued innovation with optical components and optical materials not only increases the utility and value of optical sensors and devices, it also mandates the development of new test methods and test hardware. Thus, in order to evaluate the enhanced performance of these new optical components and systems-SWIR imagers, silicon-based photodetectors, and single-photon detectors; as well as detectors that utilize novel materials for highly specific spectral regions-equally enhanced test and measurement equipment must be used. A task such as this is greatly simplified for these detectors when a minimal amount of hardware can be used to test, measure, and calibrate the benchmarks of their performance; benchmarks such as SNR, uniformity, sensitivity, linearity, and dynamic range. The role of the test hardware is driven by its ability to provide high resolution, uniform, and stable broadband output. A broadband source encompassing the UV through the SWIR region of the electromagnetic spectrum capable of producing high daylight irradiance levels down to low star light irradiance levels. All of this functionality is integrated into one calibrated test set. A test set that is robust but does not sacrifice precision and accuracy. This paper will explore characterization testing and the advantages and drawbacks of various types of broadband sources spanning UV through SWIR over a high dynamic range of output. This paper will further suggest standardization of test methods and presentation of results (for example, SNR) such that results from various detectors can be compared directly.

7934-56, Poster Session

**Design of closed-loop double-cell self-phase modulation based optical regenerator**

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Considerable attention has been given to optical regenerators as a future replacement for their electrical counterparts. A proposed scheme based on self-phase modulation has been intensely studied, culminating in design rules and methods of optimization.

Simulations were run using custom software. The field envelope propagation was modelled using the generalised non-linear Schrödinger equation. The numerical integration routine used is referred to as the 4th-order (global) Runge-Kutta in the interaction picture method and uses an adaptive step-size to reduce computation time.

The results show that a double-cell, self-phase based 2R-regenerator is advantageous over a single-cell version. It allows recovery of signal wavelength and reduces the amplitude and timing jitter. Additional loops through the device continue to show favourable reduction in amplitude jitter through the incremental Q-factor difference between successive loops. Simulations have shown that Q-factor improvement becomes negligible after few loops and that the scheme needs careful power optimization.

7934-58, Poster Session

**Performance of randomly distributed holes optical fibers under low dose gamma-ray irradiation**

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This work focuses on studying irradiation effects on randomly distributed holes optical fiber (RDHF). This type of specialty fiber could serve as both a sensing element and a data transmission medium. These fibers are advantageous over standard fibers in many ways. In particular, they can be bent around tight corners with virtually no signal loss. Thus, allowing real-time, multipoint monitoring of large structures and sensing in remote areas that are hazardous or difficult to access.

The two samples (RDHF and SMF) used in this work were similar material wise but different structural wise. The existence of air holes in RDHF provides large surface area and consequently large surface defects. The samples were 100μm long wrapped around 9cm spools. Samples were irradiated for 16 days by a 93mCi cesium-137 source emitting 0.662MeV gamma rays. The absorbed dose rate was 4mGy(Si)/hr. The total dose received by the fibers during measurement was 1.5Gy(Si).

Dose dependence of RIA was evident in both SMF and RDHF samples. Results suggested the existence of stable and unstable (short-lived) absorption centers during irradiation. Results indicated that most of the absorption centers in RDHF were of the unstable kind. Moreover, the slope of the overall trend in RIA was less in RDHF compared to SMF. This can be attributed to the existence of air voids in the case of RDHF which results in lesser number of stable absorption centers. Thus, surface defects are the dominate mode of absorption in RDHF whereas bulk defects are the dominate mode of absorption in sold fiber.

7934-59, Poster Session

**Structural and optical properties of different dielectric thin films for planar waveguiding applications**

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Thin films of Yttrium Oxide, Y2O3 were deposited by reactive sputtering and reactive evaporation to determine their suitability as a host for a rare earth doped planar waveguide upconversion laser. The optical properties, structure and crystalline phase of the films were found to be dependent on the deposition method and process parameters. X-ray diffraction (XRD) analysis on the ‘as-deposited’ thin films revealed that the films vary from amorphous to highly crystalline with a small broad peak at 29° corresponding to the reflections of Y2O3. The samples with the polycrystalline structure had a stoichometry close to bulk cubic Y2O3. SEM imaging revealed a regular column structure confirming their crystalline nature. The thin film layers which allowed guiding in both the visible and infra-red had lower refractive indices, higher oxygen content and had a more amorphous structure. Higher oxygen pressures during the deposition leads to a more amorphous layer.
The effect of hydrogenation on the photoconductivity of exfoliated mono- and multi-layer graphene

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Graphene samples exfoliated from highly ordered pyrolytic graphite are deposited using the standard scotch-tape method on 300nm thick SiO2 covered and slightly conductive Si substrates. Devices with 2 silver electrical pads on a micron-scale graphene sample are made with a simple evaporation procedure by using transmission electron microscopy grids as masks. In order to accommodate photoconductivity measurements, a 3-step evaporation procedure is used for extending the size of the electrical pads from micron-scale to millimeter-scale. A substrate biased H2 plasma process is used for graphene hydrogenation. During the plasma hydrogenation process, the substrates are biased with +60V to attract electrons in the plasma for graphene hydrogenation and repel ions in the plasma to avoid possible damage to the graphene. We use 220°C and a vacuum of 10^-6 torr for one hour to de-hydrogenate graphene samples. Micro-Raman is employed to monitor the quality and change in the graphene at each process step. At room temperature, with light of wavelength from 300nm to 700nm, we measure the photoconductivity of exfoliated mono- and multi-layer graphene samples before plasma hydrogenation, after plasma hydrogenation and then after de-hydrogenation. We compare the photoconductivities of pristine, hydrogenated, and de-hydrogenated mono- and multi-layer graphene.
Optimization of organic NLO materials for integration with silicon photonic, plasmonic (metal optics), and metamaterial devices

L. R. Dalton, Univ. of Washington (United States)

The fast response of organic nonlinear optical materials together with the potential for large optical nonlinearities makes these materials attractive for the integration with silicon photonic, plasmonic, and metamaterial device architectures. For example, incorporation of organic nonlinear optical materials into slotted silicon photonic waveguide device structures leads to dramatic improvement in the “effective” nonlinearity of organic materials. Drive voltages approaching 0.1 V have been realized for electro-optic modulation and low control power all-optical modulation has been demonstrated to approximately 10 THz. While organic nonlinear optical materials in general exhibit excellent processability—being amenable to both solution and vapor phase deposition and to a variety of processing methodologies ranging from crystal growth, to sequential-synthesis/self-assembly, to electrical and optical field poling—the special device architectures of silicon photonics, plasmonics (metal optics), and metamaterials can present challenges to useful integration. New organic nonlinear optical material concepts, materials, and processing options will be introduced and discussed.

Materials development for both 2nd and 3rd order materials for Si and other waveguide devices

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

No abstract available

Third-order optical nonlinearity of C60 dispersed LB films and its charge-transfer complexes

M. Era, Saga Univ. (Japan); T. Senokuchi, Kyushu Univ. (Japan)

In this study, we prepared four kinds of C60-dispersed LB films; C60-dispersed polystyrene, C60-dispersed poly(methyl methacrylate), C60-dispersed arachidic acid and C60-dispersed stearylamine. And we also prepared three kinds of its charge transfer complexes; C60/aniline, C60/N,N'-dimethyl aniline, and C60/N,N'-dimethyl aniline.

The LB films were prepared using the horizontal dipping method. Third-order optical nonlinearity of the materials was evaluated by third-harmonic generation measurement using Nd:YAG laser (wavelength=1064 nm, and pulse width=20 nsec) as a fundamental light source.

In the surface pressure-area isotherms of the LB films, very small limiting source.

Enhanced light extraction in OLEDs using nanostructures

J. Kim, Seoul National Univ. (Korea, Republic of)

No abstract available

High performance DNA-based phosphorescent organic light emitting diodes

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

Natural (salmon sperm) DNA has been utilized as a material for photonic applications [1], including biopolymer based organic light emitting diodes [2] and lasers. For these solid state devices, thin films of DNA are required with properties which enable their incorporation into complex multi-layer structures. DNA thin films have been produced using both solution (spin-coating) and evaporation by molecular beam deposition [3]. To facilitate the device fabrication process, the DNA is modified by combination with the surfactant cetyltrimethylammonium chloride (CTAC). The interactions among DNA, CTAC, and the laser dye sulforhodamine (SRh) have been investigated through the use of optical spectroscopy, electrophoresis [4], and circular dichroism (CD) spectroscopy [5]. Lasing with low threshold has been obtained [6] from SRh incorporated in a DNA/CTMA thin film fabricated with a grating that provided distributed feedback gain. Fluorescent BIOLEDs incorporating DNA as an electron-blocking layer have demonstrated [2-4] improvements in brightness, efficiency, and lifetime over conventional OLEDs (i.e. without DNA layers). Fine line structures have been fabricated in DNA thin films by direct-write electron-beam lithography.

Concentration variation of quadratic NLO susceptibility in PMMA-DR1 side chain polymer

F. Kajzar, Univ. d’Angers (France); O. Krupka, National Taras Shevchenko Univ. of Kyiv (Ukraine); A. Mitus, G. Pawlik, Wroclaw Univ. of Technology (Poland); I. Rau, Polytechnical Univ. of Bucharest (Romania)

A serie of PMMA-DR1 functionalized polymers, with different chromophore concentrations, were synthesized in view of the study of concentration dependence of optical quadratic susceptibility in such systems. Thin films of synthesized polymers were obtained by the corona poling method and the two second order NLO tensor components: and were measured by the optical second harmonic generation technique. The results show that for small chromophore concentrations the NLO susceptibilities follow linearly the density number of active chromophores, reach a maximum, than decrease and stabilize. The observed concentration dependence is simulated by the Monte Carlo calculations obtaining a good description of its behavior.

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We report on the operation of BioOLEDs that incorporate phosphorescent emitting layers. Significant increases in brightness and efficiency over fluorescent BioOLEDs have been obtained. The electro-optical characteristics of the Bio-PhOLEDs will be described in detail, including brightness and quantum efficiency versus applied voltage and current.


7935-07, Session 2

Flexible top-emitting organic light-emitting diodes with highly reflective Ni/Ag/Ni/ITO reflective anode

S. Kim, K. Hong, K. Kim, I. Lee, Pohang Univ. of Science and Technology (Korea, Republic of); K. Kim, D. Y. Lee, T. Kim, Pohang Iron & Steel Co., Ltd. (Korea, Republic of); J. Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Top-emitting organic light-emitting diodes (TEOLEDs) have been attracting considerable attention because of their potential application to flat panel display technology. Achieving improved device performance requires anode which has high reflectivity and hole injection efficiency. Silver (Ag) has been used for anode of TEOLEDs because of its high reflectivity (~90%) at the visible region and low electrical resistivity (1.47 \(\mu\)Ω·cm). However, Ag anode has poor hole-injection property due to its low work function (~4.3 eV). Recently, Ag/indium tin oxide (ITO) bilayer is used as the anode, where Ag is used as the reflector and ITO is used for increasing the surface work function (~4.8 eV). To achieve high reflectivity of Ag/ITO, high transparent ITO film was required. It is previously reported that ITO film deposited above 300 °C showed high crystallinity and transmittance properties. In Ag/ITO bilayer structure, however, ITO deposited at high temperature induce agglomeration of Ag, resulting reduction of reflectivity. A number of attempts have been conducted to suppress this agglomeration of silver, such as additional heat treatment after deposition at room temperature, and employing various metal alloys instead to Ag. However, even if these methods can suppress the agglomeration of Ag, it might not enough to solve the structural problems of Ag/ITO because of the poor transmittance and sheet resistance. In this work, we demonstrate flexible TEOLED using Ag/Ni/ITO reflective anode. With employing Ni overlayer on Ag, agglomeration in the Ag films is significantly reduced. Ni/Ag/Ni maintains flat surface and high reflectivity (89.9%) after ITO deposition at 300 °C while Ag-monolayer has low reflectivity (68.5%) and rough surface after ITO deposition. Using Ni/Ag/Ni/ITO anode, compared to Ag anode, the operation voltage of devices at 1 mA/cm\(^2\) was decreased from 6.2 V to 5.3 V, and the luminance at 222 mA/cm\(^2\) promoted from 9500 to 21,000 cd/m\(^2\).

7935-08, Session 2

Hybrid organic light emitting device with silicon-rich oxide as hole transporting layer

G. Ran, D. F. Jiang, W. Xu, Peking Univ. (China)

Organic light-emitting devices (OLEDs) are getting more and more attention from public. However, compared to inorganic semiconductors, an organic semiconductor exhibits inferior charge transport properties as well as weak chemical stability resulting in the shortening of the operation lifetime for the OLEDs. As a promising approach to solve these problems, a concept of organic-inorganic hybrid structure was proposed, which combines the advantages of both organic and inorganic materials and tries to avoid their shortcomings. Many organic light emitting materials have very high luminescence efficiency and are easy to fabricate; at the same time, many inorganic semiconductors have relatively high chemical stability and are adjustable in electrical transport. In this paper, we adopt silicon-rich silicon oxide (Si\(_{1+x}\)O\(_2\)) film as hole-transport layer (HTL) in organic-light emitting device. We report a hybrid organic light emitting device with HTL of Si\(_1+x\)O\(_2\), whose mobility can be tunable by changing the degree of excess silicon x. The structure of HOLED is designed as ITO/ Si\(_1+x\)O\(_2\) (30 nm)/ buffer/AlQ (45 nm)/ Bphen:Cs2CO3 (15 nm)/ Sm (5 nm)/ Au (15 nm). When x is equal to 3.7, the corresponding mobility of Si\(_1+x\)O\(_2\) is about 3.32×10^-5 cm\(^2\)V\(^{-1}\)s\(^{-1}\) which is close to that of AlQ, this HOLED has achieved a maximum current efficiency of 3.63 cd/A at 20 mA/cm\(^2\), which is even higher than that of the typical OLED having NPB as HTL.

7935-09, Session 3

Approaches to widely-tunable and highly-efficient liquid crystal microlasers

F. Araoka, Tokyo Institute of Technology (Japan)

No abstract available

7935-10, Session 3

Characterization of fluorescence resonance energy transfer of a nanopatterned fluorophore doped polymer film fabricated using nanoimprint lithography

R. A. Furukawa, The Univ. of Electro-Communications (Japan)

Recent study of the bacterial photosynthetic systems had suggested that the two light harvesting proteins are distributed in approximately 100 nm diameter domains inside the two-dimensional plane of the lipid bilayer. Photosynthetic bacteria are being able to absorb two wavelength regions that correspond to each protein species, which are passing the harvested energy towards the reaction center by fluorescence resonance energy transfer (FRET). In this study, we had fabricated such two-dye distributing surface by using Rhodamine doped PMMA and characterized the FRET behavior by a fluorescent microscope. The purpose of this study is to simulate the efficient light harvesting system of nature by using robust materials instead of the extremely sensitive light harvesting proteins. The patterned substrate was fabricated by dispensing two methyl methacrylate solutions in which each doped with different Rhodamines. Each monomer solution was polymerized into oligomers with sufficient energy towards the reaction center by fluorescence resonance energy transfer (FRET). In this study, we had fabricated such two-dye distributing surface by using Rhodamine doped PMMA and characterized the FRET behavior by a fluorescent microscope. The purpose of this study is to simulate the efficient light harvesting system of nature by using robust materials instead of the extremely sensitive light harvesting proteins. The patterned substrate was fabricated by dispensing two methyl methacrylate solutions in which each doped with different Rhodamines. Each monomer solution was polymerized into oligomers with sufficient energy towards the reaction center by fluorescence resonance energy transfer (FRET). In this study, we had fabricated such two-dye distributing surface by using Rhodamine doped PMMA and characterized the FRET behavior by a fluorescent microscope. The purpose of this study is to simulate the efficient light harvesting system of nature by using robust materials instead of the extremely sensitive light harvesting proteins. The patterned substrate was fabricated by dispensing two methyl methacrylate solutions in which each doped with different Rhodamines. Each monomer solution was polymerized into oligomers with sufficient energy towards the reaction center by fluorescence resonance energy transfer (FRET). In this study, we had fabricated such two-dye distributing surface by using Rhodamine doped PMMA and characterized the FRET behavior by a fluorescent microscope. The purpose of this study is to simulate the efficient light harvesting system of nature by using robust materials instead of the extremely sensitive light harvesting proteins. The patterned substrate was fabricated by dispensing two methyl methacrylate solutions in which each doped with different Rhodamines. Each monomer solution was polymerized into oligomers with sufficient energy towards the reaction center by fluorescence resonance energy transfer (FRET). In this study, we had fabricated such two-dye distributing surface by using Rhodamine doped PMMA and characterized the FRET behavior by a fluorescent microscope. The purpose of this study is to simulate the efficient light harvesting system of nature by using robust materials instead of the extremely sensitive light harvesting proteins. The patterned substrate was fabricated by dispensing two methyl methacrylate solutions in which each doped with different Rhodamines. Each monomer solution was polymerized into oligomers with sufficient energy towards the reaction center by fluorescence resonance energy transfer (FRET). In this study, we had fabricated such two-dye distributing surface by using Rhodamine doped PMMA and characterized the FRET behavior by a fluorescent microscope.
**Energy transfer processes in conjugate polymer lasers**

M. AlSalihi, Z. Suliman AM, V. Masilamani, King Saud Univ. (Saudi Arabia)

This paper may be regarded as the continuation of the preceding paper on liquid excimers. In that paper, we had shown that in the conjugate polymer, MEH-PPV, ASE and laser action occur only from the excimeric state. In the present paper, we show how we had employed energy transfer processes for obtaining laser action both from the monomeric and excimeric state of MEH-PPV simultaneously.

A coumarin dye, C485 has a strong emission band at 470 nm, which has a fairly good overlap with the absorption band of MEH-PPV. Hence, the energy transfer from the donor C485 to the acceptor MEH-PPV was used. A solution of MEH-PPV (10μM) in THF gave laser at 600 nm only. A solution of C485 (3mM) in THF gave laser at 485 nm only. But when C485 and MEH-PPV were taken together, there were 2 bands of ASE, one at 560 nm and another around 600 nm, due to monomeric and excimeric states of MEH-PPV. There was no laser due to C485, that is energy transfer from C485 is so effective, that monomer and excimers, both have enough population inversion to produce ASE.

In the another experiment MEH-PPV was mixed with LD700, the latter being an acceptor of energy from MEH-PPV. We could observe three lasers, one at 560 nm (due to monomer of MEH-PPV), another at 600nm (due to the excimer) and third at 690nm (due to LD 700nm).

**Laser from liquid excimer**

V. Masilamani, M. AlSalihi, I. Khalid, King Saud Univ. (Saudi Arabia)

Conjugate Polymers are novel optoelectronic materials with wide range of applications. In this paper we present the results of fluorescence spectra and laser excited amplified spectrometric emission spectra of MEH-PPV, which has some surprising Laser Properties.

(MEH-PPV) is a complex macro molecules. When this is dissolved in liquids like, Tetra hydra furan (THF), it is very fluorescent, with quantum yield comparable to conventional laser dyes.

This polymer has an absorption around 490nm and emission band at 560nm for a low concentration (1 micro molar). However for higher concentration (20 micro molar) it has a new band at 600nm, in emission only without any new band in absorption. This is a strong indication of excimer formation.

When this particular solution is pumped by a 3rd harmonic of Nd:YAG laser (355nm; 18 ns and 20 mJ), the polymer underwent strong excitation, population in version and amplified spontaneous emission (ASE) at 600 nm only. For lower concentration, we could get fluorescence only with peak at 560 nm. That is, this particular polymer produce ASE and hence laser only from the excimeric state. This appears to e the only liquid excimeric state laser.

It is important note that most of the liquid laser dyes do not produce laser from the excimeric state; other solutions which are easily forming excimeric state do not lase. Another important feature of the solution it is at least four times more stable than the conventional laser dyes.

**Preparation and characterization of DNA-aromatic surfactant complexes for optoelectronic applications**

T. Lin, C. Chang, C. Lien, Y. Chiu, W. Hsu, C. Su, Y. Wang, Y. Hung, National Tsing Hua Univ. (Taiwan)

DNA biopolymer has emerging as a promising material in photonic applications. In this paper, we present the preparation and characterization of a series of DNA-surfactant complexes based on aromatic surfactants, including vinylbenzyltrimethylammonium chloride, benzyltrimethylammonium chloride, and phenyltrimethylammonium chloride. Fourier-transform infrared spectroscopy (FTIR) and UV-VIS spectroscopy were used to characterize the presence of specific chemical groups in the materials. These synthesized DNA complexes show high transparency from 400nm to 1100nm. These materials can be spin casted into thin films from nm to um and the morphology was examined by SEM and AFM. Thermal property was characterized by thermal gravimetric analysis. Conductivity was examined to investigate the effect of aromatic surfactants on the electrical properties of DNA complexes. In addition, the photoluminescence and lasing properties for DNA-aromatic surfactants with rhodamine dyes were investigated to study the amplified spontaneous emission where the ASE emission wavelength, lasing threshold, and gain were presented and discussed.

The results were compared with DNA complex with single chain aliphatic surfactant complex (DNA-cetyltrimethylammonium bromide).
alters the photoconductive response of the systems. In particular, exciton and charge carrier dynamics can be varied, even at picosecond timescales after photoexcitation, using a competition between photoinduced charge and energy transfer in a guest-host system. Finally, ADT molecules can be imaged on a single-molecule level using fluorescence microscopy, which enables studies of properties of individual ADT molecules in different host matrices and their relation to the performance of bulk guest-host films.

7935-16, Session 4

Charge transport anisotropy in a pentacene transistor with an underlying photo-alignment layer

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

Improving molecular packing of semiconductor materials in the vicinity of an insulating layer is of primary interest for efficient charge transport in an organic thin-film transistor. Self-assembled monolayers (SAMs) are often employed for this purpose. In other cases, a thin alignment layer is placed on a gate insulator in an attempt to order organic molecules along a specific direction. We fabricated bottom-gate, top-contact pentacene transistors with an underlying photo-alignment layer as follows. Azobenzene-polymeric acid was spun-coated on SiO2 and was irradiated with linearly polarized ultraviolet light at various energies. The material was converted to polyimide by heating and a thin pentacene layer was evaporated on it. Finally, source and drain electrodes were formed by sputtering gold through a shadow mask. The transistors fabricated with the polarization perpendicular to the current direction in the channel showed higher field-effect mobility and the maximum value was 1.0 cm2/Vs. This is close to the value reported for the conventional pentacene transistors having SAMs. The mobility decreased as the irradiation energy density increased. Hence, we attribute the anisotropy introduced by the photo-alignment layer to degradation in charge transport in the specific direction.

7935-17, Session 4

Chemical mechanisms and electrical characteristics of C60/Al and C60/LiF/Al cathodes studied by electron spin resonance, infrared reflection-absorption, and impedance spectroscopy

E. D. Glowiacki, Johannes Kepler Univ. Linz (Austria) and Univ. of Rochester (United States); K. L. Marshall, C. W. Tang, Univ. of Rochester (United States); N. S. Sariciftci, Johannes Kepler Univ. Linz (Austria)

We report our investigations of the chemical mechanisms responsible for improved electron injection from LiF/Al cathodes into fullerene thin films. Electron spin resonance (ESR) and infrared reflection-absorption spectroscopy (IRRAS) are utilized to characterize C60/Al and C60/LiF/Al interfaces. ESR shows that deposition of LiF followed by Al generates C60 radical anions with 1-mol% conversion to C60-1, and also the presence of an additional paramagnetic species of lower concentration. We report the effects of annealing and light-stressing on these two signals. IRRAS clarifies the mechanism occurring at the C60/LiF interface, showing that interaction between LiF and C60 followed by deposition of Al causes LiF clusters to break apart. We correlate our ESR and IRRAS data with observed electrical characteristics - current-voltage, capacitance-voltage and impedance spectroscopy. We demonstrate for the first time conclusive evidence for the lithium-doping mechanism behind barrier-lowering in the LiF/Al cathode. We demonstrate the utility of using spin population-calibrated ESR and correlating carrier populations to capacitance-voltage and frequency-dependent capacitance.
in order to study the solvent influences on forming thin films of high uniformity. As the result of the experiments we conclude that (1) solvent evaporation rate plays an important role in the thin film preparation. The solvent with lower evaporation rate (e.g. Toluene and Benzene) produces more uniform films. The thin films prepared by using the solvent with high evaporation rate (e.g. Chloroform) have poor uniformity of film thickness, especially when spin speed is low. (2) As expected, higher spin speed and high ramping speed produce thinner films. No strong relationship between spin speeds and film uniformity has been observed when spin speed is high (4000 and 6000 rpm). However, the film uniformity begins to decline when lower spin speed (e.g. 2000rpm) is used.

7935-22, Session 6

Photopatternable quantum dots forming quasi-ordered arrays

K. Lee, Hannam Univ. (Korea, Republic of)

We have functionalized core-shell CdSe/ZnS quantum dots (QDs) with a photosensitive monolayer, rendering them solution-processable and photopatternable. Upon exposure to ultraviolet radiation, films composed of this material were found to polymerize, forming interconnected arrays of QDs. The photoluminescence properties of the nanocrystal films increased with photocuring. The material was found to be suitable for spin-casting and was used as the active layer in a green electroluminescent device. The electroluminescence (EL) efficiency of devices containing photocured active layer was found to be largely enhanced when compared to devices containing non-photocured active layers. The material also showed excellent adhesion to both organic and inorganic substrates because of the unique combination of a siloxane and a photopatternable layer as ligands. The pristine functionalized nanocrystals could easily be used for 2D patterning on organic and inorganic substrates. The photopatternable quantum dots were uniformly dispersed into a photopolymerizable resin to fabricate QD embedded 3D microstructures.

7935-23, Session 6

Construction of organic-inorganic perovskite superlattice LB film having amphiphilic phenylenevinylene as an organic layer

M. Era, Y. Shironita, Saga Univ. (Japan)

Lead halide-based layered perovskite compounds (RNH3PbX4) are self-organized superlattice structure where two-dimensional inorganic semiconductor of corner sharing PbX6 octahedra and organic ammonium cation (RNH3+) are alternately piled up. If one could incorporate functional organic chromophore into the organic layer, construction of new functional material which is not up to now is expected. Further, if LB technique would be applied to the superlattice construction, incorporation of organic molecules, which have physically and chemically different properties, is expected; that may be lead to multi-functional superlattice materials.

In this study, mixed monolayer of a phenylenevinylene derivative and alkyl ammonium bromide are spread on the subphase of aqueous solution containing PbBr2 and methyl ammonium bromide (their concentrations were about 10-3 M). In the expand region of the monolayer, only absorption due to H-aggregate of phenylenevinylene peaking around 300 nm was observed. When more than surface pressure at plateau region was applied, however, very sharp absorption around 400 nm, which is characteristic of formation of PbBr-based layered perovskite, was observed, demonstrating that PbBr-based layered perovskite structure having the phenylenevinylene derivative as an organic layer is surely constructed. In addition, the monolayer was easily deposited by the LB technique, more than 40 layers. We are now progressing on evaluation of carrier mobility and optical non-linearity by using the FET measurement and electro-modulation spectroscopy measurement, respectively.

7935-24, Session 6

Effects of surface chemistry on nonlinear absorption, scattering, and refraction of PbSe and PbS nanocrystals

I. L. Bolotin, D. J. Asunsiskis, A. M. Jawaid, Y. Liu, P. T. Sneeh, L. Hanley, Univ. of Illinois at Chicago (United States)

Oleic acid capped lead sulfide (PbS) and lead selenide (PbSe) nanocubes were synthesized, then subjected to a post-synthesis washing in a 1:1 ethanol/hexane solution. The relationship of third order nonlinear optical properties to nanocrystal surface chemistry as affected by washing was analyzed using nanosecond 532 nm Z-scan and measurement of near-IR radiative emission. The results indicated a significant change in optical nonlineairties which emerged only after the nanocrystals were washed in the ethanol/hexane mixture. Transmission electron microscopy of the oleic acid capped PbSe and PbS nanocrystals showed a cubic shape, narrow size distribution and an average size of ~10 nm. Neither size nor shape of the nanocubes were modified by the washing process, indicating that all optical differences were related to changes in surface chemistry and the formation of deep trap states. The “as grown” PbS and PbSe nanocrystals showed high emission efficiency, weak saturable absorption, and self-defocusing refractive indices. After post-synthesis washing, the nanocrystals were converted to a reverse saturable absorbing and strongly scattering media with a self-focusing refractive indices. The fitted experimental Z-scan data for the samples after washing gave high values for the nonlinear absorption coefficient. The appearance of reverse saturable absorption in the nanocrystals was due to the presence of trap states at the nanocrystal surface which were not present in the as-grown nanocrystals that did not show similar optical nonlinearity.

7935-26, Session 7

Chromophores design for nonlinear optics in the near infrared

C. Andraud, Ecole Normale Supérieure de Lyon (France)

We present different approaches for the design of novel fluorescent probes featuring high two-photon absorption (TPA) cross-sections:

- using the unique luminescence properties of LnIIl ions, we designed a new family of ligands-based chromophores inducing lanthanides emission by two-photon antenna effect1,2. Two-photon scanning microscopy bio-imaging data with these complexes led to consider these complexes as a new generation of molecular probes 3.

- photodynamic therapy capability of chromophores, stabilizing triplet states for efficient singlet oxygen generation combined with high TPA properties, was shown.

- in order to develop efficient probes combining both second-harmonic imaging and two-photon excited fluorescence microscopies, we proposed a series of novel neutral push-pull probe molecules4, fulfilling the right balance between hydrophobicity and hydrophilicity and for which a good membrane staining, compared to existing probes, could be observed5.

Effects of ligand on two-photon absorption of platinum acetylide complexes


Organometallic compounds may combine strong multiphoton absorption with efficient intersystem crossing to triplet state, which is of interest to potential applications in nonlinear optics. Here we report two photon absorption (2PA) spectra of a series of 11 different platinum acetylide complexes, where dipolar ligands are linked to the platinum core symmetrically on both sides. We take advantage of systematic variation of the electron withdrawing- and electron donating ability of the ligand to study how the properties of the ligands affect the two-photon absorption of the complexes.

First we measure the 2PA of the ligands and show that the cross section increases with increasing permanent dipole moment difference between the ground- and excited state. Our measurements agree quantitatively with quantum chemical calculations and with estimations based on solvatochromic shift measurements. We also show how to account for non-spherical shape of the molecules, which may have a substantial effect on the estimation of permanent dipole moment difference. The measured maximum 2PA cross sections of the complexes, sigma2 ~400 GM, is notably larger than the sum of the cross sections of the corresponding ligands. This, along with the fact that the 2PA maximum of the complexes lies at higher energy indicates strong conjugation through the platinum core. However, co-occurrence of 2PA in the lowest energy transitions also suggest some dipolar contribution, which may be explained by conformational changes of the complex.

We present a detailed analysis of quantitative structure-property relationships that may be useful for designing further platinum compounds for nonlinear optics.

Multifunctional hybrid nanoparticles for two-photon fluorescence imaging and photodynamic therapy

P. L. Baldeck, Univ. Joseph Fourier (France) and CNRS (France)

We review our work on several strategies to elaborate multifunctional nanoparticles for the simultaneous two-photon imaging and near-infrared laser treatment of cancer cells. Our first strategy is based on the incorporation of two-photon lipophilic fluorophors and gold nanoparticles in bio-compatible pluronic nanodots using the mini-emulsion technique. The multifunctionality is obtained by codoping with gold nanoparticles for x-ray imaging and phototheraphy. Our second strategy is based on fluorescent organic nanocrystals grown in silicate spheres. These core-shell hybrid nanoparticles are obtained by a spray-drying process from sol-gel solutions. Our third strategy consist in the encapsulation of hydrophilic molecules in the water core of gold nanoshells. They are obtained by a stabilized emulsion in biphasic liquid medium without surfactant.

The organic molecules have been specially designed to have large two-photon cross-sections for fluorescence imaging or for photodynamic therapy by singlet-oxygen generation. All these new multifunctional nanoparticles are been characterized for their optical and biophotonics properties. We report on their applications for in vivo two-photon fluorescence imaging of mice microvasculatures, and in vitro NIR laser therapy of cancer cells.

This work is done in close collaboration with:

M. Maurin (PhD thesis) and O. Stéphan (SPECTRO, Grenoble) for pluronic nanodots.

Cécile Philipot (PhD thesis), Fabien Dubois and Alain Ibanez (LLN, Grenoble) for organic nanocrystals grown in silicate spheres.

Frédéric Lerouge, and Stéphane Parola (LLM, Lyon) for gold nanoshells with water cores.

Sanda Cosmina Boca (PhD thesis), and Simeon Astilene (University of Oulu-Napoca, Roumania) for PEGylated gold nanoparticles.

Thibault Gallavardin (PhD thesis), Olivier Maury, and Chantal Andraud (ENS Lyon) for new two-photon sensitive molecules.

This work is partially founded by the project ANR-D9-NANO-027 - NanoPDT.

New developments in molecular photonics: from photoswitchable nonlinearities to nonlinear nanoplastamons

I. N. Ledoux-Rak, K. Hoang Thi, A. Anu, J. Zyss, Ecole Normale Supérieure de Cachan (France)

The wealth of molecular structures and the exploitation of their functional and structural flexibility open-up thoroughly renewed horizons in the domain of molecular photonics for various applications ranging from optical communication to bio-imaging. We will present here new results on photoswitchable nonlinear optical (NLO) molecules on one hand, and exaltation effects due to the interaction of NLO molecules with gold nanoparticles on the other hand.

To design and realize NLO switches, we propose to use photochromic compounds like diithienylethene (DTE) derivatives, undergoing a reversible interconversion between a non-conjugated open form and a -conjugated closed form. We will show that the quadratic nonlinearities for the open forms are very weak, in strong contrast with those of the closed forms, with a strong increase (by a factor of 30) of the NLO activity.

In the second part, we will explore the quadratic NLO properties of highly NLO chromophores grafted onto the surface of gold nanoparticles (NP).

A significant increase of the nonlinear response of this dye due to surface Plasmon resonance with gold NPs is shown by Harmonic Light Scattering (HLS) at 1.64 µm. A weaker, however detectable magnification is also observed for a simple mixture of stilbazolium ligand and gold NPs . The influence of the gold NP shape on their quadratic NLO response in solution will be also reported. Preliminary results show a significant increase of the Harmonic Light Scattering emission when using rod-like gold particles, as compared to spherical ones. The influence of the aspect ratio of nanorods on the HLS signal will be discussed in detail.

Ferromagnetism in pristine polythiophene at low temperature

A. P. Persoons, Katholieke Univ. Leuven (Belgium) and Arizona Univ. (United States); P. Gangopadhyay, College of Optical Sciences, The Univ. of Arizona (United States) and Katholieke Univ. Leuven (Belgium)

Despite intense effort for over two decades aimed at developing alternatives to traditional magnets, robust ferromagnetism in organic polymers has been elusive.1 These materials are of unparalleled technological importance as they can potentially be used as plastic magnets and magnetooptic devices with the advantage of the flexibility of organic chemistry by allowing for further tuning of their properties. Physical realization of such a magnetically ordered polymer system involving only π-electrons is a rare occurrence. In parallel, although over the past century many inorganic materials have been developed for magneto-optic (MO) applications, research dedicated to developing organic materials, in particular organic polymers, for such applications has been sparse. We show that some polythiophenes possess strong
Faraday rotation with exceptionally high Verdet constants, 200 - 300 times larger than those of commercially deployed MO materials, such as, terbium doped gallium garnet (TGG) or substituted yttrium iron garnets (YIGs).

To elucidate the underlying mechanism at the origin of these effects we undertook SQUID measurements of the magnetic properties of pristine regioregular (RR) poly(3-dodecylthiophene) (P3DT) and found strong ferromagnetic ordering at low temperature, in complete contrast to the effects observed in the regiorandom (rr) counterpart. Another intriguing difference between RR and rr P3DTs is that the first one forms doughnut shaped nanostructures as observed with AFM. We believe that the nano confinement of itinerant $\alpha$-electrons of RR P3DT in an anisotropic structure such as a doughnut may be at the origin of these new magnetic phenomena.

7935-32, Session 8

Chirality appearance in molecular films of achiral molecules at the air/water interface

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Chirality is an important issue in chemistry, biology and material science. This symmetry property can be observed at different scales, from single molecule to supramolecular systems. Recently, it has been shown that achiral amphiphilic dyes can form chiral molecular aggregates at the air/water interface during the monolayer compression. The exact mechanism of chirality formation, spontaneous or compression-induced, is still an open question. To give an insight into the origin of this induced chirality, we report two examples of chiral aggregation at the air/water interface. The first example is given by the stilbazolium dye 4-(4-dihexadecylaminostyryl)-N-methylpyridinium iodide (DIA) which is an achiral cationic amphiphilic dye with a high efficiency for the frequency conversion process. In the second example, we present experiments which were performed by using amphiphile 5-(octadecyloxy)-2-(2-thiazollyazo) phenol (TARC18). This molecular system is known to form chiral Langmuir-Schaefer film. The chirality of the Langmuir monolayer at different surface densities was measured in situ at the air/water interface using the Surface Second Harmonic Generation (SSHG) which has proven in the past to be a powerful surface sensitive tool. Indeed, this technique, based on the conversion of two photons at a fundamental frequency into one photon at the harmonic frequency $2\omega$, is surface sensitive at interfaces between two centrosymmetric media. Hence, the approach is non invasive and can be used to investigate both structure and dynamics at such surfaces and interfaces. Its combination with a Langmuir trough allows non linear optical studies with a precise control of the average surface density of amphiphilic compounds spread at the liquid surface.

7935-33, Session 8

Realization of all optical AND-OR logic gates using z-scan method

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The nonlinear optical properties of organic materials have been the subject of extensive studies aimed not only at the understanding of their intrinsic origin, but also at the possible use of these systems in photonic applications. In this regard, different authors have considered the possibilities of exploiting the characteristics of large optical nonlinearities of organic materials in optoelectronic and photonic devices.

The nonlinear optical properties of organic materials such as Patent blue V have been studied with single beam Z-scan technique using CW laser beam. The material has the maximum absorption peak at 635 nm. V have been studied with single beam Z-scan technique using CW laser beam. The transmission of the beam through an aperture placed in the far field is measured using a photo-detector fed to the digital power meter (Field master Gs-coherent). A closed aperture set up has been used to plot z-scan curve and measure the nonlinear refractive index of the dye. The material exhibits negative nonlinear property. Also the optical limiting behavior has been found for this dye at various sample positions.

To demonstrate the logic gates, we modified the Z-scan setup with two input (He-Ne) laser beams. By exploiting the optical limiting property of the sample, all optical AND and OR logic gate operations are experimentally realized.

7935-34, Session 9

Organic materials chemistry in Air Force Office of Scientific Research

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The research goal of this portfolio is to gain a better understanding of the influence of chemical structures and processing conditions on the properties and behaviors of polymeric and organic materials. This understanding will lead to development of advanced organic and polymeric materials for Air Force applications. This program’s approach is to study the chemistry and physics of these materials through synthesis, processing, characterization and establishing the structure properties relationship of these materials. This area addresses both functional properties and properties pertinent to structural applications. Of particular interest are properties that are not normally associated with organic materials but because of the unique processing and other secondary properties will create new applications for Air Force applications. An overview of the portfolio will be presented. Current emphases on decoupling coupled properties and materials with switchable properties will be discussed.

7935-35, Session 9

Switching mechanism of an optically-gated optical switch using an organic dye

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A versatile optically-gated optical-switch using an organic-dye is suitable for light-path switching in an optical communication for various wavelengths of a signal light. The developed “optical switch” capable of separating the incident signal light from the optical fibers directly, without conversion to the corresponding electrical signals, under optical control and of outputting these optical signals to other multiple optical fibers. The separation of the signal light under optical control is achievable by utilizing the high-speed thermal lens effect generated in a thin layer of dye solution by applying the gating-light to an organic thin-layer optical element. By varying the types of pigment it is also possible to cover a wide range of wavelengths. An organic dye for absorbing a gating-light combined with a high-boiling solvent for forming a thermal-lens is properly selected choosing a wavelength of both a gating and a switching light. The incident gating-light passed through a short focal-length lens is absorbed around the focal point and form high-temperature region in the high-boiling solvent, which refract the signal light by a thermal-lens effect. An easy-to-use system, for example, for local derivation of large image data has been developed for optical distribution from a data server to terminal PCs without any waiting electric-power in a home.
Enhanced updatable holography using a dynamic holographic network recording system

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Updatable holography has great potential for next-generation holographic memory, true three-dimensional (3D) display and biomedical imaging applications due to its rewritability for complete wave field of a 3D realistic object. However, no any existing materials or recording mechanisms are ideal for viable updatable holographic applications which require a combination of critical holographic performances such as high diffraction efficiency, long data persistence, controllable erasure, and high spatial resolution. Photopolymer are typical holographic recording materials possessing high diffraction efficiency and high photo-sensitivity, but they are irreversible and require post processing to fix holograms. Well-studied photorefractive polymers may be the best reversible holographic recording media. However, an electrical field with high voltage has to be applied across the photorefractive polymer for both recording and readout, to achieve high diffraction efficiency and data persistence. In this paper, a dynamic holographic network that contains polymer backbone impregnated by a soft liquid crystal (LC) material is reported. The backbone of polymer chains is reconfigurable and the surrounding flowable LC molecules are reoriented collectively anchoring toward the reconfigured polymer chains, resulting in remarkable enhancement of the holographic grating. The stored hologram can persist with nonvolatility after turning off recording beams. In addition, the recording is updatable and fresh holograms can be recorded repeatedly at the same location after erasure. Compared to conventional rewritable recording systems, the new concept enables significant enhancement of holographic performance with high diffraction efficiency, facilitated implementation of 3D display, 3D imaging, and ultrahigh data storage density for a wide variety of applications.

Optical data storage in photochromic compounds

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In the present work three dimensional optical data storage in photochromic compounds is demonstrated. The optical storage materials are obtained by mixing diarylethens photochromic molecules with host polymers. In the view to better address different layers of material to achieve 3D storage on different layers of materials, multiphoton processes seems a promising tool to excite photochemical transitions in the material. We used for this purpose a femtosecond Ti:Sapphire laser coupled to either a commercial confocal microscope and an home-built confocal scanning microscope system. The possibility to effectively write data in the materials used in a multiphoton process using light in the near infrared has been demonstrated as well as the read out of the data by exciting with a continuous wave laser the luminescence of the photoconverted molecules. It is also shown that the data recorded in such a medium can be erased by irradiating the intended volume of material with light at the proper wavelength and successively other data can be rewritten. It has been demonstrated that the write, read and erase cycle can be repeated several times on the same area of the sample. In all the compounds used, a 405 nm laser was used to excite the luminescence as a read out system while a 515nm one was instead used for erasing the data, even if it has been observed that both wavelengths unfortunately deteriorate the recorded data in a different measure. Further work is in progress to improve these and other aspects of our storage system.

Nanoparticle imbedded polymer waveguide array devices with extremely low crosstalk between adjacent channels

J. Lee, J. Kim, J. Jang, M. Oh, Pusan National Univ. (Korea, Republic of)

In the WDM optical communication systems, the signal crosstalk between the adjacent channels deteriorates the transmission capability. Multi-channel functional optical waveguide devices integrated on single chip enables very efficient signal manipulation in a compact device. However, in the array device, the light signal could crossover to the adjacent channels introducing significant optical crosstalk. The radiated light in the waveguide device hardly escapes from the planar waveguide structure, so that it could be coupled into the adjacent waveguides. In order to discard the planar guided light, we introduce a nano-particle diffraction structure imbedded in the planar waveguide. Polystyrene nanoparticles are adopted for considering the compatibility with polymer waveguides. Due to the large index contrast between the polystyrene and the fluorinated polymers used for waveguide structure, strong scattering is expected, and then by the periodic structure of the polystyrene the light is diffacted toward surface normal directions. Depending on the size and period of the nanoparticles, the diffraction efficiency is simulated based on 2D FDTD method. The polymer waveguide is fabricated by a conventional lithography, a dry etching, and a UV curing process. The polystyrene nanoparticle is formed as a mono- or double-layers on the surface of cladding layer of the waveguide. The scattering efficiency is measured by preparing a sample with a different length of nanoparticle area. The device with nanoparticle exhibits cladding mode attenuation efficiency of 23 dB/cm, which could be sufficient to improve the channel crosstalk of the array device significantly.

Inspirations for EO polymer design gained from modeling of chromophore poling by Langevin dynamics

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One of the possibilities to create organic molecular material for NLO applications are polymers with dispersed NLO active chromophores. These molecules must be acentrically ordered by applying an external electric poling field. The NLO efficiency depends on dipole moment, molecular hyperpolarizabilities, concentration of the chromophores and external poling field strength. Calculating, from first principles, the extent of the alignment and via this NLO efficiency has proven to be challenging. One approach to solve this problem is pure analytic statistical mechanics treatment, what could be enhanced by Monte Carlo (MC) statistical mechanical modelling. The chromophore molecules usually have been treated as point dipoles embedded in some kind of realistic molecular shape - prolate spheroid. Another possibility is fully atomistic molecular modelling with classical force field MD methods. This method allows obtain extent of alignment and observing kinetics of poling and relaxation. Unfortunately, in case when host and chromophores are represented at atomistic level, MD approach requires huge amount of computations. One of the solutions is to reproduce the motion of the molecules of interest (chromophores) using Langevin dynamics (LD). This method simulates the effect of molecular collisions and the resulting dissipation of energy that occur in real host, without explicitly including host molecules. In this contribution chromophore load, dipole moment and poling field impact on extent of alignment and poling / relaxation dynamics of model system obtained by LD simulations will be presented. On a basis of these results we would like to come forward with some inspirations for EO polymer design.
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**7935-39, Poster Session**

**Implementation of Mach-Zehnder interferometric technique for electro-optic measurement on thin organic films**

E. Nitiss, M. A. Rutkis, O. Vilitis, Univ. of Latvia (Latvia)

An increasing interest has been devoted to new NLO active organic materials due to their potential applications as organic optical components. The most promising use in field of light manipulation and management would be the electro-optical (EO) modulators where the traditionally inorganic LiNbO3 could be substituted by poled NLO polymer. Traditionally the general criteria for the mentioned applications are the EO coefficients r13 and r33 of the material. For evaluation of thin organic film EO coefficients we have applied the Mach-Zehnder interferometric (MZI) technique. Using this method one can obtain effective EO coefficient dependence on probing light polarization and incidence angle. Based on this data one can calculate both EO coefficients - r13 and r33. In spite of many advantages of MZI technique it also possesses several significant drawbacks - high sensitivity to vibrations, stability of measurement point (phase), electro-induced false signal in the lock in amplifier and etc. We have compared transmission and reflection sample configurations in MZI and will report our experience gained from the implementation. We offer solutions to traditional mechanical stability and false electroinduced signal problems and introduce yet unsolved ones. MZI transmission configuration could restrict the extraction of genuine EO phase and intensity modulation signal in the arms of MZI due to Fabri-Pero modulator in sample configuration. MZI reflection configuration excludes the mentioned problem on the other hand complicating the preparation of the sample. We used indadione derivatives in side chain of polyurethane thin films for EO measurements, MZI configuration comparison and validity evaluation.

**7935-41, Poster Session**

**Emission behavior of active optical silica fiber with doped polymer cladding layer**

H. Mochizuki, K. Murai, National Institute of Advanced Industrial Science and Technology (Japan)

Active optical fibers have attracted much attention as key devices of information communication technologies. We fabricated an active optical fiber consisting of a silica core and a polymer cladding layer dispersed with an organic orange-red laser dye. This active optical fiber emitted doughnut-shaped luminescence from its silica core when pumped by an incident beam at 488 nm of a pulsed laser into the silica core. The doughnut-shaped luminescence was attributed to the laser dye in the cladding layer because its emission color was orange-red and no emission was observed from a non-doped optical fiber by the same pumping. The doughnut-shaped luminescence was not observed by pumping the lateral aspect of the optical fiber. Pumping on the cladding layer did not allow us to observe the doughnut-shaped luminescence. The doughnut-shaped luminescence was found to be amplified spontaneous emission (ASE,) and its spectra of the ASE became narrower with pumping energy.

**7935-42, Poster Session**

**Improvement in viewing angle properties of top-emitting organic light-emitting devices**

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Organic light-emitting devices (OLEDs) have been a promising candidate for application in display devices owing to their superior characteristics including high contrast ratio, low operating voltage, and fast response time. In addition, top-emitting OLEDs show a few technical advantages such as large aperture ratio for active-matrix OLED displays. However, the strong microcavity effects, which cause the changes of emission peak wavelength and angular intensity with viewing angle, are inherent in the top-emitting OLEDs. In this study, firstly, the recombination zone is aligned with the anti-nodal region of the standing wave to optimize the recombination rate. Secondly, the Fabry-Perot effect is considered to improve the viewing angle properties of the top-emitting OLEDs. From the comprehensive analysis by using the APSYS (Advanced Physical Model of Semiconductor Devices) simulation program, trends in the dependence of emission characteristics on device structures are explored. Consequently, a better design for optimizing the viewing characteristics of the top-emitting OLED for display application is suggested.

**7935-43, Poster Session**

**Photopatterning and electro-optical switching of redox active fluorescent polymers**

S. Seo, Y. Kim, J. You, E. Kim, Yonsei Univ. (Korea, Republic of)

The fluorescent poly(1,3,4-oxadiazole) (POD) and polypyrene (PPy) were examined for electro-optic device. The fluorescence switching device prepared using poly(1,3,4-oxadiazole) showed structure-dependent switching properties depending on the para–meta-linkage. Thin films of POD and PPy were prepared by solution process to give highly fluorescent film, of which emission intensity was switched on and off upon application of step potentials. Using a photochemical reaction, the thin films of POD and PPy were directly patterned to give a fluorescent pattern. An all solid state device containing the patterned films of POD and PPy were prepared using a solid polymer electrolyte layer. The device showed reversible fluorescence switching in response to external voltage applications. Patterning of the switching device in different dimension and scale will be demonstrated.

**7935-44, Poster Session**

**Ultrafast nonlinear optical properties and excited state dynamics of phthalocyanine thin films**

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Phthalocyanines and their metal derivatives possess interesting nonlinear optical properties and find extensive applications in photonic devices such as optical limiters and all-optical switches. For practical applications these materials need to be doped in a suitable matrix. The high stability and capability of phthalocyanines, especially, to accommodate different metallic ions in their cavity due to their architectural flexibility, which allows tailoring of their physical, optoelectronic and chemical parameters in a broad range results in the diverse optical properties that find extensive applications in optical limiting and all-optical switching. Herein we present our results on the nonlinear optical properties of alkyl and alkoxy phthalocyanine thin films studied using ~2 picosecond pulses and ~40 femtosecond pulses. The nonlinearities were studied using Z-scan technique and the excited state dynamics using the degenerate four wave mixing and pump-probe techniques. A strong nonlinear absorption was observed with both picosecond and femtosecond pulses. Degenerate pump-probe technique provided information about the excited state life times in the picosecond time scale. The effect of alkoxy and alkylation substitution on the phthalocyanine core is investigated.
**7935-45, Poster Session**

**Synthesis of thiophene-based conjugated copolymer containing ferrocene units for organic electronics**

S. Kim, Y. Kim, E. Kim, Yonsei Univ. (Korea, Republic of)

Conjugated polymer based on thiophene-ferrocene unit were synthesized by Grignard metathesis (GRIM) method. These polymers were characterized by GPC, NMR, and UV-Vis absorption spectra. The thiophene-ferrocene copolymers showed stable and reversible electrochemical redox state due to the ferrocenyl functional group which was determined by cyclic voltammogram. Their charge transfer and photovoltaic properties were examined on a three layered electrochromic device with a ITO /polymers/electrolyte/ITO structure and a solar cell having a structure of ITO/PEDOT:PSS/polymer: [6,6]-phenyl C61-butyric acid methyl ester (PCBM) /LiF/Al under the illumination of AM 1.5 (G) 100 mW/cm², respectively. The application of highly conductive thiophene-ferrocene polymer to organic electronics are very promising candidates as it shows facilitated charge transfer properties plus processibility.

**7935-46, Poster Session**

**New apparatus and processes to produce ethereal oil**

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Authors have studied a problem of the domain of ethereal oils. As we know, today we have a quietly large number of processes and apparatus designated to produce oils, and/or ethereal oils. In one or more steps of the process it is necessary to ensure a determined temperature to the moisture. Of course we could choose the most convenient heating source as gas, electric source a.s.o.

Authors experienced a thermal source, based on “concentrated energy”. From a large scale of concentrated energy, we have proved the laser beam energy because in this way we can control exactly the amount of energy which is delivered to the substance, and also the time duration of the action.

To put in action such experiment, we considered a huge number of variables like: receptacle parameters - i.e. material, shapes and dimensions; nature of heat agent; heating dynamics; insulating conditions to know exactly the thermal lost; process efficiency - how much energy is needed for a determined quantity of finite product.

Such installations could be realized as fixed or mobile units. For both cases we evaluated: the dimensions of installations; materials consumption; costs; environmental impact. The modern industry and also industrial or private customers for ethereal oils are high interested in such new projects and are tried to apply such models as soon as possible. Authors continue to study and apply different types of installations to find the most efficient one.

**7935-47, Poster Session**

**Refractometric sensor using poli (p-phenylenevinylene) PPV and poli(p-xlylenes) PPX**

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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 we present a study of the optical gas sensing properties of Poli (p-phenylenevinylene) PPV and poli(p-xlylenes) PPX deposited by spin-coating. These polymers are easy to process and can be obtained from inexpensive materials. Also, in previous works it was demonstrated that the electrical resistivity of these polymers changes when exposed to different organic solvents which allowed the developing of applications in electronic nose [2,3]. Furthermore, preliminary results showed a variation of the refractive indices of these polymers (approximately 0.1 RIU - Refractive Index Units) in the wavelength of 632.8 nm when they are exposed to ethanol gas with different concentrations.

Based in this characteristic, two different approaches were used. The first approach was through conventional fiber sensing with cladding-striped optical fiber. In this case, a single-mode optical fiber was locally stripped of its cladding layer by lapping and polishing processes. 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 [4, 5].


**7935-48, Poster Session**

**Fabrication of an organic photovoltaic cell using spray deposition on heated substrate**

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We reported the fabrication of an organic photovoltaic cell using spray deposition on heated substrate.

For the material of buffer layer, Poly (3,4ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT-PSS, Clevios PH750) was used. Phenyl-C71-butyric-acid-methyl ester (PCBM, ADS) and regioregularpoly(3-hexyliithiophene) (r-P3HT, Sigma-Aldrich) were used as an accepter and a donor for the active layers, respectively.

PEDOT-PSS was deposited with the spray-deposition method on the indium tin oxide (ITO) glassduring substrate temperature of 150 °C for 1 min with N2at 0.1 MPa pressure. Active layer was also spray deposited for 20 sec at same spray conditions. Subsequently Aluminum cathode was evaporated onto the active layer.

Low conductivity caused by pure PEDOT-PSS (PH750) was compensated by adding 5%dimethylformamide (DMF)for 5%dimethyl sulfoxide (DMSO). According to the result of this test, the conductivity of DMF added PH750 was 12.82 S/cm and that of DMSO added PH750 was 77.28 S/cm. It indicated that the additive influenced buffer layer to have better conductivity than pure PH750 (0.0064 S/cm). Consequently, the device with 5% DMSO adding PH750 obtaineda short current density of 14.02 mA/cm², an open voltage of 0.62 V andthe power conversion efficiency (PCE) of 2.952%. It showed a possibility of flexible solar cell fabrication using full spray process.

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Integrated optical wave plates fabricated by incorporating reactive mesogen in polymer waveguides

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Integrated optical wave plates are useful components due to the potential to be integrated with various optical components available in the form of optical waveguide devices, such as phase modulators, polarization splitters, or optical switches. Polymer waveguide has excellent compatibility to realize the wave plates due to the unique fabrication process. Moreover, the organic reactive mesogen (RM) material with a large optical birefringence has good miscibility with the organic polymer waveguide devices.

The polymer waveguide was prepared by using a low-loss fluorinated polymer material. Conventional fabrication procedures were conducted to obtain low-loss polymeric waveguide. In the middle of the polymer waveguide, a groove was defined by an oxygen plasma etching in a direction perpendicular to the optical waveguide. The RM solution was inserted to fill up the groove, and then it was poled by an electric field of a few V/m to define the wave plate axis of 45 degree for the guided mode. The converted output polarization states were monitored by using a polarization analyzer. After the poling, the RM material was crosslinked by illuminating the UV light. The birefringence of the RM material was optimized to have a phase shift for demonstrating the half wave plate. The polarization conversion efficiency over 95% was achieved in this preliminary experiment.

Realization of compact optical coherence tomography

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Optical Coherence Tomography (OCT) is an emerging optical imaging modality in biomedical optics and medicine. OCT performs high resolution, cross-sectional imaging of the internal microstructure in sample by measuring echoes of backscattered light. OCT can classified as time domain OCT (TD-OCT) and frequency domain OCT (FD-OCT) by methods for obtaining depth information. TD-OCT can obtain depth information by acquiring and demodulating the signal amplitude modulated by mechanical movement with the depth (axial) direction. FD-OCT needs no mechanical movement to obtain depth information of sample. Recently developed parallel OCT schemes, called Full-field OCT based on TD-OCT, eliminate the need for lateral scanning. These schemes use CCD cameras and CMOS detector array as photodetectors. In this study, we propose the compact Full Field OCT system for cosmetic field application. The most important factor for cosmetic application is compactness. For compact system, we use mirau objective lens. By using mirau objective lens, we can realize OCT system without reference arm. And we proposed two way for handheld system. First is using module system. By implement the OCT system in one module, we can grab and using easy. Second is making sample arm like a probe. We will realize the compact FF-OCT using proposed method and compare the result.

Performance analysis of interface treatments on the polymer substrate and ITO film applied for flexible solar cells

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The surface effects on polyethylene terephthalate with polymeric hard coating (PET-HC) substrates treated by different manners used as organic solar cells have been investigated by measuring the contact angle. It is observed that detergent is quite effective in removing organic contamination on the flexible PET-HC substrate. Using a DC reactively magnetron sputter, indium tin oxide (ITO) thin films of 90 nm are grown on a substrate treated by detergent. After ITO thin films are deposited, various ITO surface treatments are made for improving the performance of the developed solar cell. The organic solar cell with structure Al/P3HT:PCBM/ PEDOT: PSS/ ITO/ PET-HC is fabricated. It is found that the surface treatments change the parameters of the ITO, i.e., work function, carrier concentration, transmittance, resistivity, surface morphological and significantly influence the solar cell performance. With the optimal conditions for detergent treatment on flexible PET-HC substrates, we can obtain the ITO film with a resistivity of 5.6 ×10^-4 Ω-cm and average optical transmittance of 84.1 % in the visible region. Then, the optimal ITO surface treated by detergent for 5 minutes and by UV ozone for 20 minutes exhibits the best WF value of 5.22 eV. The current density-voltage (J-V) characteristics of the developed photovoltaic (PV) devices were measured under AM1.5G illumination at 100mW/cm². Through the treated PV measurement, 36.6 % enhancement in short-circuit current density (Jsc) and 92.7 % enhancement in conversion efficiency (α) over the untreated solar cell were obtained.
Hybrid optical polymer materials and devices for RF photonics applications

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No abstract available

Full wave analysis of a composite right/left-handed leaky wave antenna

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Leaky modes, which decay monotonically in the transverse directions to oscillatory fields, play an important role in microwave and optical devices. For metallic structures in microwave range, leaky modes always exist in the form of scattering resonances, accompanied by sufficiently small leakage rate. By nature, their properties were extensively employed in RF antennas to facilitate the interaction between the free space propagating wave and guiding waves. Based on the composite right/left-handed leaky wave antenna (CRLH LW) realized by Toyata’s Lab [1], we elaborate its working mechanism from the aspect of fundamental physics with full wave simulation.

We programmed parallel 3-D CPML-FDTD codes for the band calculation. Bloch boundary condition with real propagation constant was assumed in the array. Symmetrical and CPML boundary conditions were applied in the vertical and transverse directions, for filtering the undesired asymmetrical modes out and absorbing the outgoing waves, respectively. By doing so, the leaky waves in fast and slow wave regions can be visualized, with both the resonant frequency ( ) and the decaying factors (corresponding to the imaginary part of ). Calculations show that there is a stop band at point for the investigated structure, which inhibits the continuous beam steering. Anti-crossing points that were induced by the coupling of the slab modes and the resonant modes are clearly identified near the light line. In addition, the structural symmetry of antenna suggests that group velocities should be zero at the high-symmetric points.


Phase shifter using carbon nanotube thin-film transistor for flexible phased-array antenna

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There has been a growing interest on forming phased-array antenna (PAA) on flexible substrate using printing technique due to its light weight, low cost, and deployability. In this paper, a full 1x4 phased array antenna is fabricated using combination of ink-jet printing and stamping techniques. At first, a self-aligned CNT thin-film using 99% pure single-walled carbon nanotube is formed by dip-coat technique on sacrificial substrate and then transferred on the device substrate. Ink-jet printing technique is used to form the source, drain, gate electrodes, transmission lines and antenna elements. The CNT thin-film transistor (TFT) is characterized. Bending test on CNT-FET test structures show less than 10% variation in the performance. Multiple layer interconnect integration is also demonstrated on flexible substrate circuit. Interconnection via bending test shows less than 5% variation in resistance. The radiation pattern of the PAA system for a 5.3GHz signal is collected. The DC probes are configured to measure the steering at 0 and 27 degree steering angles. It can be seen from the far field radiation patterns that the measured and simulated far field patterns agree very well with each other. Bending test is performed on the PAA system. Measured and simulated far field radiation patterns are reported, and both data sets agree well with each other.

Traveling wave directional coupler modulator based on electro-optic polymer

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A bias-free Y-fed directional coupler modulator based on electro-optic polymer is fabricated and tested. 50wt% LPD-80/APC (amorphous polycarbonate) is used as an active core layer with an experimentally confirmed device r33 value of 79pm/V and an extinction voltage of 6.1V at 1.55 wavelength. The directional coupler consists of two parallel 5-wide waveguides separated by . The vertical structure of device comprises of 3.5 bottom-cladding (UV-15LV), 2.2 of active core (LPD-80/APC), and 3 of top-cladding (UFC-170A). The rib waveguide is etched 0.52 deep into the bottom-cladding to support TM single-mode condition. A lumped electrode with two sections is designed to achieve the inverted modulation that can improve the linearity and the distortion suppression as well as to simplify the poiling process. The electrode has two sections and the length of both sections is about 1cm which is 2.86 the normalized coupling length of directional coupler. Two-tone numerical procedure is used to find the optimum electrode design that can achieve the highest distortion suppression ratio which is defined as the ratio of fundamental signal to distorted signal. A two-tone test is performed using two fundamental signals of 19kHz and 21kHz. The fundamental signals and the third order intermodulation distortions are measured as a function of input power. The spurious free dynamic range, which is the ratio of the largest to smallest signal that can be transmitted and received in the links without introducing detectable distortions, is measured to be 119dB/Hz2/3 at 1.55 , which is 11dB higher than the conventional Mach-Zehnder modulator.

High speed electro-optic polymer phase modulator using an in-plane slotline RF waveguide

D. H. Park, Y. Leng, Univ. of Maryland, College Park (United States); J. Luo, A. K. Y. Jen, Univ. of Washington (United States); W. N. Herman, Univ. of Maryland, College Park (United States)
In this paper, we report a high-speed optical phase modulator based on a nonlinear electro-optic (EO) polymer with an in-plane slotline RF electrode structure. Design, fabrication, and characterization for the phase modulator are presented. Compared to microstrip, slotline RF electrode design has several advantages such as easy fabrication, high poling efficiency, high overlap factor, low Vpi, and suppression of DC bias drift.

A ridge waveguide structure was fabricated using reactive ion etching (RIE) directly on a fused silica substrate in order to facilitate subsequent fabrication processes such as metal deposition and EO material spin-coating without a special care of material properties for a bottom cladding. The slotline electrode was designed for both low optical loss and impedance match to 50 Ohm to minimize the RF return loss. The effective index of the optical waveguide was controlled by adjusting the width and height of the waveguide to satisfy phase matching between optical and RF signals to optimize the bandwidth of the modulator. A 35 wt. % of the nonlinear chromophore AJLZ53 in host polymer BPAPC (Bisphealon A Polycarbonate) was used for the core layer. The highly transparent amorphous fluoropolymer Cytop® was spin-coated onto an EO polymer core layer as the top cladding. The second-order nonlinearity of AJLZ53/BPAPC was separately estimated at the telecommunication wavelength of 1550 nm using several methods including reflection ellipsometry, attenuated total reflection, and FP methods. RF insertion loss was measured to be lower than 0.3 dB/cm/GHz. Optical loss and Vpi characterization will be discussed in detail.

Recent progress toward a nanoslot modulator

G. E. Betts, A. Chen, Photonic Systems, Inc. (United States); W. H. Steier, The Univ. of Southern California (United States)

Modulators using silicon waveguides with a small (<100 nm) slot in the center of the waveguide filled with an electro-optic polymer can have very low switching voltage. A variety of challenges including difficulty poling the polymer and difficulty achieving high-speed operation have so far prevented successful demonstration. Problems poling the polymer may be electrical, such as nonuniform poling fields or too much polymer conductivity compared to the silicon electrodes, or they may be more fundamental such as interaction of the polymerized system with the slot edges. High-speed operation is made difficult by the very small dimensions of the device which lead to high capacitance, high resistance, and high microwave loss in a traveling-wave structure. This paper discusses solutions to some of these problems.

High-frequency microwave signal generation in a semiconductor laser under double injection locking

Y. Juan, Y. Chen, F. Lin, National Tsing Hua Univ. (Taiwan)

We numerically investigate high-frequency microwave signal generation utilizing a double injection locking technique. A slave laser (SL) is strongly injected by a master laser 1 (ML1) and a master laser 2 (ML2) optically. Stable locking states are observed when the SL is subject to optical injection by the ML1 and ML2 individually. By utilizing the hybrid scheme consists of double optical injections, the advantages of each individual dynamical system are added and enhanced. Comparison of the performances of the spectral width, power fluctuation, and frequency tunability between the signal generated in the double injection locking scheme and the similar period-one (P1) state generated in a conventional single injection scheme is studied. A 3-fold linewidth reduction is achieved by utilizing the double injection locking scheme due to the strong phase-locking and high coherence performance when operating at the stable injection locking state. Moreover, for the double injection locking scheme, a wide continuous tuning range of about 60 GHz is obtained by adjusting the detuning frequencies of the two optical waves. A power fluctuation of less than 5 dB is found in the whole tuning range.

The performances of narrow linewidth, wide tuning range, small power fluctuation, and continuity show great advantages of the high-frequency microwave signal generated by the double injection locking technique.

Fiber ring resonator based opto-electronic oscillator phase noise and temperature stability evaluation

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To generate high spectral purity signals at microwaves, the use of optical fiber ring resonators in opto-electronic oscillators (OEO) is an efficient solution. Indeed, very high optical Q factor can be reached with these resonators, in the range of 109 to 1010. However, to be competitive with the best microwave sources, these OEOs must feature simultaneously a very high Q and a low additive loop phase noise. Another problem is related to the design of a locking system which maintains the laser signal inside the resonator bandwidth (typically, a few tens of kHz).

Different OEOs based on 20 m fiber loop resonators have been realized. In the last design, the OEO phase noise has been optimized versus the additive optical noise. However, an important 1/f like noise component is also observed in the resonator bandwidth. The measured phase noise performance of the OEO is -110 dBc/Hz at 10 kHz offset from a 10 GHz carrier. This phase noise should be improved in a near future thanks to an original modeling approach, which has been developed specifically to describe these microwave optical systems including noise and nonlinear elements.

The resonator thermal stability has also been investigated. A theoretical thermal stability constant has been computed from the variation of the fiber index and length with temperature. This theoretical constant is \( \Delta \text{FSR/FSR} = \Delta f_{RF}/f_{RF} = -6.8 \text{ ppm/°C} \). Such a thermal stability has been verified experimentally, both on the resonator and the oscillator. This is a sufficiently good performance for many applications.

Compact optoelectronic oscillator using whispering gallery mode resonators for radio-frequency and millimeter wave generation

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Optoelectronic oscillators (OEOs) are ultra-pure microwave generators based on optical energy storage instead of high finesse radio-frequency (RF) resonators. They have many specific advantages, such as exceptionally low phase noise and wide-range tunability of the output frequency. Generally, the optical storage element in OEOs is a bulky optical fiber delay line. We present in this communication a new architecture where the optical energy storage performed by trapping laser light into the ultra-high Q whispering gallery modes (WGMs) of a millimeter-size disk resonator. The specific advantage of this WGM OEO is that it is compact, it does not generate delay-induced spurious peaks in the RF spectrum, and it is compatible with compact temperature control systems. This ultra-pure microwave source is therefore easily transportable, as required in many applications (aerospace engineering, etc.). As a proof of concept, we demonstrate the generation of a 10.7 GHz microwave with a phase noise of -110 dBc/Hz at 100 kHz. We also discuss in detail the potential of this architecture for the generation of microwaves with a frequency ranging from 50 to 100 GHz.
Poling study of EO polymers in silicon slot waveguides
A. A. Szep, Air Force Research Lab. (United States)
No abstract available

Progress in millimeter-wave imaging
D. A. Wikner, U.S. Army Research Lab. (United States)
The field of millimeter-wave (MMW) imaging has progressed significantly over the last two decades. The most obvious evidence of this is the widespread use of MMW full-body scanners, now commonly found in airports. The path to this point has been the result of the work of a wide range of experts from many scientific and engineering disciplines. This article represents one perspective of this progress.
The development of MMW imagers, and all their associated component technologies, image processing techniques, clever engineering, etc. has been driven by a relatively small number of interesting applications. It has been known for about 70 years that RF energy can be used to “see” through things like clouds and detect, for example, hostile aircraft. As the RF frequency goes up to 35, 100, or 340 GHz, it becomes possible to image through obscurants with much improved resolution. However, as frequency increases, attenuation increases as well, so selecting the right frequency for the application is an important point. The challenge of seeing through obscurants such as fog, smoke and dust drives one towards a MMW imaging solution. Typical applications include guiding aircraft through low visibility conditions such as fog or dust clouds, detecting nearby watercraft in the fog, and searching for concealed weapons. So, while these capabilities have been demonstrated numerous times over the years, the practical and affordable implementation of the systems to accomplish these goals is where the real story lies.

Design and construction of an electro-optic rf metamaterial array
W. Chen, Univ. of Dayton (United States); R. L. Nelson, Air Force Research Lab. (United States)
The chair is the author, this part not necessary.

ACP-OPLL photonic integrated circuit for high dynamic range RF/photonics links
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Fiber-optic links are attractive for transmitting microwave/millimeter wave signals for radar, imaging, astronomy, and many other analog communication systems. The conventional fiber-optic links generally employ intensity modulation and direct detection (IM-DD). However, the nonlinearity in the IM-DD processes restricted the link spurious free dynamic range (SFDR). In many situations a large SFDR (>140dB-Hz2/3) is critical for high fidelity transmission of analog signals. However, the existing IM-DD fiber optic link can barely achieve an SFDR greater than 120dB-Hz2/3.
For solution, a coherent fiber-optic link using linear phase modulation and linear phase demodulation by an optical-phase-locked-loop (OPLL) has been proposed. The new link can achieve an SFDR two orders of magnitude larger than that of the current state-of-the-art. The key for this link is the OPLL phase demodulator. The OPLL contains local optical phase modulators, photodetectors, and a 3dB optical coupler. It demodulates the optical phase by tight phase tracking. The OPLL must have a large open loop gain over a wide bandwidth. For feedback stability, the OPLL only tolerates very short loop delay (~10ps or less). This is only achievable by employing a novel attenuation-counter-propagating (ACP) device design and by photonic integration.
In this paper we describe the development of the ACP-OPLL photonic integrated circuits (PIC) capable of achieving the desired link SFDR. The ACP-OPLL PIC monolithically integrates a pair of highly linear detuned shallow quantum well phase modulators in a push-pull configuration, a pair of balanced uni-travelling-carrier (UTC) high power waveguide photodetector, and a multimode interference 3dB output coupler on an semi-insulating substrate. We will present the design, fabrication and measurement results of the first generation ACP-OPLL PIC devices.

Large dynamic range electromagnetic field sensor based on domain inverted electro-optic polymer directional coupler
A. X. Wang, Omega Optics, Inc. (United States); B. Lee, R. T. Chen, The Univ. of Texas at Austin (United States)
Electromagnetic Field (EMF) sensors have broad applications in EM attack alarming, ballistic control, microwave integrated circuit testing, medical apparatuses, and health protection. Comparing with electronic competitors, Photonic EMF sensors can offer distinctive advantages in size, weight and bandwidth coverage. In this paper, we present the design and experimental measurements of a large dynamic range EMF sensor using domain inverted-electro-optic (E-O) polymer directional coupler. The E-O polymer waveguide (LPD80/APC) are inversely potted both in the two parallel waveguides and in the adjacent domains for a push-pull drive and non-linear distortion cancellation. To increase the poling efficiency and avoid dielectric breakdown between the poling electrodes, alternative voltage pulse (1Hz, 1000V) is applied across the polymer layer. Due to its intrinsically symmetric structure, the photonic EMF sensor can faithfully record the frequency and amplitude of the electromagnetic wave. In contrast to many photonic EMF sensors that require the assistance of microwave antennas to drive E-O modulator, our EMF sensor is totally electrode-free, and generates no disturbance to the electromagnetic field. The photonic EMF sensor can detect a large power range from milliwatts to kilo-watts per square centimeter, and has a uniform responsivity from DC to 20GHz.
the transmitted power level and extend the error-free propagation distance. Experimental results and documented atmospheric attenuation values for clouds, fog and rain are used to estimate link budgets for ground-based point-to-point wireless data transmission links and for a millimeter-wave satellite downlink operating near 100 GHz. System requirements, including carrier frequency, transmitted power and antenna gain are presented for a 10 Gb/s downlink from a low-earth-orbiting satellite to a stationary ground station.

7936-18, Session 5

Design of a millimeter-wave full-Stokes polarimeter utilizing optical up-conversion

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The polarization properties of radiation can contain additional information beyond what is available with only an intensity measurement. A full-Stokes polarimeter is capable of measuring the four Stokes parameters which completely characterizes the polarization of detected radiation. A division of time full-Stokes polarimeter often uses a rotating polarizing element to measure all four Stokes parameters and this rotation can introduce artifacts due to wobbling. In this paper a system is proposed which uses an electrically controlled phase bias instead of a rotating element to create a full-Stokes polarimeter for a millimeter-wave system which utilizes optical up-conversion.

The optical up-conversion of millimeter-wave energy to optical energy involves a phase modulator. This modulator can produce a phase bias on the optical signal with an electrical bias applied to it. An orthomode transducer is used to split incident millimeter-wave radiation into two orthogonal linear polarizations states which are both up-converted to telecom frequencies. By phase locking both signals together, it is possible to use the bias introduced by the modulator to act as a phase retarder. By adjusting this signal in time it is possible to create a full-Stokes polarimeter without a rotating element by also introducing a linear polarizer orientated at 45 degrees relative to either axis of the two original polarization states. In addition, a division of amplitude full-Stokes polarimeter can also be created by phase locking the two linear polarization states and then optically splitting the beam into four parts with different polarizing elements in their respective beam paths.

7936-19, Session 5

RF photonic wave integration for distributed millimeter wave imaging applications

C. A. Schuetz, Phase Sensitive Innovations, Inc. (United States)

No abstract available

7936-20, Session 5

Millimeter wave image processing through point spread function engineering

J. N. Mait, U.S. Army Research Lab. (United States)

No abstract available

7936-21, Session 5

Phase modulated radio-over-fiber systems: linearization and photonic downconversion

T. E. Murphy, Univ. of Maryland, College Park (United States)

Although most radio-over-fiber (RoF) systems use intensity modulation to impose the microwave signal onto an optical carrier, there is a growing interest in using phase modulation instead. Compared to intensity modulators, phase modulators not only eliminate the need for active bias control circuitry at the transmitter, but also offer lower insertion loss and higher optical power handling capability. Despite these advantages, phase modulation systems have yet to be widely accepted, in part because phase modulated optical signals are harder to detect at the receiver. We describe our ongoing efforts to develop new types of phase-modulated RoF communication systems that offer the advantages of linearized performance for extended dynamic range, together with optical photonic downconversion at the receiver.

7936-22, Session 5

Novel WDM to OTDM wavelength converter system for transmission of discrete sampling spectrum in single wavelength channel

T. Yang, C. Wang, J. Wang, C. Ge, M. Sang, Tianjin Univ. (China)

Normally the WDM-to-OTDM conversion can be realized by frequency conversion in nonlinear crystal materials or semiconductor materials combining with the various asynchronous retiming schemes, such as an array of several delay lines of various lengths of fibers in which each line has an optical switch connected, which results in a complex setup. In this paper, a novel WDM-to-OTDM conversion system which has a simple setup is proposed. The system is a type of fiber loop consisting of an optical single-side-band (SSB) modulator that is driven by a RF signal source at 10 GHz (0.08 nm), a fiber circulator, a fiber coupler, a fiber amplifier and an ultra-narrowband high reflectivity fiber Bragg grating (FBG). A frame multi-wavelength signals \( n = 1 + (n-1) \times 0.08 \) nm are inputted into the system in which the FBG has a high reflectivity at the minimum carrier-wave wavelength 1 of the input signals. Then signal at wavelength 1 is reflected first by the FBG and exits from the system first. The other carrier-wave wavelength signals will go further into and though the SSB where the signal at 2 is up-converted to 1 and exits from the system at the 1 by the FBG reflection with a delay of optical round loop time. Finally, this process will be continued until all signals at \( n \) of the frame are transformed to the single wavelength 1 after the \( (n-1) \) optical round loop times.
Ultrafast few-fermion dynamics in single self-assembled InGaAs/GaAs quantum dots and dot molecules

M. Betz, Technische Univ. Dortmund (Germany)

We report a comprehensive study of the ultrafast optoelectronic properties of a single self-assembled InGaAs/GaAs quantum dot. While manipulation of the artificial atom relies on two widely and independently tunable picosecond pulses trains, sensitive readout is achieved via the p-shell transitions in the presence of s-shell population. In addition, time-resolved data directly maps the picosecond tunneling times of electrons and holes out of the dot. Beyond these incoherent phenomena, we also realize coherent QD manipulations. Those comprise well-known excitonic Rabi-oscillations as well as single-pulse bieexciton generation and conditional Rabi-oscillations of the exciton-bieexciton transition after deterministic exciton preparation.

Ultrafast carrier capture and THz resonances in InGaAs quantum posts

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Semiconductor quantum posts (QPs) - nanowire-like InGaAs heterostructures [1] in a GaAs matrix - resemble many properties of regular self-assembled quantum dots (QDs), to which they are closely related. Due to their increased size as compared to QDs, QPs have proven to be suitable for very low threshold interband lasers. However, their well controllable height makes them attractive for precise tuning of core size, much shorter than the radiative lifetime in the nanosecond range. Transient density grating data taken in the same experiment reveal a strongly non-exponential dephasing. While the combined electron-hole dynamics are studied using time-resolved photoluminescence spectroscopy, optical pump - THz probe experiments were performed in order to study the electron dynamics. The results of the THz experiment show that after ultrafast excitation, electrons relax within a few picoseconds into the quantum post states, which act as efficient traps [2]. The saturation of the quantum post states, probed by photoluminescence, was reached at approximately ten times the quantum post density in the samples. Recently, we also studied the response of possible electronic resonances after direct photoexcitation into QPs where a broad absorption line as well as previously unobserved p-shell transitions were observed. In addition, we provide direct evidence that the macroscopic response of the gain recovery dynamics in electrically-pumped InGaAs/GaAs QD ensembles is a superposition of intradot relaxation dynamics from microstates with discrete numbers of carriers, not described by a mean-field approach. Using pump-probe differential-transmission spectroscopy with an optical pre-pump we measured the ultrafast gain recovery dynamics from 15K to 300K. We find that the gain recovery dynamics of an ensemble prepared by a pre-pump fully depleting the ground-state gain with a variable lead time is faster than without pre-pump. This finding is contradicting the widely used rate equation models for mean-field carrier distribution functions, and exemplifies a conditional gain recovery in which microstates with slow internal dynamics are suppressed by the pre-pump. This behaviour is particularly evident at low temperatures, but is still present at room temperature, and is actually beneficial for practical applications aiming at the ultrafast amplification of an optical pulse sequence for high-speed optical signal processing.

Spin-flip limited exciton dephasing in CdSe colloidal quantum dots

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The dephasing time inversely proportional to the homogeneous linewidth of an optical transition is a fundamental physical quantity in light-matter interaction. Semiconductor quantum dots (QDs), in which carriers are confined in all three directions, exhibit a peculiar coupling of excitons with phonons as a result of the local lattice distortion associated with the excitonic excitation. This coupling gives rise to a strongly non-Lorentzian excitonic homogeneous lineshape at low temperatures consisting of a Lorentzian zero-phonon line (ZPL) superimposed onto a broad acoustic phonon band, and in turn a strongly non-exponential dephasing. While extensive work has been reported on the ZPL weight and dephasing as a function of temperature and dot size in epitaxially grown QDs, less has been shown for colloidal QDs which have a stronger confinement. In this work we have measured the exciton dephasing using transient four-wave mixing in a series of CdSe/CdS colloidal QDs with core size ranging from 3.3nm to 5.7nm and shell thickness from 0.6nm to 3.3nm, in the temperature range from 5K to 150K. The large dynamic range of the measurements enabled us to observe a strongly non-exponential dephasing with a ZPL weight increasing with decreasing temperature and increasing extension of the excitonic wavefunction. The zero-temperature extrapolated dephasing of the ZPL is several 10ps even for the largest core size, much shorter than the radiative lifetime in the nanosecond range. Transient density grating data taken in the same experiment reveal that this dephasing originates from exciton relaxation within the non-degenerate spin states.
Influence of Coulomb interactions on emission dynamics in semiconductor quantum dot systems

K. Gradkowski, T. J. Ockhalski, N. Pavarelli, D. P. Williams, E. P. O'Reilly, Tyndall National Institute (Ireland); J. Tatebayashi, B. Liang, D. L. Huffaker, Univ. of California, Los Angeles (United States); D. J. Mowbray, The Univ. of Sheffield (United Kingdom); G. Huyet, Tyndall National Institute (Ireland)

Novel self-assembled quantum dots based on GaSb/GaAs technology are investigated for possible applications in the near- and mid-infrared, i.e. telecommunication networks, solar cells, gas sensors and imaging systems. These heterostructures exhibit a type-II band alignment, which means that one species of carrier is confined to the dot, while the other is outside in the surrounding matrix. This physical separation of carriers leads to profound Coulomb interactions, which makes the optical properties of these structures dependent on the injected charge density. The relationship between the emission energy and transition probability leads to an intricate and complex emission dynamic.

The mechanism responsible for this behaviour is investigated by employing experimental and theoretical techniques on several structures that provide diverse confinement scenarios, i.e. where the electrons are confined in the dot and holes are outside, as well as the converse situation. The experiment is based on time-resolved photoluminescence, which allows for simultaneous observation of spectral and temporal evolution of the emission. The results are then corroborated with a self-consistent model based on an 8-band $k\cdot p$ formalism, which provides an explanation for the observable features.

For comparison, a novel type-I InAs/GaAs quantum dot system design based on a tunnel injection scheme is investigated under a high-excitation regime, where it also exhibits interesting emission dynamics that involve an inhibition of the optical transition probability in a charged quantum dot.

Ultrafast density- and temperature-dependent carrier dynamics in a quantum dots-in-a-well heterostructure

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The incorporation of semiconductor quantum dots into different heterostructures for applications in nanoscale photodetection, lasing and amplification has been an active area of research in recent years. Here, we use ultrafast differential transmission spectroscopy to temporally and spectrally resolve density-and-temperature-dependent carrier dynamics in an InAs/InGaAs quantum dots-in-a-well (DWELL) heterostructure. In our experiments, electron-hole pairs are optically injected into the three dimensional GaAs barriers, after which we monitor carrier relaxation into the two dimensional InGaAs quantum wells and the zero dimensional InAs quantum dots by tuning the probe photon energy. We find that for low photoexcited carrier densities, carrier capture and relaxation are dominated by Auger carrier-carrier scattering at low temperatures, with thermal emission playing an increasing role with temperature. At low temperatures we also observe excitation-dependent shifts of the quantum dot energy levels. In contrast, high density measurements reveal an anomalous induced absorption at the quantum dot excited state that is correlated with quantum well population dynamics. Our experiments provide essential insight into carrier relaxation across multiple spatial dimensions and reveal unique Coulomb interaction-induced phenomena, with important implications for DWELL-based lasers and amplifiers.
we propose that quantum dot devices might be used to realize an optically fed microwave phase shifter in the frequency range of 100GHz.

7937-09, Session 3

Tapered terahertz plasmonic waveguides

D. M. Mittleman, H. Zhan, J. Liu, R. Mendis, Rice Univ. (United States)

Concentrating optical energy into an ultra-small spot beyond the diffraction limit has long been an interesting topic in photonics. One of the most popular methods is to use subwavelength-sized plasmonic waveguides, based on the excitation of localized surface plasmon polaritons (SPPs) on metallic surfaces. While most of the studies on plasmonic waveguides have been focused in the optical regime, subwavelength plasmonic waveguides in the THz spectral regime have recently attracted a great deal of attention. Here, we show that finite-width parallel-plate waveguides (PPWG) can provide strong lateral confinement of THz radiation, even parallel to the plate surfaces, although there is no physical boundary along that direction. This complete two-dimensional confinement is realized by the excitation of SPPs near the plate edges, similar to what is observed in the optical regime for metallic slot waveguides [2]. Based on this principle, we study tapered PPWG as a means for concentrating THz radiation onto an ultra-small spot. We also characterize the impedance mismatch that occurs at the end of the PPWG. This impedance mismatch, which occurs even though the waveguide is air-filled, can lead to a diminished efficiency for emission from the waveguide into the far field. Structuring the output facet of the waveguide may permit improvements to the far field emission efficiency, as well as enabling engineering of the near field intensity distribution.

7937-10, Session 3

Ultrafast optical control of terahertz surface plasmons in subwavelength hole-arrays at room temperature

A. K. Azad, Los Alamos National Lab. (United States)

Extraordinary optical transmission through subwavelength metallic hole-arrays has been an active research area since its first demonstration. The frequency selective resonance properties of subwavelength metallic hole arrays, generally known as surface plasmon polaritons, have potential use in functional plasmonic devices such as filters, modulators, switches, etc. Such plasmonic devices are also very promising for future terahertz applications. Ultrafast switching or modulation of the resonant behavior of the 2-D metallic arrays in terahertz frequencies is of particular interest for high speed communication and sensing applications. We demonstrate optical control of surface plasmon enhanced resonant terahertz transmission in two-dimensional subwavelength metallic hole arrays fabricated on gallium arsenide based substrates. Optically pumping the arrays creates a conductive layer in the substrate reducing the terahertz transmission amplitude of both the resonant mode and the direct transmission. Under low optical fluence, the terahertz transmission is more greatly affected by resonance damping than by propagation loss in the substrate. An ErAs:GaAs nanosiland superlattice substrate is shown to allow ultrafast control with a switching recovery time of ~10 ps. In addition, we demonstrate a large dynamic transition between a dipolar localized surface plasmon mode and a surface plasmon resonance mode under near infrared optical excitation. The reversal in transmission amplitude from a stop-band to a pass-band and up to 90 degree phase shift achieved.

7937-11, Session 3

Controlling THz plasmons with the electron spin state

C. J. E. Straatsma, A. Y. Elezzabi, Univ. of Alberta (Canada)

We investigate the effects of photonic magnetoresistance on the propagation of terahertz (THz) radiation in multilayered metallic media. These subwavelength plasmonic structures contain alternating layers of ferromagnetic and non-magnetic metal thin films, which allow for control over the electron spin state. In particular, using THz time-domain spectroscopy, a photonic analogous giant magnetoresistance effect is observed and its application in actively controlling THz plasmons is studied. We demonstrate the possibility of implementing this effect to produce active THz guided wave devices.

7937-12, Session 3

Semiconductor plasmons for THz frequency plasmonics

E. Hendry, The Univ. of Exeter (United Kingdom)

In this contribution we discuss the viability of semiconductor SPs for THz sensing and spectroscopy applications. We illustrate a proof of principle by aperture coupling THz radiation to propagating SPs on a flat semiconductor (InSb) interface, attaining field confinement of THz radiation on a length scale that is considerably smaller than the wavelength of free space radiation [1]. We then demonstrate that it is possible to utilize this confined electric field to detect and measure thin dielectric regions above a semiconductor surface with high sensitivity, measuring the THz response of low dielectric films of thickness three orders of magnitude smaller than the wavelength of free space radiation. Finally, we demonstrate the tunability of plasmonic properties: by modifying plasma frequencies through photoexcitation, something which generally cannot be achieved with metals, the interaction of THz light with the material can be enhanced and controlled by a visible frequency laser source. In this way, the properties of THz SP modes on a semiconductor surface can be tailored and switched simply by externally controlling the free electron density [2, 3, 4].


7937-13, Session 3

THz patterned antennas for THz-TDS

P. Maraghechi, A. Y. Elezzabi, Univ. of Alberta (Canada)

To date, investigation of high-field THz via photoconductive (PC) emitters has involved implementation of various types of THz PC emitters. However, there has not been any research on utilizing antennas with high directivity for producing high THz radiation power. We report on a comprehensive investigation of radiation characteristic of THz emitters using structures with specific patterns. Such unique geometrical properties in these antennas result in improving the coupling radiation to the free space. It is shown that these novel antennas produce higher radiation power when compared to the well know bow-tie antenna and their un-complementary structures. Interestingly, the radiation power of the emitted THz showed an enhancement as the complexity order of these complementary antennas was increased. To compare the radiation power of such antenna, the un-complementary antennas were tested as well. It was found that the complimentary structure having the highest structure complexity gave the best radiation power compared to all other antennas. To the best of our knowledge this is the first time that complimentary antennas have been used as emitters for generating THz radiation.

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Ultrafast photoconductors based on subwavelength metallic gratings for the next generation of photoconductive terahertz sources

C. W. Berry, M. Jarrahi, Univ. of Michigan (United States)

Short carrier lifetime semiconductors, such as low-temperature grown and ion-irradiated GaAs and InGaAs compounds, have long been used to offer the sub-picosecond photocurrent response times required in photoconductive terahertz sources. The high defect density of these semiconductors degrades their carrier mobility and thermal conductivity, which limits the quantum efficiency and maximum output power of conventional photoconductive terahertz sources in response to an optical pump. In this work we present a new generation of high quantum efficiency and ultrafast photoconductors, which are fabricated on high quality crystalline semiconductors with long carrier lifetimes. The device consists of a metal-semiconductor-metal photoconductor with a subwavelength contact electrode grating at the optical pump wavelength. By engineering the contact electrode geometry, the excited surface plasmon waves at the metal surface lead to extraordinary pump intensity enhancement in close proximity to the contact electrode gratings and pump transmission coefficients of up to unity through contact electrode gratings. As a result, high quantum efficiency and ultrafast photoconductor operation can be achieved simultaneously. Using a finite element solver, we have analyzed the interaction of an optical pump in the visible wavelength range with a variety of subwavelength contact electrode gratings on a germanium substrate, as a function of pump wavelength and polarization. Based on the photo-generated carrier distribution profile in the substrate, ultrafast photocurrent impulse response times as low as 100fs FWHM are estimated, which are faster than the photocurrent impulse response times in previously demonstrated photoconductors with short carrier lifetime semiconductors.

Optoacoustic response of a single submicronic gold particle revealed by the picosecond ultrasonics technique

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Elasticity at a nanometer scale is a key parameter to understand physical and biological processes involved in various current researches. For instance, nanometric polymer layers show reduced viscosity compared to the bulk phase [Bodguel et al., Phys. Rev. Lett. 97, 268105 (2006)]. In biology, physiological and mechanical states of a cell are highly correlated. Recent experiments in our group highlighted the strong potential of laser induced GHz acoustic waves to monitor the mechanical properties of a single cell [Appl. Phys. Lett. 93, 123901 (2008)]. A promising way to probe elasticity at a nanometer scale is to consider a single nanoparticle as an opto-acoustic nanotransducer, with generated acoustic frequencies reaching tens of GHz. The strong advantage over thin films is that nanoparticles can be incorporated inside the medium under investigation to locally characterize its elastic properties. Since the late 90’s, pump-probe experiments have revealed as a powerful way to investigate elastic properties of nanoparticles. Van Dijk et al. [Phys. Rev. Lett. 95, 267406 (2005)] reported on the ultrafast acoustic response of a single gold nanoparticle, measuring its transient transmission. We report here on pump-probe measurements which revealed a new detection mechanism of elastic vibrations of a single submicron gold particle embedded in a silica matrix, through the measurement of its transient reflectivity [Appl. Phys. Lett. 95, 061909 (2009)]. We then demonstrate, for an optimized gold particle size, that we detect the sound propagation in an agar gel matrix (a biological phantom), through the enhancement of the Brillouin scattering.

Damping of acoustic vibrations in gold nanoparticles

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When an ultrafast laser pulse pump is absorbed by a metal nanoparticle, the particle quickly heats up and expands, making it vibrate at high frequencies. In noble-metal nanoparticles, the acoustic vibrations cause the modulation of plasmon resonance frequencies, allowing a probe pulse tuned near a plasmon resonance to serve as a highly sensitive probe of the vibrations. Although these vibrations have been studied for several years, decay of the measured signal has previously been dominated by inhomogeneous dephasing due to variations in nanoparticle size. We have overcome this limitation by investigating a highly monodisperse sample of bipyramidal gold nanoparticles. The inferred homogeneous damping is due to the combination of damping intrinsic to the nanoparticles and damping by the surrounding solvent; the fluid damping, in particular, is quantitatively described by a parameter-free analytical model. Comparison of the model predictions to experimental damping rates in a range of different solvent mixtures provides fundamental insight into the mechanisms for mechanical energy loss and fluid flow at high frequencies and on the nanometer scale. Thus understanding will be essential for development of applications such as molecular-scale biological sensing and ultra-sensitive mass detection.

Ultrafast energy transfer between water molecules

T. N. Jahnke, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany)

At the transition from the gas to the liquid phase of water a wealth of new phenomena emerge, which are absent for isolated H2O molecules. Many of those are important for the existence of life, for astrophysics and atmospheric science. In particular the response to electronic excitation changes completely as more degrees of freedom become available. Here we report on the direct observation of an ultrafast transfer of energy across the hydrogen bridge in (H2O)2 (a so called water dimer). This intermolecular Coulombic decay leads to an ejection of a low energy electron from the molecular neighbor of the initially excited molecule. The relaxation occurs via an Intermolecular Coulombic Decay (ICD), a process first predicted by Cederbaum and coworkers 12 years ago. ICD occurs when the excited particle is only loosely attached to neighboring particles by e.g. Van-der-Waals forces or hydrogen bonding. In such a scenario an intermolecular decay involving the emission of an electron from a neighboring partner of the initially excited molecule may become the dominant channel for deexcitation. ICD is an highly efficient ionization mechanism and happens for species investigated so far on time scales < 100 fs.

The talk will present an introduction to the phenomenon of ICD and the experimental technique of COLTRIMS that was employed to identify its occurrence. Apart from the case of water dimers two more benchmark experiments showing unveiling that ultrafast interatomic decay mechanism will be presented.
7937-18, Session 4

**Femtosecond laser-induced protein crystallization in a gel solution**

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X-ray crystallography is a useful tool for determining the three-dimensional structure of proteins. As to the protein crystallization, however, nucleation techniques have not been so developed. We have previously developed a new technique for control of nucleation by femtosecond laser irradiation, and succeeded in obtaining high-quality crystals. Our next aim is to clarify the nucleation mechanism with femtosecond laser irradiation and enhance the nucleation rate. Focused irradiation of a femtosecond laser causes multiphoton absorption, leading to the formation of shockwaves and cavitation bubbles. In order to clarify the influence of such mechanical stimulations on nucleation, we conducted the spatial mapping of the protein molecules around cavitation bubbles with fluorescent-labeled lysozyme. Agarose gel was added to suppress the diffusion of lysozyme molecules to facilitate the observation. As a result, we found that the cavitation bubbles moved lysozyme molecules and created high concentration regions at the focal point, which could be the trigger for nucleation. In the agarose-free condition, on the other hand, a local increase of protein was not detected. This result indicates that use of agarose gel retained the high concentration regions. So, we conducted lysozyme crystallization in the 1 wt% agarose gel, and realized the nucleation of lysozyme at three to five times lower supersaturation than those by the femtosecond laser or agarose alone. These results clearly indicate that use of the combination of a femtosecond laser and agarose gel is a very practical technique for protein crystallization.

7937-19, Session 5

**Toward determinism in surface damaging of dielectrics using few-cycle laser pulses**

N. Sanner, O. Utéza, B. Chimier, M. Sentis, Lasers, Plasmas et Procédés Photoniques (France); P. Lassonde, F. Légaré, J. Kieffer, Institut National de la Recherche Scientifique (Canada)

We focus here on the so-called “deterministic” character of the laser-dielectrics interaction at femtosecond timescales. This peculiarity is linked to the ability of ultrashort pulses to produce their “own” seed electrons via direct photoionization from the valence band, so that no statistical fluctuation of the damage threshold due to initiating electrons is expected. Nevertheless, in reality a fluence range where the damage occurrence is stochastic –or probabilistic- exists even in the femtosecond regime. We propose a methodology to quantitatively evaluate the degree of determinism as a function of pulse duration. Using laser pulses ranging from 7 to 300 fs, we demonstrate that laser damage occurrence turns dramatically deterministic with few-cycle pulses, which is attributed to the increasing importance of tunneling ionization as the major channel for the generation of free-carriers in the conduction band.

Besides, the study of laser-induced damage (irreversible alteration of the surface) is accompanied with a systematic investigation of the evolution of ablation threshold (removal of matter), providing essential knowledge for industrial implementation of laser-based micromachining applications. The reduction of pulse duration causes an abrupt decrease of both damage and ablation thresholds, that tends to merge for few-cycle pulses. A numerical model based on Keldysh theory is implemented, that reproduce accurately the evolution of both thresholds on the whole sub-picosecond range, using appropriate thresholds criteria. Finally, we propose a fine analysis of the physical characteristics of surface ablation craters machined under a wide excursion of pulse duration and applied fluence ($F_{th} < F < 10 F_{th}$).

7937-20, Session 5

**355 nm and 1064 nm-pulse mixing to identify the laser-induced damage mechanisms in the nanosecond regime**

S. Reyné, G. Duchateau, Commissariat à l’Énergie Atomique (France); J. Natoli, Institut Fresnel (France); L. Lamagnère, Commissariat à l’Énergie Atomique (France)

Nanosecond laser-induced damage (LID) in potassium dihydrogen phosphate (KH2PO4 or KDP) remains an issue for light-frequency converters in large-aperture lasers such as NIF (National Ignition Facility, in USA) and LMJ (Laser MegaJoule, in France). In the final optic assembly, converters are simultaneously illuminated by multiple wavelengths during the frequency conversion. In this configuration, the damage resistance of the KDP crystals becomes a crucial problem and has to be improved. In this study, we propose a refined investigation about the LID mechanisms involved when multiple-wavelength irradiations are combined. Experiments based on an original pump-pump set-up have been carried out in the nanosecond regime on a KDP crystal. In particular, the impact of a simultaneous mixing of 355 nm and 1064 nm pulses has been experimentally studied and compared to a model based on heat transfer, the Mie theory and a Drude model. This study sheds light on the physical processes implied in the KDP laser damage. In particular, a three-photon ionization mechanism is shown to be responsible for laser damage in KDP.

7937-21, Session 5

**Spin dynamics of carriers injected across interfaces with organic semiconductors**

M. Cinchetti, S. Neuschwander, N. Großmann, K. Koffler, J. Wüstenberg, M. Aeschlimann, Technische Univ. Kaiserslau (Germany)

Organic semiconductors (OSCs) are a class of materials belonging mainly to the family of π-conjugated molecules. The study of their spin properties is recently receiving great attention [1]. This is mainly motivated by the weak spin-orbit coupling associated with such light-elements compounds and electronic transport proceeding mainly through π-delocalized orbitals, leading to very long spin relaxation times. Engineering spintronics devices based on OSCs relies on two fundamental properties: (i) the efficient injection of spin-polarized carriers at a hybrid inorganic-organic interface (where the inorganic material acts as a source of spin-polarized carriers), and (ii) a suitable spin diffusion length in the OSC itself. In this contribution, we will show that the spin- and time-resolved two-photon photoemission (STR-2PPE) can be successfully used to obtain direct information on the properties (i) and (ii). For simplicity, we can distinguish between two regimes of applicability for STR-2PPE: For thin coverage of the OSC (sub-ML up to 2-ML range), the measurements give direct information about spin transfer efficiency across the interface [2] and additionally about the microscopic spin-dependent scattering mechanisms taking place at the considered interface [3]. For thicker coverage of the OSC the measurements can be performed either in the space domain [2] (by varying the OSC thickness) or in the time domain [4] (by fixing the OSC thickness and varying the time delay between the two photons involved in the 2PPE process). In both cases, direct information about the spin-dependent transport properties of the OSC and the spin-relaxation mechanisms in the OSC can be determined. The results obtained for interfaces between the OSCs copper phthalocyanine (CuPc), tris[8-hydroxyquinoline]aluminium (Alq3) and the inorganic spin-injector materials cobalt, iron and GaAs will be presented.

References:

Ultrafast dynamics of femtosecond laser-induced nanostructure formation on metals
C. Guo, Univ. of Rochester (United States)

In this talk, I will discuss our recent study on femtosecond laser-induced nanostructures on metals. We found that nanostructure formation can vary greatly among different metals, and the differences are attributed to the competition of ultrafast processes involved, including electron-phonon coupling and hot electron diffusion, following femtosecond laser heating of metals.

Tip-enhanced ultrafast spectroscopy and microscopy of organic solar cell blend film
A. J. Meixner, D. Zhang, Eberhard Karls Univ. Tübingen (Germany)

Poly(3-hexylthiophene) (P3HT) and [6, 6]-phenyl-C61 butyric acid methyl ester (PCBM) are widely employed in the field of organic solar cells as the electronic donors and acceptors. The exciton creation, dissociation and separated charge transportation in the P3HT and PCBM blends are critical for achieving a high performance of the solar cells. To investigate the excitation diffusion and dissociation, both high spatial resolution and ultrafast optical techniques are required. We studied the local chemical composition and photo physics of the blends on a length of a few nanometers using tip-enhanced spectroscopic mapping with the continuous wave laser [1, 2]. We discuss the correlations among the blend film morphology, the local P3HT:PCBM molecular distribution and the P3HT photoluminescence quenching efficiency based on the simultaneously recorded morphology and spectroscopic information. We will report about our progress in combining our parabolic mirror assisted tip-enhanced near-field optical microscope with an ultrafast laser system and report about nonlinear excitation behavior of inverted tip antennae. In addition, we will show new results on finite-difference time-domain (FDTD) simulations for different tip-sample distances in order to understand the interaction of the tip antenna with the sample materials.

References:

Ultrafast gain switching of quantum cascade lasers
S. S. Dhillon, N. Jukam, D. Oustinov, R. Rungsawang, J. Madeo, Ecole Normale Supérieure (France); S. Barbieri, C. Manquest, C. Sirtori, Univ. Paris 7-Denis Diderot (France); S. P. Khanna, E. H. Linfield, G. Davies, Univ. of Leeds (United Kingdom); J. Tignon, Ecole Normale Supérieure (France)

Terahertz (THz) time domain spectroscopy (TDS) is a powerful technique used to generate and detect ultrafast pulses of broadband THz radiation. In order to generate THz pulses, near-infrared femtosecond lasers are used to excite photoconductive antennas or nonlinear crystals. Although the peak THz electric fields generated by these sources can be relatively high, the field amplitude per unit frequency is small owing to the large spectral bandwidth of the generated THz pulse. A compact, practical and direct amplifier of THz pulses is therefore of great interest.

A promising candidate for a THz amplifier is the recently realised THz quantum cascade laser (QCL). In this semiconductor-based source laser action takes place through intersubband transitions. Recently, THz TDS has been used to measure the gain spectra of QCLs. In these experiments, the QCL essentially acts as an amplifier of THz probe pulses that are transmitted through the laser. However, the amplification is limited by gain clamping, which fixes the gain to the sum of the waveguide and mirror losses during laser action. Here we circumvent gain clamping and demonstrate large amplification of THz pulses by ultrafast gain switching of a QCL. The latter is turned on at picosecond time scales before the onset of laser action using an integrated Auston switch. This unclamps the gain by placing the laser in a non-equilibrium state that allows large amplification of the electromagnetic field within the cavity. This technique offers the potential to produce high field THz pulses that approach the QCL saturation field.

Carrier dynamics investigation in quantum cascade lasers using ultrafast pulses
S. Liu, E. Lalanne, R. A. Kuis, A. M. Johnson, Univ. of Maryland, Baltimore County (United States)

Quantum cascade lasers (QCLs) are unipolar semiconductor devices based on intersubband transition and resonant tunneling. We employ femtosecond Mid-IR time-resolved pump-probe technique to investigate the nature of carrier transport through the active and injector regions of pulse biased QCLs at room temperature. Gain recovery of probe pulses are observed when the QCLs are biased close to threshold. At low bias, on the contrary, amplification of probe signal is seen in the first 3ps. The gain recovery and amplification are caused by the interaction between strong pump pulses and electrons, which reveals the population difference between upper and lower lasing levels. Different pump power is used to explore the nonlinear effects in the QCLs, while the ratio between pump and probe is kept the same (20:1). When biased near threshold, following a fast (shorter than 200fs) gain recovery, oscillation of the probe signal is observed within the first picosecond. This oscillation cannot be seen when the pump power is attenuated. Later, slower gain recovery with lifetime of 3-4ps is observed. This fast gain recovery is likely due to two main reasons: the depopulation of the lower laser level by LO-phonon scattering; and the electron compensation by resonant tunneling from injector region to the next upper lasing level of the active region. The slower recovery of the gain is due to the electron transport through the injector region and tunnel further into the upper laser level of the next period. The mechanisms causing the oscillation need further investigation.

Broadband bulk solid-state laser mode-locking based on carbon nanostructures
F. Rotermund, Ajou Univ. (Korea, Republic of)

Saturable absorbers based on semiconductor heterostructures, i.e. semiconductor saturable absorber mirrors (SESAMs), have revolutionized femtosecond laser technology. They provide a robust nonlinear optical switching mechanism, which enabled real-world applications for ultrafast lasers. However, SESAMs provide a spectrally narrowband nonlinearity, require complex manufacturing processes and additionally mandate controlled defect implantation to reduce the response time. To overcome such limiting characteristics, single-walled carbon nanotubes (SWCNTs) were suggested as one alternative. In recent years, SWCNT-based saturable absorbers (SWCNT-SAs) were successfully employed for mode-locking of different lasers. These absorbers exhibit broad absorption with large third-order nonlinearities and require relatively simple fabrication processes. The absorption band of SWCNT-SAs is controllable by varying the nanotube diameter and chirality. Depending on the electronic transitions of semiconducting nanotubes, SWCNT-SAs are readily available within a broad spectral range throughout the near-infrared from < 1 up to > 2 µm. Most recently, graphene, a two-dimensional lattice of carbon atoms arranged in a hexagonal structure, was also considered as potential saturable absorber. Since graphene is a zero-bandgap semiconductor with a linear energy dispersion relation for both electrons and holes, it indicates great potential for applications as laser mode-locker in an extremely-broad spectral range without bandgap heating of metals.
Passively mode-locked two section laser diode with intracavity dispersion control

T. Schlauch, J. Balzer, M. R. Hofmann, Ruhr-Univ. Bochum (Germany); A. Klehr, G. Erbert, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

Laser diodes are attractive sources for ultrashort pulse generation. Due to their compactness and cost effectiveness they have a high potential to replace commercial short pulse lasers like Ti:sapphire laser systems in many applications in communication technology, ultrafast spectroscopy or material processing.

Although there are several advantages for the use of laser diodes, there are two major disadvantages, too. First, modelocked laser diodes usually provide only average output powers of some mW. To increase the power up to the range of several W, we implement a tapered amplifier. Second, ultrashort pulses in the sub-ps range are also rather difficult to achieve in practice because of the strong chirp due to the inherent coupling of real and imaginary part of the susceptibility in the semiconductor.

We solve this problem by intracavity and extracavity dispersion management of a passively mode-locked laser diode. The laser diode consists of a gain section and an absorber section. The latter has a length of 80 micrometer and acts as a saturable absorber with reverse bias, while the complete diode has a length of 1200 micrometer. One facet is antirefection coated to allow for coupling to the Fourier transform external cavity. This geometry enables intracavity dispersion control which allows to increase the spectral bandwidth of the emitted pulses significantly.

We analyze the influence of intracavity dispersion control on the pulse chirp by SHG-FROG measurements and demonstrate the generation of ultrashort 200 fs light pulses with combined intracavity dispersion management and external pulse compression.

Spin-controlled switching of lasing circular polarizations in (110)-oriented VCSELs

N. Yokota, I. Ikeda, S. Koh, H. Kawaguchi, Nara Institute of Science and Technology (Japan)

We discuss high speed switching of lasing circular polarizations in VCSELs by optical spin injection. We conducted time- and polarization-resolved measurements of two consecutive lasing outputs from a (110)-InGaAs/GaAs VCSEL at 77 K with different time delays between the two optical excitations for alternately spin-polarized electrons. 1-GHz switching of lasing circular polarizations has been demonstrated with taking advantage of the long electron spin relaxation time in (110)-QWs. Rate equation analysis closely reproduced the measured electronic spin relaxation time a straightforward solution for faster switching since the residual unpolarized carriers limit the switching speed. Thus, we dry-etched the (110)-QWs into micro-posts to introduce the surface non-radiative recombination using ECR-RIE and EB lithography, and investigated the carrier lifetime and electron spin relaxation time. Spin-polarized carriers were optically excited in square posts with different sizes from 0.5 um to 30 um, and the time evolutions of two orthogonal circular polarization components of photoluminescence were measured by a streak camera. The long electron spin relaxation time (~1.3 ns) in the (110)-QW wafer is found to be preserved even when the sidewall boundaries with fast surface recombination are introduced and the carrier lifetime is drastically shortened. The same rate equation analysis indicated that spin-controlled VCSELs with such (110)-QW micro-posts will exhibit faster switching of lasing circular polarizations thanks to the shortened carrier lifetime and preserved long electron spin relaxation time. In particular, 20-GHz switching is expected with 0.5-um posts.
Ultrafast coherent optoelectronics of semiconductor-metal hybrid structures
C. Ruppert, Technische Univ. München (Germany); M. Betz, Technische Univ. Dortmund (Germany)

We report on two sets of experiments whereby femtosecond near-infrared pulses are utilized to demonstrate optoelectronic functionalities of nanodevices. First, coherent control techniques are used to generate ballistic photocurrents in nanowires. In particular, illuminating a GaAs nanowire with a phase stable superposition of 1550 nm femtosecond pulses and their second harmonic, −µA ballistic electrical currents are generated without an external bias. The second part is related to the excitation of surface plasmon polaritons (SPPs) in plain and unstructured gold films. In contrast to established SPP launchers based on permanent gratings, we utilize LiNbO₃ surface acoustic waves underneath a metal thin film to create dynamic gratings with variable period and amplitude as well as nanosecond switching times.

Identification of extremely radiative nature of AlN by time-resolved photoluminescence and time-resolved cathodoluminescence measurements
S. F. Chichibu, K. Hazu, T. Onuma, Tohoku Univ. (Japan); T. Sota, Waseda Univ. (Japan); A. Uedono, Univ. of Tsukuba (Japan)

We report on two sets of experiments whereby femtosecond near-infrared pulses are utilized to demonstrate optoelectronic functionalities of nanodevices. First, coherent control techniques are used to generate ballistic photocurrents in nanowires. In particular, illuminating a GaAs nanowire with a phase stable superposition of 1550 nm femtosecond pulses and their second harmonic, −µA ballistic electrical currents are generated without an external bias. The second part is related to the excitation of surface plasmon polaritons (SPPs) in plain and unstructured gold films. In contrast to established SPP launchers based on permanent gratings, we utilize LiNbO₃ surface acoustic waves underneath a metal thin film to create dynamic gratings with variable period and amplitude as well as nanosecond switching times.

Ultrafast hot carrier dynamics in lnN epitaxial films
T. Tsai, C. Chang, C. Kuo, C. Chang, National Taiwan Ocean Univ. (Taiwan); S. Gwo, National Tsing Hua Univ. (Taiwan)

Ultrafast hot carrier dynamics in lnN epitaxial films were investigated by femtosecond time-resolved pump-probe reflectivity measurements. Carrier density and carrier energy dependence of the hot carrier dynamics in lnN were studied by varying the pump laser power and wavelength, respectively. Experimental results show that the hot carrier relaxation can be fitted by a biexponential relaxation process. The fast relaxation rate increases with increasing carrier density (N), which is measured as N0.5. The fast relaxation rate also increases with increasing carrier density (E), which is measured as E0.5. These observations reveal that the electron-electron scattering plays an important role in hot carrier relaxation. In addition, the slow relaxation is dominated by Auger scattering and the slow relaxation rate is independent of the carrier energy. The defect-related trapping time in lnN was estimated to be ~515 ps.
Long room-temperature electron spin lifetimes in bulk cubic GaN
J. H. Buss, J. Rudolph, Ruhr-Univ. Bochum (Germany); T. Schupp, D. J. As, K. Lischka, Univ. Paderborn (Germany); D. Hägele, Ruhr-Univ. Bochum (Germany)

We report on very long electron spin lifetimes in cubic GaN measured by time-resolved Kerr-rotation-spectroscopy. The spin coherence times with and without external magnetic field exceed 500 ps at room temperature, despite a high n-type doping level of more than 10^{19} cm^{-3} in the bulk sample under investigation. GaAs shows for comparison spin lifetimes below 20 ps at such conditions. Our findings are therefore highly relevant for spin optoelectronics in the blue wavelength regime. The spin lifetimes are found to be almost temperature independent in accord with a prediction for degenerate electron gases of Dyakonov and Perel from 1972. [1] For moderate doping levels cubic GaN bears prospects for the longest room temperature spin lifetimes in a III-V bulk semiconductor. These results are discussed also in comparison to wurtzite GaN, which shows much shorter spin lifetimes and a dependence of spin lifetimes on the spin orientation. [2, 3] Both effects are caused by additional spin orbit coupling due to the strong polar fields along the c-axes in wurtzite GaN. Suppression of this effect in cubic GaN is the key for the very long spin lifetimes, making cubic GaN a powerful competitor of e.g. ZnO for spintronic applications.


Photoexcited carrier relaxation dynamics of InN films and nanocolumns
K. Ema, M. Hashimoto, K. Fukunaga, H. Kunugita, J. Kamimura, A. Kikuchi, K. Kishino, Sophia Univ. (Japan)

Indium nitride (InN) is one of the most promising of the III-V semiconductors due to its great potential for applications in high-speed electronic devices. For such applications, it is necessary to understand indium nitride’s intrinsic carrier relaxation properties (i.e., those not affected by impurities). Recently, InN films and nanocolumns with high crystal quality and low electron concentration have been produced using molecular beam epitaxy [1]. Consequently, the basic properties of InN are gradually becoming clear. In our previous work, we found that the photoexcited carrier dynamics of InN films show strong dependence on energy and density which originates from the competition between band-filling (BF) and bandgap-renormalization (BGR) effects [2]. In this paper we study the detailed relaxation dynamics of photo-excited carriers of InN films and nanocolumns (1 μm in height and 100-400 nm in radius) using degenerate pump-probe measurements at room temperature. We have measured two films and two nanocolumns with different background carrier densities. To quantitatively analyze the experimental results, we have performed a numerical calculation involving BF and BGR effects as well as LO phonon scatterings. The results suggest that indium nitride’s intrinsic relaxation properties may be understood by considering the density of states and the electron occupation number in the conduction band. In addition, we have found that the decay dynamics is not affected by the carrier recombination time under the appropriate conditions.


Internal field shielding and the quantum confined stark effect in single and multiple InGaN1-xN quantum disks
R. A. Taylor, M. J. Holmes, Univ. of Oxford (United Kingdom); Y. S. Park, Dongguk Univ. (Korea, Republic of); J. H. Warner, J. Luo, X. Wang, A. Jarjour, Univ. of Oxford (United Kingdom)

Ill-Nitride semiconductor based structures are enjoying success in optoelectronic device applications, not least due to the wide direct band gap exhibited by GaN, enabling efficient high-energy emission. When in the Wurtzite crystal structure these structures will be at the mercy of an inbuilt electric field that has components due to both a spontaneous polarization and a strain induced piezoelectric field, which in nanostructures can have a combined magnitude of order MVcm^{-1}. This field alters the energy spectrum by the quantum confined Stark effect and causes a space separation of negative and positive charge carriers, hence limiting the internal quantum efficiency. Here, we report on experimental investigations into the quantum confined Stark effect, and the screening of the internal field by carriers, in single and multiple InGaN quantum disks grown near the tip of a GaN nanocolumn. Time-integrated and time-resolved microphotoluminescence studies were carried out, as well as calculations of strain distributions using the nextnano3 device simulator. The distribution is inhomogeneous in the plane of the disks due to strain relaxation at the edges of the disks. Emission at ~333eV from confined states was detected and observed to blueshift with excitation power; a result of charge screening and the quantum confined Stark effect. The lifetime of the emission was measured to decrease with increasing excitation power, attributed to reduced band bending and resulting increased overlap of the confined electron and hole wave functions.

Making the molecular movie: first frames
D. R. J. Miller, Univ. Hamburg (Germany) and Deutsches Elektronen Synchrotron (Germany) and Univ. of Toronto (Canada)

Femtosecond Electron Diffraction has enabled atomic resolution to structural changes as they occur, essentially watching atoms move in real time - directly observe transition states. This experiment has been referred to as “making the molecular movie” and was first discussed in the context of a gedanken experiment. With the recent development of femtosecond electron pulses with sufficient number density to execute single shot structure determinations, this experiment has been finally realized. A new concept in electron pulse generation was developed based on a solution to the N-body electron propagation problem involving up to 10,000 interacting electrons that has led to a new generation of extremely bright electron pulsed sources that minimizes space charge broadening effects. Previously thought intractable problems of determining t=0 and fully characterizing electron pulses on the femtosecond time scale have now been solved through the use of the laser ponderomotive potential to provide a time dependent scattering source. Synchronization of electron probe and laser excitation pulses is now possible with an accuracy of 10 femtoseconds to follow even the fastest nuclear motions. The camera for the “molecular movie” is now in hand. Atomic level views of the simplest possible structural transition, melting, have been obtained for a number of systems involving both thermal and purely electronically driven atomic displacements. Optical manipulation of charge distributions and effects on interatomic forces/bonding can be directly observed. New phenomena involving cooperative phase transitions in strongly correlated electron systems have also been observed. The primitive origins of molecular cooperativity has also been discovered. These new developments will be discussed in the context of developing the necessary technology to directly observe the structure-function correlation in biomolecules - the fundamental molecular basis of biological systems.
Time-resolved x-ray scattering
M. Bargheer, Univ. Potsdam (Germany)

Ultrafast x-ray diffraction has become more and more prevalent in various scientific disciplines that are interested in directly observing atomic motion in real time. The timescale, amplitude and phase of the collective atomic motion can be determined with high accuracy, even when the induced amplitude is smaller than thermal fluctuations.

The structural rearrangements induced by an ultrafast stimulus (charge carriers excited or heat deposited by a laser pulse) can be recorded in real time with a timeresolution down to 100 fs. This yields additional information of physical properties such as the electron-phonon or spin-lattice interaction.

We discuss examples for semiconductor multilayers and for nano-layered perovskite structures such as SrTiO3, SrRuO3, (LaSr)MnO3 and Pb(Zr,Ti)O3, including the direct observation of an indirect magneto-electric coupling. We briefly discuss the connection of atomic motion and ultrafast all-optical spectroscopies.

We report data recorded on laser-based plasma-sources and synchrotron based setups including FEMTO-slicing. As an outlook the current future availability of these instruments is discussed.

Quasi-ballistic thermal transport from nanoscale interfaces observed using ultrafast coherent soft x-ray beams
M. E. Siemens, Univ. of Denver (United States); Q. Li, R. Yang, Univ. of Colorado at Boulder (United States); K. A. Nelson, Massachusetts Institute of Technology (United States); E. H. Anderson, Lawrence Berkeley National Lab. (United States); M. M. Murnane, H. C. Kapteyn, Univ. of Colorado at Boulder (United States)

As the scale of functional, dissipative systems shrinks to significantly smaller than the mean-free-path (MFP) of phonons in a material, thermal transport becomes nondiffusive. Heat dissipation from a nanoscale hot-spot into a substrate-the nanoscale heat-sink problem-is of particular relevance to many technologies such as nanothermal therapy, thermoelctric conversion, and heat-sinking in microcircuits.

This problem has not been extensively studied experimentally because of both the small length and short time scales involved. In this work, we apply a new technique of time-resolved coherent soft x-ray diffraction to definitively characterize this nanoscale heat-sink problem for the first time.

In our experiment, the sample consists of arrays of thin nickel lines with width from L=65-2000nm, patterned on a sapphire substrate by electron beam lithography. The nickel lines are impulsively heated by a near-infrared laser pulse from a Ti:Sapphire laser amplifier, and the thermal expansion and subsequent cooling are observed interferometrically, by monitoring the diffraction of a soft x-ray probe beam from the nanostructured surface. These coherent soft x-ray pulses allow for very high resolution (-pm) of surface distortion, as well as femtosecond time resolution well-suited to observing fast dynamics.

We successfully model our experimental results with a diffusive transport model, modified to include an additional boundary resistance. This resistance characterizes the error of the diffusive model and is proportional to the Knudsen number (K = MFP/L). These results confirm the importance of considering ballistic transport away from a nanoscale heat source, and identify a simple correction accounting for this ballistic transport.

Trends in nanoplasmonics: ultrasmall, ultrafast, ultrastrong
M. I. Stockman, Georgia State Univ. (United States)

Nanoplasmonics deals with collective electron dynamics on the surface of metal nanostructures, which arises as a result of excitations called surface plasmons. The surface plasmons localize and concentrate optical energy in nanoscopic regions creating highly enhanced local optical fields. They undergo ultrafast dynamics with timescales as short as a few hundred attoseconds. From the latest developments and original work in nanoplasmonics, we will consider SPASER (quantum nanoscale optical generator and ultrafast amplifier), ultrafast coherent control on the nanoscale, generation of ELV radiation by plasmonic enhancement, adiabatic nano-concentration of optical energy, and SPIDER (surface-plasmon-induced drag-effect rectification) that leads to generation of nanoscale THz fields by femtosecond polaritonic pulses in metal nanowires.

Ultrafast active plasmonic coupling
N. Rotenberg, M. Betz, J. N. Caspers, H. M. van Driel, Univ. of Toronto (Canada)

One of the key components of a plasmonic-based nanophotonic device for information processing is an active element, where a plasmonic signal is switched or modulated. Here, we present several approaches demonstrating active control of plasmonic coupling on picosecond time scales. Existing plasmonic coupling resonances, on gold films with grating overlayers, are spectrally shifted by the optically changing the permittivity of either the gold or the adjacent dielectric. Further, plasmonic coupling resonances are all-optically introduced on planar gold films, which show no such coupling initially; the resonant coupling window is shorter than a picosecond. These effects are characterized, both spectrally and in terms of the pump fluence.

Amplification of surface plasmons
I. De Leon, P. Berini, Univ. of Ottawa (Canada)

The amplification of surface plasmon polaritons (SPPs) in planar metallic waveguides via propagation through an optically pumped dipolar gain medium (dye) incorporated into one of the claddings is discussed. Physically realisable arrangements based on the single-interface and on the thin metal film are described theoretically. The gain non-uniformity close to the metal (due to the position-dependent dipole lifetime and the pump irradiance distribution) is taken into account in the modelling and found to limit the mode power gain available from the system. Nonetheless, amplification of the long-range SPP is possible using a reasonable pump power and dipole concentration. On the other hand, amplification of the single-interface SPP requires a much higher dipole concentration and pump power. Experimental results are also given, demonstrating amplification of the long-range SPP along thin metal stripes at near infrared wavelengths using a dye gain medium. Low amplified spontaneous emission noise into this mode is simultaneously observed.

Metal nanoring fabrication and its biomedical application
H. Tseng, C. Lee, S. Wu, T. Chi, K. Yang, J. Wang, National Taiwan Univ. (Taiwan); M. Tsai, Chang Gung Univ. (Taiwan); Y.
Robust quantum dot state preparation via adiabatic passage with frequency-swept laser pulses

C.-M. Simon, B. Urbaszek, T. Belhadj, T. Amand, P. Renucci, X. Marie, B. Chatel, Université de Toulouse (France); A. Lemaître, O. Krebs, Laboratoire de Photonique et Nanosciences CNRS (France); R. Warburton, Department of Physics, University of Basel (Switzerland)

We report a new experimental approach to the optical preparation of a quantum state in an individual dot, namely rapid adiabatic passage (RAP) from the ground to an excited state through excitation with laser pulses whose frequency is swept slowly across the resonance. Using these chirped pulses we are able to induce a complete and robust photoluminescence contrast in an individual dot, namely rapid adiabatic passage with frequency-swept laser. Robust quantum dot state preparation via.

Photon statistics and phonon signatures in the quantum light emission from semiconductor quantum dots

A. Carmele, J. Kabuss, A. Knorr, Technische Univ. Berlin (Germany); M. Richter, Univ. of California, Irvine (United States); W. W. Chow, Sandia National Labs. (United States)

Cavity quantum electrodynamics (CQED) addresses the properties of atom-like emitters such as InAs/GaAs quantum dots (QDs) strongly coupled to a single light mode in a microcavity. QD excitons not only interact with the cavity photons, but also with their solid-state environment. Recent work incorporates several aspects of many-body phenomena into the calculation of QD-CQED, e.g. Coulomb contributions in single QD lasers and phonon-based cavity feeding. Common approaches to treat several interactions rely on a perturbation approach often within the Markovian approximation. Here, we investigate theoretically the photon statistics and phonon signatures in quantum light emission from a QD based on a non-perturbative equation of motion approach. Our model includes non-Markovian effects in the calculation of the combined electronic, photon, and phonon dynamics. As a first result, we present a numerically solvable model to study the QD-CQED in presence of LO phonons, assuming a fixed number of electrons inside the QD.

Picosecond charge state dynamics of CdTe/ZnTe quantum dots studied by excitation correlation spectroscopy

T. Kazimierczuk, Univ. of Warsaw (Poland)

Self-assembled semiconductor quantum dots (QDs) represent an important area of research in solid state physics. However, in spite of the intensive studies, the dynamics of excitonic states in time-scales shorter than their radiative lifetime is not fully understood. This problem has been studied in many experiments under resonant and quasi-resonant excitation directly into given excited QD states, while less attention has been paid to the dynamics of excitons under typical conditions of a photoluminescence (PL) experiment.

In the talk, I will focus on the dynamics of carriers in a single CdTe/ZnTe quantum dot excited non-resonantly, i.e., at photon energies above the barrier energy gap. We employed various experimental techniques to address this problem. While basic dynamical properties of the system could be obtained by simple time-resolved PL measurement, deeper study required advanced methods, such as single photon correlations or two-pulse excitation scheme. In the latter case - excitation correlation measurements - we used time-integrated detection with a CCD camera and excitation by pairs of laser pulses separated by a controlled delay. These experiments allowed us to create an effective model describing QD excitation and to conclude that the main excitation mechanism in non-resonant regime is by capture of single carriers. Moreover, data obtained in the excitation correlation experiment show that the capture of...
both types of carriers takes place in different time-scales: characteristic capture time of electrons equals about 30 ps while the hole capture is much faster.

7937-50, Session 11

Two-photon excited fluorescence from colloidal quantum dots on SiN photonic crystals

X. Xu, Institute of Semiconductors (China); Toshiki Yamada, National Institute of Information and Communications Technology (Japan)

The two-photon excited fluorescence from CdSe/ZnS quantum dots on SiN photonic crystals is investigated using a femtosecond laser. It is found that the spectrum of two-photon excited fluorescence (TPF) is modified, and TPF is enhanced in the vertical direction by photonic crystal. The spectrum of two-photon excited fluorescence is observed to shift to blue for photonic crystals as compared to that for a blank material. The blue shift of the TPF spectrum changes with the lattice constants of PCs, and the variation tendency is accord with that of enhancement factor of TPF.

7937-51, Session 11

Effect of donor-acceptor concentration ratios on nonradiative energy transfer in closely packed CdTe quantum dots

Y. Lin, W. Chou, National Chiao Tung Univ. (Taiwan)

This study investigates the dependence of Förster resonance energy transfer (FRET) on donor-acceptor (D/A) concentration ratios in mixed-size CdTe quantum dots (QDs) films by using photoluminescence (PL) and time-resolved PL spectroscopy. Experimental results indicate that an increasing donor concentration significantly quenches the emission intensity and lifetime in donor QDs and enhances that in acceptor QDs, providing clear evidence of increased FRET efficiency. When D/A ratio exceeds 6, however, the emission intensity and the lifetime of acceptors start to decline, reflecting a decreasing FRET efficiency because of a markedly declining availability of acceptor QDs.

7937-52, Session 12

Novel terahertz emission devices based on efficient optical frequency conversion in GaAs/AlAs coupled multilayer cavity structures on high-index substrates

T. Kitada, F. Tanaka, T. Takahashi, K. Morita, T. Isu, Univ. of Tokushima (Japan)

We have proposed GaAs/AlAs coupled multilayer cavity structures for novel terahertz (THz) emission devices. Two cavity modes are realized in the center of the high reflection band when two cavity layers are coupled by an intermediate distributed Bragg reflector (DBR) multilayer. The optical frequency difference between two modes can be precisely defined in the THz region by the number of periods of the coupling DBR multilayer. We can expect a strong frequency mixing signal from the cavity modes in the GaAs/AlAs coupled multilayer cavity grown on the high-index GaAs substrate.

7937-53, Session 12

Efficient generation of coherent mid-infrared and far-infrared waves in highly lossy second-order nonlinear media at polariton resonances under transverse-pumping geometry

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

Due to strong coupling between transverse-optical phonons and mid-infrared or far-infrared waves, second-order nonlinear coefficients are dramatically enhanced within the forbidden band of each polariton resonance. Transverse-pumping geometry is exploited for achieving efficient mid-infrared and far-infrared generation at each resonance. A pump power of 100 mW is sufficient for efficient conversion.

This is an invited talk.

7937-54, Session 12

Nanosecond large aperture optical switcher

O. V. Asmolova, P. A. Molchanov, T. Curran, Ampac Inc. (United States)

The nanosecond optical switcher with aperture 2 square inches shows 86% transmission and about 20 dB switching contrast at 532 nm. Application of low molecular weight, polymer dispersed liquid crystal (PDLC) materials with combination of high-voltage (200-500V) pulses allows to decrease switching time up to 20-100 nsec. Applied pulse electric field was about 10 V/µm. Combination of two serial switches allows to increase attenuation in OFF state to 30 dB. Universal large aperture switcher was designed for one pixel or multi pixel LIDAR systems application and can be used for any LIDAR systems for photodetector protection and increasing signal/noise ratio.

7937-55, Session 12

Ultrafast switching of light by absorption saturation in vacuum ultraviolet region

H. Yoneda, The Univ. of Electro-Communications (Japan); Y. Inubushi, Osaka Univ. (Japan); F. Sato, The Univ. of Electro-Communications (Japan); S. Morimoto, T. Kumagaya, Osaka Univ. (Japan); M. Nagasono, A. Higashiyama, M. Yabashi, T. Ishikawa, H. Ohashi, H. Kimura, T. Togashi, RIKEN (Japan); H. Kitamura, Kyoto Univ. (Japan); R. Kodama, Osaka Univ. (Japan)

Recent sub-picosecond pulses of extreme-uv quantum light from free electron lasers open new possibilities for nonlinear optics in higher photon energy science. In this work we report observation of nonlinear phenomena in the 50-60 nm EUV wavelength region. We have observed (1) high contrast saturable absorption in Sn1, and (2) multi-step photon absorption in Ti. According to optical data for the cold Sn, we expect strong absorption at this wavelength. The light is completely absorbed over several tens of nanometers. This means we can achieve ultrafast,
high contrast saturable absorption with laser light that is sufficiently intense for bleaching and with a pulse short enough to avoid expansion or other large changes of material conditions during the pulse. For confirmation of this idea, we irradiate thin Sn layers with 10 J - 100fs EUV lasers. The wavelength matches absorption by ionization of N-shell electrons. We observe a strong gating of Sn transmission at energy fluences above 63 J/cm² at wavelength of 51nm. The ratio of the transmission at high intensity to low intensity is typically greater than 100:1. The estimated saturated transmittance is about 0.25. In Ti, there is weak absorption at the photon energy, but strong absorption at energy of two photons. In EUV interaction experiments, we shoot 20nm thickness Ti foil and observe increased absorption at higher intensity. The intensity dependence of transmission is consistent with two photon absorption.

Based on these two typical experimental results, we can start to develop new nonlinear photonic devices such as auto-correlator and pulse slicer for the EUV region.

7937-56, Session 12
In vivo harmonic generation biopsy of human skin
C. Sun, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

Optical higher harmonic-generations, including second harmonic generation (SHG) and third harmonic generation (THG), leave no energy deposition to the interacted matters due to their energy-conservation characteristic, providing the “noninvasiveness” nature desirable for clinical studies. Combined with their nonlinearity, harmonic generation microscopy provides three-dimensional sectioning capability, offering new insights into live samples. By developing the femtosecond Cr:forsterite lasers working in the high penetration window, we have recently developed a non-invasive in vivo light microscopy with submicron 3D resolution and high penetration, utilizing endogenous and resonantly-enhanced multi-harmonic-generation signals in live specimens, with focused applications on the developmental biology and clinical virtual biopsy. In this presentation, we report our recent clinical trial result on the harmonic generation biopsy of human skin. To the best of our knowledge, this is the first clinical trial of THG imaging. No damage is reported throughout our clinical trials. Skin aging, photaging, and various skin diseases were studied and will be briefly discussed in the presentation. This work is sponsored by National Health Research Institute, NTU Research Center for Medical Excellence, and National Science Council of Taiwan.

7937-57, Session 12
Fiber-optic Cherenkov radiation excited by few-cycle pulses
G. Chang, L. Chen, F. Kaertner, Massachusetts Institute of Technology (United States)

Fiber-optic Cherenkov radiation (CR) has emerged as a wavelength conversion technique to achieve isolated spectra in the visible wavelength range. Most published results have reinforced the impression that CR forms narrowband spectra with poor efficiency. We have both numerically and experimentally investigated CR in the few-cycle pulse regime.

The modeling of CR inside a photonic crystal fiber (PCF) employed the generalized nonlinear Schrödinger equation. We simulated an optical pulse centered at 0.8 μm propagating inside a commercially available PCF with zero-dispersion at 0.71 μm. After 2 cm propagation of a 10-fs hyperbolic-secant pulse of 0.3-μJ energy, CR has developed a separated spectrum centered at 0.5 μm. By varying input pulse duration, we found that CR can be a highly efficient (~40%), broadband (~60 nm) process when pumped by few-cycle (~4 cycles for 10 fs pulses at 0.8 μm) pulses. Experimental results have verified our modeling and suggest three evolution stages corresponding to three fiber length scales: 1) CR within several millimeters, 2) CR spectral broadening due to self-phase modulation within a few centimeters, and 3) blue-shift and splitting of CR’s spectrum due to decelerating Raman soliton, which normally occurs beyond several centimeters propagation distance. The experiments for different input pulse energy coupled into a 15 cm PCF revealed the dependence of CR on pump pulse energy: 1) below 70 pJ, no distinguishable CR is observed while a Raman soliton at longer wavelength has developed due to stimulated Raman scattering; 2) 70-200 pJ, CR’s conversion efficiency and bandwidth grow dramatically with increasing input pulse energy; 3) beyond 200 pJ, these two quantities saturate and stay nearly constant (~40% for conversion efficiency and 55 nm for bandwidth).

Our results have demonstrated that CR, when pumped with 10 fs pulses of more than 200 pJ pulse energy, exhibits high conversion efficiency (~40%), broad bandwidth (>50 nm), and low threshold (<100 pJ for pulse energy). These three merits allow achieving broadband visible-wavelength spectra from relatively low energy ultrafast sources which opens up new applications. For example, the demonstrated low threshold CR can efficiently convert a near-IR frequency comb into its broadband counterpart at visible-wavelengths. With a proper Fabry-Perot filtering cavity to increase the line spacing of the CR source comb, the resulting astro-comb at visible wavelength holds the promise to locate Earth-like extra-solar planets orbiting around stars similar to the Sun.

7937-58, Session 13
Coherent magnetization dynamics in ferromagnetic materials
J. Bigot, Institut de Physique et des Matériaux de Strasbourg (France)

There are fundamental questions related to the ultrafast dynamics of the magnetization of ferromagnetic materials induced by femtosecond laser pulses. In particular the conservation of angular momentum and the coupling of the laser field with the spins are important mechanisms to understand. They are important aspects to investigate for potential applications in spin-photonics which aims at using short laser pulses for controlling the information on magnetic recording media. Until now, the understanding of the ultrafast demagnetization induced with a laser pulse was understood as a sequence of processes that can be fairly well described with several interacting baths: the charges, the spins and the phonons. After excitation, first the electrons and spins thermalize to a hot Fermi distribution (~100 fs) by electron-electron scattering. Then both the charges and spins cool down by relaxing their excess energy to the lattice (~1 ps) by interacting with the phonons. Subsequently the energy is dissipated into the environment, up to a few nanoseconds depending on the material and its substrate. This approach is satisfying from the point of view of the energy balance. However it lacks a good understanding of the dynamics of the angular momentum which can also be separated into : the photon field that can be polarized, the orbital moment of the electrons, the spin angular moment and the moment of the nuclei constituting the lattice.

In our presentation, we will consider the different mechanisms that play a role in the dynamics of the momentum. First, we will show that there is a coherent coupling of the spins with the laser field, as demonstrated with femtosecond magneto-optical experiments performed on Ni and CoPt thin films [1]. Second, we will show that there is an important contribution of the spin-orbit coupling in the dynamics of the spins, by determining the transfer time between the orbital and spin angular moments with time resolved femtosecond Xrays magnetic circular dichroism experiments performed in CoPd films [2]. Last, we will show that the laser induced modification of the anisotropy in the magnetic system is at the origin of the precession of the magnetization around the demagnetizing field [3,4].

**Photocarrier recombination dynamics of SrTiO₃**

Y. Yamada, Y. Kanemitsu, Kyoto Univ. (Japan)

Perovskite oxide SrTiO₃ is a key material of oxide electronics because of its unique and multifunctional electronic properties. With a small amount of electron doping, SrTiO₃ turns from insulating to semiconducting, metallic, and even superconducting. The interest to SrTiO₃ is further increased by unique electronic and magnetic properties of two-dimensional electron gases formed at the interfaces between SrTiO₃ and other oxides. Our discovery of room-temperature blue photoluminescence (PL) in SrTiO₃ provides a new chance for understanding of carrier recombination dynamics. Here, we studied PL spectrum and dynamics of SrTiO₃ by PL and transient absorption (TA) spectroscopy.

Room-temperature PL is observed in the blue spectral region in highly photoexcited, chemically doped, and Ar⁺-irradiated SrTiO₃ crystals. The PL spectral shape in these three samples is similar to each other. In nondoped samples, the PL decay curves are consistent well with the TA decay curves: No difference between TA and PL decay times shows that the intrinsic recombination process determines the blue PL dynamics under high excitation density. The PL spectrum and dynamics are sensitive to the photoexcited carrier density in the undoped sample and the electron density in chemically doped and Ar⁺-irradiated samples. We found that the photocarrier recombination dynamics is well described by a simple model including radiative bimolecular recombination and nonradiative Auger recombination. We determined the Auger coefficient in the wide temperature range between 10 and 450 K. From the PL decay measurements, we determined spatial profiles of carriers and defects in SrTiO₃ crystals.

**Electron relaxation in metals and high-Tc superconductors on the 10-fs timescale**

D. Brida, Politecnico di Milano (Italy); C. Gadermaier, Jožef Stefan Institute (Slovenia); D. Polli, Politecnico di Milano (Italy); V. V. Kabanov, D. Mihailovic, Jožef Stefan Institute (Slovenia); G. Cerullo, Politecnico di Milano (Italy)

The energy relaxation dynamics of a Fermi liquid are important to understand the physical properties of solids, with both fundamental and applied relevance. In particular, electron-electron and electron-phonon scattering mechanisms are crucial in determining many functional material properties, such as electrical and thermal conductivities. The early steps of such processes occur on the 100-fs timescale, thus challenging the temporal resolution of currently available ultrafast spectroscopy systems.

In this study, we perform two-colour pump probe experiments on metals and superconductors using synchronized 10-fs pulses generated by optical parametric amplifiers, tunable from the visible to the near-infrared [1]. The unique combination of high temporal resolution and broadband detection enables mapping with unprecedented detail the equilibration dynamics of the electronic distribution.

In thin films of polycrystalline gold we create an out-of-equilibrium electron distribution with an impulsive infrared excitation and probe electron thermalization by a broadband visible pulse resonant with the d-band to Fermi level transition. We observe dramatic changes of the differential reflectivity spectrum occurring on the 100-fs timescale, corresponding to the establishment of the thermal electron distribution, with dynamics dictated by the excess energy. We also study electron dynamics in two high-Tc cuprate superconductors (YBCO and LSCO), which display relaxation time constants of 100 and 50 fs respectively [2]. These results allow us to retrieve large values for the electron-phonon coupling parameter, in good agreement with recent theoretical predictions [3], and suggest that electron-phonon coupling may play a key role in the electron pairing mechanism responsible for high-Tc superconductivity.


**Ultrafast carrier and phonon dynamics in graphene: relaxation, recombination, and transport**

F. Rana, H. Wang, J. H. Strait, Cornell Univ. (United States)

In this talk, we discuss our experimental and theoretical results on the ultrafast dynamics of carriers and phonons in graphene. Ultrafast optical and terahertz spectroscopy results show that photoexcited carriers in graphene exhibit multiple timescales while undergoing relaxation dynamics. Photoexcited carriers thermalize within tens of femtoseconds and acquire a Fermi-Dirac distribution with a very high temperature. Carriers then lose most of their energy to optical phonons within few hundred femtoseconds resulting in a hot phonon population which then becomes the main bottleneck for carrier cooling. Hot optical phonons in turn decay into acoustic phonons via anharmonic processes within a few picoseconds. Acoustic phonon energy is then coupled into the substrate within tens of picoseconds depending on the number of graphene layers and the nature of the interlayer phonon couplings. Ultrafast spectroscopy has also been used to study in plane thermal transport on short time scales and it has been found that on picosecond time scales carriers, as opposed to phonons, are the dominant carriers of thermal energy via hot carrier diffusion. Carrier recombination times in graphene are found to be extremely short and in the femtosecond to a few picosecond range. We will present experimental results at different temperatures and discuss the relevance of our experimental and theoretical results to graphene based optoelectronics.

**Microscopic theory of ultrafast processes in carbon nanomaterials**

E. Malic, T. Winzer, A. Knorr, Technische Univ. Berlin (Germany)

In this work, we present microscopic calculations of the coupled population and coherence dynamics describing the relaxation of photoexcited carriers in graphene and single-walled carbon nanotubes. The strength of our approach is the possibility to access the time-, momentum-, and angle-resolved relaxation dynamics.

For studies on graphene we take all relevant Coulomb- and phonon-induced relaxation channels into account focusing in particular on Auger-type processes. As a zero-bandgap semiconductor graphene is an ideal model structure to study the carrier relaxation channels, which are inefficient in conventional semiconductors. In particular, it is of fundamental interest to study the importance of Auger-type processes, which bridge the valence and conduction band and allow carrier multiplication - a process that has been suggested in literature for improving the efficiency of solar cells. Our calculations show that Auger processes do play an unusually strong role for the relaxation dynamics of photoexcited carriers in graphene. We also observe that a considerable carrier multiplication takes place due to the efficient impact ionization. Our studies on single-walled carbon nanotubes focus on the Coulomb-driven relaxation dynamics of non-equilibrium carriers. We go beyond the Markov description treating the Coulomb interaction up to the second order Born approximation. We observe a relaxation towards the Fermi distribution on the femtosecond timescale. While the dependence on the chiral angle is negligible, the relaxation dynamics is considerably slowed down for nanotubes with large diameters. Furthermore, our calculations reveal an excitation induced dephasing on the picosecond time scale depending on the excitation strength.
Phonon dynamics of carbon nanotubes and graphene using broadband time-resolved CARS microscopy

Y. Lee, S. H. Parekh, J. A. Fagan, M. T. Cicerone, National Institute of Standards and Technology (United States)

The dephasing and population decay dynamics of optical phonons are studied using broadband time-resolved coherent anti-Stokes Raman scattering (TR-CARS) and time-resolved incoherent anti-Stokes Raman scattering (TR-IARS). By simply adjusting the spectral bandwidth of a continuum pulse, we are able to measure the total dephasing time, T2, and the population decay time, T1, of the G-band sequentially in the same sample. For two different SWCNT samples (bundles on glass and isolated dispersion in water), T2/2 is measured to be shorter than T1. Assuming that inhomogeneous broadening is small, the T2/2 and T1 measurements at the identical sample regions are used to determine the pure dephasing time, T2/2. The determined pure dephasing time is faster in bundled SWCNTs than in isolated dispersion, suggesting stronger perturbation by neighboring tubes than by surfactants. For a few layer graphene we present similar measurement and data analysis to discuss phonon dynamics for different number of layers.

Ultrafast terahertz spectroscopy of few-layer graphene


Graphene is attracting significant interest due to the unique physics of its 2D charge carriers in a linear electronic bandstructure, and due to possible applications in e.g. high-speed electronics. Here, we discuss the broadband optical conductivity and ultrafast THz dynamics of graphene in the few-layer limit. The measured optical conductivity of these atomically-thin layers can be compared to a model of intra- and interband transitions of Dirac fermions. In epitaxial graphene, we find that the optical response is consistent with the electrodynamics of a dense Dirac electron plasma, arising from highly-doped layers at the graphene-substrate interface. The ultrafast transient THz response, in turn, yields insight into the relaxation and recombination dynamics of photoexcited electrons and holes. We will discuss a detailed model analysis, comparing the measured response with a theory of the nonequilibrium Dirac fermion conductivity. In the presence of a strong electron plasma, the nonequilibrium hole response by far supersedes the electron contribution despite a balance of electron and hole photoexcitations. This confirms the unusual intra-band conductivity of graphene, which for a given density is sensitive to the carrier distribution function.

Ultrafast exciton and charge transfer in small aggregates of carbon nanotubes

L. Lüer, Instituto Madrileño de Estudios Avanzados (Spain); J. Crochet, Los Alamos National Lab. (United States); T. Hertel, Univ. of Würzburg (Germany); S. Hoseinkhani, Italian Institute of Technology (Italy); G. Cerullo, Politecnico di Milano (Italy); G. Lanzani, Italian Institute of Technology (Italy)

Carbon nanotubes (CNT) are intensively studied because of their high potential for optoelectronic applications. Their quasi one-dimensional electronic structure leads to strongly bound excitons in semiconducting (S-) CNT, with binding energies on the order of a few hundred meV, depending on diameter. We have shown that excitons in the (6,5) SCNT have an electron-hole correlation length (“exciton size”) of about 2 nm and show a high intra-tube mobility.

Near future applications of CNT will rely on CNT networks rather than isolated CNT. It is therefore important to assess inter-tube interactions, especially with respect to energy and charge transfer. Recently, inter-tube excitation energy transfer (ET) has been demonstrated in SCNT bundles. We show that in small aggregates of SCNT at van der Waals distance, ET rates can exceed 10^{-2} s^{-1}. To this end, we prepared SCNT samples from CoMoCat starting material by density gradient ultracentrifugation, allowing us to compare two samples with different relative weight of small aggregates against isolated tubes. We followed the transient photobleach of the excitonic resonances of the different SCNT chiralities by means of femtosecond spectroscopy with down to 7 fs pulse duration. After resonant excitation of the first excitonic transition (S1) of the (6,5) tubes, we found a clear delay in the formation of the transient photobleach of the (7,5) tubes. After separation of coherent contributions from the original transient absorption spectra by a numerical procedure, we obtained the pure population contribution, showing a population transfer time below 10 fs. After resonant excitation of the second excitonic transitions (S2) in SCNT, we found a population transfer towards acceptor tubes within 50 fs. We show that this longer population transfer time results from a two-step process whereby internal conversion (S2 → S1, on a 40 fs time scale) precedes ultrafast ET in S1 on a time scale of 10 fs. We did not observe ET directly from the second excitonic manifold, which we explained by significant exciton momentum mismatch between the available chiralities in our aggregates.

The presence of free mobile charge carriers has been shown in isolated SCNT e.g. by means of photoacoustic spectroscopy. In order to get insight into the dynamics of inter-tube charge transfer, we performed pump-probe spectroscopy on SCNT aggregates at high excess energy where the oscillator strength of direct inter-band to-band transition (leading to unbound carrier pairs) overwhelms that of the excitonic transitions. We find clear signatures for free charge carriers in the transient absorption spectra, forming on a subpicosecond time scale. This allows us to trace and characterize charge trapping and recombination in SCNT.

Phonon-sideband spectroscopy: plasma contribution and interaction mechanisms

A. Chernikov, T. Feldtmann, C. Böttge, Philips-Univers. Marburg (Germany); T. A. Wassnher, Technische Univ. München (Germany); M. H. Eickhoff, Justus-Liebig-Univ. Gießen (Germany); M. Koch, M. Kira, S. W. Koch, S. Chatterjee, Philips-Univers. Marburg (Germany)

The emission spectra of direct semiconductors are usually accompanied by several replicas of the main excitonic transition. These replicas, commonly referred to as phonon-sidebands (PSBs), originate from the interaction between the charge carriers and lattice vibrations, i.e., phonons. PSB - spectroscopy was established in the last decades as an extremely useful tool to investigate a wide range of properties in the complex many-particle system of a semiconductor. Traditionally, the origin of PSB emission is associated with the presence of excitons in the system. Also, the interaction mechanism in typical polar semiconductors, like GaAs, CdS, and ZnO, is attributed to the Coulomb-mediated Frenkel coupling.

Here, we present experimental evidence supported by a microscopic many-particle theory, contradicting and expanding the traditional picture. PSBs of CdS, CdSe, and ZnO are studied by time-resolved photoluminescence as function of the excitation energy, the lattice temperature, and the pump density. The experimental data is quantitatively analyzed and compared with the theoretical predictions. Our results clearly demonstrate that both excitons and plasma are involved in the PSB emission. Additionally, Coulomb-related polar coupling does not necessarily dominate the PSB scattering process, surprisingly even for material systems with strong polar interaction. Instead, an apparently weak and often neglected deformation-potential coupling may act as the main source for the PSB generation. These findings generally affect the interpretation as well as the theoretical treatment of the phonon replicas.
7937-67, Session 15

**Time-resolved nonlinear optical-holographic techniques for investigation of nonequilibrium carrier dynamics in semiconductors**

K. Jarasiunas, Vilnius University (Lithuania)

The growth of new semiconductor materials of superior performance requires innovative techniques for characterization of their advanced electronic properties. We present the development and implementation of a novel metrological approach which bridges two streams of research - dynamic holography and photoelectrical phenomena. It is based on excitation of a semiconductor by light-interference pattern in order to create a spatially-modulated nonequilibrium carrier structure - a transient diffraction grating. The simultaneous modulation of the photoelectrical and optical properties are monitored by a time-resolved defraction of a delayed probe beam. Different optical schemes have been developed for optical determination of electronic parameters: recombination rates, diffusivity, mobility, drift, and spin relaxation processes. Various optical nonlinearities based on refractive index modulation (by free-carrier/FC density, space-charge/SC electric field) or absorptive index modulation (due to deep trap recharge, space phase filling, or free carrier absorption) have been explored for investigation of photoelectric processes at interband or deep-impurity related carrier generation.

Experimental studies in subnanosecond and nanosecond time domains provided nonradiative, radiative, and nonlinear recombination rates, bipolar diffusion coefficients in GaN films on different substrates, in free-standing HVPE GaN layers, InGaN heterostructures with varying In content, InN layers, GaAs, AlGaAs, CdTe epilayers, SiC, and diamond films. The coexisting FC and photoreflective SC gratings provided a type of photogenerated carriers in semi-insulating CdTe, InP, GaAs crystals, enabled selective discrimination of recombination rate in deep traps from others recombination pathways, while polarization gratings allowed comparison of carrier lifetime, mobility, and spin relaxation time in quantum-well structures.

7937-68, Session 15

**Probing correlated electron dynamics with attosecond pulses**

Z. Chang, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Electron correlation plays important roles in determining the properties of semiconductors and nanostructures. However, direct observation of correlated electron motion in them is still a challenge. On the contrary, atoms are simpler, which can serve as the springboard. Bridging the gap between atomic physics and the complex systems requires in-depth study of electron correlation in multi-electron atoms first. One of the most interesting processes governed by electron-electron correlation is autoionization. An attosecond transient absorption setup was established to study time-resolved autoionization in atoms. High contrast single isolated XUV pulses with duration less than 150 as were generated with a generalized double optical gating method without the need of locking the carrier-envelope phase of the driving laser. In the case of Ar, attosecond pulses in the 20 to 30 eV range excited the 3s electron to 4p, 5p and 6p states. The autoionization of these states was disturbed by a 5 fs laser pulse centered at 750 nm. We demonstrated that the resonance position, line width and split can be controlled by the intensity of the near infrared laser. Numerical simulations reproduced the experimental observations and revealed the dynamics in the atom under the two-color field. It revealed that the experimentally observed splitting of the 3s3p64p 1P line is caused by the coupling between two short-lived highly excited states in the strong laser field.

7937-69, Poster Session

**GAWBS and its effect on SBS based slow light in optical fibers**

C. K. Horne, C. Yu, K. Tranh, North Carolina A&T State Univ. (United States)

We have studied extensively stimulated Brillouin scattering (SBS) based fiber ring and its effect on slow light. The ring is indeed observed to increase slow light by lowering the SBS threshold, increasing SBS gain and reducing SBS linewidth. The price to be paid for such improvements is the increase in distortion not only due to dispersion, but also multiple SBS lines originating by guided acoustic wave Brillouin scattering (GAWBS) modes in the fiber. The former occurs naturally by the Kramers Kronig principle, and has been reported by many researchers, studying slow light. The latter has not been noted in the literature. We will report on our efforts to study the effect of GAWBS modes on SBS based slow light in optical fibers. GAWBS modes in straight optical fibers have been investigated by us and others in the 80’s and early 90’s. Most of the studies involved GAWBS in forward scattering. Such modes were readily detected in singlemode fibers in the forward direction. Many of their properties were exploited for sensor applications and not much attention was paid to the effect of GAWBS to the backward propagating Stokes wave. We would therefore like to address the question: if GAWBS modes were readily observed in the forward direction, then what would be their effect on the SBS backward Stokes wave in an open fiber and a fiber ring? Experiments were performed on an open fiber and a fiber ring and we report our results on the GAWBS effect in slow light devices.

7937-72, Session 15

**Quantum turbulences in semiconductor microcavities**


With the demonstrations of exciton polariton condensation [1] and superfluidity [2], semiconductor microcavities appear as an ideal tool for the study of quantum gases. Exciton polaritons are hybrid light-matter quasiparticles that gather the advantages of being easily optically manipulated and detected, and of exhibiting spectacular non-linear behaviours. Here we experimentally study the scattering of a polariton wavepacket on a structural defect. Similarly to conventional superfluids, quantum turbulences are expected to appear in a polariton fluid at the breakdown of superfluidity, as a friction mechanism [3,4]. We report on the nucleation of quantized vortex pairs in the polariton fluid, as quantum turbulences in the wake of an obstacle. Using a phase and time resolved imaging setup based on off-axis digital holography, we image the nucleation mechanism and track the motion of the vortices along the flow, on a picosecond time scale. Our experimental results are reproduced by simulations based on the realization of the nonlinear Schroedinger equation, which allows to establish the nucleation conditions in terms of polariton density and velocity on the obstacle perimeter. This work shows the potential of semiconductor heterostructures to experimentally access the physics of quantum turbulences, otherwise laboriously studied in ultra-cold atomic gases experiments.

REFERENCES

7937-70, Poster Session

**Generation of femtosecond asymmetric beam with helical geometry**

C. Ceroici, A. Y. Elezzabi, Univ. of Alberta (Canada)

We investigate the possibility of generating a femtosecond beam with a helical wavefront and an asymmetric intensity distribution along the x-y plane by combining a radial polarization and a left or right handed circular polarization. Polarization electric field vectors, and the resulting poynting vectors, combine constructively on one quadrant and destructively on the opposite quadrant. The position of the axis of the asymmetry is dependent on the phase difference between the two beams. We then investigate the helical nature of this polarization by introducing a slanted wavefront between the two beams, and also interfering with a third linearly polarized beam with a spherical wavefront. This polarization has interesting applications in particle trapping and quantum computing since the location of the maximum intensity of the beam can be manipulated simply by adjusting the phase difference between the two input beams.

7937-71, Poster Session

**Pulse shaping properties of multi-layer volume holographic gratings**

A. Yan, J. Sun, Y. Zhou, L. Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Volume holographic gratings (VHG) are of wide interest in many applications because of their properties of high diffraction efficiency, excellent wavelength selectivity and angular selectivity. Recently, the potential application of VHG for manipulating laser pulses to achieve functional waveforms with large bandwidth that can be used for a variety of applications has attracted a significant amount of attention because of the flexibility and the possibility of using VHG to implement dynamic processing. However, these studies have dealt with the properties due to a single VHG rather than with a class of novel diffraction elements - multi-layer volume holographic gratings (MVHG).

In this paper, we extend the coupled wave theory of multi-layer gratings to study the Bragg diffraction properties of ULP, and present a systematically theoretical analysis on the spectrum distribution of the diffracted intensities, the diffraction bandwidth, and the total diffraction efficiency of a system of MVHG. The analysis and observations of this paper will be valuable for the accurate analysis of the interaction of ultrashort optical pulses and a variety of periodic structures, facilitating the design and the investigation of novel optical devices based on multiple layers of VHG.

7937-74, Poster Session

**Inhomogeneous spin-dependent spatial distribution of excitons in an integrated magnetic-multiple quantum wells system**

A. M. Abdelrahman, Edith Cowan Univ. (Australia); H. Kang, Gwangju Institute of Science and Technology (Korea, Republic of); M. Vasiliev, Edith Cowan Univ. (Australia); S. Y. Yim, Gwangju Institute of Science and Technology (Korea, Republic of); K. E. Alameh, Edith Cowan Univ. (Australia) and Gwangju Institute of Science and Technology (Korea, Republic of); Y. Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

We report on the observation of an inhomogeneous spatial spin-dependent distribution of heavy-hole excitons generated by a localized inhomogeneous magnetic weak field. Large exciton energy splitting between spin-up and spin-down states is observed with an energy gap that dependence on the magnetic field.

7937-73, Poster Session

**Magnetic micro-trapping of excitons in multiple quantum wells system using local field minima**

A. M. Abdelrahman, Edith Cowan Univ. (Australia); H. Kang, Gwangju Institute of Science and Technology (Korea, Republic of); M. Vasiliev, Edith Cowan Univ. (Australia); K. E. Alameh, Edith Cowan Univ. (Australia) and Gwangju Institute of Science and Technology (Korea, Republic of)

We propose a simple method to create a local magnetic field minima for the magnetic trapping and confining of excitons. We observe an enhanced spatially resolved photoluminescence of the optically active heavy-hole excitons concentrated at the confining region in a multiple quantum wells system. We draw the attention to consider the proposed trapping mechanism as an approach to reach the Bose-Einstein condensate limit of excitons.
Some aspects of far infrared spectroscopy of explosive materials

N. Palka, M. Szustakowski, T. Trzcinski, Military Univ. of Technology (Poland)

This paper presents some potentially interesting aspects of spectroscopic measurements of explosive materials in Far-Infrared (Terahertz) range: preparation of the samples, influence of grain size of particles inside the sample, influence of covering by clothes and influence of phlegmatization of explosives - addition an agent to an explosive material to stabilize or desensitize it. Moreover, two commonly used techniques - Far Infrared Fourier Spectroscopy and Time Domain Spectroscopy are presented and compared.

Advancements in photomixing and photoconductive switching for THz spectroscopy and imaging

E. R. Brown, Wright State Univ. (United States) and Physical Domains, LLC (United States)

Ultrafast photoconductive devices have been an important breakthrough in THz technology during the past two decades. Photoconductive switches have become the workhorse in moderate-resolution time-domain systems, and photomixers have been widely implemented in high-resolution spectrometers of various types. The primary photoconductive material has been low-temperature-grown GaAs. More recently, this has been rivalled by ErAs-GaAs: a nanocomposite consisting of ErAs nanoparticles embedded in a GaAs matrix. ErAs-GaAs photomixers have produced very useful THz output power levels between 1.0 and 10.0 microwatt when pumped by low-cost DFB lasers operating around 780 nm. ErAs-GaAs photoconductive switches have produced average output power approaching 1 mW, and peak power exceeding 1 W when pumped by frequency-doubled fiber model-locked lasers. The photomixer performance has been utilized in the first U.S. commercial THz photomixing spectrometer which has already been demonstrated on a variety of interesting materials including polar vapors, solid explosives, polysaccharides, nucleic acids, and nonlinear-optical crystals. The photoconductive switch performance has been utilized in a THz impulse radar having a broadband power spectrum centered at around 500 GHz, and a relatively simple gated-receiver to provide pulse averaging and noise reduction. The impulse radar has been used for several applications in biomedical imaging, such as imaging of skin burns, skin cancer, and the ocular cornea.

Efficient material parameters estimation with terahertz time domain spectroscopy

O. S. Ahmed, M. A. Swillam, M. H. Bakr, X. Li, McMaster Univ. (Canada)

Existing parameter extraction techniques in the terahertz range utilize the magnitude and phase of the transmission function at different frequencies. The number of unknowns is larger than the number of available information thus creating a nonuniqueness problem. The estimation of the material thickness suffers from inaccuracies. The minimal error is dependent on the number of tested suggested sample thickness.

We propose a novel optimization technique for the estimation of material refractive index in the terahertz frequency range. The algorithm is applied for materials with arbitrary frequency dependence. Dispersive dielectric models are embedded for accurate parameter extraction of a sample with unknown thickness. Instead of solving N expensive nonlinear optimization problems with different possible material thickness, our technique obtains the optimal material thickness by solving only one optimization problem. The solution of the utilized optimization problem is accelerated by estimating both the first order derivatives (gradient) and second order derivatives (Hessian) of the objective function and supplying them to the optimizer.

Our approach has been successfully illustrated through a number of examples with different dispersive models. The examples include the characterization of doped semiconductors used in surface plasmon plaritons in the THz regime. The technique has also been successfully applied to materials characterized by the Cole-Cole, Debye, and Lorentz models [1].
9738-08, Session 2

Semiconductor-coated deep subwavelength spoof surface plasmonic waveguide for THz and MIR applications

R. Yang, W. Zhao, Z. Lu, Rochester Institute of Technology (United States)

With more and more discoveries in terahertz (THz) technology made for the applications of detecting, imaging, communications and spectroscopy, a robust and versatile platform is required to provide an interface for seamless integration of novel designs and broaden the application range of THz research. Compared to other types of THz circuitry, spoof plasmonic waveguides have been regarded as lossless, compact and flexible to harbor multiple devices together, such as...
waveguides, power splitters, ring resonators and directional couplers. One of the most attractive advantages of spoof plasmonic circuitry is its ability to confine propagation electromagnetic (EM) waves in deep sub-wavelength scale in both transverse directions, and therefore increases the overall density of functional components in unit area. Metal gratings have been studied extensively in microwave region in last century, mostly limited to 2-dimensional case. Recent progress in 3-dimensional (3D) computational tools and fabrication techniques have provided rich details for demonstration of 3D periodic metallic structures as waveguides. In this report, we propose semiconductor coating over periodic metal posts, which is different from the conventional configuration to expose the metal surface to the air. Based on 3D numerical simulations, high-index coatings can further decrease the relative mode size (normalized to wavelength in vacuum) to smaller than \(/50\), compared to \(/10\) when in the air. Silicon and germanium are considered respectively for terahertz (0.6 THz) and mid-infrared (30 THz) regions. The propagation loss is estimated from the quality factor of each repetitive cell, which is below 0.1 dB per cell.

7938-09, Session 2

Optical frequency conductance model of teraHertz/infrared emission and detection in quantum wells, quantum dots, and narrow-gap semiconductors

T. Szkopek, E. Ledwosinska, McGill Univ. (Canada)

The optical frequency conductance is derived for quantum wells and quantum dots, and the optical frequency conductivity of bulk narrow-gap semiconductors is revisited. The teraHertz (THz) and infrared (IR) response of these semiconductor structures, in both free-space and guided-wave geometries, is described in a simple manner within the optical frequency conductance formalism. Familiar concepts form the microwave domain, including transmission lines and impedance matching, are extended into the THz and IR domains. We show that the fine structure constant of quantum electrodynamics sets the natural scale for the optical conductance of semiconductor structures, from which rules of thumb and physical limits to THz/IR gain and absorption can be derived. The optical conductance formalism is applied to MCT photodetectors, quantum well IR photodetectors, quantum dot IR photodetectors, and quantum cascade lasers. The coupling of THz/IR far-field radiation to active devices via antennae is investigated using the optical frequency conductance model.

7938-10, Session 3

THz lasing concepts based upon InAs/GaSb broken-gap heterostructures

D. L. Woolard, U.S. Army Research Office (United States); W. Zhang, North Carolina State Univ. (United States)

An efficient man-portable and powerful radiation source is of great potential importance for teraHertz frequency spectroscopy in future field applications. Achieving such a THz source has long proven to be a formidable challenge in physical electronics. In this presentation, three new approaches to realizing THz lasing based upon InAs/GaSb broken-gap structures will be explored. The first is a double-barrier GaSb/InAs/GaSb heterostructure that utilizes ultrafast heavy-hole interband tunneling to achieve electron depopulation of a quasi-bound, heavy-hole level located in the valence-band of the right GaSb barrier region. A population inversion is then created using electron injection into the conduction-band resonant state of the double-barrier structure. Depgrading nonradiative processes such as acoustic phonon, optical phonon and Auger recombination are shown to be suppressed. Hence, heavy-hole interband tunneling prevails over nonradiative transition rates and establishes a population inversion at high operating temperatures. Detailed simulations predict a significant optical gain of ~103/cm which is comparable with GaAs/AlGaAs quantum well laser in spite of the small overlap of conduction band and heavy-hole wavefunctions. The second THz laser concept consists of an array of InAs/GaSb quantum dots subject to short wavelength illumination. Here the quantum confinements of the electron and hole are spatially separated in a broken-gap quantum dot. Thus the electron needs extra energy in order to transit from a lower heavy-hole level to an upper conduction-band level because of strong Coulomb attraction between the resulting dipole. This leads to an imbalance between stimulated emission and absorption. Hence single-exciton optical amplification is shown to be feasible in typb/broken gap hetero-quantum dots and this offers the possibility for suppressing Auger effects since multi-photon excitation isn’t required for this source concept. The third concept is to explore tunable far-infrared laser based upon Raman oscillations among interband levels that involve the lowest conduction band level, the highest heavy-hole level and a free heavy-hole level. The structure to be studied is a periodic undoped InAs/ GaSb superlattice sandwiched between two p-type heavily doped GaSb contacts. The calculations indicate Raman gain could reach the order of 10-4cm/W in long-wavelength infrared and far-infrared regions. Therefore, this presentation will illustrate the potential of InAs/GaSb broken-gap structures in helping to close the well-known and long-standing THz frequency source technology gap.

7938-11, Session 3

A mechanically tunable terahertz modulator based on antiresonant reflecting hollow waveguide

J. Lu, H. Chen, National Cheng Kung Univ. (Taiwan); C. Lai, H. Chang, National Taiwan Univ. (Taiwan); B. You, National Cheng Kung Univ. (Taiwan); T. Liu, J. Peng, Industrial Technology Research Institute (Taiwan)

We have experimentally demonstrated a broadband tunable terahertz (THz) modulator based on one-dimensional anti-resonant reflecting hollow waveguide (ARRHW), which consisting of a dielectric slab cladding and a pair of motorize-controlled metal plates located outside that. By continually varying the distances d between the dielectric slabs and the metal plates, we found that the transmission spectrum will firstly shift half period toward the high frequency range for TE polarization and then gradually shift backward to the original frequency as d changes from zero to several millimeters, but will not for TM polarization. The spectrum shift phenomenon arises from the phase change of THz wave in the cladding region which is remote controlled by the movable metal plates, and it enables dynamical tuning of the transmission band and linear attenuation of THz power for a specific frequency. The measured maximum spectrum tuning range of 60GHz and the power modulating depth of 20dB are achieved by mechanically translating the aluminum plate relative to the PMMA cladding. The low loss THz-ARRHW based device is also promising for the polarization filter application with extinction-ratio of 20dB.

7938-12, Session 3

THz thermal emission from a 1D photonic crystal

I. A. Zimmerman, Z. Wu, H. Xin, R. W. Ziolkowski, The Univ. of Arizona (United States)

We are exploring the degree to which one can control the spectral emission of heated electromagnetic crystal structures in the THz frequency range. Because THz frequencies are well below the room temperature thermal emission maximum, this configuration may realize a low power but extremely cheap incoherent broadband THz source. Electromagnetic crystals are structures whose periodicity either enhances or reduces the associated photonic density of states over some frequency range. Consequently, they either enhance or reduce its thermal emission over the same frequency range. Thermal radiation from electromagnetic crystals has been studied theoretically
and experimentally for higher frequency ranges, but usually for infinite lattices. We have experimentally and theoretically investigated a simple 1D, bi-layered electromagnetic crystal structure composed of air and silicon slabs. We have calculated the emissivity using Kirchoff’s thermal radiation law, as well as by calculating the density of states directly, and have compared successfully those results to the experimental values. Our ultimate goal is to be able to control the spectral emission of an electromagnetic crystal in the THz region (or other wavelength ranges, such as the infrared) by engineering its band structure. Controlled thermal emission could be used for applications as diverse as solar energy.

7938-13, Session 3
Room temperature Nb5N6 microbolometer for detecting signals at terahertz region
L. Kang, X. Tu, J. Chen, P. Wu, Nanjing Univ. (China)

Onto a double layer, which is made of a Si substrate (\(>1000\ \text{µm}\)) and a SiO2 layer 100 nm thick on top of it, a Nb5N6 thin film microbridge is deposited and integrated with an dipole planar antenna. With a SiO2 air-bridge further fabricated underneath the microbridge and operated at room temperature, such a combination behaves very well as a microbolometer for detecting signals at 210 GHz, thanks to a temperature coefficient of resistance (TCR) as high as -0.7% K\(^{-1}\) of the Nb5N6 thin film. According to our measurements and estimations, the best attainable electrical responsivity and the response bandwidth of Nb5N6 microbolometer are about -530 V/W and 21 GHz respectively, at a current bias of 0.35 mA. The electrical noise equivalent power (NEP) is 8.27×10^{-12} \text{W/Hz}^{1/2} for the modulation frequency above 600 Hz. A quasi-optical receiver based on such a bolometer is constructed and measured.

7938-14, Session 3
THz and millimeter wave vacuum electronic sources
L. P. Sadwick, InnoSys, Inc. (United States)

We will present recent work on a new class of vacuum electronic devices designed for high power operation in the millimeter wave (mm-wave) to low THz frequency region. These vacuum electronic devices are built using microfabrication and micromachining techniques. Power levels ranging from watts to milliwatts can be produced in a reproducible fashion. Some potential applications of these mm-wave and THz sources will also be presented.

7938-15, Session 4
Applications of holography in the millimeter-wave and terahertz region
I. McAuley, R. J. Mahon, J. A. Murphy, National Univ. of Ireland, Maynooth (Ireland)

In this paper we report on the holographic techniques developed for applications in a number of areas of interest in the millimeter-wave and terahertz range of the electromagnetic spectrum. An experimental arrangement based on off-axis near-field holography configurations traditionally employed at visible wavelengths was adapted using a raster scanning detector to digitally record the holograms. The object and reference beams were produced using two radiating horn antennas fed by a single coherent source via a cross-guide coupler.

Among the applications investigated was the measurement of the phase centres of non-standard radiating antennas (such as a planar lens antenna). Using phase retrieval methods, the recorded holographic interference pattern can be used to determine the effective phase centres by numerically propagating the recovered object beam back towards the source plane in order to recover the object beam in the vicinity of the waist (the effective phase centre) using efficient MATLAB® code. The system has also been applied to the investigation of the effects of dielectric materials on millimeter-wave radiation, in particular, the generation of increased co-polarisation levels by the scattering of radiation from surface features. For this, two hologram recordings are made, each with the detector and reference beam source orientated appropriately to select the desired field component. In situations involving complex surfaces, such polarisation measurements can enhance the quality of images by including the horizontal field component which would normally be undetected.

7938-16, Session 4
Electromagnetic crystal (EMXT) based THz components
Z. Wu, W. Ng, M. E. Gehm, H. Xin, The Univ. of Arizona (United States)

An all-dielectric Terahertz waveguide is designed based on hollow-core electromagnetic crystal fiber. Simulation shows a waveguide transmission loss as low as 0.022 dB/mm near 112 GHz with a working bandwidth of 16 GHz. Several waveguides of identical cross-section and differing lengths have been fabricated using a polymer-jetting THz rapid prototyping technique. They are characterized by THz time-domain spectroscopy (THz-TDS), following the “cut-back” method in optical fiber measurement so that the waveguide intrinsic propagation loss can be extracted. Measurement results agree very well with simulation. This as an initial example demonstrates a waveguide with low propagation loss of 0.03 dB/mm at 105 GHz.

Based on the waveguide, an EMXT antenna is also constructed by modifying the defect shape from straight cylinder into tapered horn. Simulation shows that the antenna works around 114, 132, and 162 GHz, with below -29 dB return loss and highly directional radiation beam at those functioning frequencies. The EMXT antenna also exhibits quite comparable performances with a copper horn antenna of exactly the same dimensions at low frequency, however with much higher boresight directivity than the copper horn antenna at high frequency. The antenna is fabricated by the same THz rapid prototyping method, and its far-field radiation pattern is measured using the two photodetector transceiving antennae available from the THz-TDS. Experiment is currently undergoing and the results will be reported.

7938-17, Session 4
Modelling of detector cavities at THz frequencies
S. D. Doherty, National Univ. of Ireland, Maynooth (Ireland)

Far-IR space telescopes, such as the SAFARI instrument of the proposed JAXA/ESA SPICA mission, use horn antennas to couple cavity bolometers to achieve high levels of sensitivity for Mid-IR astronomy. In the case of the SAFARI instrument the bolometric detectors susceptibility to currents coupling into the detector system and dissipating power within the bolometers is a particular concern of the class of detector technology considered. Unfortunately, at THz frequencies, ray tracing approaches no longer prove completely reliable and the large electrical size of the structures in question present significant computational difficulties for the more generic EM approaches applied at other wavelengths. The Finite Difference Time Domain method for example and other such similar approaches result in excessive computational requirements.

Work being carried out at NUI-Maynooth is considering a mode matching approach to the simulation of such devices. This approach is based on the already proven Scatter code, developed at NUI-Maynooth, which is a piece of mode matching code that operates by cascading the S-matrices across, and conserving power, at each junction. This talk will examine various approaches to simulating such cavities, focusing primarily on the...
waveguide modal Scatter approach, and outline how the introduction of additional reflection matrices can be employed to model a closed cavity structure. The introduction of an absorption matrix, determined by the dielectric properties of the material in question, to determine the optical performance of a cavity enclosed absorber will also be examined.

7938-18, Session 4

**Terahertz antiresonant reflecting hollow-core waveguides for sensing applications**

B. You, J. Lu, National Cheng Kung Univ. (Taiwan); C. Chan, C. Yu, National Sun Yat-Sen Univ. (Taiwan); H. Chen, National Cheng Kung Univ. (Taiwan); T. Liu, J. Peng, Industrial Technology Research Institute (Taiwan)

A dielectric hollow-core tube has been demonstrated to detect the minute variation of both the refractive index and thickness in macromolecule layers deposited on the tube-wall, and to identify different liquid vapors from the various core indices. Based on the mechanism of antiresonant reflecting optical waveguide, the terahertz (THz) waves resonated in a tube-wall are satisfied with Fabry-Pérot condition to form distinct dips in the transmission spectrum, and the spectrum dip shift is sensitive in the optical-path-difference from the resonant tube-wall. In this presentation, a polypropylene tube is applied as a THz antiresonant reflecting hollow-core waveguide (THz-ARRHW) sensor to detect the subwavelength-thick macromolecular layers loaded on the tube-wall and the minimum detectable variations of sample-quantity and concentration are down to 1.2picomole/mm^2 and 0.2%, corresponding to the variation of 2.9µm-thickness and 0.001-refractive-index, respectively. Additionally, a THz-ARRHW sensor is demonstrated for dangerous-liquid-vapor detection to distinguish different volatile liquids with transparent appearances and the detectable vapor density in a hollow-core is down to 0.0001g/cm^3 calculated from the ideal gas law. The sensitivity of the polypropylene THz-ARRHW sensor is presented up to 7.17×10^5nm/RIU (refractive-index-unit) and 0.003mm/µm for refractive index and thickness detections, respectively. Potentially, the THz-ARRHW sensor would be applied in the environmental detections and biological or chemical reactions for molecular dynamics studies.
Growth of bulk GaN crystal by Na flux method

Y. Mori, Y. Kitaoka, M. Imaide, Osaka Univ. (Japan)

Na flux method developed by Yamane can grow GaN crystal in a Ga-Na mixed solution at relatively low pressure of nitrogen atmosphere (<5MPa) and at temperature range of 750~900 deg.C. In order to realize the technology for the growth of bulk GaN crystals by Na flux method, it is important to control the nucleation and growth processes. Controlling the nucleation is common issue in the solution growth, because crystal quality and growth rate are limited by unfavorable spontaneous nucleation. We found that the addition of carbon can greatly suppress spontaneous nucleation on any area other than the substrate. It was also found that stirring the solution during growth makes it possible to grow GaN crystals of higher quality with a higher growth rate. In order to make a large diameter GaN crystal, we have utilized the seed crystal fabricated by the vapor phase growth method. In spite of the poor quality seed substrate with high dislocation density, high quality GaN crystal could be obtained. It is possible to grow 2-4-inch GaN crystals having a thickness of over a few mm by using the Na flux LPE method. Other approach is to try to enlarge the spontaneously nucleated GaN crystals by repeatedly using them as seed substrates. The advantage of this approach is that the spontaneously nucleated GaN crystals show high crystal lattice perfection. The relatively large crystal with a diameter of >10 mm could be obtained from small seed crystals.

Growth and optoelectrical properties of single III-nitride nanowires

R. Calarco, Paul-Drude-Institut für Festkörperelektronik (Germany) and Forschungszentrum Jülich GmbH (Germany); T. Stoica, Forschungszentrum Jülich GmbH (Germany); T. Gotschke, Paul-Drude-Institut für Festkörperelektronik (Germany) and Forschungszentrum Jülich GmbH (Germany); T. Schumann, Forschungszentrum Jülich GmbH (Germany); F. Limbach, Paul-Drude-Institut für Festkörperelektronik (Germany) and Forschungszentrum Jülich GmbH (Germany); E. Schaefer-Nolte, T. Schaepers, D. Gruetzmacher, Forschungszentrum Jülich GmbH (Germany); E. Sutter, P. Sutter, Brookhaven National Lab. (United States); A. Cavallini, L. Polenta, Univ. degli Studi di Bologna (Italy)

We have studied III-nitride NWs obtained by catalyst-free plasma assisted molecular beam epitaxy on Si(111) in N-rich conditions [1-3]. For future development of reliable and reproducible nanodevices a crucial topic is the precise control on NW sizes and position. We present selective area growth of single GaN nanowires, with an average diameter of about 70nm, by a self-organized process. We give a quantitative description of the growth phenomena using a model, which takes into account the direct impinging and the collection of adatoms on the substrate around the nanowires. Electric and optoelectric measurements on GaN NWs [4] demonstrate the effect of surface Fermi-level pinning. Surface Photovoltage Spectroscopy and Spectral Photoconductivity measurements have been carried out to analyze the near band-edge absorption in GaN nanowires [5-7]. For InN nanowires an electron accumulation layer at the surface was found [8]. In this work we present the doping effect of Si and Mg on the crystalline, optical and electrical properties of InN NWs in comparison to those of their undoped counterparts. [9,10]

in InGaN QWs. This detrimental effect becomes more severe when the emission wavelength for InGaN QWs is extended toward the green emission region.

In this work, the growths of linearly-shaped (LS) staggered InGaN QWs LEDs are investigated for emission wavelength in the green regime. Here, the InGaN QWs with LS staggered In-content profile were grown by metalorganic chemical vapor deposition (MOCVD). The linearly-shaped staggered In-content profile is accomplished by employing the triangular growth temperature profile during the MOCVD growth of InGaN QW. The use of LS staggered In-contents in InGaN QWs results in improved electron-hole wavefunction overlap, in comparison to that of conventional InGaN QW. The power dependent cathodoluminescence (CL) measurement shows 2.5-3.5 times enhancement of CL intensity for LS staggered InGaN QWs as compared to that of the conventional InGaN QWs. Theoretical calculations using self-consistent 6-band k.p method were performed for both LS staggered InGaN QWs and conventional InGaN QWs. The experimental measurements show good agreement with the theoretical calculation. The electroluminescence of both LS staggered and conventional InGaN QWs LEDs are compared.

7939-05, Session 1
Impact of thermal treatment on the luminescence properties of InGaN/GaN MQWs grown on GaN-on-Si(111) templates
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Two identical 5x InGaN/GaN multiple quantum wells (MQW) were MOVPE grown on an optimized GaN-on-Si(111) template and covered by a thin, non-doped GaN capping layer. After growth one sample was tempered to simulate the thermal activation of p-type GaN. Highly spatially, spectrally and time-resolved low temperature cathodoluminescence (CL) microscopy was performed to investigate the impact on the luminescence properties. While the spatially integrated CL of the as-grown MQW is centered at 2.80eV (443nm) the thermally treated MQW is significantly red-shifted and emits at 2.77eV (447nm). CL peak wavelength mappings reveal lateral fluctuation of the MQW luminescence on a length scale of up to several µm with a standard deviation of 11meV (1.8nm) for both samples. The statistical distribution, primarily asymmetric for the as-grown MQW becomes more randomized after tempering and can be fitted by a Gaussian. The spectrally integrated CL transients exhibit a strongly non-exponentially decay, a typical fingerprint for relaxation processes. We will compare our results with a standard MQW structure. However, the tempered sample also exhibits a red shift already during the first 70ns of decay after excitation for both samples. The decay time of the ABE for the ABE and the DAP spectra, and is interpreted as a transformation of the Mg acceptor species from the A1 to the A2 configuration. The observed optical data are compared with the recent model of Lany and Zunger, predicting two acceptor levels for MgGa in GaN. Transient PL measurements indicate a similar decay time for the A1 and A2 ABEs, about 900 ps at 2 K. The decay time of distant DAPs is of the order 1 µs at 2 K. At the highest doping level (> 1020 cm-3) there is in addition a low energy broad PL peak at about 2.9-3.0 eV, presumably related to another Mg acceptor level. The studies of Mg-doping in m-plane GaN are relevant for the development of III-nitride nanowire-based LEDs for solid state lighting.


7939-20, Session 2
Photoluminescence of Mg-doped m-plane GaN grown on bulk GaN templates
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A set of Mg-doped GaN layers were grown by MOVPE at Virginia Commonwealth University on m-plane bulk GaN substrates supplied by Kyma Inc. The Mg concentration was varied from nominally undoped (less than 1017 cm-3) to about 3 x 1020 cm-3. The samples have been studied by photoluminescence (PL) spectroscopy at temperatures 2 K - 300 K. The PL spectra at 2 K from undoped samples exhibit the known donor bound exciton (DBE) line at 3.4723 eV and 3.4714 eV, associated with the shallow Si and O donors, and in addition a weak A1 acceptor bound exciton (ABE) line at about 3.466 eV, composed of at least two sharp lines about 0.7 meV apart. The latter line is related to residual Mg acceptor doping. At Mg concentrations above 1018 cm-3, a second broader and strong ABE line at about 3.455 eV appears, related to a second Mg-acceptor A2, similar to the spectra obtained in c-plane Mg-doped GaN [1]. In the spectral range 3.45-3.35 eV a large number of PL lines appear. These were previously reported in c-plane GaN, and suggested to be discrete donor-acceptor pair (DAP) lines [2]. The distant DAP transitions related to A1 in the 3.27 eV peak, along with well resolved LO phonon replicas. The A2 DAP spectrum peaking at about 3.15 eV is broad and typically very weak, best observed in annealed samples, or after long term excitation of virgin samples. The shape of the DAP spectra for A1 and A2 indicate that the electronic binding energies of the two acceptors are very similar, just slightly higher (by about 10-20 meV) for A2. For virgin samples, a transformation of the PL spectra occurs with prolonged excitation at 2 K, so that the dominant A1 related spectra fade with time of excitation, and are replaced by A2 related spectra. This is observed for both the ABE and the DAP spectra, and is interpreted as a transformation of the Mg acceptor species from the A1 to the A2 configuration. The observed optical data are compared with the recent model of Lany and Zunger, predicting two acceptor levels for MgGa in GaN. Transient PL measurements indicate a similar decay time for the A1 and A2 ABEs, about 900 ps at 2 K. The decay time of distant DAPs is of the order 1 µs at 2 K. At the highest doping level (> 1020 cm-3) there is in addition a low energy broad PL peak at about 2.9-3.0 eV, presumably related to another deeper Mg complex related acceptor level. The studies of Mg-doping in m-plane GaN are relevant for the development of III-nitride nanowire-based LEDs for solid state lighting.


7939-21, Session 2
Optimization of p-type doping for GaN-based blue light emitting devices
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In this work we report on the optimization of p-type conductivity for GaN-based light emitting diodes (LEDs) and laser diodes (LDs). A first set of epilayers was grown by metal organic vapour phase epitaxy (MOVPE) on c-plane sapphire substrates. The structures consist of 1 µm thick GaN:Mg layers, with different p-type doping concentrations, grown on top of a GaN:Si buffer layer. The optimization was based on results obtained from different characterization techniques. Electrical measurements were also performed using standard p-type metalization and transmission line model (TLM) structures. Standard p-type layers exhibit a resistivity of 1.5 Ω cm and a contact resistivity of 1.4 x 10^-4(−3) Ω x cm^−2. Optimized layers show a resistivity of 0.4 Ω cm and an exceptionally low contact resistivity of 2 x 10^-4(−4) Ω x cm^−2. Finally LD structures with optimized p-type doping were grown on c-plane freestanding GaN substrates and narrow ridge devices (800 x 2 µm2) were fabricated. The optimized devices layer allowed decreasing the operating voltage from more than 7 V to less than 6 V at high-injection current regimes (200 mA).
Detailed photoluminescence study of the magnesium related acceptor states in GaN

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Magnesium still represents the only technologically useful p-type dopant for GaN which can be activated by e.g. post-growth thermal annealing procedures in order to obtain p-type conductivity. Our films consist of a 700 nm thick GaN:Mg layer deposited on 1.3 μm GaN:nid/sapphire. The full set of specimen with a Mg-doping concentration of 2x10E19 cm^-3 was annealed under N2- and/or H2- atmosphere within a temperature window of 450 °C to 650 °C and activation was achieved by different time spans of above band gap light exposure.

In order to characterize the effects of the various annealing and activation conditions we performed a series of photoluminescence (PL), photoluminescence-excitation (PLE) and time resolved PL (TRPL) measurements which gives deeper insight into the nature of the Mg acceptor doping application in GaN. High resolution PL and intensity dependent PL measurements reveal a clear three-part spectral structure in the energetic regime of the Mg related acceptor bound excitons in GaN at around 3.45 eV. PLE measurements of the bound excitons and the DAP region (3.27 eV) allow detailed insight into the different excitation channels and their by the different annealing and activation procedures altered efficiencies. TRPL measurements support the analysis of in PL and PLE measurements not clearly resolvable spectral features which are e.g. related to the incorporation of hydrogen.

In conclusion, it is demonstrated how an extensive study of the optical transitions of GaN:Mg exemplarily facilitates the physical understanding of an annealing- and photo-assisted point defect control in the nitride system.

Fermi level effect on the strain of Si doped GaN

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As a primary n type dopant, Si also has a strong influence on the structural properties of III-nitrides that has been well documented in the literature. Si doping could reduce the dislocation density and change the dislocation arrangement toward a more random distribution [Appl. Phys. Lett. 69 (1996) 990], or cause tensile strain in Al1-xGaxN grown on SiC [J. Appl. Phys. 106 (2009) 023506]. Since the size of the Si atom is not sufficient to significantly change the lattice constant, dislocation inclination has been modeled by Ruvimov [Appl. Phys. Lett. 83 (2003) 2569] to explain the tensile strain, and confirmed lately by several TEM studies. However, the mechanism causing dislocation inclination still remains unclear.

Using an X-ray diffraction study, we found that Si doping in GaN caused a tensile strain that was strongly correlated with the free carrier concentration. For the same Si doping level, when carbon co-doping was increased to compensate the donors, the tensile strain in GaN was reduced, eventually becoming un-measurable for a completely compensated film. This result suggested that dislocation inclination in Si doped GaN is related to dislocation climbing through vacancies whose formation is under a strong influence of the Fermi level position. At a high carrier concentration, the formation energy of vacancies is largely reduced, resulting in higher vacancy concentrations. Therefore, there is a higher probability for dislocation climbing to cause larger tensile strain. This phenomenon is similar to the well-known Fermi level effect on diffusion governed by gallium vacancies in the GaAs system.

The role of fluorine ions in GaN heterojunction transistors: applications and stability

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Wide-bandgap gallium nitride (GaN) and related compound semiconductor materials possess attractive characteristics including high breakdown voltage, high polarization-induced carrier density and high electron saturation velocity. Rapid progress has been made in material growth and device processing technologies during the last decade. Meanwhile, there remain technical challenges to overcome. For example, unlike the silicon MOSFET technology, in which the devices' threshold voltage can be locally adjusted in the processing stage by ion implantation, the threshold voltage of AlGaN/GaN high electron mobility transistors (HEMTs) is mainly determined in the material growth stage, and exhibits large negative values due to the strong spontaneous and piezoelectric polarization effect, even without any intentional doping. Recently, a robust approach to modulating the local potential and local carrier concentration in AlGaN/GaN HEMTs was developed based on the fluorine plasma process for ion implantation. The most significant development based on this technology is the demonstration of self-aligned enhancement-mode (or normally-off) AlGaN/GaN HEMTs with low on-resistance.

In this paper, a comprehensive overview of the fluorine plasma ion implantation technology will be presented. Underlying physical mechanisms will be discussed, together with detailed dc and RF device characteristics. Examples of extending this technology to various circuit applications as well as power rectifiers will be shown. The reliability issues related to the fluorine plasma ion implantation will be discussed based on results from stress test and molecular dynamics simulation.
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7939-26, Session 3

500 GHz GaN transistors: when and how?
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Nitride-based semiconductors have outstanding properties for the development of high-frequency electronics. Recently, AlGaN/GaN high electron mobility transistors (HEMTs) with a 60 nm gate length have demonstrated current gain cut-off frequencies \( f_{\text{max}} \) in excess of 220 GHz and power gain cut-off frequencies \( f_{\text{T}} \) in excess of 300 GHz. This high frequency performance has been achieved while maintaining breakdown voltages well above 30 V, which allows for unprecedented RF output power at mm-wave frequencies. This talk will review the new technologies that have enabled the recent breakthroughs in the frequency performance of nitride transistors, as well as the advanced device concepts that are currently being pursued to take these devices beyond 500 GHz. Some of the technologies that will be discussed include the use of InAlN/GaN structures to minimize short channel effects, Si-ion implantation for sub-0.05 ohm.mm contact resistances, and new methods to engineer the electron velocity.

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7939-27, Session 3

Effect of substrate offset on Al incorporation in AlGaN/GaN HFET structures on bulk GaN substrates
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Bulk GaN substrates promise to bring the full potential of nitride-based devices to bear since they offer a low thermal and lattice mismatch alternative to foreign substrates for epitaxial growth. However, due to the high cost and low availability of bulk GaN substrates, the effects such as offset, surface polishing, and preparation of such substrates on subsequent epitaxy are still not well understood. As such, AlGaN/GaN heterostructures with nominal Al compositions of 25% were grown by MOCVD on semi-insulating bulk GaN substrates with offcuts ranging from 0.06 to 1.93°. X-ray diffraction (XRD) studies indicate that the Al composition varies in a complex way in the range of \(-23\%\) - \(27\%\) as offset increases to 1.93°. Furthermore, we observe a decrease in sheet resistance as offcut increases to 1°, with a subsequent increase in sheet resistance as offcut increases further. One explanation for this observation could be related to an increase in 2DEG density with Al composition with further increases in density (when offcut >1°) coupled with a decrease in mobility due to increased alloy scattering and a greater contribution from interface roughness scattering at the highest 2DEG densities. We will discuss in detail results from XRD, reciprocal space mapping (RSM), cathodoluminescence (CL), and variable temperature Hall Effect studies of the structures to provide insight into the epitaxial growth and corresponding 2DEG quality.

7939-28, Session 4

Power electronics for hybrid and all electronics automobiles
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Hybrid vehicle (HV) and electric vehicle (EV) are promising for next generation automobiles. These systems will contribute to the problems of global warming and fuel consumption. In this system, power control circuits play important roles for driving performance, efficiency (mileage) and cost.

A main motor is controlled by a power control unit (PCU). The PCU consists of an inverter and a control circuit. It also used for energy recovery by a regenerative brake. DC-DC converters are also used as the key component. Buck and boost converters are used to distribute DC power. For EV system, AC-DC and DC-DC converters are used for charging the battery from an AC power source. Wireless charge system is also developing as the future charge system.

For these applications, there are following requirements of performance of power devices. There are two categories of the breakdown voltages of 1.2kV and 600V for the inverter. The battery voltage used in HV and EV is around 300Vmax because of safety of the maintenance. Source voltage of 650V boosted up from the battery voltage is used in TOYOTA hybrid system, which requires breakdown voltage over 1kV for the power devices. One other state-of-the-art technology is power system which uses battery voltage directly, required breakdown voltage is about 600V. For the DC-DC converter and the charging system, high frequency operation, over several hundred kHz, is required because high frequency results in small capacitors and inductors.

To improve the performance of the HV and EV systems, higher performance power devices superior to Si-IGBT used in present system are strongly required. GaN has high potential for post Si power devices. Lateral and vertical structure devices are now developing. Both structures are suitable for the automotive applications.

7939-29, Session 4

GaN power device and its future prospects
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Recent demand for energy saving is strongly pushing the introduction of widegap semiconductors as power switching transistors. GaN is very promising for it taking advantages of the superior material properties. In this paper, we review state-of-the-art technologies of GaN power devices which solve technical tasks for the commercialization. The fabrication cost as the most critical task can be reduced by the use of large diameter Si substrate for the epitaxial growth. A novel epitaxial structure including superlattice interlayer successfully enables crack-free and smooth surfaces over 6-inch in diameter. A normally-off operation which is strongly desired for safe operation of the system is achieved by a new operating principle called Gate Injection Transistor (GIT). The p-type AlGaN-gate lifts up the potential, which enables a normally-off operation. In addition, injected holes from the p-type gate increase the drain current by the conductivity modulation. An additional advantage of GaN power devices is that the lateral and compact device configuration enables the integration of a switching system into a single chip as long as the device is electrically isolated each other. Fe ion implantation technique is applied for the isolation with high thermal stability so that the world first GaN-based inverter IC is demonstrated. The IC consisted of six GITs on Si successfully derives a motor with low operating loss which is strongly desired for safe operation of the system.

The presented technologies are very promising for wide-spread use of GaN power switching transistors in the future.

7939-30, Session 4

New factors affecting HFET stability, 1/f noise, and reliability
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We have explored the practical applicability of our recently found stability criterion [1], [2] for HFETs with spontaneous polarization of the gate
In-segregation and large band gap bowings are widely disputed effects. For instance, in (In,Al,Ga)N. Using ab initio calculations we examine: i) band gap, Eg, bowings in ternary alloys: In$_x$Ga$_{1-x}$N, In$_x$Al$_{1-x}$N, and Al$_x$Ga$_{1-x}$N, ii) bowings of pressure dependence of Eg, i.e., dEg/dp, and iii) a role of In-segregation/clustering in i) and ii). New relations between the band gaps of nitride alloys and their chemical composition are presented and limits to tuning of the fundamental gap are demonstrated. In the same way relations between chemical composition and dEg/dp are examined. We found that in In$_x$Ga$_{1-x}$N and In$_x$Al$_{1-x}$N with homogeneous distribution of In it is a mixing of the wave functions at the conduction band edge that determines strongly nonlinear evolution of Eg vs. x. The same effect is crucial for changes of dEg/dp with In-content. In contrary, in case of In-segregation (one nitrogen atom surrounded by 3 or 4 In-cations) the wave functions mixing at the valence band edge leads to the decrease of Eg and to anomalously large bowings of Eg and dEg/dp. For AlGaN our calculations show almost linear dependence of Eg and dEg/dp vs. x. Finally, we compared a variety of experimental data (including our new unpublished ones) on composition dependence of Eg and dEg/dp finding that their large dispersion can be explained by In segregation in In-containing alloys.

7939-33, Session 5

Electroluminescence analysis of patterned ZnO nanorod array on light-extraction efficiency of GaN-based light-emitting diodes

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Enhancing the light-extraction efficiency of GaN-based light-emitting diodes (LEDs) is one of the critical issues in the solid-state lighting field. In this study, vertically-aligned patterned ZnO nanorod array was fabricated on the ITO electrode layer of patterned sapphire substrates (PSS) applied GaN-based LEDs with nanoimprint lithography technique. UV-assisted bi-layer imprint lithography was applied to form growth-inhibition mask layer during the hydrothermal growth of ZnO nanorod array. To analyze the effect of nano-scaled structures of ZnO nanorod array on the light-extraction efficiency of GaN-based LEDs, various shapes and sizes of ZnO nanorod arrays were obtained by controlling the concentration of nutrition solution and growth time during the hydrothermal growth process and electroluminescence (EL) was measured after the device fabrication. According to the EL measurement, 25% of EL intensity enhancement was observed when 100nm sized ZnO nanorod array was formed on ITO electrode. This enhancement of EL intensity can be explained with gradual refractive-index change of materials since refractive index of ZnO nanorod array was smaller than ITO (n=2.01) and bigger than air (n=1). Moreover, when patterned ZnO nanorod array was formed on the ITO electrode, EL intensity was increased about 34% compared to conventional LED device. This drastic increment of EL intensity was due to the existence of nano-scaled surface protrusion pattern, which efficiently suppress the total internal reflection (TIR) occurred inside of the GaN-based LEDs since it has unique design of nano-scaled structures in nano pattern.

7939-34, Session 5

Exciton binding energies and energy splittings in aluminium nitride bulk and epilayers

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We calculate the eigen energies and wave functions of the Rydberg problem in case of anisotropic effective masses and dielectric constants. The calculation is extended to GaN and AlN two wurtzitic semiconductors with anisotropic conduction and valence band dispersions. The experimental value of 1s-2s splitting disagrees with the theory of excitons in anisotropic semiconductors. This disagreement, we attribute it to our poor knowledge of the valence band dispersion relations of AlN and to
7939-35, Session 6

Bowing of biexciton binding in AlGaN ternary alloys

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We have studied intrinsic recombination processes of high density excitons in nitride-based wide-gap semiconductors by means of photoluminescence (PL), time-resolved PL, and PL excitation spectroscopy. In particular, we have clarified biexcitonic effects experimentally in AlxGa1-xN ternary alloy systems. The binding energy of the biexciton in GaN and AlN was evaluated to be 5.6 and 19.3 meV, respectively. The binding energy of the biexciton in Ga-rich AlxGa1-xN ternary alloys was also evaluated as a function of aluminum composition. The binding energy in the ternary alloys increased linearly with aluminum composition and reached to 16.6 meV for x=0.092. This value was three times as large as the biexciton binding energy in GaN and was almost comparable to the biexciton binding energy in AlN. Such a strong enhancement of the biexciton binding was attributed to the effect of localization due to alloy disorder and was explained by considering a restriction of the exciton-exciton motion rather than a change of the biexciton binding potential. On the basis of our experimental findings, it is important to note that a linear interpolation between GaN (x=0) and AlN (x=1) does not apply to the biexciton binding energy in AlxGa1-xN ternary alloys (0<x<1). We consider that a large bowing exists in the biexciton binding energy in the ternary alloys, which is supported by our recent experimental observations on biexcitonic effects in Al-rich AlxGa1-xN ternary alloys. We present a quantitative discussion on the bowing of the biexciton binding energy.

7939-36, Session 6

Inhomogeneous carrier distribution in InGaN multiple quantum wells and its influences on device performances

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Carrier distribution in InGaN multiple-quantum-well (MQW) structures has been reported to be quite inhomogeneous, mainly caused by inefficient hole transport through QWs. Such inhomogeneities in the carrier distribution could have a significant influence on device performances of light-emitting diodes (LEDs) and laser diodes (LDs). In this work, we investigate carrier distribution characteristics of InGaN MQWs and the effect of the carrier distribution on LED and LD performances both experimentally and theoretically.

The inhomogeneous carrier distribution owing to inefficient hole transport is clearly demonstrated by comparing photoluminescence (PL) and electroluminescence (EL) spectra of dual-wavelength InGaN MQWs. While emission from all InGaN layers is observed in the PL spectra, the EL spectra show a dominant peak only from the QW located close to the p-side layers. High carrier density at a specific QW could result in large decrease of efficiency at high current density, so-called efficiency droop phenomena. Therefore, by employing well-designed MQW structures with uniform carrier distribution, improvement in the high-current efficiency is observed. In addition, carrier distribution along the QW plane is found to have a significant influence on the efficiency droop, implying the importance of uniform current injection in the LED chip. It is also found that the dominant droop-causing mechanism of polarization fields in InGaN QWs lies in inhomogeneous carrier distribution rather than electron leakage.

In InGaN blue/green MQW LDs, anomalous temperature characteristics such as temperature-stable operation or even negative characteristic temperature can be observed, which is attributed to the peculiar gain-temperature characteristics due to the inhomogeneous hole distribution.

7939-37, Session 6

Thermoelectric properties of MOCVD-grown AlInN alloys with various compositions

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In recent years, the increasing miniaturization and integration of electronics or photonics and the demand for high power density devices lead to high requirements for solid state thermoelectric cooling technology. The thermoelectric and device cooling applications of III-Nitride alloys has drawn significant attentions due to the potential of direct integration with nitride-based devices widely used in high power, high temperature situations.

In this work, we present the growth and thermoelectric characterization of high quality AlInN alloys grown on GaN template on sapphire substrate by metalorganic chemical vapor deposition (MOCVD). The thermal conductivities of n-type AlInN alloy with In-contents from 0.37 % up to 21% are measured by 3 differential method. The absolute Seebeck coefficients are measured using thermal gradient method. The electrical conductivities of AlInN alloys are obtained using Hall measurement setup with Van der Pauw method. The thermoelectric figure of merit (Z''T) of the samples grown AlInN were measured in the range of 0.4 up to 0.53 at room temperature (T = 300 K), which is higher than those grown by RF sputtering. The highest thermoelectric figure of merit, which is measured as high as 0.53 at 300 K, is obtained for one AlInN sample lattice matched to GaN, with thermal conductivity of 4.87 W/(mK), Seebeck coefficient of - 6.012×10^-4 V/K and electrical conductivity of 2.38×10^4 / (Ω.m). This finding represents the highest thermoelectric figure of merit reported for any III-Nitride semiconductors, which indicates AlInN alloy as an excellent material candidate for thermoelectric device applications.

7939-38, Session 6

Hydrogen etch of GaN and its application to produce porous GaN caves

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Although it is known that GaN tend to decompose in hydrogen environments, there has been few investigations in hydrogen etch of GaN. This study performs a systematic research on hydrogen etch of GaN under various temperatures, pressures, H2 flow rates, and etc. It is observed that hydrogen attack initially etch into GaN to form pinholes. Dislocations are usually the preferred places for initial hydrogen etch, but not all etched holes result from dislocations. When etched at low pressure and high temperature, deep vertical holes extending several microns can be formed by the hydrogen etch. However, when etched at high pressure, apparent lateral etch are observed under the initial holes, leading to ballor-like GaN posts. From this systematic study, a model has been proposed to explain the vertical and the lateral etching mechanisms. The activation energy of the controlling etching mechanism has been determined to be 3.7 eV.

With the established model, a sequential etch of GaN in hydrogen under varying pressure has been designed to successfully maintain a smooth GaN front surface, but to etch the underlying GaN to form a porous cave structure. Thick GaN films are then overgrown on such GaN layers with the hydrogen vapor phase epitaxy technology. It is demonstrated that the overgrown GaN thick films can self-separate from the underlying Al2O3 substrates.

7939-39, Session 7

Plasmonic effects in InGaN

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This paper reports on two plasmonic systems based on III-Nitrides: (i) InGaN - Au nanoparticles; (ii) InN with buried In nanoparticles formed either spontaneously or by periodical deposition of metal In insertions. Application of NSOM and micro-PL has permitted us to establish necessary conditions for the efficient interaction of localized plasmons, excited in a gold nanoparticle approached to the InGaN layer surface, with localized excitons placed nearby. The tens-fold PL intensity enhancement has been observed for the ~100 nm Au nanoparticle, as well as significant shortening of the exciton radiative decay (Purcell effect). The narrow lines of single excitons have been registered at low temperature, which are promising prerequisites for the fabrication of InGaN/Ga-based single-photon emitters.

Due to specific thermodynamic properties InN shows a good example of a semiconductor whose optical properties are strongly influenced by plasmons in spontaneously formed In nanoparticles. The study of MBE grown InN/In structures with periodic 2-48 ML In insertions by micro-CL technique has shown that the bright CL spots (peaked spectrally at ~0.7eV) coincide always with the agglomerations of the In nanoparticles. The intensity increase by the factor of ~102 is in good agreement with the calculations of the average enhancement factor in InN/In nanocomposites comprising the nanoparticles of an arbitrary shape and orientation. The Purcell factor as high as 30-40 has been derived for the InN/In structures with the large In nanoparticles from time-resolved data obtained by up-conversion technique.

7939-40, Session 7

LPP coupling in AlGaN
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AlGaN is still one of the most promising compounds for UV LEDs and lasers. Furthermore, silicon is the most used dopant for n-type AlGaN. For the fabrication of high quality AlGaN based devices an understanding of the electronic and vibronic properties is indispensable. In this contribution we investigate the effect of silicon on AlGaN thin layers with different aluminum and Si content by means of Raman spectroscopy. An analysis of the strain sensitive \( E_2 \) (high) mode reveals a tensile strain caused by silicon doping. A broadening and shift to higher energies of the A \(_{1g}\) (LO) mode is explained by longitudinal phonon plasmon coupling (LPP) due to elevated carrier concentrations in the Si doped samples. The line shape of the LPP+ mode is modeled using an amended model of Irmer et al. with composition dependant Faust-Henry coefficients and high frequencies. Subsequently, the charge carrier concentration and mobility are calculated and compared to results from Hall measurements. Finally, the Al content dependent position and FWHM are computed and displayed. This work will help to establish Raman spectroscopy as a powerful tool for the determination of the electronic properties of group III nitrides.

7939-41, Session 7

Cathodoluminescence microscopy of planar semipolar (11-22) and (10-11) GaN grown directly on pre-patterned sapphire substrates
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Highly spatially and spectrally resolved cathodoluminescence (CL) microscopy was performed on planar semipolar (10-11) and (11-22) GaN MOVPE grown directly on pre-patterned (11-23) and (10-12) sapphire substrates, respectively. The sapphire templates were structured into trenches by reactive ion etching providing c-plane like sidewalls. The subsequent selective GaN growth takes place mainly on this sidewall of the groove structure resulting in semipolar GaN stripes with their c-axis tilted by ~60° with respect to the surface of the sapphire substrate. Hence, the coalescence of the stripes with semipolar (11-22) facets yields a flat and planar semipolar surface, which is finally covered by an InGaN/GaN SQW.

CL measurements revealed a direct microscopic correlation of the stripe structure and the optical properties. In CL intensity images dark spots are observed exactly above the trenches indicating nonradiative centers like threading dislocations running from the GaN/sapphire interface to the surface. From the trenches luminescence from basal plane stacking faults (BSF) is found spreading into the projected -c-direction, consistently with TEM results. Lateral overgrowth (ELO) into the projected -c-direction improves the crystal quality of the GaN stripes resulting in intense and homogenous (002) emission (nearly relaxed GaN). The evolution of the semipolar growth and the coalescence process of the stripes was investigated using Si-doped marker layers. We found a corrugating coalescence boundary significantly affecting the properties of the InGaN SQW. At the boundary, an emission at lower energies indicates thicker well and/or higher indium content with respect to the luminescence from the semipolar stripes.

7939-42, Session 7

Optical pump-terahertz probe studies of AlGaN
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We report on ultrafast above-band-gap optical pump and terahertz probe studies of free-carrier dynamics in AlGaN materials grown with and without nano-scale compositional inhomogeneities (NCI) by plasma-assisted molecular beam epitaxy and hydride vapour phase epitaxy, respectively. The broadband THz radiation is generated with a bulk InAs source and detected using electro-optic sampling with a ZnTe crystal. After excitation with a 200 fs pump pulse at 266 nm, we observe an initial fast decrease of the transmitted THz signal in both AlGaN samples due to the generation of photoexcited free-carriers. The NCI AlGaN material shows a subsequent fast decrease in THz absorption with a decay time of 40 - 50 ps, as compared to the NCI-free AlGaN with a decay time of several hundred picoseconds. The faster decay time in the NCI AlGaN sample could be due to the transfer of free-carriers into NCI states from the AlGaN matrix as well as exciton formation and carrier recombination.

7939-86, Session 7

Optical, EPR and PAS measurements on Gd doped GaN as material for spintronics
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Gadolinium doped Gallium nitride (GaN:Gd) has recently gained considerable interest as a potential material for spintronics applications producing a large number of publications. The results, however, are inconsistent: While some authors claim to have achieved ferromagnetic behavior at RT with a high magnetic moment per Gd atom, others did not find any ferromagnetism at all. Optical measurements also showed varying results and there were several contradictory theories describing the role of defects and vacancies for the magnetization. In an attempt to bring clarity to this matter, we examined MBE grown layers of this diluted magnetic semiconductor with Gd concentrations ranging from \(10^{16}\) cm\(^{-3}\) to \(10^{18}\) cm\(^{-3}\). We present low temperature photoluminescence (PL) spectra of excitonic, DAP and defect luminescence that are related to the incorporation of Gd but also point to
other defects and impurities. These impurities are identified as transition metals that originate from the substrates of the samples. Electron paramagnetic resonance (EPR) data shows that Gd is incorporated in the Gd^{3+} state as it was already claimed in other publications. These results are discussed concerning the ferromagnetic behavior reported for GaN-Gd. The role of Ga vacancies is investigated by positron annihilation spectroscopy (PAS). Both EPR and PAS results show that Ga vacancies are not responsible for ferromagnetic coupling in this DMS as it was claimed in other publications. In fact, our PL and PAS results rather point to an unknown acceptor that takes part in ferromagnetic coupling via an impurity band.

7939-43, Session 8

Recent developments in AlGaN based laser diodes for short ultraviolet region

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Ultraviolet photonic devices have recently gained considerable interest for a number of applications such as bio-chemical analysis and material processing. Laser diodes and light-emitting diodes (LEDs) with (Al, Ga, In)N active layers have great potential to provide light emission at an ultraviolet wavelength shorter than 365 nm corresponding to the GaN band gap of 3.4 eV. The emission wavelengths of nitride based LEDs have already demonstrated down to a deep ultraviolet wavelength of 210 nm. In contrast, progress in developing ultraviolet laser diodes has so far been limited. Laser diodes require a more complex structure and higher crystalline quality than LEDs to meet all the requirements of suitable optical and electrical confinements as well as high emission efficiency. To improve the emission efficiency, the previously reported ultraviolet lasers have the benefit of indium in the active layers (excluding GaN/AlGaN active layer). However, due to the very small band gap energy of InN and delicate growth conditions, adding indium into AlGaN active layer inhibits to extend the emission toward deeper ultraviolet region in the future.

In this talk, we will focus on indium-free AlGaN based laser diodes for shorter ultraviolet spectral region far beyond the GaN band gap. We have achieved room-temperature laser operations down to a wavelength of 336 nm under pulsed current mode. The typical characteristics of the ultraviolet laser diodes will also be presented and discussed. The results will be important for the further development of laser diodes emitting much shorter wavelength.

7939-44, Session 8

An overview on the physical mechanisms determining the degradation of GaN-based LEDs and lasers

E. Zanoni, G. Meneghesso, M. Meneghini, Univ. degli Studi di Padova (Italy)

With this paper we give an overview on the physical mechanisms responsible for the optical degradation of InGaN-based optoelectronic devices, LEDs and lasers. A number of reliability tests are presented and specific degradation mechanisms of state-of-the-art optoelectronic devices are analyzed. In particular, we present data on: (i) the degradation of the active layer of the devices; (ii) the role of defects in limiting the lifetime of optoelectronic devices; (iii) the role of the different driving forces (current, temperature, optical power) in determining the worsening of the electro-optical characteristics of LEDs and lasers; (iv) the role of structural defects in determining the failure of LEDs submitted to Electrostatic Discharge events. Presented results provide important information on the current weaknesses of InGaN technology, and on the design of procedures for reliability evaluation. Results will be compared to literature data throughout the paper, in order to provide arguments for a complete understanding of the topic.

7939-46, Session 8

Nano-scale correlation of structural and optical properties of lattice matched AlInN/GaN DBRs using helium temperature scanning transmission electron microscopy cathodoluminescence


The combination of luminescence spectroscopy - in particular at liquid He temperatures - with the high spatial resolution of a scanning transmission electron microscopy (STEM) (dx < 1 nm at RT, dx < 5 nm at 10 K), as realized by the technique of low temperature scanning transmission electron microscopy cathodoluminescence microscopy (STEM-CL), provides a unique, extremely powerful tool for the optical nano-characterization of semiconductors, their heterostructures as well as their interfaces.

Our CL-detection unit is integrated in a FEI STEM Tecnai F20 equipped with a liquid helium stage (T = 10K / 300K) and a light collecting parabolic mirror. Panchromatic as well as spectrally resolved (grating monochromator) CL imaging is used. In CL-imaging mode the CL-signal is collected simultaneously to the STEM signal at each pixel. The TEM acceleration voltage is optimized to minimize sample damage and to prevent luminescence degeneration under electron beam excitation.

We will present our results from nanoscale optical and structural properties obtained at 300K and 10K on lattice matched AlInN/GaN DBRs and correlate the optical properties to the strength and appearance of structural defects. In cross-sectional measurements we observe that each of the AlInN layers with a thickness of 50 nm exhibit a rough surface in growth direction with a modulation of about 10 nm. The rough surfaces are completely planarized during growth by the following GaN layers.

Panchromatic CL images prove a reduced emission from the rough AlInN tips while the emission is recovered at the smooth interface to the GaN layers.

7939-47, Session 8

High-performance blue and green laser diodes based on nonpolar/semipolar InGaN


We present state-of-the-art performance from green and blue InGaN-based laser diodes fabricated on nonpolar and semipolar substrates. Using these novel crystal orientations, we demonstrate high-power, high-efficiency, and long-lifetime continuous-wave laser operation. For green wavelengths above 520nm, we report on continuous wave single mode lasing with more than 30mW of output power. We describe single mode blue lasers operating with over 20% wall-plug-efficiency and with output powers greater than 500mW. To the best of the author’s knowledge, this efficiency represents the highest reported to date for a single-mode blue laser. Additionally, higher-power multimode operation from lasers fabricated on these novel crystal orientations will be reported. These InGaN-based devices offer dramatic improvement in performance, size, weight, and cost over conventional gas and solid state lasers and will enable a variety of new applications in defense, biomedicine, and consumer projection displays.
Quantum cascade detectors based on III-nitride heterostructures

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Quantum Cascade Detectors (QCDs) are tailor-made infrared photodetectors based on intersubband transitions in semiconductor quantum wells (QWs). The device active region comprises multiple periods of active QWs and extractor regions. The extractor is a short-period-superlattice structure designed to form a phonon ladder (energy spacing equal to the LO-phonon energy) which collects the electrons in the excited state of the first active QW and injects them in the ground state of the next active QW. In contrast with standard QW infrared photodetectors (QWIPs), QCDs do not require an external bias voltage due to their asymmetric conduction band profile. Therefore, they present zero dark current and hence intrinsically low noise levels. The operation spectral range of these devices, first demonstrated in the mid-infrared, can be extended to the near-infrared thanks to the large conduction band offset of III-nitride semiconductors. Moreover, the design of the phonon ladder is simplified thanks to the band asymmetry introduced by the spontaneous and piezoelectric polarization in this material family. In this work, we summarize the design, growth, fabrication and performance of nitride-based QCDs operating in the 1.4-2.5 µm spectral range at room temperature.

The development of monolithic alternating current light-emitting diode

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The monolithic alternating current light emitting diode (on-chip ACLED) has been revealed for several years and was regarded as a potential device for solid state lighting. In this study, we will discuss the characteristics, development status, future challenges, and ITRI’s development strategy about ACLED, especially focusing on the development progress of the monolithic GaN-based Schottky barrier diodes integrated ACLED (SBD-ACLED). The SBD-ACLED design can not only improve the chip utilization ratio but also provide much higher reverse breakdown voltage by integrating four SBDs with the micro-LEDs array in a single chip, which was regarded as a good on-chip ACLED design. According to the experimental results, higher chip efficiency can be reached through SBD-ACLED design since the chip area utilization ratio was increased. Since the principle and the operation condition of ACLED is quite different from those of the typical DCLED, critical issues for ACLED like the current droops, the flicker phenomenon, the safety regulations, the measurement standards and the power fluctuation have been studied for getting a practical and reliable ACLED design. Besides, the “AC LED application and research alliance” (AARA) lead by ITRI in Taiwan for the commercialization works of ACLED has also been introduced.

Ill-nitride resonant tunneling devices from growth to fabrication

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The resonant tunneling diodes (RTDs) with their strong negative differential resistance (NDR) at room temperature (RT) are promising for high frequency generation up to terahertz enabling many applications such as ultra speed wireless communications, spectroscopy, and imaging. III-nitride materials are emerging candidates for RTD application due to their properties such as high peak electron velocity, saturation velocity, and thermal stability. AlN/GaN RTDs are expected to have high peak-to-valley ratio (P/V) and performance at RT due to large conduction band discontinuity of 2.1 eV. However, high lattice mismatch of conventional substrate such as sapphire which leads to high dislocations density in epilayer and requirement for precise material, thickness, and abrupt interface control are the biggest challenges hindering nitride-based quantum-effect device technology.

In the first part of this work, we study metal-organic chemical vapor deposition (MOCVD) of AlN/GaN RTDs. MOCVD growth conditions are optimized to achieve smooth heterojunctions as well as abrupt transition between nano-scale layers with a precise thickness control. Effects of material quality on RTDs’ performance are investigated by growing RTD structures on various templates on conventional sapphire substrate. Negative differential resistances with P/V as high as 2.2 are realized in AlN/GaN RTD MOCVD-grown material at RT for the first time.

The alternative to reduce dislocation densities in epilayers is homoepitaxial growth on freestanding (FS) GaN substrates. In the second part of this work, we study MOCVD of AlGaN/GaN RTDs on polar (c-plane) and non-polar (m-plane) freestanding GaN substrates. In this talk we compare the performance of MOCVD-grown RTDs on different substrates.
with good uniformity across the whole wafer. Perpendicular etching sidewall was achieved, with small surface RMS roughness which is a significance feature used for laser diodes (LDs) device.

7939-53, Poster Session

Helical deposition with alternating indium composition in growing an InGaN nanoneedle with the vapor-liquid-solid growth mode

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Because of the application potential in fabricating high-efficiency solar cells and light-emitting devices, growth of quasi-1-D InGaN structures is important, particularly those grown with MOCVD. Among various growth techniques, the vapor-liquid-solid (VLS) growth mode has been widely used for growing quasi-1-D structures. In this growth mode, either self-melt or extrinsic-metal catalyst is needed for transferring vapor elements into a crystalline structure through the molten catalyst metal droplet. In other words, the molten metal absorbs composition elements to reach a super-saturation condition, under which the composition elements are precipitated on the seeding semiconductor beneath the catalyst metal droplet. With this approach, quasi-1-D semiconductor structures can be formed following the trace of the catalyst metal droplet. In this paper, the helical deposition behaviors of InGaN with alternating indium composition in growing InGaN nanoneedles with the VLS mode are reported. Au nanoparticles formed with laser irradiation onto an Au thin film on a GaN template are used as catalyst in such an MOCVD growth. From the transmission electron microscopy measurements, including high-angle annular dark field and energy dispersive X-ray operations, we observe the alternating “anti-symmetric” indium content distribution with respect to an almost vertical axis along the c-direction near the center of an InGaN NN. Also, along the growth direction, indium content varies quasi-periodically. It is deduced that the VSL growth follows a helical deposition pattern of InGaN with a quasi-periodical indium composition variation in a nan scale.

7939-54, Poster Session

Characteristics of InGaN/sapphire-based photovoltaic devices with different superlattice absorption layers and buffer layers

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Compound semiconductors of group III-nitrides, gallium nitride (GaN) and its ternary alloys of aluminum and indium, with bandgap energy ranging from 0.7 to 3.4 eV have been proposed an excellent candidate for full-solar-spectrum photovoltaic (PV) devices since 2002. Such tunable wavelengths optical devices

7939-55, Poster Session

Feasibility study on large area optical devices with PSD grown group III nitrides

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Group III nitride optical devices have been believed to exhibit high performance but to be extremely expensive because their fabrication process involves low throughput high temperature epitaxial growth by MOCVD or MBE. It is quite natural to believe that III nitride devices prevail quickly among various fields once low cost fabrication process is established. To fabricate large area nitride devices such as solar cells and displays at a reasonable cost, development of a high throughput low temperature growth technique is inherently important. We have recently found that the use of growth technique called PSD (pulsed sputtering deposition). PSD has attracted much attention of industry engineers because its productivity is much higher than that of MOCVD or MBE. 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 metals or mica 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.

7939-57, Poster Session

Growth of a-plane GaN on vicinal r-plane sapphire substrates

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Device-grade high quality nonpolar GaN layers are required to overcome the quantum confined Stark effect in conventional polar GaN based light emitting diodes. However, the planar anisotropic nature of growth mode in non-polar GaN makes it still difficult to get a high quality nonpolar GaN with pit-free surface and low defect density. [1, 2]

In this presentation, we report the control of islands formation in high temperature (HT)-GaN nucleation layers with change of carrier gases during buffer layer growth and its effects on the material quality of the overgrown a-plane GaN on r-plane sapphire substrates. Based on the control method of initial stage of nucleation layer, the effects of tilt angle from 0.65 to 0 degree toward m-axis of sapphire on the initial stage of nonpolar a-plane GaN growth was investigated. In addition, the relationship between the surface step configuration of substrates with tilt angle and resulting a-plane GaN properties was investigated with the pre-growth thermal treatment of sapphire substrates at high temperatures. The experimental results clearly show that the initial stage of HT nucleation step can be controlled by change of carrier gas as well as the modification of substrate surface atomic configuration by thermal treatment. The crystal quality including the structural, optical, and surface morphology of a-plane GaN grown with different tilt angle and HT GaN nucleation layers will be discussed in detail.


Plasma-assisted MBE growth of semipolar quantum dots
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Semi-polar GaN deposited on AlN(11-22) by PAMBE can follow the Frank-Van der Merwe or the Stranski-Krastanov growth mode as a function of the Ga/N ratio. N-rich grown GaN relaxes elastically at a critical thickness, but the resulting GaN islands present multiple crystallographic orientations. In contrast, after deposition of a few GaN monolayers under Ga excess, a growth interruption induces (11-22)-oriented islanding. The dominant QD morphology comprised a non-polar (11-20) and semi-polar (10-11) nanofacets. The red shift of the Raman signal is proportional to the biaxial stress. The Raman shift red shifted with increasing GaN flux (30% to stoichiometric value). The resulting QDs are elongated with average base width ~20 nm. Optical studies show a systematically blue shift of the luminescence when decreasing the substrate temperature, as a result of the enhanced In incorporation.

Raman scattering spectroscopy for epitaxial AlN films
S. Yang, R. Miyagawa, H. Miyake, K. Hiramatsu, Mie Univ. (Japan); H. Harima, Kyoto Institute of Technology (Japan)

Due to its wide band-gap and outstanding thermal and chemical stability, aluminum nitride films are commonly used in the area of high-power high-temperature electronic devices, especially high-efficiency deep-ultraviolet light-emitting diodes. However, due to the lack of native substrate, the AlN grown on foreign substrate were in high strain state, which influenced the performance of devices. Therefore, in this work the strain states of AlN grown on different substrates by MOVPE and HVPE were studied by Raman scattering spectroscopy. Raman scattering was used to study the strain state of AlN with different crystalline and lattice constants, which were deposited by MOVPE and HVPE. Figure 1 shows the Raman shift E2(high) as a function of lattice constant a and the biaxial stress. The Raman shift red shifted with increasing the lattice constant a. Due to the small lattice and thermal misfits between AlN and 6H-SiC, the strain in AlN grown on 6H-SiC(brackets in Fig.1) is less than those on sapphire, which results in the smaller Raman (E2(high) bulk AlN= 657 cm^-1 1)). We found that the Raman shift E2(high) showed a linear relationship with biaxial stress. The biaxial stress coefficient is 4.04 ± 0.3 cm^-1/GPa. It is very close to the value obtained from sputtered AlN2). The Fig.2 shows the correlation in the smaller Raman (E2(high) bulk AlN= 657 cm^-1 1)). We found that the Raman shift E2(high) showed a linear relationship with biaxial stress. The biaxial stress coefficient is 4.04 ± 0.3 cm^-1/GPa. It is very close to the value obtained from sputtered AlN2). The Fig.2 shows the correlation in the smaller Raman (E2(high) bulk AlN= 657 cm^-1 1)). We found that the Raman shift E2(high) showed a linear relationship with biaxial stress.

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Two-dimensional drift-diffusion simulation of GaN HFETs
Q. Fan, H. Morkoc, Virginia Commonwealth Univ. (United States)

Two-dimensional drift-diffusion model was developed to simulate the transport properties of GaN based heterojunction field effect transistors (HFETs). The model solves the Poisson and Schrödinger equations self-consistently using numerical Newton-Raphson method to obtain the cross-sectional potential profile of the devices. The simulation was reinforced by the conservation condition of the one-dimensional drift-diffusion current along source-drain direction. The polarization charges distributed at heterojunction interface was taken into account for nitrides which determine the carrier distribution and electron sheet density. Both constant mobility and field-dependent saturation velocity models are considered. The simulated channel electrical field shows that the peak position locates at the gate edge to the drain side, reaching 106 V/cm at high bias condition. It is also found that the surface boundary conditions changes the simulation results significantly. It indicates that the surface states, traps, defects can bring profound influence on the HFETs performance.

HFETs designs for enhanced performance and reliability in GaN HFETs
J. H. Leach, H. Morkoc, Virginia Commonwealth Univ. (United States); A. Matulionis, Semiconductor Physics Institute (Lithuania)

The electric fields present in a heterostructure field effect transistor (HFET) give rise to large densities of hot electrons and hot phonons not in equilibrium with the lattice (thus the term “hot”). It has been established that hot phonons play a deleterious role in device performance and reliability, particularly as two-dimensional electron gas (2DEG) densities increase. The hot phonon effect is strong in GaN where LO phonon (longitudinal optical phonon) scattering is the primary electron scattering mechanism at high fields, and LO phonons tend to accumulate in the 2DEG channel due to long lifetimes and low group velocity. Thus, it is imperative for further advancement of HFET devices that hot phonon effects be mitigated. That said, the lifetime of the LO phonons decaying into propagating LA modes is not constant, and it is through the exploitation of this fact that one gains the ability to enhance the performance and reliability of HFETs. This has been evidenced by operating HFETs at particular bias conditions which support short LO phonon lifetimes. Alternatively, minimization of hot phonon lifetimes may be achieved through novel device designs. In this work, we outline designs for minimizing hot phonon effects in HFET devices with high electron density. We propose “camel-back” structures with wavefunction “spreading layers” to maximize 2DEG charge while mitigating hot phonon effects arising from high electron density.

AIN homo-epitaxial growth on sublimation-AlN substrate by low-pressure HVPE
T. Nomura, K. Okumura, H. Miyake, K. Hiramatsu, Mie Univ. (Japan); O. Eryu, Nagoya Institute Technology (Japan); Y. Yamada, Yamaguchi Univ. (Japan)

Introduction
AIN is an attractive substrate for short-wavelength optoelectronics devices based on AlN, GaN and it alloys. The advantages of AlN include a close lattice constant match, a high thermal conductivity, high electrical resistivity, and large band gap. Hydride vapor phase epitaxy (HVPE) is expected to be employed for the fabrication of
We start from the quantum 1/f expression of the spectral density noise to individual diodes of this type, to back-to-back ErAs contacted wavelength imaging. The present paper applies the quantum theory of 1/f best suited for use in focal plane arrays for millimeter and sub-millimeter MBE-grown ErAs:InAlGaAs metal-semiconductor Schottky diodes are presented. Morkoç, Virginia Commonwealth Univ. (United States); P. H. Handel, Univ. of Missouri-St. Louis (United States); H. M. Kim, Korea Advanced Institute of Science and Technology (Korea); H. Kamei, Tokyo Institute of Technology (Japan); A. Tuominen, University of Oulu (Finland); H. Horiuchi, Kyushu Institute of Technology (Japan); M. Iwaya, University of Tokyo (Japan); N. Sakai, Osaka University (Japan); K. N. Tu, National Taiwan University (Taiwan); S. Cho, LG Display (Korea, Republic of); S. Han, Tencor Corp. (United States). 

7939-64, Poster Session

Fabrication and lasing characteristics of GaN nanopillars

M. Lo, National Chiao Tung Univ. (Taiwan); Y. Cheng, Academia Sinica (Taiwan) and National Chiao Tung Univ. (Taiwan); H. Kuo, S. Wang, National Chiao Tung Univ. (Taiwan)

We report the fabrication of GaN nanopillars and their lasing characteristics under optical pumping at room temperature. The nanopillars were fabricated from a GaN epilayer wafer by self-assembled Ni nanomasked etching, followed by epitaxial regrowth to form crystalline GaN nanopillars. The regrowth process is intended to reduce surface defects created during ICP-RIE etching. The fabricated GaN nanopillars exhibit a random distribution with hexagonal pillar geometry. The density of GaN nanopillars is about 8.5×108/cm2 and the diameter and height of GaN nanopillars are about 250 nm and 650 nm, respectively. The fabricated sample is optically pumped by a frequency-tripled Nd:YAG pulsed laser at 355 nm wavelength with a Gaussian beam spot size of about 1.8 μm. At low pumping intensity, the emission has a broad spontaneous emission spectrum with a peak around 363 nm. As pump intensity increases, a narrow peak at 363 nm emerges quickly from the broad spontaneous emission background. The lasing action occurs at a threshold pump power density of about 122 MW/cm2. The laser emission linewidth decreases with increasing pump power and reaches a lowest value of about 0.38 nm beyond the threshold. The excitation-power-dependent spectra show that the lasing wavelength has a slight blue shift as pump power increases. This shift could be due to the band filling at high carrier density.

7939-66, Poster Session

The defect characterization of GaN epitaxial layers using optical defect detection methods

J. Jhin, LG Display (Korea, Republic of); S. Cho, S. Han, KLA-Tencor Corp. (United States)

This work employs optical detection methods to examine defect behavior through various process conditions on GaN buffer layers grown in MOCVD. The splitting of the GaN buffer layers was carried out using various temperatures, process times, TMG flow rates in the MOCVD process. This resulted in various epitaxial characteristics of GaN nanopillars on sapphire substrates. The wafers were wet-etched with a selective solution of NaOH and KOH to exaggerate the pit size of dislocations at the wafer surface. Hence, we were able to detect and count the dislocation density on the GaN epitaxial layers. For defect and dislocation characterizations, we used optical defect detection (KLA-Tencor CS20), PL (Photoluminescence), CL (Cathode luminescence), and AFM (Atomic force microscope) techniques. It was shown that an optically detected defect trend is well correlated with the PL, CL, and AFM observations.

7939-65, Poster Session

Realization of high-conversion-efficiency GaInN based solar cells

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Since the bandgaps of GaInN ternary alloys have broad range from 0.65 to 3.43 eV, its materials are suitable for fabricating high efficiency tandem solar cells. When a tandem solar cell is designed, the material with a wide band gap range exhibits a high degree of freedom. The conversion efficiency of a four-junction solar cell designed to use sunlight with minimum energy loss is as high as 62%. In this paper, we fabricated and characterized the GaInN based solar cells with strained-layer GaInN/GaInN superlattice active layer on a GaN substrate. The GaInN strained-layer superlattice with thick GaInN barrier layers can be stopped the misfit dislocation generated from the interface between GaInN and GaN. By this technology, the appropriate open-circuit-voltage of GaInN based solar cell can be realized. Moreover, the high external quantum efficiency and short circuit current of GaInN based solar cell can be realized using the very thin GaInN barrier layer. We found that high performance GaInN based solar cells with high open-circuit voltage, short current circuit, and fill factor can be realized by using the combination of the thick and thin GaInN barrier layers technology. In summary, the energy conversion efficiency of the GaInN based solar cell is approximately 2.46%, which is the highest to date in this GaInN based solar cell.
AFM results on the various split conditions of the GaN buffer layers. Based on these results, we were able to optimize the process condition of the GaN buffer layer in MOCVD for high quality GaN layers. Thus, this work presents the optical defect characterization method on GaN buffer layers grown by various process conditions to reduce defect density.

7939-67, Poster Session

Fabrication of high efficiency LED using moth-eye structure

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The moth-eye structure consisting of periodic cones with submicron scale pitch on surface/interface is known to enhance light extraction efficiency on light-emitting diodes (LEDs). Previously, nitride-based flip-chip blue LEDs with the moth-eye structure on the backside of the substrate were demonstrated to show high light extraction efficiency. In this report, face-up blue LEDs with double moth-eye structures is described. One moth-eye structure was formed on the sapphire substrate, and another one was on the ITO contact, where the pitches of the cones are both 500 nm. The patterning of such small pitch was carried out by the low-energy electron-beam lithography technique. The output powers were measured under the wafer probing setup, where a photo detector was set onto the normal to the LED surface. As references, face-up LED without moth-eye structure and that with single moth-eye structure on ITO contact were also examined. The single moth-eye LED has 1.4 times higher output power than non-moth-eye LED, and the double moth-eye LED has 1.7 times higher than none-moth-eye LED. As shown above, the double moth-eye structure in the blue LED exhibits significant improvement of light extraction efficiency.

7939-68, Poster Session

Optical and structural properties of m-plane GaN grown on Si(112) patterned substrates

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At the present time, GaN-based light emitting diodes (LEDs) are produced on c-plane GaN, which is a highly polar orientation. Consequently, polarization charge substantially reduces the electron and hole wavefunction overlap, and therefore, reduces light emission efficiency and causes a blue shift with increased injection. This drawback can be alleviated by using a non-polar m-plane orientation which is free of polarization charge. The m-plane of GaN is well-suited for optical applications because its matrix elements for optical transitions are relatively high.

In this work, we studied the effects of the growth conditions (substrate temperature, chamber pressure, NH3 and TMGa flow rates) on the growth habits of GaN, and found optimal growth conditions for achieving coalesced m-plane GaN films. Morphology and structural properties of m-plane GaN were studied by scanning electron microscopy (SEM), x-ray diffraction, and transmission electron microscopy (TEM). For further evaluation of the optical quality, InGaN LED structures were grown on the m-plane GaN. Optical properties of the m-plane GaN and the InGaN LED structures were studied by micro-photoluminescence (PL), near-field scanning optical microscopy, spatially resolved cathodoluminescence (CL), and time-resolved PL. In order to investigate the relationship between the optical processes and defect distribution in GaN, TEM data were correlated with results of CL measurements.

7939-69, Poster Session

Growth of semi-polar GaN-based light-emitting diodes grown on an patterned Si substrate

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The optical properties of our samples were examined by photoluminescence (PL) measurements conducted at room temperature. A strongest emission peaking at about 443.6 nm with a smallest full-width at half-maximum of 33.3 nm was achieved for the GaN-based LED grown on patterned Si substrate with 8°-off. Moreover, transmission electron microscopy (TEM) images demonstrate the threading behaviors of dislocations in the films fabricated. The threading dislocation density (TDD) through the GaN-based LED grown on patterned Si substrate with 8°-off is about 10 times lower than those grown on planar Si substrates. Molten KOH etching was also performed on all specimens to recognize their TDD. Etch pits with various sizes are observable for all the films etched and the GaN-based LED grown on patterned Si substrate with 8°-off still shows a lowest average etch-pit density, which was estimated to be about 10^8 cm^2.

7939-70, Poster Session

High efficiency GaN-based light emitting diodes grown on nano-patterned substrates

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The GaN film showed improvement in crystal quality through x-ray diffraction FWHM and photoluminescence measurement. The light output power and internal quantum efficiency of the fabricated LED were enhanced compared to those of conventional LED. The improvements could be attributed to both the enhanced light extraction by utilizing SiO2 NRA and the improved crystal quality through the NELO method.

7939-71, Poster Session

Enhancement in light extraction efficiency of GaN-based vertical light-emitting diodes by AgCu-based reflectors

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Two-step alloyed indium-tin-oxide (ITO)/Ni/AgCu/Pt reflectors for high-performance GaN-based vertical light-emitting diodes (VLEDs) were investigated. The reflectance of the ITO/Ni/AgCu/Pt reflectors at 460 nm was slightly increased from 82% to 87% after two-step annealing. Based on the secondary ion mass spectrometry depth profiles, this improvement was attributed to the formation of a transparent Ni-oxide and the existence of Cu atoms near ITO/AgCu/Pt interface regions suppressing the inter and out-diffusion of Ag. The VLEDs fabricated with the ITO/Ni/AgCu/Pt reflectors showed an approximately 4.4 % higher output power.
Enhancement of light power for green strain-compensated hybrid InGaN/InGaN/MgZnO light-emitting diodes

S. Park, Catholic Univ. of Daegu (Korea, Republic of); Y. Moon, J. S. Lee, H. K. Kwon, J. S. Park, LG Electronics Inc. (Korea, Republic of); D. Ahn, The Univ. of Seoul (Korea, Republic of)

Electronic and optical properties of green strain-compensated InGaN/InGaN/MgZnO quantum well (QW) structures using a MgZnO substrate are investigated using the multiband effective mass theory. A strain-compensated InGaN/InGaN/MgZnO quantum well (QW) structure with a larger strain shows larger matrix element than that with a smaller strain. This is mainly due to the fact that the well width to give the transition wavelength of 530 nm is greatly reduced for the QW structure with a larger compressive strain in the well. The spontaneous emission peak rapidly increases with increasing compressive strain because the matrix element is enhanced for the strain-compensated QW structure with a larger strain. In addition, we find that the strain-compensated QW structure with the larger Mg composition in the substrate has a larger spontaneous emission peak than the strain-compensated QW structure with the smaller Mg composition in the substrate. Optical properties of strain-compensated InGaN/InGaN quantum well structures using a InGaN substrate are also investigated using the multiband effective mass theory. These results are compared with those of conventional InGaN/GaN QW structures using a GaN substrate. The spontaneous emission peak of a strain-compensated QW structure is shown to be much larger than that of a conventional QW structure.

Domain matching epitaxy of Mg-containing Ag contact on p-type GaN

Y. Song, J. Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Silver has been investigated as an alternative interconnection material for ultra-large-scale integration technology due to its lower electrical resistivity (1.58, Al 2.65, Cu 1.67 µΩcm). However, pure Ag thin film has a poor thermal-resistivity. Agglomeration has been observed at high temperatures and considered as a weak point of silver metallization. It was reported that the physical mechanism of Ag agglomeration was related to the surface diffusion of Ag atoms which are driven from surface energy. For Ag film, Ag atoms in poly-grain move toward (111)-oriented one to reduce the surface energy at high temperature because the (111)-oriented grain is energetically most stable. Thus, the diffusion of Ag atoms could be suppressed if the Ag film has (111)-orientations in the growth of film. No works, however, have been done yet, because the lattice mismatch between GaN(0.318 nm) and Ag(0.286 nm) is too large (1.66%) to use Ag film on p-GaN substrate.

We present the growth mechanism of Mg-containing Ag film on p-GaN using domain matching epitaxy scheme. Synchrotron x-ray diffraction and fourier-filtering of the basal plane using high resolution transmission electron microscopy was used to identify the structure of domain matching. Based on these experimental results, we investigated effects of Mg addition to Ag contact. The Mg additive reduces the surface diffusion of Ag atoms because Mg-containing Ag film is epitaxially grown on the GaN substrate with (111)-orientation. The preferentially formed Mg-O bonding in Ag film shrinks the surrounded Ag atoms, which in turn reduce the lattice-mismatch with GaN substrate. Therefore Ag agglomeration resistance is significantly enhanced in Ag(Mg) contact, leading to the thermal stability.

Numerical study on AlGaN-based ultraviolet light-emitting diodes

M. Tsai, National Changhua Univ. of Education (Taiwan); S. Yen, Epistar Corp. (Taiwan); Y. Chen, S. Chang, Y. Kuo, National Cheng Kung Univ. (Taiwan)

Enhancing the light-extraction efficiency is one of the critical issues in light-emitting diodes (LEDs). Micro or nano structure on the surface of LED device have been reported to increase light-extraction efficiency, but mostly these surface structures effects could be drastically reduced when the epoxy resin was filled into the micro or nanostructure on the surface in packaging process. In this study, nanocavity array structure was fabricated on the ITO electrode of GaN based light-emitting diodes (LEDs) to increase light-extraction efficiency. The nanocavity fabrication in light-emitting diodes for enhancing light extraction efficiency was reported that the physical mechanism of Ag agglomeration was related to the surface diffusion of Ag atoms which are driven from surface energy. For Ag film, Ag atoms in poly-grain move toward (111)-oriented one to reduce the surface energy at high temperature because the (111)-oriented grain is energetically most stable. Thus, the diffusion of Ag atoms could be suppressed if the Ag film has (111)-orientations in the growth of film. No works, however, have been done yet, because the lattice mismatch between GaN(0.318 nm) and Ag(0.286 nm) is too large (1.66%) to use Ag film on p-GaN substrate.

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Changhua Univ. of Education (Taiwan)

With the technology of blue InGaN light-emitting diodes (LEDs) approaching maturity, current research on nitride emitters is moving toward AlGaN LEDs emitting in the ultraviolet (UV) spectral region. UV LEDs have many important applications such as biodetection, fluorescence spectroscopy, photolithography, nonline-of-sight communications, curing of ink, paint, or polymers, and purification or sterilization of air, water, and surfaces. Generally, the conduction band offset and valence band offset of the quantum well in the ultraviolet spectral region are smaller than those in the blue spectral region due to the increased band gap energy. Therefore, the electron leakage out of the active region is speculated to be a possible factor causing the poor optical performance. Upon this issue, the usage of an electron-blocking layer (EBL) plays an important role. In this work, in order to improve the blocking capability for electrons, some specific designs around the EBL of AlGaN-based UV LEDs are numerically executed by using the APSYS (Advanced Physical Model of Semiconductor Devices) simulation program. Specifically, the energy band diagrams, radiative recombination rates, distribution of electrons and holes in the active region, and electron overflow are studied. The effect of EBL on the optical properties of the UV LEDs will be concluded.

7939-77, Poster Session

Enhanced hydrogen gas generation rate by n-GaN photoelectrode with immersed finger-type indium tin oxide ohmic contacts

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Using sunlight to split water into hydrogen and oxygen is a promising method. The InxGa1-xN materials’ band-edge potential not only can satisfy the conditions for splitting water, but is also potentially resistant to aqueous solutions. Further, the band gap can vary once the content of In is modified, allowing the production of a photoelectrochemical (PEC) cell that can fit the solar spectrum to enhance light absorption. In this study, we use n-GaN epitaxial films as working electrodes to absorb light and then produce hydrogen gas. To enhance the efficiency of photo-generated electron collection in the n-type working electrode, Indium Tin oxide (ITO) finger-type ohmic contacts were immersed in NaCl electrolyte because ITO is a well-known transparent and conductive optical film. We found that the performances of the n-GaN photoelectrochemical cells with finger-type ITO ohmic contacts in photocurrent densities and hydrogen gas generation rates were both better than the n-GaN without finger-type ITO ohmic contacts. Related analyses have been performed and we try to explain the possible mechanism from the point of view of electrochemical analysis. Besides, after the photoelectrochemical measurements we observed that the adhesion of ITO/n-GaN contacts was pretty good. Finally, we did the surface analysis by scanning electron microscope before and after the photoelectrochemical measurements to conform the surface morphology of ITO almost did not change. This indicates that ITO is a good candidate material for the immersed ohmic contact in water splitting system.

7939-78, Poster Session

Diffusion barrier combined n-type electrodes for GaN-based vertical light-emitting diode

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For general lighting applications, the realization of high-power and high-efficiency LEDs is essential. In this respect, vertical-configuration LEDs (VLEDs) have been widely studied. The formation of low-resistance and thermally stable ohmic contacts to N-face n-GaN is important for developing high-performance VLEDs. Unlike lateral LEDs having n-ohmic contacts to Ga-polar n-GaN, VLEDs require n-type ohmic contacts to N-face n-GaN, which are difficult to form. For instance, Ti/Al-based contacts to Ga-face n-GaN were ohmic when annealed at 700 °C, while the same contacts to N-face n-GaN produced non-ohmic behavior. The dependence of the electrical characteristics on the polarity was attributed to the resulting opposite directions of the spontaneous polarization fields. It was also shown that TiN/Al contacts to N-face n-GaN exhibited better electrical properties than Ti/Al contacts. Both the TiN/Al and Ti/Al contacts underwent electrical degradation at 300°C. The electrical degradation of the Ti/Al contacts to N-face samples was attributed to the presence of deep acceptor-like Ga vacancies near the n-GaN surface region caused by the outdiffusion of Ga. This indicates that preventing Ga outdiffusing from n-GaN would allow the formation of low-resistance ohmic contacts to N-face n-GaN. Thus, in this work, we investigated the use of different diffusion barriers to suppress the outdiffusion of Ga atoms into the n-electrodes. It is shown that the diffusion barrier combined Ti/Al contacts become ohmic with a contact resistivity of ~10-4 ohm.cm2 when annealed below 300°C. The Ohmic and degradation mechanisms are described and discussed.

7939-79, Poster Session

High modal gain in Ga(NAsP)/(BGa)((As)P) heterostructures grown lattice-matched on (001) silicon

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The implementation of a semiconductor laser on silicon could allow for combining optical data processing with the well-established silicon microchip-technology, possibly leading to optoelectronic integrated circuits (OEICs) with unique novel functionalities and drastically improved performance. One promising approach is the implementation of a direct band-gap laser material pseudomorphically grown on silicon. This direct band-gap material has to match the lattice constant of silicon because otherwise threading dislocations will be formed decreasing optical and electrical properties of the material drastically. These threading dislocations limit device lifetime significantly, which makes the development of electrically pumped lasers on silicon with long term stability to a big challenge. The novel dilute nitride system GaNAsP/BGaAsP is a very promising candidate for lasers on silicon, because it is a direct band gap material, which can be grown lattice matched on (001) Si-substrates without the formation of any misfit dislocations.

Here we present a detailed study for the optical gain in this new material system, depending on a variety of different growth and sample parameters. High modal gain values of up to 80 cm-1 can be found at room temperature. The experimental results show good agreement of the main features to calculated gain spectra using a microscopic model of our samples. Our results demonstrate the high optical quality of the novel dilute nitride system and its qualification as an active material for electrically pumped lasers on Si.

7939-80, Poster Session

Electrical properties of laser-annealed n-contacts to N-face GaN for vertical light-emitting diodes

J. W. Jeon, S. Park, T. Seong, S. Y. Lee, J. Song, Korea Univ. (Korea, Republic of)

For the application of LEDs to solid-state lighting, high-power and high-efficiency vertical injection GaN-based LEDs fabricated by wafer bonding (or electroplating) combined with a laser lift-off (LLO) process have been extensively investigated. Vertical LEDs (VLEDs) require the development of high-quality ohmic contacts to N-face n-GaN. N-face
ohmic contacts were found to be difficult to form. For example, Ti/Al-based contacts to Ga-face samples were ohmic when annealed, while contacts to N-face samples were non-ohmic. The poor electrical characteristics was attributed to the absence of polarization-induced 2DEG formed at the AlN/GaN interface due to the opposite direction of spontaneous polarization built from bulk to surface. Ti/Al contacts were also shown to be electrically degraded at 300°C, which was attributed to the outdiffusion of Ga atoms from n-GaN. Furthermore, the fabrication of VLEDs requires relatively low processing temperatures, because annealing at temperatures > 300°C can damage the conducting substrates formed by wafer bonding or electroplating. Thus, the formation of low-temperature ohmic contacts is essential from the standpoint of the production of VLEDs. In this work, to minimize the annealing damage of LLO-processed LED chips and the outdiffusion of Ga atoms from n-GaN, a laser-annealing process along with a conventional RTA process was introduced. It is shown that Ti/Al contacts laser-annealed at different powers of 400, 500 and 600 mJ/cm2 become ohmic even after RTA at 300°C, while reference samples without laser-anneal experience electrical degradation. Based on XPS and AES results, the Ohmic and degradation mechanisms are described and discussed.

7939-81, Poster Session

Probing electrical properties of single GaN nanorod p-n junctions by electron microscopy

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One-dimensional α-nitride (AlN, GaN, InN) nanorod structures are well known to have great prospects for fundamental studies and novel technological applications. Especially, α-nitride nanorods grown by plasma-assisted molecular-beam epitaxy (PAMBE) have been demonstrated to be dislocation-free single crystals, which can be used as strain-free growth templates due to their unique nanoscale geometry. In addition, α-nitride alloys are direct band gap semiconductors whose emission wavelengths can be tuned continuously with emission colors spanning from ultraviolet to the near-infrared region. Most significantly for practical applications, contrary to other wide-band gap semiconductor materials, GaN nanorods can be doped as n- and p-type materials, which are prerequisite for electrically driven photonic devices. However, direct determination of the carrier concentrations by Hall effect is not easy if not impossible for nanorod structures. Here, we demonstrate a method which can be applied to study single GaN nanorod p-n junctions grown by PAMBE with an in-situ multiple-probe system installed in a field-emission scanning electron microscope (FESEM). In particular, we show that this method can be used for estimating the carrier concentration in single GaN nanorod p-n junctions. The measured current-voltage characteristics of GaN nanorod p-n junctions exhibit a clear rectifying behavior and no reverse-bias breakdown is observed for voltage up to ~10 V. Furthermore, we can directly observe the electrostatic potential variation across the depletion region in the reversely biased nanorods, and the electrostatic potential can be determined directly from secondary electron images. We find that the increasing reverse bias enhances both the potential barrier and the depletion width across the p-n junction. The results are consistent with the predicted p-n junction behavior. Furthermore, we can use the relationship between applied bias and depletion width to estimate the carrier concentrations of both p- and n-regions.

7939-82, Poster Session

Growth GaN single crystals by Ca- and Ba-added Na flux method


GaN substrates are desirable for fabricating ultra-violet LEDs and LDs, and high-power and high-frequency transistors. One of the most economically effective ways to commercially produce such devices is the development of bulk growth with subsequent wafer slicing. Na flux method is one of the useful techniques for fabricating high-quality GaN single crystals. It is necessary to control the growth habit during the growth of bulk crystals, as the shape of the bulk determines the number of wafers that can be produced. In this study, we investigated an effect of additives (Ca, Ba) on growth habit and impurity concentration in the crystals.

A seed GaN thin film, Ga, Na, carbon and Ca (0 – 0.1 mol%) or Ba (0 – 1 mol%) were charged into an alumina crucible in an Ar-filled glove box. After the crucible was transferred into a stainless-steel tube, the stainless-steel tube was connected to a N2 gas line inside electric furnace. The temperature and the nitrogen pressure of the tube were maintained at 850 oC – 870 oC and 2.0 MPa – 4.0 MPa, respectively, for 96 hours.

The aspect ratio (c/a) of the crystals was increased with increasing the amount of additives, showing that the growth habit changed from the pyramidal shape to the prism shape. Ca was incorporated in the crystals grown at Ca-added conditions. Whereas, Ba concentration was below the detection limit (1 x 1015 atoms/cm3) in the crystals grown at Ba-added conditions. We concluded that Ba additive is an effective element to grow prismatic GaN crystals.

7939-83, Poster Session

Measurement of nonuniform bowing in GaN/ sapphire epi-wafers and subsequent stress analysis by using a theoretical model

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During the high-temperature epitaxial growth of GaN light-emitting diodes (LEDs) on a sapphire substrate, the wafer undergoes different stresses due to the mismatch in lattice constant and thermal expansion coefficient. After the epitaxial growth is over and the wafer is cooled down to room temperature, the epi-wafer has non-zero curvature which tends to be not uniform across the wafer. This nonuniformity requires analysis beyond the simple Stoney’s formula typically used for uniformly bent wafer. The wafer bending issue is becoming ever more important as the industry is pushing forward to a larger size wafer for cost-reduction. In this work, we first present our approach to measure the profile of the nonuniformly bent GaN epi-wafer grown on a sapphire substrate. The measurement system informs us of displacement between a wafer and laser sensor and maps the entire profile of the wafer. From the measured profile data, we analyze stress distributions in nonuniformly bent wafers by using a theoretical model. We find from the analysis that the nonuniformity in bowing of the LED wafer induces stress variation over the wafer. The stress tensors might be related with optical properties such as time-resolved or time-integrated photoluminescence. Furthermore, the stress tensors might also affect the LED performances such as average emitting light wavelength or light intensity. The correlation between the analyzed stress tensors and the above-mentioned optical properties are discussed.

7939-84, Poster Session

Surface-plasmon-mediated photoluminescence enhancement from red-emitting InGaN coupled with colloidal gold nanocrystals: origin of luminescence enhancement or quenching

C. Wu, C. He, H. Lee, H. Chen, S. Gwo, National Tsing Hua Univ. (Taiwan)

Local electromagnetic fields can be strongly enhanced by gold
nanostructures under surface plasmon resonance conditions. This phenomenon has important implications for subwavelength optics and biosensing. In addition, surface plasmon mediated luminescence has been extensively studied in the recent years because of the applicability for light emitting devices. In this study, we utilized colloidal gold nanocrystals (including triangle and hexagon plates, nanorods, and nanoparticles), self-assembled gold nanoparticle superlattices, and sputtered gold films to investigate the plasmon-coupling effects on the photoluminescence from a red-emitting InGaN film. We observed a strong enhancement of PL intensity at the positions of gold hexagon- and triangle-plate-covered regions on the InGaN film, in comparison with the PL intensity from the neighboring uncovered InGaN region. Moreover, peculiar PL intensity spatial distributions were observed for both gold triangle and hexagon plates deposited on the InGaN film. From the PL images, the maximum local enhancement occurs at the tips and/or edges of triangle and hexagon plates. These positions are predicted to be maxima positions of plasmonic density of states (PDOS). This is a convenient way to directly observe this local-enhancement phenomenon in the far-field. Recent literature results show that the coupling between semiconductors and noble metals can lead to either luminance enhancement or quenching. The exact mechanism of plasmon coupling is still under current debate. Here, by comparing extinction and scattering spectra of gold nanostructures with the PL spectra in InGaN-gold hybrid systems, we have found consistent occurrence of luminance enhancement or quenching, depending on the outcoupling efficiency of plasmons into the far-field photons.

7939-85, Poster Session

**Direct observation of lattice constant variations depending on layer structures in an InGaN / GaN multiple quantum-well LED**

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We have directly observed that InGaN quantum well (QW) layers were incoherently grown on thinner GaN barrier layers in active layers of blue light-emitting diodes (LEDs) by using lattice images of high-resolution transmission electron microscopy (HRTEM) and fast Fourier transform mapping (FFTM) analysis of the lattice images. FFTM is a powerful tool to visually investigate the variation of lattice constant in active layers.

With a view to various applications, including general lighting, blue LEDs have been widely studied in an effort to improve their characteristics, such as by the amelioration of efficiency droop. The blue LED structures were grown by metal-organic chemical vapor deposition on Al2O3 (0001) substrates. The active layers in the blue LEDs consist of 2.5-nm-thick In0.15Ga0.85N QW layers and 5-nm-thick or 10-nm-thick GaN barrier layers.

FFTM of the active layers with the 10-nm-thick barrier layers showed the intervals of the (01-10) lattice planes were homogeneous. On the other hand, the intervals of the (01-10) lattice planes are incoherent between the InGaN QWs and GaN barrier layers whose barrier width is 5 nm. The lattice disordering was also observed in the HRTEM images of QWs. It indicates that the QWs were relaxed and the defects were induced from the excess strain with the thinner barrier layers. Controlling the strain and reducing the defect density are important for improving the internal quantum efficiency of LEDs.

7939-87, Poster Session

**Optimization of ZnO:Ga properties for application as a transparent conducting oxide in InGaN based light emitting diodes**

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Transparent conducting oxides (TCOs) as transparent electrodes are inevitable components in GaN based LEDs, which can greatly improve the current spreading on the p-side, light extraction efficiency and consequently the external quantum efficiency. ZnO heavily doped with Ga (GZO) is one of the most promising TCOs used in GaN based LEDs, which has the potential to replace the currently dominant indium tin oxide (ITO). [1] We have previously demonstrated that in addition to the negligible light output degradation as well as much better contact stability under high current density of up to 4700 Acm-2 the InGaN LEDs with GZO as their transparent contact p-electrode (GZO LEDs) provided 50% more light output compared with LEDs employing Ni/Au as their p-electrode (Ni/Au LEDs) [2]. The use of GZO also reduced the efficiency droop by improving current spreading on p-type GaN. [2] In this work, we have studied the effects of growth parameters (substrate temperature, oxygen pressure) as well as morphology and structural properties of p-GaN templates on the properties of GZO layers grown by plasma-enhanced molecular-beam epitaxy (MBE) for LEDs’ application.

The InGaN LEDs emitting at 400-410 nm were grown on (0001) sapphire substrates in a vertical low-pressure metalorganic chemical vapor deposition system. GZO layers were grown epitaxially on the top n-type GaN of the LED structures at substrate temperatures varying from 150 to 450 °C by MBE. Electrical properties of the films were studied by the Hall-effect method in the van der Pauw configuration. X-ray diffraction (XRD) and atomic force microscopy (AFM) were used for structural characterization. The contact behaviors between the GZO electrode and the underneath p-GaN were characterized by current-voltage (I-V) method. Pulsed electroluminescence (EL) measurements were employed to evaluate the performances of these LEDs with GZO electrode. As compared with the oxygen pressure during the growth, substrate temperature was found to have only minor effect on the electrical properties of GZO but greatly affects the surface morphology of the GZO films, a parameter very important for light extraction in LEDs.

7939-88, Poster Session

**Measurements of generation-recombination effect by low-frequency noise technique in AlGaN/GaN MOSHFETs**

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We report on the low-frequency phase-noise measurements of AlGaN/ GaN metal-oxide-semiconductor heterostructure field-effect transistors (MOSHFETs) employing HfAlO as the gate dielectric. Some devices tested exhibited noise spectra deviating from the well-known 1/f spectrum. These devices showed broad peaks attributed to generation-recombination (GR) in the noise-spectral-density vs. frequency plots, which shifted toward higher frequencies at elevated temperatures. From the temperature dependence of the frequency position of this peak the energy level of these excess traps were determined to be 0.22 ± 0.06 eV below the conduction band for the bias conditions employed. We also monitored the effect of source-drain bias on the excess GR noise. The broad peaks shifted toward higher frequencies in the spectrum with increasing source-drain bias. The time constant of the traps decreased from 4.6 ms to 0.27 ms as we increased the VDS from 10 V to 18 V. This effect can be explained by the potential barrier lowering (Frenkel-Poole effect) of the traps due to high electric field applied.
Low-frequency noise measurements of degradation in AlGaN/GaN heterostructure field-effect transistors
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We employed a low-frequency noise (LFN) technique measuring the residual phase noise on AlGaN/GaN heterostructure field-effect transistors (HFETs) to investigate the high electric field degradation effect. The devices were stressed by applying 20V DC drain bias for up to 64 hours duration at different gate voltages. Stressing at the bias conditions of VDS=20V and VGS=-2V shows negligible degradation. On the other hand, stressing at the bias conditions of VDS=20 V and VGS=0V surprisingly reduces the noise monitored about 4 to 15 dB gradually in the frequency range of 1 Hz-100 kHz. Moreover, annealing the sample exhibited similar LFN results as well, which also reduced the noise up to 10 dB. Data in aggregate suggest that the reduction in noise might be related to the annealing of deep level defects.

Electrical properties of In-doped ZnO films grown by plasma-assisted molecular beam epitaxy on GaN(0001) template
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ZnO has the potential to be an alternative to indium-tin oxide (ITO) as a transparent conductive oxide for optoelectronic devices and displays. Because its lattice constant is close to that of GaN, high-quality ZnO films can be epitaxially grown on GaN. To date, Ga and Al doped ZnO films (dubbed GZO and AZO) with low resistivity and high transparency have been demonstrated. Indium, another group III element, might also be an effective n-type dopant for controlling the conductivity of ZnO. However, not so many studies on In-doped ZnO have been reported. In this work, In-doped ZnO films grown by plasma-assisted molecular beam epitaxy on undoped GaN(0001) templates were investigated. For as-grown samples, carrier concentration of 3.4×10^{20} cm^{-3} and electron mobility of 10 cm/V-s are observed. After thermal annealing at 700 °C, carrier concentration decreased to 1.4×10^{20} cm^{-3} while electron mobility increased to 30 cm/V-s.

Current spreading effect in vertical GaN/InGaN LEDs
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Conventional lateral LEDs encounter various problems, such as current crowding, poor heat dissipation, and high forward voltage drop. Hence, the vertical LEDs have attracted much attention due to their better current spreading and heat dissipation. However, the current spreading is still a severe problem especially under high injection condition. In this work, the current spreading effect of vertical LEDs for different contact pattern design is studied. A fully 2D and 3D model by solving drift-diffusion and Poisson equations are used to investigate the current flow paths and radiative recombination region. Our studies show the conventional vertical LEDs is not good enough to spread the current and enhance the light output even with a TCL. Therefore, we designed separated electrode patterns to obtain a higher light extraction. The result shows that the current spreading length is about 1-2 μm of our model and is strongly depending on the number of current flow paths. The effect of spatial modulation of TCL conductivity is also studied. If the number of current spreading patterns is increased, the current spreading effect decreases.

Free-standing GaN-based photonic crystal surface emitting laser with honeycomb lattice
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Recently, two-dimensional photonic crystal (PC) structures have been applied to GaN-based materials to develop highly functional laser devices operating at short wavelengths. In particular, surface-emitting lasers that utilize the photonic band-edge effect are expected to substitute the conventional bulky and hard-to-implement GaN-based vertical-cavity surface-emitting lasers. Here we report on the GaN-based honeycomb-lattice -point band-edge laser (BEL) that is formed in an air-bridge membrane structure. This BEL structure also has the surface-emitting property, but requires much smaller area for lasing action than the previous surface-grating-based lasers. Numerical calculations using finite-difference time-domain method was performed to design the PC BEL structure. We employed the 1 band-edge that is a non-degenerated monopole mode. For a = 130 nm and r = 0.3a, the calculated frequency of the 1 band-edge is /a = 0.298. The designed BEL was prepared using an MOCD-grown InGaN/GaN multiple quantum well structure. When optically pumped using 355-nm Nd:YAG pulsed laser (pulse width of 5 ns and repetition rate of 10 Hz), the BEL devices lased at room temperature. Optical pump energy density at laser threshold was measured to be ~10 mJ/cm². Above the threshold, a single dominant laser peak appeared at ~436.1 nm with the linewidth of 0.8 nm at full-width half-maximum (FWHM). A Fourier-transformed emission pattern in a regular honeycomb shape was imaged by lens, a clear indication that the lasing occurred at a -point band-edge of honeycomb-lattice.
flow paths increases, the current crowding can be significantly improved. Also, with the modulation of TCL conductivity by changing the thickness of doping density, it is possible assist better current spreading. For a better light extraction, the electrodes should not be overlapped because the current will directly flow under the top-electrode to the bottom due to the smallest resistance path. Thus, we apply the stripe-shaped electrodes with a modulation of TCL condition to find the optimization condition for better current spreading.

7939-06, Session 12
InGaN/GaN nanorod light-emitting diodes as white and full-color light sources
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The development of InGaN light-emitting diodes (LEDs) over the entire visible spectral range is crucially important for solid-state lighting and display applications. However, conventional InGaN LEDs based on planar InGaN/GaN multiple quantum well structures do not allow for efficient long-wavelength (high-in-content) operation beyond the blue region due to a strong quantum confined Stark effect (QCES) in lattice-mismatched polar InGaN quantum wells. Here we overcome the QCES limitation by using self-assembled GaN nanorod arrays (diameter <100 nm) as strain-free growth templates for thick InGaN nanodisks (10–40 nm). The absence of QCES, in combination with enhanced carrier localization and high crystalline quality, allows us to realize full-color InGaN nanodisk emitters. By tailoring the numbers, positions, and thicknesses of polychromatic nanodisk ensembles embedded vertically in the GaN nanorod p-n junction, we are able to demonstrate natural white (color temperature ~6,000 K) electroluminescence (EL) from InGaN/GaN nanorod arrays. Furthermore, we show that the EL from individual nanorod LEDs (monochromatic) spans the entire visible spectrum with large polarization ratio (~0.85). In particular, the EL intensity and external quantum efficiency from a single nanodisk increase monotonically with increasing current densities up to 8,000 A/cm2. This indicates that the thick and strain-free InGaN nanodisks embedded in GaN nanorods could be an excellent device structure for the development of high-power-density light emitters.

7939-07, Session 12
High voltage LED for general lighting application
In the past, GaN flip chip, vertical thin GaN LED and the horizontal GaN power chip are some typical structures used for high power LED in various LED lighting applications, including indoor and outdoor market segments. The horizontal GaN power chip LED possess the advantages includes, easy manufacturing, robust structure and low cost. However, due to the poor mobility of the p-GaN property, an ITO layer has been widely used as a Transparent Contact Layer (TCL). The relative poor conductive capability of the TCL has restricted the application of the horizontal GaN power chip at very high current density condition. In this study, a novel structure with series connection of several LEDs junctions in single die for high voltage LED was proposed. These high voltage LED structures convert the high driving current to a very low driving current but keeping same input power or even higher. Such property has improved the current spreading issue and electrical efficiency significantly. An efficiency around 130lm/W@1W has achieved by using high voltage LED design.

7939-08, Session 12
Unified model for the GaN LED efficiency droop
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Nitride-based light-emitting diodes (LEDs) suffer from a reduction (droop) of the internal quantum efficiency with increasing injection current. This droop phenomenon is currently the subject of intense research worldwide, as it delays general lighting applications of GaN-based LEDs. Many proposals have been forwarded to explain the efficiency droop. Among them are carrier delocalization, enhanced Auger recombination, and electron leakage. However, different sample preparation and measurement conditions as well as the application of different models lead to a confusing and sometimes contradicting variety of efficiency droop observations and explanations. This paper combines different droop models in a simple yet unified framework and it helps to bring more clarity to the ongoing droop discussion. The unified model considers both Auger recombination and carrier leakage as potential explanations of the efficiency droop. The paper also reveals some weaknesses of the existing explanations and it encourages a continuing search for additional and improved models of the LED efficiency droop.

7939-09, Session 12
Impact of ballistic electron transport and increased hole concentration on efficiency of InGaN based LEDs
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InGaN light emitting diodes (LEDs), which have become key components of the lighting technology owing to their improved power conversion efficiencies and brightness, still suffer from efficiency degradation at high injection levels. Experiments showing sizeable impact of the barrier height provided by an electron blocking layer (EBL) and of the electron cooling layer prior to electron injection into the active region strongly suggest the electron overflow resulting from ballistic and quasi-ballistic transport as the major cause of efficiency loss with increasing injection. A first order simple overflow model based on hot electrons and constant LO phonon scattering rates describes well the experimental observations of electron spillover and the associated efficiency degradation in both nonpolar m-plane and polar c-plane LEDs with different barrier height EBLs and electron injection layers. LEDs without EBLs show efficiencies lower than 35% of those with A0.15Ga0.85N EBLs due to significant electron overflow to the p-type region in the former. For effective means of thermalization in the active region within their residence time and possibly longitudinal optical phonon lifetime, the electrons were cooled prior to their injection via a staircase electron injector, i.e. an InGaN staircase structure with step-wise increased In composition. Although optimized injector designs have significantly reduced if not totally eliminate the electron loss, the underlying and unfortunately inescapable principle is that electrons must have holes with which to recombine for photon generation. Therefore, increase of hole concentration is imperative and cannot be circumvented by any design of the active region. This paper discusses hot electron effects on efficiency loss, means to cool the electrons prior to injection as well as means to increase the hole concentration.

7939-10, Session 13
InGaN/AlInGaN optical emitters: novel solutions from the visible to deep UV
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We describe recent work on InGaN lasers and AlGaN UV LEDs at the Palo Alto Research Center (PARC). The presentation includes results from InGaN laser diodes in which the usual epitaxial upper cladding layer is replaced with an evaporated or sputtered non-epitaxial material, such as indium tin oxide, silver, or a silver-palladium-copper alloy. Non-epitaxial cladding layers offer several advantages to long wavelength InGaN laser diodes, such as eliminating the need to expose vulnerable InGaN active layers to the high temperatures required for growing conventional p-AlGaN cladding layers subsequent to the active layer growth. The presentation also describes demonstrations of InGaN LEDs and optically-pumped 500 nm lasers grown on 2-inch-diameter semi-polar (11-22) GaN on m-plane sapphire substrates. The semi-polar crystal orientation features a lowered polarization field in the active layer, while enabling efficient indium incorporation at high growth temperatures. The presentation also discusses our recent results on AlGaN UV LEDs. UV LEDs with 300 micron square geometries operating at \( \lambda = 325 \) nm exhibit output powers of 13 mW with differential quantum efficiencies of 0.054 W/A measured under wafer-level, unpackaged condition with no heat sink. LEDs operating at \( \lambda = 280 \) nm under similar test conditions display output powers of 1.6 mW for large-area 300 um X 1 mm devices.

7939-11, Session 13

Properties of TCO anodes deposited by APCVD and their applications to OLED lighting

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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 deposited by APCVD 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 ellipsometer measurements, wherever as structural depth profiles are studied using x-ray diffraction. 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 \( \times 1021 \) 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. Observed electrical properties correspond well to the columnar trapezoidal grain growth model with the grain growing from the substrate towards the films surface as confirmed by cross-section TEM and x-ray diffraction measurements. 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.

7939-12, Session 13

An efficiency droop model of the saturated radiative recombination rate and its verification by radiative and nonradiative carrier lifetime measurements in InGaN-based light emitting diodes

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InGaN-based light-emitting diodes (LEDs) for the blue-green wavelength range are known to suffer from the reduction of the internal quantum efficiency (IQE) at high injection current, the so-called “efficiency droop”. Various carrier loss mechanisms for the efficiency droop have been proposed such as electron overflow assisted by the piezoelectric field, Auger recombination, and carrier delocalization. However, each model is not sufficient to explain observed experimental results all together.

We have proposed a model which can comprehensively explain experimental IQE droop phenomena occurring at different temperatures, materials, and quantum well (QW) structures. In our model, carriers are located and recombined both radiatively and nonradiatively inside randomly distributed In-rich areas of InGaN-based QWs and the IQE droop originates from the saturated radiative recombination rate and the monotonically increasing nonradiative recombination rate there. Due to small effective active volume and small density of states of In-rich areas, carrier density is rapidly increased even at small current density and the radiative recombination rate is easily saturated by different distributions of electrons and holes in the momentum k-space.

A measurement method that can separately estimate the radiative and nonradiative carrier lifetimes just at room temperature is theoretically developed by analyzing the time-resolved photoluminescence (TRPL) response based on the carrier rate equation. The method is applied to a blue InGaN/GaN QW grown on a sapphire substrate. The experimental results show that the radiative carrier lifetime increases and the nonradiative carrier lifetime saturates with increasing TRPL laser power, which is one of direct evidences validating our IQE droop model.

7939-13, Session 13

Investigating the cause of droop in InGaN quantum well LEDs using a temperature and pressure dependent analysis

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InGaN/GaN based LEDs and lasers are of considerable importance in terms of developing energy efficient solid-state lighting, full colour displays and projection systems. Despite recent advances in achieving higher overall light output, devices based upon this material suffer from “efficiency droop”, an effect where the efficiency peaks at a low current and decreases with further injection. The droop issue is particularly problematic for green LEDs. Possible explanations for efficiency droop include Auger recombination, carrier leakage from the quantum well and recombination through defects. Intra-band Auger recombination in large band gap semiconductors is unexpected, however recent theoretical work by Delaney et al predicts an inter-conduction band Auger recombination resonance at 2.5eV in InGaN [1].

In this study, InGaN quantum well LED devices with ambient band gap energies either side of the suggested resonance are investigated using temperature and high pressure techniques. The application of pressure causes a reversible change in band gap with little influence on other parameters, such as internal electric fields, which vary with composition. It is therefore a useful means of probing intrinsic band gap dependent properties of the InGaN LEDs. Preliminary results show efficiency decreases with increasing band gap for devices below the suggested resonance energy, but increases with increasing band gap for devices with a band gap above the resonance. Such behaviour,
shown experimentally for the first time, is consistent with an Auger recombination resonance. The relative likelihood of such Auger processes and/or carrier leakage occurring in InGaN LEDs will be discussed further at the conference.


7939-14, Session 14

Modeling of III-nitride LEDs: progress, problems, and perspectives

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Recent progress in modeling III-nitride light-emitting diodes (LEDs) is reviewed. The challenges originated from multi-scale geometry of state-of-the-art LEDs and coupling between the electrical, thermal, and optical processes involved are discussed. Different approaches to simulation of LED operation, from heterostructure to LED lamp, are considered, including the hybrid approach based on coupled solution of relevant subproblems with optimal dimensionality and numerical algorithms.

Theoretical contribution to understanding of such issues as the efficiency droop, electron leakage from the active region, current crowding, light extraction and conversion, and thermal management is discussed in terms of modeling. Effectiveness of using simulations to invoke or rule out physical mechanisms suspected for limiting the LED efficiency is demonstrated. Examples of successful applications of simulations to improve the LED performance are given and confirmed by comparison of the theoretical predictions with available experimental data.

Still lacking but vital physical models to be developed in future are considered, like those intended for excessive conductivity of LED structures, Auger recombination in III-nitride semiconductors, localized states produced by compositional fluctuations in ternary and quaternary alloys, etc. Possible coupling between the device simulation and modeling of heterostructure epitaxial growth is discussed as well.

7939-15, Session 14

Enhancing the external quantum efficiency in GaN based LEDs

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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.

Here, we demonstrate that the combined use of highly reflective p-contact and nanotexturing of n-face n-GaN with photonic crystal and photochemical etching significantly improved the LEE of vertical LEDs (V-LEDs). Our experimental results that the enhancement of light output power by the nanotexturing is remarkably influenced by reflectance of the p-contact suggests that not only enhancing light extraction at the air/n-GaN interface but also improving light reflection at the metal/p-GaN one is of vital importance for improving the light extraction efficiency. We also present the enhanced light extraction by forming a MgO nano-pyramids and ZnO refractive-index modulation layer on the surface of V-LEDs. The MgO nano-pyramids and ZnO layer enhanced the LEE of V-LEDs with by 49 %, comparing with the V-LEDs with a flat n-GaN surface.

Finally, we present a method of increasing light output power and suppressing efficiency droop in V-LEDs without modifying the epitaxial layers. These improvements are achieved by reducing the quantum-confined Stark effect by reducing piezoelectric polarization that results from compressive stress in the GaN epilayer. This compressive stress is relaxed due to the external stress induced by an electro-plated Ni metal substrate. In simulations, the severe band bending in the InGaN quantum well is reduced and subsequently IQE increases as the piezoelectric polarization is reduced.

7939-94, Session 14

Vertical composition variation in nominally uniform InGaN layers revealed by aberration-corrected STEM imaging

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We have found composition variations along the growth direction in MOCVD InGaN LED structures within regions of nominally constant In composition using atomic resolution Z-contrast imaging in a scanning transmission electron microscope. Within nominally In0.01Ga0.99N layers, we find periodic enhancements in the In concentration into bands ~4 wide, separated by 11 nm. Active layers with high In composition (In 0.06 to 0.20) show a thin additional band of higher In concentration above the active region. In contrast to the popularly held view, there is no evidence of lateral composition fluctuations in any layer.

7939-18, Session 15

Optical polarization characteristics of near and deep ultraviolet light emitting diodes

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We have investigated the polarization dependent in-plane emission characteristics of (In)AlGaN multiple quantum well (MQW) light-emitting-diodes (LEDs). LEDs with InGaN, InAlGaN, and AlGaN MQW active regions emitting in the UV-A and UV-B spectral range have been compared. The LED heterostructures were grown by metalorganic vapor phase epitaxy on (0001) c-plane sapphire substrates. Details on the LED heterostructures and the growth process can be found in [1-3]. The electrical and optical characteristics of the LEDs were measured on-wafer under cw operating conditions. Electroluminescence measurements show a decrease of the emission intensity for transverse-electric-field (TE) polarized light (E perpendicular to c) relative to the transversal-magnetic (TM) polarization (E parallel to c) with decreasing emission wavelength. For example, the TE to TM polarization ratio of the in-plane emitted light decreases from 3.4 for 380 nm LEDs to 0.7 for 288 nm LEDs. This behavior can be explained by the different band structures of GaN and AlN. The increasing aluminum content of the LEDs results in a change of the crystal-field splitting and thus the arrangement of the valence-bands at the gamma-point of the Brillouin zone. With shorter wavelength the split-off hole band moves closer to the conduction-band and as a consequence the TM polarized emission becomes more dominant [4].

REFERENCES:

Fabrication of photonic crystal patterns with various refractive-indexed materials on GaN-based light-emitting diodes to improve light extraction efficiency

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Recently, GaN-based light emitting diodes (LEDs) have been noticed as a future illumination due to their low power consumption, eco-friendly and long life time. However, their external quantum efficiency should be elevated in order to realize solid state lighting. Low light extraction efficiency of LEDs is a main cause which degrades external quantum efficiency. Most of the light generated from InGaN/GaN multi quantum well is trapped inside a LED device by total internal reflection at the interface between GaN and air and is converted to heat.

To enhance the light extraction efficiency of LEDs, photonic crystal structures have been researched. However, plasma etching process is required to fabricate the photonic crystals and it generates plasma damages in the GaN epitaxial layer. Plasma damage makes defect levels such as carrier trapping center in the GaN lattice and degrades the electrical property of LED devices.

In this study, photonic crystal patterns with various refractive-indexed materials were formed on the ITO top electrode of GaN-based LEDs without plasma etching. TiO₂ and ITO-based photonic crystal patterns were formed on the ITO electrode by lift-off process after zero residual UV nanoimprint. And ZnO and SnO₂-based photonic crystal patterns were directly fabricated on the ITO electrode of a LED structure by sol-gel imprinting process. As a result, the LED device with photonic crystal patterns showed enhanced light output power without electrical degradation. And finite-difference time-domain (FDTD) simulation will be discussed for analyzing photonic crystal patterns with different refractive index on light extraction effect of a LED.
7940-01, Session

**ZnO technical challenges and market opportunities**

F. H. Teherani, D. J. Rogers, Nanovation (France)

No abstract available

7940-02, Session 1

**Pursuit of ultrahigh conductivity in ZnO**

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Significant improvement in Ga-doped ZnO deposited by pulsed laser deposition can be obtained by growing in pure Ar rather than the usual O2 [1]. Growth on Al2O3 at 200°C in 10-mTorr of Ar produces a 300-K bulk resistivity $\rho = 1.8 \times 10^{-4}$ ohm-cm, carrier concentration $n = 1.2 \times 10^{21}$ cm$^{-3}$, mobility $\mu = 29$ cm$^2$/V-s, and optical transmittance about 90% in the visible and near-IR spectral regions. A theoretical analysis of $n$ and $\mu$ shows that the major reason for this outstanding performance is a very high value of donor concentration, $ND = 2.3 \times 10^{21}$ cm$^{-3}$, which can be explained by an efficient transfer of Ga from the ZnO:3wt%Ga2O3 target. However, the acceptor concentration is also high, $NA = 1.1 \times 10^{21}$ cm$^{-3}$, and much better performance would result if the condition $NA/ND < 1$ could be achieved. In that case, theory predicts values of $\mu = 71$ cm$^2$/V-s and $\rho = 7.3 \times 10^{-5}$ ohm-cm, for the same $n = 1.2 \times 10^{21}$ cm$^{-3}$. The only impurity with a concentration in the 1021-cm$^{-3}$ range is Ga, and the only defect that might contribute at this level would be the Zn vacancy, V$_{\text{Zn}}$. Therefore, the major donor is likely Ga$_{\text{Zn}}$, and the major acceptors, V$_{\text{Zn}}$ and Ga$_{\text{Zn-V}}$. Other measurements will be performed to confirm these hypotheses. Attempts to reduce the active acceptor concentration by annealing in forming gas appear to be promising.


7940-03, Session 1

**Deep level luminescence in lithium doped ZnO**

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Deep level luminescence in Li doped ZnO has been studied using temperature, depth and power-density resolved cathodoluminescence (CL) spectroscopy and microscopy. Li doping was attained by evaporating 50 nm of Li metal at ~ 1 mPa onto the top surface of 1 mm thick, 5 x 5 mm a-plane polished on both sides ZnO sections (hydrothermally grown by the MTI Corporation) and then heating to 950°C for 30 min without breaking vacuum. The as-received crystals exhibited two broad defect CL bands at 80K centred at 2.10 eV (yellow, YL, FWHM = 0.60 eV) and 2.40 eV (green, GL, FWHM = 0.35 eV) as well as a near band edge emission at 3.25 eV. Heating from 80 to 300K, the GL red shifted to 2.0 eV (orange, OL) at 140K and then blue shifted to GL again with further heating to 300K. This behavior can be explained by thermalization of shallow donors in donor-acceptor pair (DAP) centers and indicates that the GL is due to different defect centers. Li doping produced an strong CL peak that significantly increased in intensity and red shifted from 2.10 eV (YL) to 2.04 eV (OL) from 300K to 80K consistent with a DAP transition involving a Li acceptor on a Zn site. A weak red luminescence (RL) centered at 1.70 eV (FWHM = 0.15 eV) was also observed in these specimens. A significant decrease in CL was found on the uncoated ZnO side compared with a undoped control sample suggesting that interstitial Li acts as a non-radiative center in ZnO.

7940-04, Session 1

**ZnO: from single crystals to 1D nanostructures - excitons, strain fields, and recombination dynamics**

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We study the excitation, luminescence and recombination dynamics of exciton-polaritons, localized impurity and defect related excitons and phonons as function of external pressure and magnetic fields. Hydrostatic pressure Raman experiments are used to investigate the relationship between bonding and lattice-dynamical properties and the scaling of bond ionicity and phonon effective charges. For the shallow bound excitons, a clear dependence of the individual exciton pressure coefficients on the localization energy is found which allows an estimation of donor binding energies independent of the ob-servation of two electron satellites (Haynes Rule). Furthermore, several excitonic transi-tions are observed which do not obey this relation but can be described by a model for defect bound exciton states.

The second part of the contribution focuses on the promising class of ZnO nanowires with potential applications as biocompatible sensors and polariton lasers. The large surface to volume ratio and the confined dimensions of the nanowires alter the electronic structure and recombination dynamics as demonstrated by finite-size effects influencing the lifetimes of free and localized exciton states. With decreasing diameter, shorter life-times of bound excitons are observed. Since the nanowires act as cavities, the lifetimes of the localized states are determined by the polariton modes which are strongly influenced by the size and shape of the wires. Different growth catalysts further demonstrate that the formation of structural defects strongly depends on each particular precursor. Finally, an outlook including latest results on functionalization and dynamics of single ZnO nano-wires will be provided.

7940-05, Session 2

**Photoluminescence and Hall study for the production and recovery of defects in phosphorus implanted ZnO films**

S. Nagar, A. Mandal, S. Chakrabarti, Indian Institute of Technology, Bombay (India); S. K. Gupta, Bhabha Atomic Research Ctr. (India)

ZnO (002) films of thickness 0.5 µm were deposited on c-plane sapphire substrates by PLD at 400°C in an oxygen ambient of 75 mTorr and implanted with 8x10$^{18}$ cm$^{-2}$ dose of phosphorous ions of energy 50 keV (Sample A) followed by Rapid Thermal Annealing at 750°C for 30 seconds in both Ar (Sample B) and oxygen atmospheres (Sample C). AFM images depicted root-mean-square roughness for Sample A (10.072 nm), B (9.314 nm) and C (4.9 nm). Room-temperature Hall study revealed n-type conductivity with carrier concentrations of 9.69x10$^{19}$ cm$^{-3}$, 1.36x10$^{20}$ cm$^{-3}$, 4x10$^{18}$ cm$^{-3}$ and Hall mobility of 0.727 cm$^2$/V-s, 12.44 cm$^2$/V-s,

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54.3 cm$^2$V$^{-1}$s for Sample A, B and C respectively. Possible reasons might be the formation of vacancy clusters by implantation for Sample A, eradication of oxygen vacancies with agglomeration of vacancy clusters and without further aggregation of vacancy clusters with higher annealing temperature for Sample B and C respectively. Dominance of donor-bound exciton (D$^0$X) peaks were found to be at 3.295 eV, 3.284 eV, 3.281 eV and 3.272 eV for unimplanted sample, Sample A, B and C respectively from room-temperature photoluminescence study. Donor-to-acceptor pair (DAP) transition peak for Sample A (3.031 eV) was absent in Sample B and C due to probable decrease of oxygen vacancies. Free electron-acceptor (FA) recombination emissions were similar for Sample A and C (3.218 eV) but decreased for B (3.199 eV), supportive to lower donor concentration in Sample C compared to B. DST, India is acknowledged.

7940-06, Session 2
Exploring polymorphism in ZnO: a prospective route to new properties and applications
S. T. Bromley, Univ. de Barcelona (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain); D. Stradi, F. Illas, Univ. de Barcelona (Spain)

A possible alternative strategy to control optical/electronic properties of ZnO is not to induce modifications to the standard wurtzite crystal structure, but to attempt to change its polymorphic form. ZnO can exist in the zincblende structure, undergoes a transition to the rocksalt phase at ~9GPa and has been prepared as the h-BN structure in thin films. Recently we have predicted that the polymorphism is ZnO is likely to be much more wide-ranging [1], potentially allowing one to choose the properties of interest by changes in the crystal structure. Of all the new stable low density ZnO polymorphs, we predict one nanoporous structure, analogous to the silicate zeolite sodalite (SOD-ZnO) [2], to be particularly thermodynamically stable under appropriate conditions [3]. Via accurate electronic structure calculations we show that such low-density nanoporous ZnO polymorphs have surprising new properties suitable for extending the range of current ZnO applications. We specifically highlight the relative ease with which nanoporous ZnO polymorphs may be p-doped (extremely difficult in wurtzite ZnO), and their prospective role in hydrogen purification applications due to a novel multi-centre bond assisted transport mechanism [3].


7940-07, Session 2
Nitrogen incorporation in ZnO thin films grown by chemical vapor deposition (CVD)
B. K. Meyer, S. Lautenschläger, S. Eisermann, A. Lauber, Justus-Liebig-Univ. Giessen (Germany); M. Pinnisch, M. Hofmann, Justus-Liebig-Univ. Magdeburg (Germany)

Bipolar conduction of electron and holes is mandatory for many electronic and opto-electronic applications of ZnO and its ternary alloys. Among the impurity atoms suited for acceptor formation nitrogen is the prime candidate. Controlling the Nitrogen incorporation without the formation of deep dopants and acceptors and avoiding the deterioration of the materials quality is a major goal. The incorporation of nitrogen using ammonia as a precursor was investigated as a function of the substrate temperature as well as surface polarity in homo-epitaxially grown ZnO films prepared by chemical vapour deposition. Over a wide range of nitrogen concentrations (quantified by secondary ion mass spectrometry) we can control the optical and electrical properties of the ZnO films.

7940-08, Session 3
Zinc oxide nanostructures with metal particles based on surface plasmons for optoelectronic device applications
J. S. Yu, Y. H. Ko, H. K. Lee, J. W. Leem, Kyung Hee Univ. (Korea, Republic of)

There have been intensive research efforts to achieve high efficiencies in photodetectors and solar cells. Au or Ag nanoparticles and nanostructures have great potential to enhance the light absorption and trapping due to the (localized) surface plasmon resonance (SPR). The Au nanoparticles deposited on conventional TiO2 films also served as a Schottky barrier which blocks the escape of electrons transferred from the nanoparticles to the TiO2 conduction band in solar cells for higher device performance. Recently, zinc oxide (ZnO) nanostructures are attracting much interest instead of TiO2 in the field of solar cells due to the wide band gap energy, high electron mobility, direct charge transport path way, and large surface area. However, it is still a challenge to obtain high absorption over a broad wavelength range.

In this work, we present the ZnO nanostructure with Au (or Ag) particles based on surface plasmons for applications in optoelectronic devices such as solar cells, light emitting diodes, and biosensors. The optical properties of ZnO nanorods and nanotips, which are fabricated on aluminum-doped ZnO/glass and fluorine-doped SnO2/glass by hydrothermal growth, coated with evaporated Au (or Ag) are investigated over a wide wavelength region for high solar efficiency. The structural properties of ZnO nanostructures were analyzed from X-ray diffraction and SEM/TEM measurements. The optical properties were measured by using UV-Vis-NIR spectrophotometer. The detection enhancement in surface reactions such as self-assembled monolayer formation is also explored using a highly sensitive SPR substrate incorporating ZnO nanorod arrays.

7940-09, Session 3
Intrinsic white light emission from zinc oxide nanorods heterojunctions on large area substrates
M. Willander, Linköping Univ. (Sweden)

ZnO is being intensively investigated for the possibility of developing new photonic devices. We will here present our recent findings on the controlled low temperature chemical growth of ZnO nanorods (NRs) on different large area substrates. Many different heterojunctions of ZnO NRs and p-substrates including those of crystalline e.g. p-GaN or amorphous nature e.g. p-polymer coated plastic and p-polymer coated paper will be shown. Moreover, the effect of the p-electrode of these heterojunctions on tuning the emitted wavelength and changing the light quality will be discussed. An example using ZnO NR/p-GaN will be shown and the electrical and electro-optical characteristics will be analyzed. For these heterojunctions the effect of post growth annealing and its effect on the electroluminescence spectrum will be shown. Finally, intrinsic white light emitting diodes based on ZnO NRs on foldable and disposable amorphous substrates (plastic and paper) will also be presented.

7940-10, Session 3
ZnO nanorods for light emitting diode applications
A. B. Djurisic, A. M. C. Ng, X. Chen, F. Fang, W. K. Chan, The Univ. of Hong Kong (Hong Kong, China)

One of the potential advantages of ZnO is the possibility of growth of nanostructures by a number of different techniques (including low temperature, low cost methods) and in a variety of morphologies.
However, ZnO has a very complex defect chemistry which has a significant effect on the optical and electronic properties of ZnO nanostructures. Therefore, different growth methods, growth conditions and post-growth treatments result in variations in the properties of nanostructures and differences in the performances of devices based on ZnO nanostructures, such as light emitting diodes (LEDs). We have investigated the influence of the growth method, growth conditions, and post-growth treatments on the ZnO nanorod properties and the performance of heterojunction LEDs based on ZnO nanorods. While a variety of p-type materials can be used for ZnO-based heterojunction LEDs, due to relatively small lattice mismatch and the availability of mature technologies for obtaining p-type films GaN represents a convenient material choice. Therefore, we will focus on the p-GaN/n-ZnO heterojunction LEDs and discuss the influence of the properties of both GaN and ZnO on the device performance. The influence of p-GaN substrate and the influence of growth method, post-growth annealing, seed layer, and precursor used for ZnO nanorods on the LED performance will be discussed in detail. The obtained results indicate that the device performance is strongly affected by the native defects, and the control over the native defects is essential for optimizing the device performance.

7940-12, Session 3

Synthesis and characterization of layer structured ZnO nanowire for ultraviolet light emitting diode


We have been succeeded in growing vertically aligned ZnO nanowires by a newly developed nanoparticle-assisted pulsed-laser deposition (NAPLD) without any catalyst. In this study, layer structured ZnO nanowires, such as film-wire layered structure and core/shell structure, were synthesized using multi-target changer system. In this presentation, characteristics of the layer structured ZnO nanowires and application to UV light emitting diode will be discussed.

7940-14, Session 3

Strong blue emission of ZnO colloids dispersed in hexane

J. R. Oliva-Uc, E. De La Rosa, Ctr. de Investigaciones en Óptica, A.C. (Mexico); P. Salas, Univ. Nacional Autónoma de México (Mexico); A. Torres, Univ. Autónoma de Nuevo Leon (Mexico)

This work reports the morphological and luminescent properties of ZnO colloids synthesized with a simple wet chemical method. The introduction of a surfactant during synthesis not only changes the morphology of nanoparticles but also it capped such colloids, providing excellent stability when they are dispersed in hexane because precipitation has not been observed during months. TEM images showed spherical nanoparticles with sizes ranging from 3-5 nm for concentrations from 0 to 0.7 ml. of surfactant, and nanorods with average length of 4.2 nm from a concentration of 1.1 ml. of surfactant. In addition, calculations of energy band gap (EG) from absorption spectra suggest that the values of EG for the nanoparticles with the same morphology increases as the nanoparticle size decreases. In fact, nanorods presented higher values of EG than spheres since the confinement effects in those nanoparticles are stronger. Furthermore, our experimental results indicate that the strong blue emission at 429 nm obtained when ZnO colloids are dispersed in hexane, increases as the content of surfactant augments. According to FTIR spectra, this increase in the luminescence of ZnO with surfactant is associated to a decrease of OH impurities on the surface of nanoparticles. Also, the blue emission is caused by surface defects which are independent of surfactant, since the blue emission was observed without the use of surfactant, which is opposite to reported by other authors. Finally, it was obtained a quantum yield (QY) of 81% by taking as reference the commercial quinine sulfate and under 350 nm excitation, suggesting that ZnO colloids could be used to fabricate efficient electroluminescent devices for solid state lighting applications.
Use of PLD-grown ZnO thin films and nanostructures on SiO2/Si substrates as templates for MOVPE growth of GaN

D. J. Rogers, V. E. Sandana, F. H. Teherani, Nanovation (France); S. Gautier, Supélec (France) and Univ. de Metz (France); T. Moudakir, Supélec (France); G. Orsal, Supélec (France) and Univ. de Metz (France); M. Molinari, M. Troyon, Univ. de Reims Champagne-Ardenne (France); M. Peres, M. J. Soares, A. J. Neves, T. Monteiro, Univ. de Aveiro (Portugal); D. McGrath, J. N. Chapman, Univ. of Glasgow (United Kingdom); M. Razeghi, Northwestern Univ. (United States); H. M. Drouhin, Ecole Polytechnique (France); A. Ougazzaden, Georgia Institute of Technology (France)

Since ZnO nanostructures and thin films can be grown much more readily than InGaN on a whole range of amorphous and highly mismatched substrates, a template approach could open the way to the growth of GaN based devices and nanostructures on technologically important substrates which have been inaccessible till present.

ZnO was grown on Si (111) substrates by pulsed laser deposition. Depending on the growth conditions, either thin films or self-forming, vertically-aligned nanostructure arrays could be obtained. In view of these interesting properties, it was decided to investigate whether such ZnO/SiO2/Si layers and nanostructures could be used as templates for the overgrowth of InGaN. InGaN was grown on the ZnO/SiO2/Si using metal organic vapor phase epitaxy (MOVPE). The dissociation of ZnO observed during conventional MOVPE growth of InGaN has now been combated through the use of a low pressure/temperature approach.

A density functional theory study on the electronic and magnetic properties of (Mn,N)-codoped ZnO

L. Zhao, P. Lu, Z. Yu, H. Ye, Y. Shen, X. Guo, G. Yuan, Beijing Univ. of Posts and Telecommunications (China)

A first-principles study has been performed to evaluate the electronic and magnetic properties of the Zn1-xMnxO1-yNy system. Doping Mn atoms introduces local magnetic moments, while doping N atoms introduces carriers. It is worth noting that intrinsic Mn-doped ZnO favors antiferromagnetic (AFM) ordering, and this cannot be changed by raising Mn ions concentration continuously. However, by the doping of N and Mn, it is possible to change the ground state from no-metallic AFM to half-metallic ferromagnetic (FM) and make ZnO as a dilute magnetic semiconductor. We have succeeded in describing the change (from AFM to FM) by using the magnetic interaction that is hole-mediated FM semiconductor. We have succeeded in describing the change (from AFM to FM) by using the magnetic interaction that is hole-mediated FM semiconductor.

Using conventional MOVPE growth of InGaN/GaN was combated during the use of a low pressure/temperature approach.

Role of Yb3+ ions in the IR to visible upconversion of Er3+ ions in LTT glasses

M. B. A. S. K. Jakka, Sri Venkateswara Univ. (India); B. Jamalaiah, Pukyong National Univ. (Korea, Republic of); N. K. Giri, S. Rai, Banaras Hindu Univ. (India); R. M. Lalapenta, Sri Venkateswara Univ. (India)

In order to develop efficient upconversion lasers and optical fiber amplifiers, the detailed spectroscopic and upconversion properties of singly doped Er3+ and co-doped Er3+/Yb3+ ions in lead tungsten tellurite (LTT) glasses have been investigated. The glasses were prepared by conventional melt quenching technique. Absorption, upconversion and NIR emission spectra were recorded as a function of Yb3+ ion concentration. Judd-Ofelt (J-O) analysis has been performed for the absorption spectral intensities of Er3+ and Er3+/Yb3+ absorption bands. Spontaneous emission probabilities (AR) and branching ratios were calculated by using the phenomenological J-O intensity parameters. Under 976 nm excitation, three strong up-conversion emission bands centered at 525, 546 and 656 nm were observed due to the energy transfer process from 2F5/2 level of Yb3+ to 4I11/2 level of Er3+ ions. The green emissions centered at 527 and 546 nm are due to 2H11/2/4I15/2 and 4S3/2/4I15/2 transitions and the red emission at 656 nm is attributed to 4F11/2/4I15/2 transition of Er3+ ions respectively. The relative variations in the intensities of 2H11/2/4I15/2 and 4F11/2/4I15/2 transitions are explained on the basis of variation in radiative transition probabilities (AR) values obtained from J-O theory. The radiative branching ratios (R) and the peak emission cross section (e) of 2H11/2/4I15/2 transition of Er3+ ions in different glass hosts were compared. The results of these investigations reveal that the lead tungsten tellurite (LTT) glasses could be used as promising host materials for the design and development of optical fiber amplifiers and upconversion lasers.

Electro-optical properties of hybrid metal oxide complexes

D. M. Steeves, U.S. Army Natick Soldier Research, Development and Engineering Ctr. (United States); J. Im, J. Singh, J. E. Whitten, Univ. of Massachusetts Lowell (United States); J. W. Soares, U.S. Army Natick Soldier Research, Development and Engineering Ctr. (United States)

Metal oxide nanostructures are being explored in many important applications ranging from catalysis to optoelectronics. Inorganic-inorganic hybrid devices, it is often desirable to covalently attach organic molecules to metal oxide surfaces such that electrons and holes may be transported across the inorganic-organic interface. Zinc oxide (ZnO) is a promising semiconductor material for future hybrid devices; however, inadequate electron transport efficiencies are currently limiting its use. Here, we present the creation of supramolecular inorganic-organic complexes on the surface of zinc oxide via thiol linkages, to overcome current limitations. One such hybrid, formed from nano-ZnO and a thiol-terminated ruthenium-based dye, was created and the electronic structure was characterized using ultraviolet photoelectron spectroscopy. Measurements of the electro-optical properties of the complex were also conducted. Another hybrid system, ZnO nanorods tethered to gold nanoparticles (AuNPs) via dithiol linkers, has been investigated toward the goal of changing the photoluminescence (PL) spectrum of the nano-ZnO. X-ray photoelectron spectroscopy and electron microscopy confirm attachment of gold nanoparticles to the nanorod surface. Photoluminescence studies of the ZnO/dithiol/AuNP assemblies indicate that the PL spectrum can be influenced by varying the chain length of the dithiol and the ZnO/AuNP ratio. Lastly, a novel thiol encapsulation methodology for ZnO and other nano-metal oxides and its impact on future hybrid inorganic-organic devices will be discussed.
Studies of PLD-made thin ZnO layers by x-ray scattering methods: beyond the restrictive (00.2)rocking curve linewidth as a figure-of-merit

O. Durand, A. Letoublon, Univ. Européenne de Bretagne (France); D. J. Rogers, F. H. Teherani, Nanovation (France)

X-ray scattering methods were applied to the study of thin mosaic ZnO layers deposited by Pulsed Laser Deposition on c-Al2O3 substrates. High Resolution (HR) studies revealed two components in the scans (transverse scans) which were not resolved in conventional “open-detector” rocking curves: a narrow, resolution-limited, peak, characteristic of long-range correlation, and a broad peak, due to defect-related diffuse-scattering giving a limited transverse structural correlation length. Thus, for such mosaic films, the conventional rocking curve Full Width at Half Maximum linewidth was found to be inadapted as an overall figure-of-merit for the structural quality, in that the different contributions were not meaningfully represented. A "Williamson-Hall like" integral breadth (IB) metric for the HR (00.1) transverse-scans was developed as a reliable, fast, accurate and robust alternative to the rocking curve linewidth for routine non-destructive testing of such mosaic thin films. For a typical ZnO/c-Al2O3 film, the IB method gave a limited structural correlation length of 93.3 nm ± 6.6 nm. It was deduced from the presence of satellite peaks in transverse scans for films of various thicknesses that this finite lateral correlation length probably arises from misfit dislocations which exhibit some periodic ordering to accommodate the lattice-mismatch at the film-substrate interface.

Electroluminescence studies on n-type wide-band-gap oxides/n++-Si isotype heterojunction

J. Zhao, Tianjin Univ. (China) and Nanyang Technological Univ. (Singapore)

Wide-band-gap oxide semiconductors (ZnO, SnO2, Ga2O3, etc.) have been emerging as the potential substitute for the nitrides for the light emitting diode (LED) applications. The main advantage of oxides is the abundance of the source materials, which results in the lower cost LEDs. However, the p-type bottleneck has hindered the progress of practical oxide based LEDs. As a result, a lot of efforts have been devoted to hybrid heterojunction LEDs by growing the n-type oxide films on a variety of p-type substrates and epilayers. In our study, we developed n-ZnO/ n++-Si based isotype heterojunction LED by metal-organic chemical vapor deposition (MOCVD). It is found that the electroluminescence (EL) performance of n-ZnO/n++-Si isotype heterojunction is better than the EL of n-ZnO/p++-Si device. Near-band-edge UV emission can be realized in the n-ZnO/n++-Si LED while the device on p++-Si did not show significant UV emission peak. The EL mechanism can be understood from the interface band diagram analysis. The valence band of n++-Si can be closer to the valence band of ZnO, which facilitates the hole injection from Si into ZnO. Based on this mechanism, we further developed n-SnO2/n++-Si and n-Ga2O3/n++-Si isotype heterojunction LEDs, which also shows better EL performance than the oxide/p++-Si heterojunction devices. Our developed wide-band-gap oxides based n-n isotype heterojunction is promising for low cost Si-integrated photonic applications.

Electronic structure, doping, and lattice dynamics of LiGaO2 - an alternative to Zn(1-x)Mg(x)O alloys: first-principles computational predictions

W. R. L. Lambrecht, A. Boonchun, Case Western Reserve Univ. (United States)

LiGaO2 is a material with a crystal structure closely related to wurtzite ZnO, obtained by replacing the group Zn by Li and Ga atoms in an ordered manner. While recently mainly viewed as a potential substrate for GaN or ZnO growth, we here point out its possible advantages as an active opto-electronic material. FP-LMTO quasiparticle self-consistent GW calculations were carried out obtaining a band gap of 6.2 eV, consistent with experimental reports of transparency up to 5.7 eV at room temperature. We determined its lattice dynamical properties, including the lattice structural parameters, the vibrational modes at the Brillouin zone center and the corresponding infrared spectra, the elastic constant, piezo-electric tensor, and dielectric tensors[1] using density functional perturbation theory with the ABINIT pseudo-potential plane wave implementation. We find overall good agreement with experimental data reported in the literature and compare the same properties with those in ZnO and GaN. We point out the possible advantages of this type of ternary semiconductors over conventional isovalent cation alloys, such as Zn(1-x)Mg(x)O because of the opportunity of doping on two different cation sites of different valency. P-type doping could be realized by Zn_Ga substitution, under Li-rich, Ga-poor conditions, which favors additional native defect acceptors Li_Ga and V_Ga rather than compensating donors. The possibility of magnetism for Zn_Ga is discussed. We also discuss the opportunities of this material as n-type transparent conducting oxide by Ge_Ga, Mg_li and Zn_Li doping.

strong dynamic annealing during implantation keeping damage levels low. ZnO was found to be more radiation resistant than GaN and also post-implant annealing is more efficient. The implantation technique was applied to dope both materials with optically active rare earth (RE) ions. Despite the better radiation properties of ZnO, optical activation of RE could not be achieved due to a low solubility limit and out-diffusion of the RE. GaN:RE, on the other hand, shows bright RE emission in the three primary colors.

The radiation response of the two materials was further investigated using neutron irradiation which produces similar damage as ion implantation but within the whole semiconductor film due to the large penetration depth of the neutrons.

7940-25, Session 6

Away from silicon era: the paper electronics
R. Martins, E. Fortunato, Univ. Nova de Lisboa (Portugal)

No abstract available

7940-26, Session 6

Emergence of new phases on oxide surfaces by electric-field charge accumulation
K. Ueno, Tohoku Univ. (Japan)

No abstract available

7940-27, Session 7

Band gaps and electronic structure of alkaline-earth and post-transition-metal oxides
J. McLeod, R. G. Wilks, A. Moewes, Univ. of Saskatchewan (Canada); N. A. Skorikov, L. D. Finkelstein, E. Z. Kurmaev, Institute of Metal Physics (Russian Federation); M. Abu-Samak, Al-Hussein Bin Talal Univ. (Jordan)

We have investigated the electronic structure in bulk alkaline earth AeO (Ae = Be, Mg, Ca, Sr, Ba) and post-transition metal oxides MeO (Me = Zn, Cd, Hg). These materials have been probed with oxygen K-edge X-ray absorption and emission spectroscopy, and our experimental data is compared with density functional theory electronic structure calculations. We use our experimental spectra of the oxygen K-edge to estimate the band gaps of these materials, and compare our results to the range of values available in the literature. From the calculated partial DOS we conclude that the position of main O K-edge X-ray emission feature in BeO, SrO and BaO is defined by the position of the np-states of the cation while in the other oxides studied here the main O K-edge X-ray emission feature is defined by the position of the (n-1)d (for CaO, SrO, and BaO) or nd-states of the cation.

7940-28, Session 7

Optical and electrical properties of deep-UV ZnMgAlO thin films grown by RF magnetron sputtering
J. H. Park, J. B. Lim, B. Lee, Chonnam National Univ. (Korea, Republic of)

Recent research on optical-devices is moving toward deep UV region, which has many important applications such as energy-saving illumination, light sources for high density optical recording, biological agent detection, and sterilization. Recently, ZnMgAlO films lattice matched to ZnO have been reported, with large band-gap energy (~4.1eV). It was proposed that the ZnMgAlO film would be a potential material for optoelectronic devices such as LED’s and TCO’s, operating at the deep UV range. In this work, optical and electrical properties of the ZnMgAlO films and effects of process variables and doping concentration are studied.

The ZnMgAlO/Al2O3 films are grown by the magnetron sputtering, and characterized by the UV-Vis spectroscopy, the X-ray diffraction (XRD), the four-point probe, cathodoluminescence, and the thermal luminescence technique. Initial results indicate that the transmission of the ZnMgAlO films is ~85% in ~300–800nm range. The band gap energy is 4.1 eV for the Zn0.78Mg0.16Al0.06O films, and the films are lattice matched to the ZnO; the (0002) and (0004) peaks of the XRD spectra appear at the same position, 34.42 and 72.56. Resistivity of the ZnMgAlO films is measured to be 7–105 Ωcm, depending upon various growth conditions. Further studies are in progress to understand defect chemistry of the films and to improve the optical/electrical properties by controlling the growth environment as well as the doping conditions, whose results will be discussed during the presentation.


7940-29, Session 7

Probing complex oxide interfaces
T. Chien, Argonne National Lab. (United States); J. Liu, J. Chakhalian, Univ. of Arkansas (United States); N. P. Guisinger, J. W. Freeland, Argonne National Lab. (United States)

Recently, interfaces between novel oxide materials have become a playground for manipulation of new functionalities. At interfaces, the broken symmetry and modified local interactions have been shown to generate wholly new electronic phases (e.g. magnetism, metallicity, superconductivity etc.) distinct from the composite bulk materials. However, to date our understanding of these interface driven phases is still limited. While there exist powerful spatially resolved tools for visualizing the chemical and magnetic structure of an interface, a direct observation of electronic behavior across the interface presents a major experimental challenge.

After the success of creating flat fractured surfaces on Nb-doped SrTiO3 (Nb:STO) accessible to scanning tunneling microscopy (STM)[1-3], we further harness the high-sensitivity to electronic local density of states (LDOS) of the scanning tunneling spectroscopy (STS) in cross-sectional geometry to visualize complex oxide interface electronic properties. By extending XSTM to the interface between colossal magnetoresistive manganite La2/3Ca1/3MnO3 (LCMO) and semiconducting Nb-doped SrTiO3, we were able to map the LDOS across the boundary, unambiguously visualize the interface by the location of the valence band, and elucidate the fundamental issue of band alignment at a complex oxide heterointerface[4].

Figure 1: The left figure shows the morphology near LCMO/Nb:STO interface overlaid with LDOS at +3V (white color represents high contrast against brown color). The right figure shows the measured spectrum as function of the distance to the interface. The conduction band alignment is observed across the interface.

Reference:
ZnO/ZnMgO QW Schottky photodiodes sensitive to light polarization

A. Hierro, G. Tabares, Univ. Politécnica de Madrid (Spain); C. Deparis, C. Morhain, J. Chauveau, Ctr. de Recherche sur l’Hétéro-Epitaxie et ses Applications (France)

The detection of the polarization state of light is key in numerous applications, from medical/chemical analysis to detection of man-made objects. It is particularly interesting to develop intrinsic polarization-sensitive photodetectors, which do not need external polarizers. Wurtzite ZnO has the potential to become a solution for this technology, since it has a low symmetry crystal structure and thus can show a strong in-plane anisotropy in its absorption coefficient.

In this work we analyze Schottky photodetectors using a-plane ZnO/ZnMgO QWs, i.e., where the c- and x-axis are found in-plane. The photodetectors contain 3 or 10 ZnO/ZnMgO QWs with varying thicknesses from 1.5 to 5.7 nm. Different strain states have been obtained in the QWs by varying the Mg contents in the barrier, from 22 to 37%, and using both r-plane sapphire and a-plane ZnO substrates. These photodetectors show absorption edges ranging from 3.36 to 3.52 eV, responsivities for unpolarized light up to 10 mA/W, and 10^4 UV/VIS rejection ratios. When analyzed with linearly polarized light parallel and perpendicular to the c-axis, a clear selectivity to light polarization is observed, with a difference in the responsivity absorption edge energy (R(//)/R(_/)) in the range of 22-30 meV. The sensitivity to polarization of the absorption edge clearly correlates with the amount of accumulated in-plane strain, decreasing from 30 to 22 meV as the strain moduli along the c- and x-axis are increased. In addition, the responsivity, R(//)/R(_/), also decreases with decreasing strain modulus, possibly resulting from a change in the oscillator strengths along the c- and x-axis.

n-ZnO/CdZnO/ZnMgO/p-GaN multiple-quantum-well light-emitting diodes with MBE/MOCVD growth

S. Ting, J. Huang, W. Chang, C. Liao, C. Chen, C. Lin, H. Hsieh, C. Yang, National Taiwan Univ. (Taiwan)

Since GaN has a very small lattice mismatch (only 1.8%) with ZnO, it has been proposed to combine p-GaN and ZnO-related quantum well structures for fabricating light-emitting diodes (LEDs). In this paper, the growths and fabrications of n-ZnO/CdZnO/ZnMgO/p-GaN multiple quantum-well (QW) LED structures based on MBE/MOCVD hybrid growth are reported. The p-GaN is grown with MOCVD and the rest structure is grown with MBE. The epitaxial layer of p-GaN on a u-GaN layer is grown on c-sapphire substrate with MOCVD. Then, the CdZnO/ZnMgO QW structures are grown with plasma-assisted MBE on the p-type GaN template. Three to seven pairs of CdZnO/ZnMgO QWs are grown. On the top, a 100 nm Ga-doped n-ZnO layer is deposited at 550 degree C. Finally, the sample is in situ annealed at 600 degree C for 10 min. Room-temperature photoluminescence spectra show peaks in the blue to green range, which originate from the CdZnO/ZnMgO QWs. No low-energy defect luminescence is observed. Various QW thickness and well/barrier compositions are grown for comparing their emission wavelengths and efficiencies. Transmission electron microscopy and secondary ion mass spectrometry are used for understanding the material structures and compositions of the grown epitaxial samples. LED devices are also fabricated based on the grown structures.

MgZnO/ZnO/MgZnO double heterojunction light emitting diodes on c-plane sapphire

S. Chu, J. Zhao, Z. Zuo, J. Liu, Univ. of California, Riverside (United States)

Zinc oxide is a promising material with bandgap of 3.37 eV and a large exciton binding energy of 60 meV, which makes it very attractive for future ultraviolet light emitting diodes and laser diodes applications. Much progress on ZnO growth and p-type doping has been achieved in recent years especially for Sb-doped p-type ZnO films and optoelectronic devices. Previously, we demonstrated a ZnO homojunction light emitting diode with Sb doped p-type layer on c-plane sapphire with emission power of 32 nW. In this presentation, we report stronger emission by an order of magnitude with a diode consisting of p-type Sb-doped ZnO, MgZnO/ZnO/MgZnO double heterojunctions, and n-type undoped ZnO layers grown on c-plane sapphire substrate using plasma-assisted molecular-beam epitaxy. Hall effect measurement shows that the top p-type ZnO: Sb layer has a hole concentration of 1×10^{17}/cm^3, indicating an improved p-type film has been achieved. Mesa geometry light emitting diodes were fabricated with Au/Ni and Au/Ti ohmic contacts on top of the p-type and n-type layers, respectively. The current-voltage measurement shows a p-n junction characteristic. Strong ultraviolet emission was achieved with the device, which yields an output power of 457 nW at 140 mA. The drastic enhancement of the power output is attributed to current confinement in the double heterojunction as well as the improved p-type doping in the Sb-doped ZnO films. Furthermore, the random lasing feature and the effect of the intrinsic layer in the double heterojunction are discussed as well.

Novel lift-off approach for (In)GaN LEDs and PV using ZnO template layers

D. J. Rogers, F. H. Teherani, Nanovation (France)

Recently a number of groups have demonstrated the use of ZnO thin films as sacrificial templates for the lift-off of (In)GaN thin films from insulating/costly substrates. In this talk we will give an overview of the recent developments in this domain.

Growth and characterization of ZnO nanostructures for UV sensor applications

A. K. Sood, Y. R. Puri, Magnolia Optical Technologies, Inc. (United States); T. Manzur, Naval Undersea Warfare Ctr. (United States); D. L. Polla, Defense Advanced Research Projects Agency (United States); Z. L. Wang, Georgia Institute of Technology (United States); A. F. M. Anwar, Univ. of Connecticut (United States); M. B. Soprano, U.S. Army Research, Development and Engineering Command (United States)

E-O Sensors are being developed for a variety of Military Systems Applications. These include UV, Visible, SWIR, MWIR and LWIR Nano Sensors. In this paper, we will discuss growth and characterization of ZnO Nanowires on a variety of substrates that include Si, ZnO, GaN, SiC and flexible substrates.

The critical technologies being developed include ZnO nanowires with wide band gap for UV detection for a variety of threat warning applications. We will present experimental results on the electrical and optical properties of ZnO nanowire UV detectors. Experimental results on ZnO based nanowires demonstrate enhanced UV sensitivity and path forward for larger arrays.


9740-58, Session 8
Application of dilute boron B(Al,Ga)N alloys for UV light sources
S. Gautier, Supélec (France); M. Abid, Georgia Institute of Technology (France); T. Moudakir, G. Orsal, Supélec (France); V. Ravindran, Georgia Institute of Technology (France); O. Naciri, Univ. de Metz (France); A. Migan-?Dubois, Z. Djebbour, Lab. de Génie Electrique de Paris (France); D. Troade, A. Soltani, Institut d’Electronique, de Microélectronique, et de Nanotechnologie (France); G. Patriarche, Ctr. National de la Recherche Scientifique (France); A. Ougazzaden, Georgia Institute of Technology (France)

In the last decades, (Al,Ga,In)N nitride materials have been at the core of the development of new generations of opto- and micro-electronic devices. More recently, new B(Al,Ga,In)N alloys has been proposed for optical applications in the UV range. Since BN material has numerous unique properties, one might expect the B(Al,Ga,In)N materials system to exhibit new and very attractive properties to facilitate nitrides devices design. To that purpose, a sufficient knowledge of the physical properties of these new materials is required.

In this work, investigations on the physical properties of dilute boron B(GaN)N ternary materials grown through Metalorganic Vapor Phase Epitaxy (MOVPE) will be presented. Highly valuable properties were demonstrated and some of their potential applications will be discussed. For instance, for the use in Distributed Bragg Reflector (DBRs) or Distributed Bragg Confinement layers (DBCs), GaN offers a large refractive index contrast with only small boron incorporation. A 1% of boron GaN/GaN multilayers structure has a refractive index contrast of more than 0.1, which is equivalent to that of AlGaN/GaN with 22% of aluminum.

9740-35, Session 9
Preparation of conductive Ti-oxide thin-films by mix-phase substitution
Y. Liu, Y. H. Lin, C. Liu, National Central Univ. (Taiwan)

Typically, Ti-oxides have a poor conductivity due to the low free-carrier concentration produced by oxygen-vacancy. In this study, Ti-oxide thin-films with fair conductivity were prepared on quartz substrates with DC sputtering technique by manipulating the percentage of O2-introducing and the DC power. The conductivity of Ti-oxide thin-films were found to depend on the percentage of O2-introducing. With 12.5 % O2-introducing, the lowest resistivity, 2.30 × 10-2 Ω·cm, of the sputtered Ti-oxide thin-film can be achieved. From the XPS analysis, we found that the Ti2 and Ti3+ ions in the TiO2 phase have a poor conductivity due to the low free-carrier concentration. So, another possible mechanism creating the free carriers for the conductive oxides, i.e., the substitution mechanism, likely serves as the major source of the formation of free carriers for the Ti-oxide thin-films, composed of Ti2O3 and TiO2. The Ti4+ ions in the TiO2 phase could possibly substitute Ti3+ ions in the Ti2O3 phase, which creates the free electrons. The substitution mechanism to create the free carriers of the Ti-oxide thin-films has been verified by curve-fitting the oxygen binding energy. In the talk, the detail methodology of the curve-fitting on the oxygen binding energy in the Ti-oxide thin-films would be reported.

9740-36, Session 9
Patterning of indium-tin-oxide (ITO) films using laser-induced forward transfer (LIFT) technique
H. Sakata, Tokai Univ. (Japan); A. Yoshikado, Zeta Photon Co., Ltd. (Japan); E. Yokoyama, M. Wakaki, Tokai Univ. (Japan)

Indium-tin-oxide (ITO) films are transparent and conducting, and are widely used for electronic and optoelectronic devices. Easy and rapid patterning of ITO films is required for the basis of device applications. This study attempts to fabricate ITO film patterns (dot or line) using the laser-induced forward transfer (LIFT) technique. LIFT of ITO films has been reported using excimer laser (KrF, 238nm), but no such study using laser with visible wavelength is found.

In this study, a SHG laser beam (530nm) of a Nd:YAG laser (5.1W) was irradiated on a glass substrate with an ITO film on the rear side, and ITO film was transferred to another receiving glass slide placed in direct contact or with air gap against the ITO film. The beam was scanned in the X direction by using a galvano-mirror and then moved to Y direction during the laser irradiation. Dot- or line- patterned films were deposited on the receiver glass. These patterned films were observed by SEM. In and Sn elements are confirmed to be present almost as same as in the original ITO film from the XPS analysis of the patterned ITO films. Optimization of the laser operation for irradiation on ITO films is needed to obtain good patterning of the film.

9740-37, Session 9
Layer-by-layer epitaxial growth of polar MgO (111) films
K. Matsuzaki, H. Hosono, T. Susaki, Tokyo Institute of Technology (Japan)

We have observed layer-by-layer epitaxial growth mode of MgO (111) films on YSZ (111) substrates with atomically flat NiO buffer layers by pulsed laser deposition despite a strong electrostatic instability of the [111] polar growth direction. Layer-by-layer growth has been realized up to ~ 10 MgO layers. For thicker films with 10 - 500 MgO layers, although clear step and terrace structures disappear, the root-mean square surface roughness remains as small as ~ 0.2 nm with high crystalline quality comparable to bulk single crystals.

9740-38, Session 10
Growth of oxide nanoparticles using pulsed laser ablation technique
M. A. Gondal, Q. A. Dmosh, T. A. Saleh, Z. H. Yamani, King Fahd Univ. of Petroleum and Minerals (Saudi Arabia)

Nano particles exhibit physical and chemical properties distinctively different from that of bulk due to high number of surface atoms, surface energy and surface area to volume ratio. In general there are two major approaches to synthesize nanomaterials: top-down and bottom-up. In the top-down approach nanoparticles are synthesized by etching of smaller structures from larger ones, laser ablation and milling are good examples of top down approach. On the other hand, Bottom-up approach refers to the build-up of a material from the bottom: atom-by-atom, molecule-by-molecule, or cluster-by-cluster. Laser is a unique source of radiation and has been applied in the synthesis of nanostructured metal oxides. The technique of pulsed laser ablation (PLA) in liquid medium has been proven an effective and simple technique for preparing nanoparticles. Pulsed laser deposition (PLD) is another way to fabricate nanostructured single crystal thin films of metal oxides. PLA technique has been applied in our laboratory for the growth of metal oxides such as nano-ZnO, nano-ZnO2 nano-SnO2, nano-Bi2O3, nano-
Al2O3, nano-Nio and nano-MgO2. Different techniques such as HRTEM, FE-SEM, AFM, UV, FT-IR, PL and XRD were applied to characterize these materials. We will present our latest development in the growth of nano metal oxides using PLA and PLD.

*The author is thankful to KFUPM for supporting this work.

7940-39, Session 10

**P-type oxide based thin film transistors deposited at low temperatures**

E. Fortunato, R. Barros, P. Barquinha, V. Figueiredo, E. Elamurugu, G. Gonçalves, Univ. Nova de Lisboa (Portugal); S. K. Park, C. Hwang, Electronics and Telecommunications Research Institute (Korea, Republic of); S. Sajy, R. Martins, Univ. Nova de Lisboa (Portugal)

No abstract available

7940-40, Session 10

**The influence of crystallographic polarity on the optical properties of ZnO**

M. Allen, Univ. of Canterbury (New Zealand); S. M. Durbin, Univ. at Buffalo (United States); R. J. Reeves, Univ. of Canterbury (New Zealand)

ZnO is a strong candidate for next-generation optoelectronic devices due to a unique combination of material properties. These include a wide direct band gap in the UV spectrum, efficient above room temperature free excitonic emission, and large spontaneous and piezoelectric polarizations. In recent years, crystallographic polarity has emerged as an important variable in the characterization and performance of ZnO-based materials and devices. In this paper we will show that polarity-related effects can significantly influence a number of the optical and electrical properties of ZnO (including photoluminescence emission, optical reflectivity, and Schottky contact barrier heights) and introduce models which seek to explain this unusual behavior.

7940-41, Session 11

**Effects of annealing on optical properties of TiO2 planar waveguides**


Titanium dioxide possesses a high second order nonlinear index, making it a potential material for all-optical switching. In order to exploit these properties, TiO2 thin films with high refractive indices and low losses are required. We deposit TiO2 waveguides via RF reactive sputtering onto oxidized silicon substrates. We find that film characteristics vary greatly with deposition temperature, suggesting that they may also exhibit strong sensitivity to post-deposition annealing. We annealed TiO2 thin films at various temperatures in an oxygen environment using a tube furnace. The annealed films are then characterized using Raman spectroscopy, variable angle scanning ellipsometry and prism coupling to observe changes in crystalline phase, refractive index, and planar waveguide losses, respectively. As-deposited amorphous films demonstrate an increase in crystallinity after annealing, with the development of the anatase, and, at higher temperatures, rutile crystalline phases. We report on the changes in refractive index and planar waveguide loss that accompany these phase changes, and their consequences for the viability of TiO2 as a device medium. Furthermore, we will study the changes in the nonlinear properties of these films upon annealing using the Z-scan technique.

7940-42, Session 11

**Pedestal anti-resonant reflecting optical waveguides**

D. Orquiza de Carvalho, M. I. Alayo Chavez, Univ. de São Paulo (Brazil)

Anti-resonant reflecting optical waveguides (ARROW) fabricated on silicon substrates have been studied for a variety of sensor applications [1, 2]. In particular, it has been shown that conventional type ARROWS have a smaller sensitivity than TIR waveguides when evanescent field sensing schemes are used [3]. Additionally, rib waveguides fabricated using Reactive Ion Etching (RIE) can present high sidewall roughness if metallic mask is used, which lead to undesirable losses. This can be improved if the RIE step is done in the lower layers, leading to smoother but smoother core sidewalls.

We present an alternative method for achieving the lateral confinement in ARROW waveguides fabricated with silicon technology. 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. Pedestal hollow core ARROWS have been proposed and fabricated [4] but in the case of conventional ARROW waveguides this has not been done, to our best knowledge.

Furthermore, depending on the gases used in the RIE process, the pedestal is formed with an isotropic or anisotropic profile, respectively. For this reason, we present a study of the isotropy of silicon etching and its influence on the guiding properties of the ARROWS. Also, simulations results regarding propagation losses, mode profile and sensitivity to refractive index variation of liquid surrounding the core are contrasted with regular rib ARROW waveguides.

References

The threshold of the random laser realized in this structure is about 43 mA in a simple Au/MgO/ZnO metal-oxide-semiconductor (MOS) structure. The largest challenges for the future development of this kind of laser are anticipated that the future application of this technique will provide important insights into the physical mechanisms behind strain-induced changes to the optical, electronic and magnetic properties of complex oxides. Supported by the U.S. Department of Energy (DOE), Office of Basic Energy Sciences under contract DE-AC02-06CH11357 and the NSF under grant # DMR 0940420.

**7940-55, Session 12**

**Fluorescent oxide nanoparticles adapted to active tips for near-field optics and light conversion in white LEDs**

B. Masenelli, Univ. Claude Bernard Lyon 1 (France); A. Cuche, O. Mollet, J. F. Motte, Institut NÉEL (France); G. Ledoux, D. Amans, C. Dujardin, P. Melinon, Univ. Claude Bernard Lyon 1 (France); S. Huant, Institut NÉEL (France)

We present a new kind of fluorescent oxide nanoparticles with properties well suited to active-tip based near-field optics or light conversion in white LEDs. These particles are nanophosphors with an average diameter in the range 5-10 nm and are produced by Low Energy Cluster Beam Deposition (LECBD) from a YAG:Ce3+ target. Contrary to conventional semiconductor nanocrystals, the luminescence results from doping ions (Ce3+). This enables the light emission to be intense and stable with respect to blinking or bleaching. Working at the nanoscale also allows contemplating the design of heavily doped nanophosphors (otherwise not possible in the bulk phase).

The particles are studied by transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), classical photoluminescence, cathodoluminescence and near-field scanning optical microscopy (NSOM). Particles of extreme photostability as small as 10 nm in size are evidenced [1].

In the last step, we show that these nano-emitters can be used efficiently as building blocks of active NSOM tips by coating a standard optical tip with a 10 nm thick layer of YAG:Ce3+ and by subsequently performing NSOM imaging of test surfaces.

hybridised in that they have the same wurtzite structure, similar lattice parameters and comparable bandgaps. This approach allows us to assess some key potential advantages of the two materials systems. Firstly, bandgap engineering in InGaN allows tailoring of the bandgap to the solar spectrum, so as to augment the photocurrent. Secondly, the ZnO surface has a proven propensity for catalysis of the oxidation reaction. Finally, the use of ZnO nanostructuring will be investigated in order to assess the impact on the efficiency of increasing the surface area of the photodiode.

7940-47, Poster Session

**Influence of Li implantation on the optical and electrical properties of ZnO film**

S. Nagar, A. Mandal, S. Chakrabarti, Indian Institute of Technology, Bombay (India); S. K. Gupta, Bhabha Atomic Research Ctr. (India)

ZnO has been a subject of intense research in the optoelectronics community owing to its wide bandgap (3.3eV) and large exciton binding energy (60meV). However, difficulty in doping it p-type posts a hindrance in fabricating ZnO-based devices. In an attempt to make it p-type we have studied Li-implanted (Energy=40keV, dose=5x10^13cm^-2) ZnO films grown over sapphire substrates by Pulsed Laser Deposition technique at 400°C (sample A). The samples were subsequently subjected to Rapid Thermal Annealing at 650°C and 750°C (samples B and C) for 30 seconds. Room temperature Photoluminescence study of as-deposited sample reveal consistent Donor-bound exciton (D°X) peak at 3.3eV, which shifts to 3.298eV, 3.298eV, and 3.288eV for samples A, B and C respectively. This data validates the n-type conductivity of the samples with a carrier concentration and Hall mobility of 8.68x10^19cm^-3, 1.13x10^18cm^-3 and 2.9x10^20cm^-3 and 2.14cm^2/V-sec, 35.2cm^2/V-sec, 16.9cm^2/V-sec for samples A, B and C respectively. The reduced energy of D°X center is probably due to lesser oxygen vacancies leading to lower carrier concentration as seen for samples A and B. While the higher carrier concentration in sample C can be attributed to aggregated vacancy clusters at high temperature annealing. Since Li acts as an acceptor for ZnO, so a free electron-acceptor (FA) peak at 3.227eV, 3.217eV and 3.225eV in samples A, B and C is evident. A third peak at 3.128eV may be due to the donor-acceptor pair, a reason for a lower energy FA peak for sample B. DST, India is acknowledged.

7940-49, Poster Session

**Rutile TiO2 nonlinear optical waveguide**

T. Kita, A. Koichi, E. Y. Morales Teraoka, H. Yamada, Tohoku Univ. (Japan)

High pump powers are required to generate nonlinear optical effects in conventional optical fibers. Channel waveguides with small cross-sectional areas are one choice for realizing such high power density. At high power densities two-photon absorption becomes a problem, but the wide band-gap of rutile TiO2 prevents it. It also has a large third-order nonlinear coefficient n2, which determines the strength of third-order nonlinear optical effects. Atomically smooth single-crystal rutile TiO2 can be grown on sapphire (Al2O3) substrate by laser MBE technique, and the large difference in refractive index between rutile TiO2 and sapphire makes it possible to realize the channel waveguide structure.

To verify which nonlinear optical effects are to be expected, the group velocity dispersion and single-mode condition of the waveguides was calculated by a mode solver based on finite element method. Dispersion engineered waveguides are fabricated by e-beam lithography and RIE. We present the details of systematic research to realize high nonlinear TiO2 optical waveguides based on our scheme.

7940-48, Poster Session

**Nonlinear optical effects-induced spectral broadening in ZnO channel waveguides**

E. Y. Morales Teraoka, T. Kita, Tohoku Univ. (Japan); D. H. Broaddus, Cornell Univ. (United States); A. Tsukazaki, The Univ. of Tokyo (Japan) and PRESTO, Japan Science and Technology Agency (Japan); M. Kawasaki, Tohoku Univ. (Japan) and WPI Advanced Institute for Materials Research, Tohoku Univ. (Japan); A. L. Gaeta, Cornell Univ. (United States); H. Yamada, Tohoku Univ. (Japan)

We report the observation of enhanced nonlinear optical effects in ZnO channel waveguides. We focus on obtaining waveguides with enhanced nonlinear properties, ZnO was chosen for its large intensity dependent refractive index n2 and its wide bandgap, which prevents two-photon absorption at wavelengths larger than 800 nm. We selected the channel waveguide structure for its small cross-section due to high confinement. The waveguides were fabricated from single crystal ZnO thin-film grown on sapphire substrate, and using Ar-ion etching. We fabricated waveguides of several widths from 0.7 to 2 um. The measured height was 380 nm, and the sidewalls showed good verticality. Cut back measurements were performed to measure the propagation losses, obtaining values from 3 to 6 dB/mm for single mode waveguides. We demonstrate spectral broadening due to self-phase modulation (SPM) using femtosecond optical pulses with a center wavelength of 840 nm. We measured the RMS spectral width and obtained a maximum of six-fold spectral broadening and a phase shift of 2 Pi. Spectral features characteristic of SPM were appreciated. From the broadening, we calculated the nonlinear parameter gamma, obtaining values from 9.3 to 13.9 W-1m-1 for the different waveguides. It represents more than 1300 times the gamma of a highly nonlinear fiber. The calculated intensity-dependent refractive index is found to be consistent with previously reported values of bulk single-crystal ZnO. Single-crystal ZnO showed to be a promising material for optical waveguides intended for nonlinear applications.

7940-50, Poster Session

**Concentration dependent luminescence characteristics of 5D4 and 5D3 excited states of Tb3+ ions in CFB glasses**

S. K. Jakka, K. Pavani, T. Sasikala, Sri Venkateswara Univ. (India); M. Jayasimhadri, Delhi Technological Univ. (India); K. Jang, Changwon National Univ. (Korea, Republic of); R. M. Lalapeta, Sri Venkateswara Univ. (India)

Calcium fluoroborate (CFB) glasses doped with different concentrations of Tb3+ ions have been prepared with molar composition of (42-x) B2O3 + 20 CaF2 +15 CaO + 15 BaO + 8 Al2O3 + x TbF3 (x=0.05, 0.1, 0.5, 1.0, 2.0 and 4.0) by melt quenching method at 1050°C by using platinum crucible. The samples were annealed for 12 hrs at 420°C for thermal stability. Optical absorption spectrum for 1.0 mol% of Tb3+:CFB glass was recorded in UV-Vis-NIR regions. Radiative parameters such as total radiative transition probabilities (AR), total radiative transition probabilities (AT), radiative lifetimes (AR), radiative branching ratios (AR) for the 5D3 and 5D4 excited states have been calculated from the experimental oscillator strengths (fexp) of Tb3+ absorption bands. The luminescence spectra recorded for different concentrations of Tb3+ ions in CFB glasses exhibit seven and four bands originating from 5D3 and 5D4 excited states respectively. As the concentration of Tb3+ ions increases the intensities of luminescence peaks originating from 5D4 state increases, whereas, the quenching of intensities has been observed for the emission peaks originating from 5D3 state due to energy transfer through cross-relaxation channel (5D3 : 7F6) (5D4 : 7F0). The experimental lifetimes of 5D4 state for all the concentrations of Tb3+ ions are equal and exhibit single exponential decay with highest quantum efficiency which confirms that these glasses can be used for high intensity green emission even at high concentrations of Tb3+ ions.
Integration of a micro-incandescent lamp and an interferometric filter for optical applications

H. Baez Medina, M. I. Alayo Chavez, Univ. de São Paulo (Brazil)

In this work is proposed an integration of two kind of optical devices already studied by our group: an incandescent micro-lamp and an interferometric filter. These devices are fabricated using dielectric silicon compounds on silicon substrates through microelectronic standard processes. We present the possibility of fabricating the devices either separately and then integrating them hybridly, or in a unique process (quasi-monolithic integration).

The first device is an incandescent micro-lamp based on a chromium micro-resistor, working as lamp filament, embedded between two oxynitrides films. Partial bulk micromachining is made in silicon substrate obtaining a self-sustained cantilever, reducing thermal dissipation and allowing micro-resistor to reach incandescent temperatures when electrical current is applied.

Second device is a multilayer stratified structure that works as an interferometric filter. We use periodically alternated PECVD SiO2-SiOxNy layers to define filter structure on silicon substrate. Total silicon etching using KOH solution is made in wafer backside in order to leave a self-sustained interferometric membrane. Furthermore, numerical simulations are accomplished in order to define the number, thickness and refractive index of the constituents films used in the fabrication of interferometric filters.

Hybrid integration is obtained by bonding together the two devices, aligning both cavities. Micro-incandescent lamp light passes through multilayer filter and is detected on its output. Otherwise, quasi-monolithically integrated device is obtained unifying the two processes described. First the multilayer filter is deposited on wafer backside, and then micro-incandescent lamp fabrication process is made on wafer front side. Afterwards, micromachining is made in silicon substrate leaving the filters as self-sustained membranes.

Optical and structural properties of polycrystalline ZnO films grown via thermal oxidation of Zn-metal on glass and c-plane sapphire substrates

J. C. Moore, Coastal Carolina Univ. (United States); R. L. Foster, E. J. Gee, M. R. Jones, S. A. Morris, Longwood Univ. (United States)

We have investigated the optical and structural properties of thin polycrystalline zinc oxide (ZnO) films grown on glass and c-plane sapphire substrates. Approximately 200 nm thick Zinc-metal films where grown via dc-sputter deposition at room-temperature with subsequent thermal annealing in air at 300, 600 and 900 C. X-ray diffraction spectra indicate that after annealing, the resulting ZnO films possess a polycrystalline hexagonal wurtzite structure without a preferred orientation. Complete transition from Zn-metal to ZnO is achieved within 9 hours at 300 C and in less than one hour for 600 and 900 C. On glass, a relatively uniform grain size of about 25 nm across orientations was observed via the Scherer formula and atomic force microscopy (AFM). On sapphire substrates, grain size is considerably larger at approximately 0.5-1 microns, depending on annealing temperature. Room-temperature photoluminescence spectra indicate two emission bands, excitonic ultraviolet (UV) and deep-level green emission. 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, which may be attributed to the generation of oxygen vacancies and interstitial Zn ions at higher temperatures. These results indicate that low-temperature annealing of Zn metal can result in high-quality ZnO films on substrates suitable for UV optoelectronics.

RTA study of of BSCCO 2201 superconductor thin films grown by MBE

D. J. Rogers, Nanovation (France); P. Bove, NANO-UV SAS (France); F. H. Teherani, Nanovation (France)

No abstract available

ZnO grown by PLD for transparent electronics applications

D. J. Rogers, V. E. Sandana, F. H. Teherani, Nanovation (France)

No abstract available
Large-scale planar lightwave circuits

S. Bidnyk, M. Pearson, A. Balakrishnan, H. Zhang, Enablence (Canada)

Planar Lightwave Circuits (PLCs) have emerged as the key enabling technology in many multi-channel fiber optic communication systems. To date, most of these PLCs have been passive, incorporating only basic optical elements. Further growth in on-chip functionality and scalability has been impeded by limited progress in the integration of active components with passive optics. By leveraging advanced wafer processing and flip-chip bonding techniques, we have succeeded in hybridly integrating a myriad of active optical components, including photodetectors and laser diodes, with our PLC platform. We have combined hybrid integration of active components with monolithic integration of other critical functions, such as diffraction gratings, on-chip mirrors, mode-converters, and thermo-optic elements. Further process development has led to the integration of polarization controlling functionality including polarization splitters, polarization combiners, and polarization rotators. Most recently, all these technological advancements have been combined to create large-scale planar lightwave circuits that comprise hundreds of optical elements integrated on chips less than a square inch in size. We believe that large-scale PLCs are poised to revolutionize the fields of high-speed telecommunications, advanced instrumentation, biomedicine, and defense.

Characterization of irradiance effects on curing of siloxane for embedded waveguide applications

T. Daunais, K. A. Walczak, C. T. Middlebrook, P. Bergstrom, Michigan Technological Univ. (United States)

In order to maintain the overall optical performance in a step index rectangular waveguide, the complex index of refraction of the core and cladding material must be maintained throughout the cycle of the lithographic fabrication process. The percentage of the core and cladding material that is cured and the irradiance that cure took place at directly affects the complex index of refraction of these materials. Siloxanes produced by Dow Corning have been selected to meet the requirements for embedded waveguides for circuit board applications due to their optical performance characteristics and their compatibility with current manufacturing techniques. The required total dose for a 50μm thick layer of siloxane is 1200mJ at an irradiance of 30mW/cm2. In order to utilize lower irradiance levels, the total dose of the ultraviolet exposure must be characterized and calibrated. By measuring the changes in the absorption peaks of the materials using transmission data from ellipsometric techniques, it is possible to define the percentage cure of the siloxane from different curing profiles. Ellipsometric techniques were also utilized to measure the complex refractive index of the materials cured using different profiles. It was found that the total dose required for a complete cure and the complex refractive index of these materials drastically changes with different irradiances and the profile for the total dose compared to the curing of the siloxane materials at all irradiances is logarithmic.

Impact of sputtering parameters on titanium dioxide thin films for nonlinear nanophotonics


We have identified titanium dioxide (TiO2) as a promising material for on-chip nonlinear optical devices. Its high refractive index and large intrinsic nonlinearity can strongly enhance confinement and non-linear interactions. In this study we optimize our deposition process to lower the linear losses in planar waveguides.

We deposit titanium oxide thin films by RF reactive sputtering titanium onto oxidized silicon wafers in an argon/oxygen environment. The oxygen partial pressure in the chamber has a large impact on the deposition rate and the film composition. We investigate the composition of our films by X-ray photoelectron spectroscopy. Titanium dioxide is known to exist in different crystalline phases of which we observe amorphous, anatase and rutile, identified using Raman spectroscopy. We will discuss the impact of the deposition parameters on the composition and phase of the films.

We measure the refractive indices and planar waveguiding losses of our thin films by the prism coupling and spectroscopic ellipsometry methods. These films have refractive indices as high as 2.4 and losses as low as 0.4 dB/cm at a wavelength of 800 nm. We will discuss the influence of the phase and composition of the material on its optical properties and consequences for nonlinear nano-photonic.

Nonreciprocal racetrack resonators for on-chip optical isolation

L. Bi, Massachusetts Institute of Technology (United States); J. Hu, Massachusetts Institute of Technology (United States) and Univ. of Delaware (United States); L. C. Kimerling, C. A. Ross, Massachusetts Institute of Technology (United States)

Magneto-optical nonreciprocal photonic components are leading a revolution in on-chip integrated photonics. However, due to material incompatibility, integration of these devices on a semiconductor platform remains challenging. Meanwhile, reducing the device footprint is also required for compatibility with other integrated photonic devices. In this study, we report the first experimentally demonstrated on-chip nonreciprocal racetrack resonator based on monolithically integration of magneto-optical oxides on an SOI platform. A single mode silicon racetrack resonator with SiO2 top cladding was firstly fabricated, with part of the SiO2 top cladding etched to expose the underlying Si resonator surface. A 20nm thick Y3Fe5O12 buffer layer was deposited on the device by pulsed laser deposition (PLD) and followed by rapid thermal annealing. A second layer of 80nm thick Bi1.8Y1.2Fe5O12 was deposited by PLD at 680°C, which crystallized into the garnet phase (>87vol.%). Such a device structure provides non-reciprocal resonance shift in the TM mode under an externally applied magnetic field due to the non-reciprocal phase shift effect in the Bi:YIG layer. By applying a magnetic field of ±1500Oe perpendicular to the Si/Bi:YIG resonator section, a reversible shift of TM mode resonance wavelength of ± (7.4±2.3)pm at 1548.6nm was observed, corresponding to a Faraday rotation of -603.7deg/cm from the Bi:YIG layer. An optical transmission loss of 75dB/cm of the waveguide was measured at 1550nm, which is mainly due to the material loss of Bi:YIG. Further improvement of the material and device figure of merit will enable stronger non-reciprocal effect for on-chip optical isolation applications using such devices.
Fully compatible magneto-optical sol-gel material with glass waveguides technologies: application to mode converters

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Integration of magneto-optical devices, such as nonreciprocal optical isolators, is still a great challenge, due to difficulties to embed 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. Using a sol gel process, a hybrid organic-inorganic silica type matrix is doped by magnetic nanoparticles (CoFe2O4). Thin films can be obtained by dip coating on several substrates (glass, silicon...). A full compatibility with these substrates is provided by the soft thermal treatment required (less than 100 °C). Such magneto-optical matrix has shown promising potentialities illustrated by a specific Faraday rotation of $510^{°}$/cm (@$1550$ nm) [1].

In this paper, we show how it can be used to realize several magneto-optical functionalities:

- A planar waveguide made of a thin film of this composite matrix coated on a pyrex substrate can produce non-reciprocal TE/TM mode conversion.
- The association of composite films with ion-exchanged glass waveguides [2], gives hybrid structures which also produce TE/TM mode conversion. Such devices are planned to be the active element of integrated optical isolators.
- The magneto-optical composite matrix has been arranged as a 3D magneto-photonics using a polystyrene opals as template. Photonic band-gap and magneto-optical activity have been evidenced. The aim is to increase the merit factor of the material.

These results confirm that such an approach is an easy and soft chemistry way to realize magneto-optical devices which are fully compatible with integrated glass technology.


Luminescence and amplified stimulated emission of quantum dot doped sol-gel waveguides

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Highly luminescent CdSe@ZnS core-shell semiconductor quantum dots (QDs) have been incorporated in both inorganic (TiO2, ZrO2) and in hybrid organic-inorganic sol-gel matrix. Depending on QDs size, luminescence waveguides emitting from green to red have been obtained and their optical properties have been characterized. Titania based composites were seen to be inherently photo-unstable due to photodarkening in the bulk matrix and subsequent nanocrystal oxidation. In comparison, zirconia composites were inherently photo-stable due to its high refractive index makes it an ideal candidate for nanocrystal based optical waveguides.

Mode-lock laser made by ion-exchange

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Mode-lock lasers have been studied a lot in the past years for producing pulses as short as possible. These devices have mostly been realized in bulk optics and they are consequently cumbersome and sensitive to vibrations. There are only a few studies on integrated optics mode-lock lasers, though this technology is very promising because of its stability, compactness and the possibility to integrate several functions on a single chip.

In this paper, we present an ion-exchange passively mode-locked laser. One of the key characteristics of this structure is its mechanical stability. Indeed, no bulk optics is needed because the saturable absorber is hybridized on the top of the waveguide in order to interact with the evanescent part of the guided mode.

Indeed, the device that has been obtained 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 realized with two multilayers dielectric mirrors stuck on the waveguides facets. We implemented a bis(4-dimethylaminodithiobenzil)nickel (BDN) dye included in a cellulose acetate thick film, which presents a saturable absorber behaviour around 1.06 µm. With this structure, pulses with repetition rates of 3.3 GHz and a single mode output have been measured. Moreover, the use of an autocorrelation set-up allowed us measuring sub-picosecond pulse durations.
range has been achieved by frequency beating of the two laser modes coming from two ridge-width varied DFB lasers in parallel by adjusting independently the driving currents injected into the two DFB lasers. All-optical clock recovery from 40Gb/s degraded data streams has been successfully demonstrated in the new device for the first time.

7941-10, Session 3
InP monolithic optical integration for 100Gbit/sec data transmission
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100Gbit/sec data transmission is often based on phase dependent data formats. In this work, results on receivers and on transmitters for these formats will be reviewed, and their potential also for shorter reach will be analyzed. One trend in InP monolithic are generic integration platforms, which are currently investigated on a European scale. Their potential implications on InP applications will also be reviewed.

7941-11, Session 3
Hybrid photonic integrated circuits for faster and greener optical communication networks
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We present current development efforts on hybrid photonic integration for new generation “faster and greener” Tb/s-capacity optical networks. On the physical layer, we present the development of a robust and versatile, silicon-based photonic integration platform that acts as a technology “blender” bringing together different material systems including InP, GaAs and SiGe. On the application layer we present optical transport and routing systems integrated on the hybrid photonic platform; 100GbE transceiver PICs and Tb/s-capacity wavelength routers can now be implemented using passive silicon interferometers and hybridly integrated III-V optical amplifiers, modulators and detectors.

7941-12, Session 3
Light-bullet routing and logic in planar waveguide arrays
M. O. Williams, J. N. Kutz, Univ. of Washington (United States)

The generation of spatially mode-locked light bullets has long been an area of interest to the photonics community. It has recently been theoretically demonstrated that slab waveguide arrays configured like a VCSEL are capable of generating light-bullets starting from noise with a uniform gain profile. By partitioning the gold layer used for current injection into discrete regions and by controlling the level of current injection into each section individually, an electronically controllable non-uniform gain profile is created. This non-uniform gain profile was included in the slab-waveguide mode-locking (SWGAML) model used to study the formation of light-bullets in this system. Numerical simulations performed on the SWGAML have demonstrated that the non-uniform gain profile is sufficient to completely control and route light-bullets. For a typical gain profile, a light bullet follows the gradient of the profile to a local maximum of the gain. This behavior can be used to produce “photonic wires”, which are capable of guiding light-bullets. Additionally, gain mediated interactions between nearby light-bullets can be exploited to produce all-optical logic gates such as the NAND and NOR gates. These gates use light-bullets as both of the inputs as well as the output. Due to the nature of gain-mediated interactions, these gates are robust and insensitive to the phase difference between the light-bullets. Due to the straightforward nature of these gates and the ease of their construction, slab waveguide arrays are a viable platform for the implementation of all-optical routing and photonic logic devices.

7941-13, Session 3
Innovative high resolution Fourier transform spectrometer based on SWIFTS technology: presentation of recent results in the 400-1000 nm wavelength range
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The SWIFTS (Stationary-Wave Integrated Fourier Transform Spectrometer) is a new concept of integrated optical spectrometry [1]. It is based on the detection of standing waves by a collection of nano-sensors placed in the evanescent field of a waveguide. The interferogram Fourier sample can be obtained in two different stationary regimes. Either the electromagnetic radiation is coupled into a waveguide ended by an integrated mirror (SWIFTS-Lippmann mode), or the electromagnetic radiation is split in two equal parts. These two parts are injected in counter-propagative scheme from the two extremities of a waveguide [2] (SWIFTS-Gabor mode).

In the frame of a scientific and industrial collaborative project named SWIFTS 400-1000*, the SWIFTS-Lippmann mode is studied to develop compact high resolution spectrometers in the spectral range from the wavelength of 400 nm to the wavelength of 1000 nm. These spectrometers combine several technologies such as integrated optical (waveguides on glass), nano-technology (dispersive nanodots set at the glass surface with a section size 50x50 nm2) and high sensitivities imaging systems (CCD). By the way, a complete integrated system without any moving part or classical dispersive optics can be obtained. The typical performance obtained in the 400-1000 nm range is a resolution of 10 pm with a numerical aperture of f/5.

In this SPIE conference, we will present the recent progress of the SWIFTS 400-1000 spectrometers, as well as first results in the application of them for the spectral analysis especially in the field of light source spectral metrology, in astronomy and for gas analysis.


* SWIFTS 400-1000: is a collaborative program in the framework of the French competitiveness cluster Minalogic

7941-14, Session 3
Multi-threshold photonic comparator by square-wave synthesis
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One of the challenges in realizing a true photonic Analog-to-Digital conversion (PADC) is a high-speed, optical level-comparator which will be incorporated into a fully monolithic device. Most known PADCs rely on electronic comparators for providing the threshold levels required for outputting distinct binary 0’s and 1’s. A level-comparator is a highly nonlinear component, and not trivial for implementation in optics. It involves materials with nonlinear behaviour, and usually requires high optical intensity to “trigger” the nonlinearity. Full photonic comparator design based on Si-SiO2 technology is
introduced. A square-like O/E response is achieved by employing Fourier series synthesis: a set of sine-wave responses of different amplitudes and phases are superimposed according to the Fourier series representation of a square-wave. The proposed comparator consists of 3 Multimode Interference (MMI) couplers and phase shifters.

Optical power enters MMI-1 where it is equally split into several arms. The arms located at the output of MMI-1 serve as constant phase shifters which, combined with MMI-2, produce a set of intensities corresponding to Fourier Series coefficients (1, 1/3, 1/5...) of a square wave. A second set of phase shifters, located at the output of MMI-2, adjust the phases in accordance with the Fourier Series formula. The electrical input signal to be converted is applied to this set of electrodes. The third coupler, MMI-3, serves as a coherent optical-field combiner. The output of this photonic comparator has sharp response and excellent distinction between digital low and high levels.

7941-15, Session 4

Fast online simulation of 3D nanophotonic structures by the reduced basis method

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We present algorithmic details and applications of the reduced basis method [1] as efficient Maxwell solver to nanophotonic applications including examples from mask optimization in photo lithography and parameter retrieval in inverse problems, e.g., in optical metrology.

The reduced basis method is a currently studied approach to the multiple solution of problems depending on a number of geometrical, material and source parameters. Such problems occur frequently in optimization tasks where parameters have to be adjusted in order to minimize some error functionals or in production environments where deviations from ideal structures have to be controlled.

The basic idea of the approach is to split the whole simulation process into a possibly expensive offline part and a very fast online part using the offline computed data. The offline part supplies so-called snapshots which are full 3D solutions, each with respect to a given, fixed parameter set. The mathematical theory of a-posteriori error bounds tells us which parameters have to be selected in order to cover the full parameter range without exceeding an pre-defined error bound. The online step consists of a Galerkin projection of the full problem to a comparatively small problem based on the pre-computed snapshots. Typically, the offline simulation time is in the range of hours whereas the online simulation time is in the range of seconds.


7941-16, Session 4

Light scattering by a waveguide-coupled nanowire optical antenna

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We study both experimentally and numerically far-field radiation patterns of single metallic nanowires coupled to weak confined optical waveguides. The radiation pattern resulting from the interaction of the nanowire and the optical mode depends strongly on the mode properties (polarization and wavenumber) and on the antenna properties (material and size). To investigate these phenomena we compare the electric far-field distributions computed with different 3D and 2D numerical methods (Green’s tensor technique, rigorous coupled wave method, Fourier modal method). We discuss on the validity of the 2D effective index approximation. Our results are also compared to experimental measurements obtained over a large spectral domain ranging from 400nm to 1000nm. This study should be useful for optimizing nanostructured photonic circuit’s elements. For example nanoantenna-based optical devices such as the recently proposed stationary wave integrated fourier transform spectrometer (SwiFTS) based on the probing of a guided interferogram by optical nanodetectors [1].


7941-18, Session 4

Accurate simulation algorithm of imperfect polarizers combination attenuator

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In infrared simulation technology in hardware-in-the-loop (HWIL) simulation, light attenuation is significant in its characteristic of dynamic range, varying continuity. The simulation of dynamic change of target distance is operated by means of controlling the beam energy. polarizers combination attenuator (PCA) is potentially well suited to perform the processing because of its continuous adjustment capability.

The optical simulation system should simulate the target’s light energy information in real word. While the radiant energy and optical loss of the simulator is unchanged, the key factor of the simulating range and precision is the attenuation ratio of the imperfect polarizer attenuator. However, polarizers in real are imperfect. To calculate the attenuation ratio of PCA by Malus’s Law will introduce large error. In optical simulation equipment with high precision, the introduced error will bring unacceptable error in simulating the target’s distance and velocity information. Based on Jones matrix of imperfect polarizer, we deduce the attenuation ratio expression of PCA by analyzing the applied electric field distribution of polarized light. It is a binary function about extinction ratio K of the polarizers and the angel enclosed by two polarizers’ transmission axes. This work is reported in Journal of the Optical Society of America A Vol. 27, No. 5.

According to this principle and the actual polarizer’s characteristics, we propose a precise control algorithm with the attenuation ratio expression of PCA, which simulates the target’s real distance by depicting the relationship of distance (R) and in figure 1. Meanwhile, as the tracking angle varies, the tested energy changes from 1 to 1/200. It is simulated by the energy attenuation in different target distances, as shown in figure 2. Furthermore, the target’s velocity can be acquired with the derivative of R in different target distance, the angular velocity is different. Their relation is demonstrated in figure 3. Experimental data shows that in the case of long-distance simulation, the attenuation ratio calculated by Malus Law would bring a big error as much as 50%, while error can be reduced to 5% when using the attenuation ratio algorithm of imperfect polarizers.

7941-19, Session 5

Integrated photonic biosensor platforms for point-of-care diagnostic devices

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Advances in micro- and nanbiosensor technology is offering the implementation of diagnostic tools with increased sensitivity, specificity, and reliability for in vivo and in vitro applications. Such a device could contain enough hard wired intelligence and robustness to be used by the patient and deliver a multitude of data to the practitioner or the central
States) evanescent field shift detection control and monitoring. The micron has been observed at concentrations below the lower exposure limit. The sensor is able to measure a continuous absorption spectrum limited only by size of device for high resolution, our 300 micron long device has been observed with ring resonators and quantum cascade sources that are limited by the refractive index (RI) of the upper cladding of the waveguide, and thus shift the evanescent field distribution up. Therefore, the LEAC biosensor not only uses evanescent field as probe to sense the RI change in the upper cladding, but also uses the evanescent field in the lower cladding to transduce this change locally into an electrical signal variation in a buried photodetector. Decreasing the waveguide thickness lead to a tradeoff in increasing both the total guided light power in the waveguide core and the portion of light power in the evanescent field. Thus, waveguide thickness needs to be optimized to improve the performance of the LEAC sensor. BPM is used to study sensitivities and evanescent field power levels of LEAC sensor with different waveguide thicknesses in both air and water, which are verified by the experimental results obtained from LEAC sensor samples with integrated photodetector arrays.

7941-22, Session 5

Carbon nanotubes coated fiber optic ammonia gas sensor

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The development of carbon nanotubes (CNTs) based gas sensors has attracted intensive research interest in recent years because of their potential for accurate, selective, continuous and rapid detection of various gaseous species. The special geometric and characteristics features of CNTs offer they are excellent candidates for chemical gas sensing with high sensitivity at room temperature. Since, CNTs are chemically reactive when exposed to electron donating (e.g. NH3) and electron withdrawing (e.g. NO2) groups that tend to influence the properties of CNTs thereby it sense the target gas molecules. We report, intrinsic fiber optic CNTs coating based sensor for the detection of ammonia gas for the first time at room temperature. Multimode step index polymethyl methacrylate (PMMA) optical fiber passive cladding is partly replaced by an active coating of purified and dispersed single and multi-walled carbon nanotubes following the dip coating technique and the reaction with analyte (NH3) is studied by measuring the change in output intensity from the optical fiber for various ammonia gas concentrations in the range 0-500 ppm in step of 50 ppm. The sensitivity is calculated for different wavelengths in the range 200-1000 nm for both single and multi-walled nanotubes coated fibers. The sensitivities are found to be 0.22 and 0.21 for single-walled (average diameter 1.3 nm, ~85 wt.%) and multi-walled (average diameter 10-15 nm, ~95 wt.%) CNTs respectively. The role of diameter and purity of CNTs towards the ammonia sensing is studied and the results will be discussed.

7941-23, Session 6

Low-noise and wide-directivity ultrasound detection using high-Q and small size polymer micro-ring resonators

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Low-noise and wide-directivity ultrasound imaging at the frequency range of 30-100 MHz is capable of resolving structures almost down to cellular level. Developing such an imaging modality for clinical use could have a significant impact on medical diagnosis. Optical detection of ultrasound can potentially avoid the difficulties of realizing high-frequency two-dimensional arrays using piezoelectric technology, which include increased noise level in small elements, complexities of electrical
interconnects, and fabrication challenges. Previously we have reported polymer micro-ring resonators with a radius of 50 micrometer for optical detection of high frequency ultrasound, and demonstrated wideband and high-sensitivity response. However, the device’s angular response is limited by the detector size, and impacts its wideband beam-forming applications.

To produce smaller microrings, two approaches were adopted to minimize optical loss: the device is designed to work close to visible wavelength to avoid water absorption loss, and sidewall roughness is reduced to minimize scattering loss. A new process was developed to fabricate small size (R = 30 micrometer) polymer micro-rings working around 800 nm range with smooth sidewalls, and a record high Q factor around 200000 among all integrated on chip polymer microrings was obtained. Such high-Q polymer micro-ring devices can achieve the acoustic sensitivity of ~18.4 mV/kPa with 100 microW coupling power. The noise equivalent pressures (NEPs) are 0.038, 0.055 and 0.077 kPa over 1-25, 1-50, and 1-75 MHz bandwidths, which improved by about 10 dB as compared to our previous best results. For beam-forming applications, the beam-width of the main lobe should extend to ±/− 40° incidence. By reducing polymer micro-ring size to R = 30 micrometer, the bandwidth can be extended from 10 MHz to 20 MHz.

7941-24, Session 6

Subwavelength palladium hole arrays 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. Our experimental results show that the main transmitted peak of the hole arrays shifts toward longer wavelengths upon hydrogen exposure. We investigated the effects of the Pd hydride formation on the extraordinary optical transmission by numerical simulation using the RCWA method. Pd forms a hydride when exposed to hydrogen, which causes a reduction in the permittivity of Pd layer and an increase in the volume of the Pd layer. Our numerical simulation results show that the reduction in the Pd permittivity induces a significant increase in the wavelength of the main transmitted peak. Also, the lateral expansion of the volume of the Pd layer induces an increase in the wavelength of the main transmitted peak. Both, the effects of permittivity decrease and lateral volume expansion contribute to shift the main peak toward longer wavelengths. It is concluded that the all-optical scheme of hydrogen detection produces peak shifts that enable the detection of hydrogen.


7941-25, Session 6

Consideration of sensitivity with respect to diaphragm thickness and waveguide position in silicon-based guided-wave optical accelerometer

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Our group has developed a silicon-based guided-wave optical accelerometer with a proof mass centered on a diaphragm. The accelerometer can be used to detect abnormal vibration due to malfunction, and monitor machine operations even in harsh environments, such as industrial plants and nuclear power plants. For this type of accelerometer, sensitivity is strongly suggested to be related to waveguide position, diaphragm dimensions, and size and weight of proof mass. In this study, sensitivity dependences on waveguide position and diaphragm thickness were considered experimentally. In order to investigate sensitivity dependence on waveguide position, an accelerometer with 17 straight waveguides spaced 0.25 mm apart on both sides of a diaphragm was fabricated. Dimensions of the diaphragm and proof mass were 10 mm x 10 mm x 50 μm and 5 mm x 5 mm x 250 μm, respectively. For each waveguide, output power, as a function of static force directly applied on the proof mass and substituting for inertial force due to acceleration, was measured using a He-Ne laser at 633 nm. From the measured output power vs. applied force characteristics, half-wave phase and force sensitivity were evaluated. The highest sensitivity of 0.45 rad/mN was obtained for the waveguide at the diaphragm edge. Moreover, in order to examine sensitivity dependence on diaphragm thickness, three accelerometers with different thicknesses, 50, 60, and 70 μm, were fabricated. The measured phase sensitivities for the waveguide located nearest to the diaphragm edge were 0.54, 0.37, and 0.28 rad/mN for thicknesses of 50, 60, and 70 μm, respectively. Measured sensitivity was found to be inversely proportional to the square of the diaphragm thickness.

7941-26, Session 6

Design of amorphous nanostructured photonic waveguides for chemical sensing in the visible and near-UV

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While extensive research has been conducted on the development and analysis of integrated photonic chemical sensors in the IR and near-IR regions, there has been relatively little work done in the visible and near-UV mostly due to the substantial absorption of group-IV and III-V materials in that wavelength range. This work focuses on the design of novel, nanoscale photonic architectures and materials for the application of enhanced chemical sensing in these wavelength regions. Specifically, this project uses ammonia (NH3) and dichloromethane (CH2Cl2) as the study analytes and focuses on platforms composed of amorphous zinc oxide (a-ZnO) and amorphous hafnium dioxide (a-HfO2). Having an effective bandgap of 3.37 eV and 5.8 eV, respectively, and grown by rf sputtering on a wide variety of substrates at low temperature, a-ZnO and a-HfO2 are highly compatible with standard photonic device fabrication processes. Utilizing a low optical overlap mode (LOOM) architecture, in which only 1% of the optical mode resides in the core region, we predict a markedly higher sensitivity than conventional evanescent wave sensors - upwards of 80%.

In this work we have invoked analytical models for the modal profiles using single and dual stage effective index methods and compared these results with those obtained via finite element modeling (FEM) and semi-vectorial beam propagation methods (BPM). All modal findings were in excellent agreement and further propagation analysis by finite difference time domain (FDTD) modeling demonstrated excellent performance for a wide range of structural designs displaying excellent fabrication tolerance.

7941-27, Session 7

New tracks toward 3D light harnessing: high Q Slow Bloch mode engineering and coupling to 0D nanophotonic structures

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In this study, we fabricate the liquid crystal waveguides by infiltrating modulators, vertical tapers and V-grooves. Through-silicon vias (TSVs) wafer encapsulation or wafer-level packaging. Therefore, we present a packaging concept based on either chip-on-board or chip-on-wafer technology. Packaging tends to dominate the total cost of optoelectronic modules. Reliability and manufacturing costs.

First, we will present results from a phenomenological approach (coupled mode theory in the time domain) of this mixed device. We derive the key factors that govern the coupling processes and show that high Q PC structures are required for efficient coupling. The design rules for the production of PC structures providing high Q resonant slow Bloch modes above the light line are presented, on the basis of 2D and 3D FDTD simulation results. We will end the presentation with the 3D FDTD simulation of the mixed structure (PC+NA), confirming the prediction of the coupled mode theory. Preliminary technological realization will be presented, together with a discussion on potential applications for optical trapping.

7941-28, Session 7
GaAs-SOI integration as a path to low-cost optical interconnects
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We present a concept where GaAs chips with dilute nitride (InGaAsN) and quantum dot (QD) optoelectronics is hybrid integrated on a silicon-on-insulator (SOI) waveguide platform and packaged into low-cost modules using silicon as the packaging material. The approach aims to offer high energy efficiency, low cost and high bandwidth for optical interconnects operating at 1.2-1.3 µm wavelengths. It presents single-mode technology that could bridge the gap between long and short range optical communication.

In particular, we present our latest results in SOI waveguide technology, dilute nitride optoelectronics and InGaAs QD optoelectronics. We then present the design and experimental results from the hybrid integration of optoelectronic chips on SOI. Studied devices include laser diodes with 135 K characteristic temperature, 40 GHz mode-locked lasers, comb lasers, semiconductor optical amplifiers and electro-absorption modulators. These allow one to implement efficient light sources, to share them between multiple communication channels, to modulate the signals and to actively route optical data packets within an optical interconnect network. Special attention is given to coupling loss and backreflection minimisation, alignment tolerances, heat dissipation, bond reliability and manufacturing costs.

Packaging tends to dominate the total cost of optoelectronic modules. Therefore, we present a packaging concept based on either chip-on-wafer encapsulation or wafer-level packaging. Through-silicon vias (TSVs) provide DC and RF contacts to the outside world. Low-loss fiber coupling with ultra-wide-bandwidth can be obtained with monolithically integrated vertical tapers and V-grooves.

7941-29, Session 7
Liquid-crystal infiltrated hollow waveguide modulators
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In this study, we fabricate the liquid crystal waveguides by infiltrating liquid crystal E7 into hollow waveguides. The reorientation of the high susceptibility of liquid crystals molecular is achieved by applying the external fields to change the optical characterization of the liquid crystal waveguides. By using the total internal reflection, the structure is based on the waveguide in which the cladding layer is SiO2 layer. By applying external voltage to the SiO2-cladded waveguide, the output intensity decreases with the increase of the applied voltage. This phenomenon is polarization-independent. The devices can serve as an electrically tunable liquid crystal modulator or attenuator with over 30dB attenuation at 5Vpp.

7941-31, Session 7
Coupling of lithium niobate disk resonators to integrated waveguides
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Whispering gallery mode (WGM) disk resonators fabricated in single crystals can have high Q factors within their transparency bandwidth and may have application both in fundamental and applied optics. Lithium niobate (LN) resonators thanks to their electro-optical properties may be used in particular as tunable filters, modulators, and delay lines. A critical step toward the actual application of these devices is the implementation of a robust and efficient coupling system. High index prisms are typically used for this purpose. In this work we demonstrate coupling to high-Q WGM LN disks from an integrated optical LN waveguide. The waveguides are made by proton exchange in X-cut LN. The disks with diameters of 5 mm and thickness of 1 mm are made from commercial Z-cut LN wafers by core drilling a cylinder and thereafter polishing the edges into a spheroidal profile. Both resonance linewidth and cavity photon lifetime measurements were performed to calculate the Q factor of the system.

7941-33, Session 8
Plasmonics: the next ten years
H. A. Atwater, Jr., California Institute of Technology (United States)

Since 2000, intensive research on plasmonic light localization in metal-dielectric nanostructures has enabled a truly nanoscale photonics discipline. Two factors have stimulated progress: widespread use of quantitative full field electromagnetic modeling and wide availability of powerful tools for nanostructure fabrication. We now have a good understanding of plasmonic modes and coupling from/to free space and localized waveguide modes, and recently, first examples of active plasmonic materials and devices that enable gain, carrier excitation and complex index modulation. What will the next ten years bring? First, powerful design and simulation methods will enable almost seamless integration of plasmonic and hybrid plasmonic/CMOS devices in Si photonic networks with low insertion loss between plasmonic and Si photonic components. Second, integration of new materials into plasmonic systems with large refractive index modulation will enable ultracompact plasmonic modulators with large dynamic range. Third, plasmonic optical metamaterials appear poised to enable comprehensive control of complex refractive index in both spatial and frequency domains.

7941-34, Session 8
Rigorous characterization of surface plasmon modes by using the finite element method

Nanoplasmonic devices and Photonic crystal (PC) are two major approaches in nanophotonics. Among plasmonic devices, nano-antennas (NA's) have proved that light could be ultimately confined in nanometric volume. However, the coupling of these devices from free space is not a trivial task and is usually done by focusing a Gaussian beam to its diffraction limit. On the other hand, the existence of slow Bloch mode above the light line in PC structures, leads itself to a very efficient resonant coupling using wide beam. We will show in this presentation that a new approach combining PC and NA allows for an efficient addressing of NA using a wide Gaussian beam. The PC structure acts here as an electromagnetic feeder to the NA.

We present a concept where GaAs chips with dilute nitride (InGaAsN) and quantum dot (QD) optoelectronics is hybrid integrated on a silicon-on-insulator (SOI) waveguide platform and packaged into low-cost modules using silicon as the packaging material. The approach aims to offer high energy efficiency, low cost and high bandwidth for optical interconnects operating at 1.2-1.3 µm wavelengths. It presents single-mode technology that could bridge the gap between long and short range optical communication.

In particular, we present our latest results in SOI waveguide technology, dilute nitride optoelectronics and InGaAs QD optoelectronics. We then present the design and experimental results from the hybrid integration of optoelectronic chips on SOI. Studied devices include laser diodes with 135 K characteristic temperature, 40 GHz mode-locked lasers, comb lasers, semiconductor optical amplifiers and electro-absorption modulators. These allow one to implement efficient light sources, to share them between multiple communication channels, to modulate the signals and to actively route optical data packets within an optical interconnect network. Special attention is given to coupling loss and backreflection minimisation, alignment tolerances, heat dissipation, bond reliability and manufacturing costs.

Packaging tends to dominate the total cost of optoelectronic modules. Therefore, we present a packaging concept based on either chip-on-wafer encapsulation or wafer-level packaging. Through-silicon vias (TSVs) provide DC and RF contacts to the outside world. Low-loss fiber coupling with ultra-wide-bandwidth can be obtained with monolithically integrated vertical tapers and V-grooves.

Conference 7941: Integrated Optics: Devices, Materials, and Technologies XV
Surface plasmons are confined to the surfaces which interact strongly with the electromagnetic waves. They occur at the interfaces where the relative permittivity of the bounding materials is of opposite sign. It is well known that some metals and highly doped semiconductor shows highly negative relative permittivity and a structure with a dielectric cladding supports surface plasmon modes. These modes decay exponentially, they can be highly localized and can also be confined inside a sub-wavelength size guided wave structure.

Plasmon-induced transparency in subwavelength metal-dielectric-metal waveguides

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Plasmonic devices, based on surface plasmons propagating at metal-dielectric interfaces, have shown the potential to guide and manipulate light at deep subwavelength scales. In addition, slowing down light in plasmonic waveguides leads to enhanced light-matter interaction, and could therefore enhance the performance of nanoscale plasmonic devices such as switches and sensors. In this paper, we introduce slow-light subwavelength plasmonic waveguides based on a plasmonic analogue of electromagnetically induced transparency (EIT). Both the operating wavelength range and the slowdown factor of the waveguides are tunable. The structure consists of a periodic array of two metal-dielectric-metal (MDM) stub resonators side-coupled to a MDM waveguide. The two cavities in each unit cell have a resonant frequency separation which can be tuned by adjusting the cavity dimensions. We show that in the vicinity of the two cavity resonant frequencies, the system supports three photonic bands, and the band diagram is similar to that of EIT systems. The middle band corresponds to a mode with slow group velocity and zero group velocity dispersion in the middle of the band. Decreasing the resonant frequency separation, increases the slowdown factor, and decreases the bandwidth of the middle band. We also find that metal losses lead to a tradeoff between the slowdown factor and the propagation length of the supported optical mode. We use a single-mode scattering matrix theory to account for the behavior of the waveguides, and show that it is in excellent agreement with numerical results obtained with the finite-difference frequency-domain method.

Proper definition of mode size for novel nanoscale waveguides from crosstalk and nonlinearity point of views

J. Shin, Y. Lee, KAIST (Korea, Republic of)

Metals have electric permittivity that is very large in magnitude and negative in sign. These two aspects gave birth to a fast growing field of plasmonics or metallic nano-optics. The strong light localization property of metallic nanostructures makes them potentially very useful for integrated optics applications, especially as waveguides of deep-subwavelength dimensions. So far, various designs have been proposed and their properties are theoretically, numerically, and experimentally studied. However, there has not been a universal definition of the transverse dimension or the mode size of plasmonic waveguides or other novel dielectric waveguides with subwavelength features (such as slot waveguides) that is agreed upon among all researchers in the field. This resulted in confusions and debates. One of the popular choices is the maximum electric field-based definition. Some authors asserted that they achieved deep-subwavelength scale confinement using only dielectric materials in the slot waveguide geometry, using this definition. This definition has some justifications but can also lead to wrong conclusions especially as the slot width decreases. Thus, a new definition of mode size is needed.

A proper definition depends on the application fields: integrated optics, nonlinear optics, quantum optics, etc. In integrated optics, mode size is important in the sense that it determines how many devices can be integrated on the given area while avoiding crosstalks. In nonlinear optics, a proper measure of mode size can help compare different waveguide geometries for nonlinearity enhancements. Here, the authors introduce a set of well-defined mode size measures and compare their usefulness from the perspectives of integrated optics and nonlinear optics.

Linear and nonlinear resonant effects in metallic arrays of sub-wavelength channels

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We investigate on the interaction of surface plasmon modes with TEM, Fabry-Perot-like cavity modes in arrays of sub-wavelength slits. A full control on the transmission process, which is mostly dictated by the geometrical parameters of the array, such as the slit length and width as well as the separation between the slits, is achieved and explained. The effects of the interaction of pure cavity modes and surface modes lead to the formation of an energy band gap, i.e. a spectral band where a drastic inhibition of transmission is induced by the coupling and back-radiation of the smooth-interface, unperturbed surface plasmon. As in classic photonic band-gap structures, the edges of this gap are characterized by the enhancement of the electromagnetic fields, and by a pi-shift in the phase of the transmission function. Such strong field localization in subwavelength regions boosts the nonlinear response of the structure. The mere assumption that the metal is nonlinear via Coulomb and Lorentz contributions, and the introduction of high-index, nonlinear media, such as III-V semiconductors, introduced in the sub-wavelength channels opens a cross-coupling of TE and TM polarizations for both pump and harmonic signals and makes it possible to generate both TE- and TM-polarized fields. These fields are generated even under high-absorption conditions, and survive thanks to a phase locking mechanism that sets in between the pump and its harmonics.

Characteristics and applications of rectangular waveguide in sensing, slow light, and negative refraction

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Rectangular waveguide is a very promising structure for different applications. It has some unique characteristics that allow for wide range of application including slow and fast light, metamaterial, low loss energy transmission, and sensing. The resemblances and differences between this waveguide configuration and metal-insulator-metal (MIM) are discussed in this paper. A Description of the guided modes and their operating band is also given. We also studied the characteristics of the fundamental TM-like mode of this structure for the first time. Its potential application in sensing and slow loss energy transporting is also demonstrated. The effect of the design parameters on the performance of the rectangular waveguide is illustrated for different application. Slow light and negative refraction effects using this waveguide design using TE-like mode is also demonstrated. Different designs are proposed using this structure for these different applications. Square shape design allow for polarization insensitive applications which is one of the unique characteristics of the configuration.
Diffractive and subwavelength waveguide structures and their applications in nanophotonics, sensing, and spectroscopy

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We review recent advances in diffractive and subwavelength structures in silicon-on-insulator waveguides. First, we present a new type of photosensitive waveguide, exploiting the subwavelength grating (SWG) effect. We demonstrate subwavelength grating waveguides made of silicon, including practical components operating at telecom wavelengths: input couplers, waveguide crossings and microspectrometer chips. The SWG technique allows for engineering refractive index of a waveguide core over a range as broad as 1.5-3.5 simply by lithographic patterning using only two materials, e.g. Si and SiO2. This technique circumvents an important limitation in integrated optics, which is the fixed value of the refractive indices of the constituent materials in the absence of active tuning mechanisms. A SWG fibre-chip coupler for Si-wire waveguides is presented with a loss as small as 0.9 dB and with minimal wavelength dependence over a broad wavelength range exceeding 200 nm. It is also shown that the SWG waveguides can be used to make efficient waveguide crossings with minimal loss and negligible crosstalk. Furthermore, we present a diffractive surface grating coupler with subwavelength nanostructures designed for silicon-wire biological sensors with excellent surface sensitivity and spiral designs that allow these sensors to be densely arrayed for compatibility with conventional microarray spotters. Finally, the first surface grating couplers for a silicon ridge waveguide of micrometer dimensions are reported, including an implementation in a multi-aperture Fourier-transform spectrometer chip presently under development for environmental sensing from microsatellites.

Long period and fiber Bragg gratings written within the same fibre for sensing purposes

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Long period gratings (LPGs) have been recently proposed as sensing elements of chemical/biochemical compounds, exploiting their sensitivity to the refractive index changes in the surrounding environment. One of the difficulties of their utilization for this purpose comes from their strong dependence also to strain and temperature effects. An intrinsic optical feedback to eliminate these effects has been developed by manufacturing on the same fiber on which the LPG is written, a fiber Bragg grating (FBG) which is immune from refractive index changes external to the fiber and is influenced by strain and temperature. A KrF excimer laser is used to write both the gratings into the same photosensitive fiber. The FBG is written with the phase mask technique and the LPG point-by-point by means of a motorized translation stage. Furthermore, we present a diffractive surface grating coupler with subwavelength nanostructures designed for silicon-wire biological sensors with excellent surface sensitivity and spiral designs that allow these sensors to be densely arrayed for compatibility with conventional microarray spotters. Finally, the first surface grating couplers for a silicon ridge waveguide of micrometer dimensions are reported, including an implementation in a multi-aperture Fourier-transform spectrometer chip presently under development for environmental sensing from microsatellites.
Optical current sensors comprised of polymeric waveguide components

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Optical current sensors are indispensable devices for the accurate monitoring of large electrical currents in environments suffering from severe electromagnetic interference. In this work, integrated optical current sensors are demonstrated based on polarization rotated reflection interferometry by incorporating polymeric optical waveguide components. Polarization maintaining 3-dB couplers, TE-pass waveguide polarizers, thermo-optic phase modulators and half-wave plates are designed and fabricated on a Si wafer as a single chip with small dimensions. The integrated optical devices are useful to increase their production efficiency and improve the sensor performance. The phase difference between the two circularly polarized waves imposed by the Faraday effect of the optical fiber is detected using the interferometric optical sensor consisting of the polymeric components. To remove the bending induced birefringence, the optical fiber wound around a ceramic frame is annealed at 850°C for 24 hours. The reflection interferometer comprising the polymer waveguide components operates with good linearity proportional to the monitoring current. In the experiment of electrical current measurement, the optical signal exactly follows the 300 A, 5 kHz rectangular waveform source current. The linearity of the output signal is within 1% up to 300 A until the limit of the high current pulse generator.

Waveguide integrated plasmonic platform for sensing and spectroscopy

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Plasmonic nano-antennas are attractive platforms for applications such as gas sensing, bio-sensing and Raman spectroscopy due to enhanced electric fields and small mode volumes. On the other hand, free space excitation and collection to and from nano-antennas are poor. For example, collection efficiency with a high NA objective from a nano-antenna on a silicon substrate is only about 2%. In this work, we propose a waveguide integrated plasmonic platform in order to deliver excitation power to and collect signal efficiently from a nano-antenna. The system consists of a silicon waveguide with an integrated nano-antenna and a fiber spot size converter coupled to the waveguide. The nano-antenna is designed to have a broad resonance around 1.5 microns with an estimated surface enhanced Raman scattering (SERS) enhancement of 7 orders of magnitude. The nano-antenna is impedance matched to the waveguide with an excitation/collection efficiency of 80% which greatly reduces the pumping power needed to get similar levels of Raman signal in free space coupled systems. The device was fabricated on a silicon-on-insulator wafer. The antenna was defined 150 nm deep inside the 220 nm thick silicon waveguide layer by successive e-beam lithography, RIE and gold evaporation steps. Then an SU8 spot size converter with 2x4 um dimensions was fabricated on top of the silicon waveguide to provide mode matching with the 4.5 um diameter core of the optical fiber. The proposed and fabricated device can be used for a number of applications: on-chip SERS spectroscopy and single photon sources with high out-coupling efficiency.
Enhanced light transmission through a metallic nanolens consisting of multiple nano-rings

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We investigated light transmission based on a metallic nanolens for imaging applications. The nanolens consists of multiple nano-rings formed in a thin metal film. Four types of nanolens structures in a 50-nm thick gold film were simulated using rigorous coupled-wave analysis. Each nanolens was modeled with two or three nano-ring apertures concentric with a single nanohole in the center of the ring apertures and two or three concentric nano-ring apertures without a center nanohole. Each nanolens is designed to operate as a lens that focuses transmitted light, which was confirmed by the numerical results. The electromagnetic field intensity, after transmission onto a focus through each nanolens, varied depending on a specific design and was calculated as 11-23 times enhanced compared to incident light. Also, imaging characteristics of the four types of considered nanolens designs were considered by calculating device parameters such as focal length, lateral full-width-half-maximum (FWHM), and depth-of-focus (DOF). Focal length was adjustable between 2.3-3.1 μm from the surface. Lateral FWHM was calculated as 305-365 nm. Numerically determined DOF was fairly large in the range of 1200-1660 nm. Lateral numerical aperture was obtained for a nanolens as 1.42-1.7, which is higher than that of a conventional water-immersion lens. A nanolens is expected to be useful for various nano-imaging applications in optofluidic system investigation, biomedical imaging, nanolithography, and optical data storage.

Analytical modeling of plasmonic-waveguide-based devices for nanophotonic applications

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The design and realization of chip-scale plasmonic devices has been considerably facilitated by computational electromagnetic simulations and sophisticated nanofabrication techniques. For rapid device optimization, numerical simulations should be supplemented by simple analytical expressions capable of providing a reasonable estimate of initial design parameters. In this work, we present several analytical models that describe transmittance of metal-dielectric-metal (MDM) plasmonic-waveguide-based devices consist of side-coupled stub structures. Employing the physical similarity between single-mode MDM waveguides and microwave transmission lines, we formulate a unique mapping between the parameters of an MDM waveguide coupled to a single stub and characteristic impedances of an equivalent transmission-line network. By application of standard network-analysis tools, we then derive analytical expressions for transmittance of waveguides with single, double, and periodic stub structures. The advantage of our analytic approach over the previous studies is in accounting for the plasmon damping due to Ohmic losses and reflection-induced phase shift at the stub end. We find that the analyzed waveguide configurations can exhibit the characteristics of submicron optical filters. Another interesting situation that is worth studying arises when the stubs form a Bragg grating with a specific period of half the guided wavelength. Thus transmission characteristics of plasmonic Bragg reflector at 1550-nm wavelength are also discussed using the proposed analytical techniques. We validate our analytical models by comparing their predictions with the results of finite-difference time-domain simulations. The proposed theoretical results are particularly useful to reduce lengthy simulation times and will prove valuable in designing and optimizing MDM-waveguide-based photonic devices.

Effects of amplitude and timing jitter on the performance of photonic sigma-delta modulators

Y. W. Tan, C. H. Nam, P. E. Pace, Naval Postgraduate School (United States)

Photonic sigma-delta modulators can directly digitize wideband signals with high resolution directly at the antenna. In our first-order, single-bit architecture, the antenna signal is applied to a pair of Mach-Zehnder interferometers and oversampled using a CALMAR 10 GS/s mode-locked laser (MLL) with a pulse width of 10 ps. The measurements of the MLL pulse-to-pulse sample time uncertainty (time jitter) and the laser pulse amplitude uncertainty (amplitude jitter) are described. Considering the jitter to be the result of non-uniform random sampling we show that a normal distribution is a good noise model for both jitter mechanisms. The sigma-delta modulator and the decimation filtering process are described. Using asynchronous spectral averaging of the reconstructed signal’s magnitude spectrum, an expression for the noise floor without jitter is developed and compared to simulation results as a function of the oversampling ratio (OSR) and record length using a 100 MHz signal bandwidth. The noise floor is then evaluated as a function of the time jitter power and amplitude jitter power for several OSRs.
NOC building blocks include: (a) the OXS employing AVC structures, (b) crossconnects. The proposed AVC-based switching technique is less based on ring resonators our approach employs AVCs at the switching photonic integrated circuits (PICs). While recent photonic NOCs are recent advances in CMOS photonics, and by development of large-scale the overall power consumption. This is possible as power is consumed Moreover, the photonic NOC approach is able to significantly reduce vertical coupler (AVC) structures. The use of this photonic NOC layer will on the optical cross-point switches (OXSs) implemented using active interfaces, (ii) multiple 3D memory layers that provide the bulk of on-chip multi-core processor layer that host multiple heterogeneous processing architecture. This architecture is composed of the following layers: (i) the we propose a three-dimensional integrated (3DI) photonic NOC chip design approach, power efficiency, limited bandwidth and low stringent requirements that these applications place on the photonic interconnection, especially for large number of connections. The DMD device allows one to route the signals dynamically. Due to the large number of individual mirror elements in the DMD, different optical path configurations are possible, thus offering the chance for optimizing the network configuration. The optimization is achieved by using an evolutionary algorithm for finding best values for a skewless parallel interconnection. Here, we present results of the optimization and experimental examples for the use of the PIFSO/DMD-setu. 

Free-space-wave add/drop multiplexing for WDM optical-interconnect system in package
S. Ura, Kyoto Institute of Technology (Japan); K. Kintaka, National Institute of Advanced Industrial Science and Technology (Japan)
This is an Invited Talk.

Three-dimensional crossbar interconnection using planar-integrated free-space optics and digital mirror-device(TM)
U. Lohmann, J. Jahns, Univ. of Hagen (Germany); S. Limmer, D. Fey, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)
We consider the implementation of a dynamic crossbar interconnect using planar- integrated free-space optics (PIFSO) and a digital mirror-device(TM) (DMD). Because of the 3D nature of free-space optics, this approach is able to solve geometrical problems with crossings of the signal paths that occur in waveguide optical and electrical interconnection, especially for large number of connections. The DMD device allows one to route the signals dynamically. Due to the large number of individual mirror elements in the DMD, different optical path configurations are possible, thus offering the chance for optimizing the network configuration. The optimization is achieved by using an evolutionary algorithm for finding best values for a skewless parallel interconnection. Here, we present results of the optimization and experimental examples for the use of the PIFSO/DMD-setu.

Photonic switching for reliable nanoscale three-dimensional integrated network-on-chips
I. B. Djordjevic, The Univ. of Arizona (United States)
As the multi-core architecture is becoming a prevailing high-performance chip design approach, power efficiency, limited bandwidth and low reliability have been recognized as major communication bottlenecks for on-chip networks (NOCs). To simultaneously tackle the above problems, we propose a three-dimensional integrated (3DI) photonic NOC architecture. This architecture is composed of the following layers: (i) the multi-core processor layer that host multiple heterogeneous processing cores together with corresponding local memories and network interfaces, (ii) multiple 3D memory layers that provide the bulk of on-chip memory, and (iii) photonic NOC layer. The photonic NOC layer is based on the optical cross-point switches (OXSs) implemented using active vertical coupler (AVC) structures. The use of this photonic NOC layer will provide ample bandwidth at reduced latencies along with high reliability. Moreover, the photonic NOC approach is able to significantly reduce the overall power consumption. This is possible as power is consumed only when the photonic switching cell is ON. This idea was inspired by recent advances in CMOS photonics, and by development of large-scale photonic integrated circuits (PICs). While recent photonic NOCs are based on ring resonators our approach employs AVCs at the switching crossconnects. The proposed AVC-based switching technique is less lossy and, more importantly, insensitive to temperature when compared to similar devices such as micro-ring resonators. The basic photonic layer NOC building blocks include: (a) the OXS employing AVC structures, (b) DFB lasers/VCSELs, (c) Mach-Zehnder silicon optical modulators, (d) SiGe photodetectors, (e) arrayed waveguide grating in silicon to perform wavelength multiplexing/demultiplexing, and (f) silicon waveguides.

Low-power high-speed SerDes with new dynamic latch and flip-flop for optical interconnect in 180 nm CMOS technology
J. Sangirov, A. I. Ukaegbu, T. Lee, M. H. Cho, H. Park, KAIST (Korea, Republic of)
A low power high-speed serializer/deserializer (SerDes) has been designed using new dynamic D-latch for the optical link in multipoint-to-multipoint data transmission architecture. As the SerDes is one of key components of serial communication architecture for high-speed optical interconnect. The power consumption of SerDes has been considered as major issue and it has been a step forward to reducing its power consumption for a low-power photonic on-chip interconnect. Here, we present results of the optimization and experimental examples for the use of the PIFSO/DMD-setu. 

Devices and architectures for large scale integrated silicon photonics circuits
R. G. Beausoleil, A. Faraon, D. Fattal, M. Fiorentino, Z. Peng, C. M. Santori, Hewlett-Packard Labs. (United States)
Silicon photonics, with its promise of large scale integration and low cost, is poised to revolutionize data links at scales ranging from the chip to the datacenter. Many groups have introduced DWDM nanophotonics architectures based on silicon photonic. Here we focus in particular two architectures based on microring resonator modulators and detectors: an on-chip interconnect for a many-core processor (Corona) and a high-radix photonic switch for an exascale datacenter network (HyperX). The stringent requirements that these applications place on the photonic circuit performance require a careful optimization of the devices’ design and fabrication strategies of large scale integrated circuits. The key technological constraints stem from the need to use DWDM to fulfill bandwidth requirements. DWDM requires modulation, multiplexing, and demultiplexing of sources with closely spaced frequencies. Ring resonators are well suited for DWDM applications but present a series of challenges because the difficulties in controlling their performance parameters such as the resonant frequency, quality factor, and extinction ratio. For example, while it is possible to actively control the resonant frequency (e.g. by temperature tuning) the amount of tuning necessary has a large impact of the system power consumption. Fabrication parameters also affect other properties of the rings such as the extinction ratio that have a large impact on the design of the integrated electronic-photonic circuit. We will present our efforts to study the effect of fabrication variations on the ring parameters and the effect of these
variations on system performance as well as ways to mitigate these effects.

7942-04, Session 2

CMOS compatible waveguides for all-optical signal processing

D. J. Moss, The Univ. of Sydney (Australia)

All-optical signal processing chips provide the promise of cheaper, faster and more energy efficient operation that will complement and enhance electronic integrated circuits for both telecom and computing applications. The challenge is to realize these in a platform compatible with CMOS technology, and in devices with linear and nonlinear optical characteristics good enough to achieve low power operation. I will review our results of the past year on nonlinear optics in a CMOS compatible platform, including four-wave mixing, supercontinuum generation, parametric gain and time-lens imaging.

7942-31, Session 2

Pure silicon - high performance: advanced optical receivers in standard silicon BiCMOS technologies

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We present the state of the art of integrated silicon photodetectors and circuits by concentrating on the progress in the last decade. Especially three highlights of own work will be presented in more detail.

In this paper a vertical pin-photodiode in a 0.8µm BiCMOS technology, consisting of an n-buried cathode, an n-epilayer, and a p+ anode will be discussed. The measured responsivities for different wavelengths were 0.26/A/W @ 850nm and 0.36/A/W @ 660nm, respectively. Really outstanding is the reached speed of the photodiodes, the -3dB cut-off frequencies of these 50x50µm² diodes were depending on the reverse bias voltage up to 2.1GHz @850nm light, and up to 3GHz @660nm light.

This high performance photodiode allows the competition of pure silicon optoelectronic integrated circuits (OEICs) even with GaAs OEICs. A silicon OEIC reaching at 2.5Gb/s [1] a higher sensitivity than a GaAs OEIC [2]. It also consumes less power and a remarkable smaller chip area.

Highly parallel integration of optical receivers enables also extremely high data rates via parallel optical receivers. A new OEIC consisting of 45 parallel channels with a data rate of 5Gb/s @850nm each allows an overall data rate of 225Gb/s.


7942-32, Session 2

High-speed CMOS optical communication using silicon light emitters

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Silicon forms the backbone of most modern integrated circuits, with CMOS representative in circuits ranging from cellphones to mainframe CPUs. Optical communication between chips is a long desired functionality promising to solve a number of interconnect related bottlenecks. The marriage between CMOS and optics therefore presents a lucrative combination supported by numerous research efforts in this field. However, an efficient silicon light source still represents the missing link to ensure the feasibility of commercial silicon photonics.

In this paper, we discuss our recent advances towards a complete silicon optical communication solution. We prove that transmission of baseband data at multiples of megabits per second rates are possible using improved silicon light sources in a completely native standard CMOS process with no post processing. Techniques for improving the internal and external quantum efficiency of silicon light emitters are used to enhance the emission of sources operating on the principle of avalanche photoluminescence. The CMOS die is aligned to a fibre end and directly modulated with driver circuitry. The signal is transmitted to a silicon APD module where subsequent amplification and filtering results in a detectable electrical signal. Signal detectability is proven through eye diagram measurements.

The results show an improvement of more than tenfold over some of our previous results and is also the fastest optical communication from standard CMOS light sources. As the devices are not operating at their intrinsic switching speed limit, we believe that even higher transmission rates are possible with complete integration of all components in CMOS.

7942-05, Session 3

Scaling technologies for terabit fiber optic transmission systems

D. V. Plant, McGill Univ. (Canada)

The past decade has seen profound changes not only in the way we communicate, but also in our expectations of what networks will deliver in terms of speed and. The coming decade promises to demand more capacity and bandwidth in these networks and it is in this context that we will present work on scaling technologies for terabit fiber optic transmission systems. We will discuss several topics that focus on increasing capacity in existing and next generation long-haul and metro fiber optic transmission systems that will carry tens to hundreds of terabits and will be based on coherent optical receivers.

7942-06, Session 3

Nanoparticle-enabled polymeric photorefractivity and their application in three-dimensional optical data storage

M. Gu, X. Li, Swinburne Univ. of Technology (Australia)

Semiconductor quantum dots (QDs) have been incorporated into photorefractive polymers to introduce a localized photorefractivity. Its application in two-photon (2P) induced high density optical data storage has been demonstrated as well. In particular, engineering of the surface of QDs by tuning the surface stoichiometry and using Type-II band gap separation and transfer. Thus, enhanced refractive-index modulation has been observed both in a 2P induced localized photorefractivity and in a typical two-beam coupling characterization.

7942-07, Session 3

Integration of RF-optical upconversion modules for millimeter-wave sensing and imaging systems

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Shrien, J. Macario, Univ. of Delaware (United States); C. A. Schuetz, Phase Sensitive Innovations, Inc. (United States); D. W. Prather, Univ. of Delaware (United States)

The integration of an opto-electronic mmW module for application in RF sensing and imaging is presented. Component integration consisting of ultra-broad band antennas, PIN switching, low noise amplifiers, and photonic phase modulator, is discussed. A fully integrated module working up to 130GHz is characterized and presented. Applications in distributed aperture RF imaging system are discussed.

7942-08, Session 4

Design and integration of functional plasmonic wires and devices for VLSI photonic circuit application

E. Lee, Inha Univ. (Korea, Republic of)

We report on the design and integration of functional plasmonic wires and devices for VLSI photonic integrated circuit application. We first analyze the modal, polarization, and propagation characteristics of the plasmonic wires, directional couplers, rings, and multimode interference devices. We then design and integrate coupled structures of plasmonic nano-wires and examine the optical mismatch problem between two wires. The plasmonic wires are modeled to be made of gold (Au) and silver (Ag). The plasmonic nano-wires are integrated not only among themselves but also with dielectric wires and devices made of silicon and polymer materials. We analyze the effective refractive indices of the dielectric waveguides and the plasmonic waveguides and design a guided directional coupler and other functional devices based on the matching of the effective refractive indices between two waveguides. We calculate the mode field of the individual plasmonic wires. We also calculate the even eigen-modes and odd eigen-modes of individual plasmonic wires and calculate the coupled eigen-modes to analyze the coupling characteristics between two nano-waveguides, either of the same or different materials. We find that, for the even mode, the magnetic field has the same direction in all the position while the odd mode has opposite field direction on the two nano-waveguides. We also examine the polarization-dependent behavior of the energy transfer between wires in terms of the optical impedance matching. We study three different forms of plasmonic structures: Single plasmonic wire, slot plasmonic wire, and stripe plasmonic wire. We identify the modal, polarization, and propagation characteristics of each waveguide by varying the sizes and dimensions of the structures and examine the propagation characteristics and coupling characteristics of the three structures from the point of view of optical impedance mismatch. We then examine the possibility of using these structures for the purpose of making functional plasmonic devices for VLSI photonic circuit application.

7942-09, Session 4

Nanophotonic devices and circuits

M. P. Nezhad, A. Simic, O. Bondarenko, B. A. Slutsky, A. Mizrahi, Y. Fainman, Univ. of California, San Diego (United States)

Advances in nanoscale fabrication techniques in dielectric and metallic material systems has opened up new opportunities in photonics and plasmonics for solving long standing problems in information systems and telecommunication systems. Optics in general has the potential to solve some of the most demanding problems in information systems. It promises crosstalk-free interconnects with essentially unlimited bandwidth, long-distance data transmission without skew and without power- and time-consuming regeneration, miniaturization, parallelism, and efficient implementation of important algorithms. The current optical technology is costly, bulky, fragile in their alignment, and difficult to integrate with electronic systems, both in terms of the fabrication process and in terms of delivery and retrieval of massive volumes of data the optical elements can process. Our most recent work emphasizes the construction of nanophotonic optical devices and circuits directly on-chip, with the same lithographic tools as the surrounding electronics. This has been made possible by the advances in these tools, which can now create features significantly smaller than the optical wavelength. Arranged in a regular pattern, subwavelength features act as a metamaterial whose optical properties are controlled by the density and geometry of the pattern and its constituents.

To advance this technology, investigations of nanostructures and their interaction with electromagnetic field are critical. Engineers also need appropriate modeling and design tools, new fabrication recipes, and test instruments capable of characterizing on-chip components. In this talk, we discuss some of the metamaterials and devices that have recently been demonstrated in our lab. These include metamaterials with space variant polarizability to realize on-chip, frequency-selective resonators and Bragg gratings, metal-dielectric nanostructures that can achieve extremely tight field confinement, as well as a metal-semiconductor-dielectric nanolaser.
for the dispersion measurement of long-fiber samples, typically longer than one meter or several tens of centimeters. In this paper we report experimentally measured chromatic dispersion coefficient spectrum of a silicon nano-waveguide of 5 mm length with a white-light Mach-Zehnder interferometry method.

7942-28, Poster Session

Measurement of the refractive index of liquids in magnetic field using common-path optical coherence tomography

H. Yim, E. Lee, S. Lee, S. Park, B. O, Inha Univ. (Korea, Republic of)

We present a measurement system of liquids refractive index based on a common-path spectral domain optical coherence tomography (OCT). Our measurement system is consisted of the circulator, broadband light source, spectrometer and sensor head. The sensor head is composed of metal mirror, fiber connector and small air gap between the mirror and the fiber end. The reflected spectrum is measured in air and liquids. In air measurement, the IFFT signal of measured spectrum gives only one peak near the mirror by the air gap. On the other hand, in liquid measurement, the mirror peak is shifted to the longer distance by the liquid refractive index. Therefore, we can calculate the refractive index of liquid using the shifted peak distance. We measure the refractive index of some liquids. The refractive index of distilled water and ethanol is 1.3468 and 1.3635 in 1550 nm. The refractive index of some liquids such as methanol, acetone and index matching oil will be discussed in presentation.

7942-29, Poster Session

Design of optical H-tree network for on-chip CMOS clock distribution

S. An, S. Lee, B. O, K. Kim, S. Park, E. Lee, Inha Univ. (Korea, Republic of)

We report on a design of an optical network for on-chip CMOS global clock distribution. The proposed optical network consists of a series of H-tree shaped waveguides containing a 1x2 power splitter and a 45°-micro mirror structure at the terminal nodes for the out-of-plane light coupling to the photodetector. The optical H-tree network receives an optical clock signal from an external source and the launched clock signal is divided and distributed equally to the terminal nodes. We assumed the CMOS chip size of 1x1cm² with 64 terminal nodes of optical network and an optical wavelength of 850nm. By using the wavelength of 850nm, silicon can be used as a detector material. The waveguide medium is set to polymer material to be fabricated by simple embossing process with an additional benefit of simultaneous fabrication of 45°-micro mirror structures. The refractive index difference between the core and cladding is more than 0.1, which enables a tight waveguide bending of as small as 500μm bending radius. The calculated network loss is about 23dB. The initial launch power is assumed to 13dBm and the photodetector sensitivity is -15dB at 5Gbps.

7942-30, Poster Session

Design of a directional-coupler-type active switch based on plasmonic nanostrip waveguides

J. Song, H. Lee, B. O, S. Lee, S. Park, E. Lee, Inha Univ. (Korea, Republic of)

The purpose of this research is to report on the design of a directional-coupler-type active switch based on plasmonic nanostrip waveguides. This device uses not only the electro-optic effects but also zero-coupling phenomenon for higher extinction ratio. Zero-coupling phenomenon means that the optical power transmission between the two parallel plasmonic nanostrip waveguides is not allowed at a certain waveguide separation because the values of the effective refractive indices of the superposed even and odd modes become the same at that waveguide separation.

For the optimized design, using 2-Dimensional Finite Element Method (FEM) we first conduct a simulation study on the beat length characteristics of the directional couplers made of plasmonic nanostrip waveguides as a function of the refractive index of the core. We found that the values of the separations which the zero-coupling phenomenon happens become smaller as the refractive index of the core increases. From the results, we designed 3D directional-coupler-type active switch. The thicknesses of metal strips and the core are 30nm and 80nm, respectively, and the waveguide width is 100nm. We set the separation between the two parallel waveguides exactly to be 56nm, which the zero-coupling phenomenon happens, when the refractive index of the core is 1.444, so the light keeps propagating along the input waveguide. In this off-state, the beat length becomes infinite. On the other hand, when we assumed that the refractive index of the core is changed to 1.644 in the on-state, the zero-coupling separation moves to 38nm. In this on-state, we find that the beat length is 14um and the optical power is transferred to the other waveguide.

This active switch will play a role as one of the basic building blocks for realization of the nanoscale photonic integrated circuits. And the zero-coupling phenomenon will be useful for the design of the plasmonic nanostrip functional devices.

7942-11, Session 5

On-chip silicon nonlinear optical circuits: letting light make decisions

J. B. Driscoll, X. Liu, J. I. Dadap, Jr., Columbia Univ. (United States); W. M. J. Green, Y. A. Vlasov, IBM Thomas J. Watson Research Ctr. (United States); W. S. Astar, The Lab. for Physical Sciences (United States) and The Ctr. for Advanced Studies in Photonics Research (United States); G. M. Carter, The Lab. for Physical Sciences (United States) and The Ctr. for Advanced Studies in Photonics Research (United States) and Univ. of Maryland, Baltimore County (United States); R. M. Osgood, Jr., Columbia Univ. (United States)

Recently the strong, ultra-fast nonlinear optical properties of Si have been harnessed to control the phase, wavelength, and timing of optical pulses propagating through Si wire waveguides on-chip. In turn, several practical applications leveraging this control for telecommunications and data processing have been demonstrated. In this talk, we briefly review these results and show their extension to more complex optical processing techniques. Interesting and subtle effects result from the use of Si wire optical properties.

7942-12, Session 5

Hybrid silicon lasers

R. G. Baets, Univ. Gent (Belgium)

No abstract available

7942-13, Session 5

Silicon photonic integrated circuits: from devices to integration

T. Liow, Q. Fang, A. E. Lim, L. Ding, Q. X. Zhang, J. Zhang, N. Duan, J. Song, F. Ren, H. Cai, S. T. H. Silalahi, M. Yu, P. G. Q. Lo,
Conference 7942: Optoelectronic Integrated Circuits XIII

D. Kwong, A*STAR Institute of Microelectronics (Singapore)

Silicon Photonics taps on the volume manufacturing capability of traditional silicon manufacturing techniques, to provide dramatic cost reduction for various application domains employing optical communications technology. In addition, an important new application domain would be the implementation of high bandwidth optical interconnects in and around CPUs. Besides volume manufacturability, Silicon Photonics also allows the monolithic integration of multiple optical components on the same wafer to realize highly compact photonic integrated circuits (PICs), in which functional complexity can be increased for little additional cost. An important pre-requisite for Si PICs is a device library in which the devices are compatibly developed around a common SOI platform. A device library comprising passive and active components was built, which includes light guiding components, wavelength-division-multiplexing (WDM) components, switches, carrier-based Si modulators and electro-absorption based Ge/Si modulators, Ge/Si photodiodes and avalanche photodiodes, as well as light emitting devices. By integrating various library devices, PIC test vehicles such as monolithic PON transceivers and DWDM receivers have been demonstrated. A challenge with Si PICs lies with the coupling of light into and out of the sub-micrometer Si waveguides. The mode size mismatch of optical fibers and Si waveguides was addressed by developing a monolithically integrated multi-stage mode converter which offers low loss together with relaxed fiber-to-waveguide alignment tolerances. An active assembly platform using MEMS technology was also developed to actively align and focus light from bonded lasers into waveguides.

7942-14, Session 6

Thin film CIGS photovoltaic modules: monolithic integration, interconnection, and packaging for low cost and high reliability

L. A. Eldada, HelioVolt Corp. (United States)

We describe the monolithic integration, interconnection, and packaging of high-efficiency photovoltaic modules based on high-uniformity Copper Indium Gallium Selenide (CIGS) thin films composed of high-quality crystals obtained with rapid and robust deposition and reaction processes performed on low-cost low-energy-consumption high-uptime capital equipment.

7942-15, Session 6

Development of a sacrificial ZnO/c-Al2O3 template approach to enable the fabrication of cost-effective, superior efficiency, InGaN-based solar cells via wafer-bonding to low cost substrates

D. J. Rogers, F. H. Teherani, Nanovation (France); V. E. Sandana, Nanovation (France) and Northwestern Univ. (United States); K. Pantzas, Georgia Institute of Technology (France); S. Gautier, T. Moudakir, Supélec (France); P. Voss, Georgia Institute of Technology (France); M. Molinari, M. Troyon, Univ. de Reims Champagne-Ardenne (France); D. McGrouther, J. N. Chapman, Univ. of Glasgow (United Kingdom); F. Jomard, Univ. de Versailles Saint-Quentin-en Yvelines (France); Z. Djebbour, Lab. de Génie Électrique de Paris (France); M. Razeghi, Northwestern Univ. (United States); A. Ougazzaden, Georgia Institute of Technology (France)

While silicon-based solar cell technologies dominate the Photovoltaics (PV) market today, their adoption remains marginal because their short, indirect, band gap severely limits the conversion efficiency and the relatively high cost per m2 of silicon wafers drives up the price of the solar cell. Recently, thin film and nanostructure-based technologies are being put forward as alternatives because they can give significantly higher efficiencies plus reduced material costs by leveraging a very small active volume of semiconductor material.

Amongst the candidate materials, InGaN-based alloys offer the highest potential solar conversion efficiency. This is because band gap engineering in InGaN spans more of the solar spectrum than any other materials system (from 0.7eV to 3.4 eV) and because the direct band gap of InGaN offers the possibility of photon recycling from radiative recombinations, which significantly enhances the potential efficiency of InGaN solar cells. Indeed, peak external quantum efficiencies over 60% have already been demonstrated. Such results have only been obtained, however, for InGaN layers grown epitaxially on c-sapphire (c-Al2O3) substrates, which are prohibitively expensive for use in solar cell applications.

We demonstrated previously that ZnO thin films grown on c-Al2O3 substrates by PLD could be used as templates for epitaxial regrowth of GaN by MOVPE. The ZnO was used as a sacrificial underlayer, allowing chemical lift-off of the GaN from the c-Al2O3 substrate. This was proposed as a step towards wafer bonding of InGaN onto conducting substrates, which would allow more efficient vertical LED structures, offering superior lifetimes and brightness.

In this study, we examine the possibility of using a similar approach to lift InGaN based solar cells off c-Al2O3 substrates in order to wafer bond them onto supports with a cost level suitable for use in solar cell applications (e.g. glass). The c-Al2O3 substrate, in this case, can be reclaimed and used again.

InGaN/GaN solar cell structures were grown on ZnO-buffered c-Al2O3 substrates by metalorganic vapour phase epitaxy (MOVPE). The dissociation of ZnO observed during conventional MOVPE growth of InGaN/GaN was combated through the use of a low pressure/temperature MOVPE approach with N2 as a carrier gas and dimethylhydrazine added to the ammonia (nitrogen precursor) in order to enhance the concentration of atomic nitrogen at relatively low temperature. Electron microscopy of cross-sections, High Resolution X-Ray Diffraction (HR-XRD), secondary ion mass spectroscopy and cathodoluminescence studies suggested that single phase wurzite InGaN layers with up to 21% indium were grown epitaxially, with no evidence of back-etching of the ZnO templates. HR-XRD also revealed highly pronounced c-axis texture for both the InGaN/GaN and ZnO. Immersion in dilute acid dissolved the ZnO such that the InGaN/GaN could be lift-off from the c-Al2O3 and wafer-bonded onto a cheaper support. Such an approach may provide a cost effective method to fabricate superior efficiency InGaN-based multi-junction concentrator PVS.

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7942-16, Session 7

Nonlinear parametric processes in photonic crystal nanostructures


We examine the control of photons in engineered photonic crystal nanostructures. First, we demonstrate the strong control of dispersion and localization in photonic crystals, leading to state-of-the-art slow-light structures, ultrahigh-Q nanocavities and zero-index superlattices. Coherent interactions in such nanostructures lead to recent observations of an optical analogue to electromagnetically-induced-transparency, and lasing cooling in chip-scale cavity optomechanics. Second, we report
our studies in nonlinear optics through the tight field confinement and long photon lifetimes in photonic crystal structures. Examples include slow-light enhanced four-wave mixing, soliton dynamics and pulse compression (together with Thales), Raman scattering, and single-photon-level nonlinearities for quantum non-demolition. Designed from first principles, these chip-scale advances have implications in ultrafast optics and communications, optical signal processing and quantum information sciences.

Record-high output power from large area photonic crystal band-edge lasers
S. Kim, S. Ahn, J. Lee, H. Jeon, Seoul National Univ. (Korea, Republic of); C. Seassal, Ecole Centrale de Lyon (France)

Enormous efforts have been devoted to develop compact and efficient laser sources, where the lasing mechanism relies on the photonic crystal (PC) effects such as a nano-cavity operating at a wavelength inside a photonic band-gap or gain enhancement at a band-edge mode. However, the issues to advance the PC lasers to practical devices, such as low output power and low fabrication throughput caused by the slow and costly electron-beam lithography, have been left unaddressed. In this study, we obtained high fiber-coupled laser output power from a large area surface-emitting -point band-edge lasers (BELs). By utilizing laser-holographic lithography, we were able to generate a large area PC pattern at high throughput. Since the BEL operation requires a large-area extended cavity, it can produce high output power. A square-lattice PC was patterned on an InAsP/InP multiple quantum wells epilayer structure bonded onto a fused silica substrate. The fabricated BEL was optically pumped and simultaneously its laser output power was collected using a single multimode butt-end fiber tip, which was connected to a 2 wavelength-division-multiplexing fiber coupler in order to distinguish the pump and output laser beams. We observed lasing at the monopole -point band-edge mode. The fiber-coupled output power reaches 2.6 mW, which we believe is record-high from any kind of PC lasers reported to date. We also investigated the area dependence of the quality factor of the BELs using three-dimensional finite-difference time-domain method, which indicates that there is much room for further improvement in the BEL output power.

Techniques for integration of quantum dot-based optoelectronic devices
H. H. Tan, L. Fu, S. Mokkapati, C. Jagadish, The Australian National Univ. (Australia)

Quantum confined structures are utilized in a variety of applications due to the quantum confinement effect that leads to device improvement. The mature epitaxy technology has allowed us to grow quantum dot (QD) structures with unique electronic and optical properties. These QDs have found applications in optoelectronic devices such as lasers and photodetectors and show superior performance in comparison their quantum well counterparts.

The monolithic integration of optoelectronic devices requires in-plane control of the bandgap. Two common methods used to achieve this are the intermixing technique and selective area epitaxy (SAE). Intermixing relies on the diffusion of the elements between the quantum well/dots and barriers. The two most common ways for intermixing is by impurity free vacancy disordering and ion implantation. SAE relies on controlling the local growth rate and composition by means of using patterned substrates during growth.

In this talk, we will highlight our work on the growth of III-V semiconductor QDs by MOCVD. The QDs are generally grown at low temperatures and hence their thermal stability (interdiffusion) is an issue since in device structures, subsequent layers are grown at higher temperatures. As such the band structure of the QDs will be modified. By using the techniques of impurity free disordering and ion implantation-induced disordering, we will show that we are able to spatially control the interdiffusion process. In addition we will demonstrate the use of SAE for in-plane bandgap energy control of quantum dots. In regions where quantum dots are formed, their composition, size and density can be varied by changing the dimensions of mask. All these techniques are promising for the integration of quantum dot-based optoelectronic devices and will be demonstrated by our results on laser-waveguide integration and multi-wavelength lasers and multi-color quantum dot infrared photodetectors.

Towards arrays of smart-pixels for time-correlated single photon counting and time-of-flight application
B. Markovic, Politecnico di Milano (Italy); S. Tisa, Micro Photon Devices S.r.l. (Italy); A. Tosi, F. Zappa, Politecnico di Milano (Italy)

We present a novel “smart-pixel” able to detect single photons and to measure and record in-pixel the time delay between a START pulse (e.g., laser excitation, cell stimulus, or LIDAR flash) and a STOP pulse given by the detection of a single photon (e.g., fluorescence decay signal or back reflection from an object). This smart-pixel represents the basic building block of SPAD arrays aimed at time-correlated single photon counting (TCSPC) applications (like FLIM, FCS, FRET), but also at photon timing and direct Time-of-Flight (dTOF) measurements for 3D ranging applications (e.g., in LIDAR systems). The pixel comprises a Single-Photon Avalanche Diode (SPAD) detector, an analog sensing and driving electronics, and a Time-to-Digital Converter monolithically designed and manufactured in the same chip.

In order to reach both long dynamic range, high time resolution and extreme linearity (requested for TCSPC setups), we devised a TDC architecture based on the interpolation technique. The long dynamic range is provided by a “coarse” counter, while the high resolution is reached by the use of two interpolators. Both interpolators have two stages, thus reaching high interpolation factor with moderate area consumption.

We report on the design and characterization of prototype circuits fabricated in a 0.35 µm standard CMOS technology containing complete conversion channels, smart-pixels and ancillary electronics with 20 µm active area diameter SPAD detectors and related quenching circuitry. With a 100 MHz reference clock, the TDC provides a time-resolution of 10 ps, a dynamic range of 160 ns and very high conversion linearity.

1024 pixels single photon imaging array for 3D ranging
S. Bellissai, F. Guerrieri, Politecnico di Milano (Italy); S. Tisa, Micro Photon Devices S.r.l. (Italy); F. Zappa, A. Tosi, Politecnico di Milano (Italy)

Three dimensional (3D) ranging systems are driving applications in many research field, such as automotive (for active security systems), industry and security. Depending on the application requirements vary, for example color sensitivity, 2D sampling resolution, distance accuracy, acquisition frame rate, field of view, etc. However for most applications, the most wanted performance is sensitivity, for operating in low light conditions and with opaque targets in the scene. Single-Photon Avalanche Diode (SPAD) arrays are imagers able to provide ultra high sensitivity (down to the single photon level) and high-frame rate response. We developed a sensor with 32x32 smart pixels with SPADs and in-pixel electronics for sensing and quenching each detector and an 8-bit counter with a memory cell for counting photons. We show how the array chip can acquire 3D movies by means of an indirect Time of Flight (TOF) approach: one single LED source enlightens the scene with sinusoidally
modulated light; the array acquires light reflected by the objects in the scene; the system computes the distance information through the phase delay recorded by each pixel. We show live movies with frame rates up to 50 fps in a range distance between 10 cm up to 7.5 m with a 20 MHz modulation at 650 nm. The measurement precision is less than 10 cm in normal operation. Then we present a second working modality, which allows to acquire every frame and then to compute the distance, with improved precision after accumulation of more samples.

7942-21, Session 8
Photonic network-on-chip architecture using 3D integration
K. Bergman, Columbia Univ. (United States)
Performance scalability of the chip multiprocessor (CMP) is becoming increasingly constrained by limitations in power dissipation of chip packaging and the data throughput achievable by the on-chip interconnection networks and off-chip communications platforms. Integrated photonics has been proposed as a revolutionary technology that could mitigate many challenges facing today’s conventional on- and off-chip electronic interconnection networks. To date, most proposed chip-scale photonic interconnects have been based on the crystalline silicon-on-insulator platform for CMOS-compatible fabrication to avoid costly changes to existing manufacturing processes. However, maintaining CMOS compatibility does not preclude the use of other silicon CMOS materials such as silicon nitride and polycrystalline silicon. This work discusses the potential advantages of using these new material systems that can provide for ultra-low propagation loss and lossless waveguide crossings, and how they can enable the design of novel 3D-integrated network devices and structures. A new non-blocking network architecture is developed using these devices and evaluated for its performance.

7942-22, Session 8
The integration of silica and polymer waveguide devices for ROADM applications
J. Fujita, R. Gerhardt, T. Izuara, W. Lin, H. Wei, B. Grek, Enablence (United States)
We report on our efforts to integrate silica and polymer waveguide devices, such as arrayed waveguide gratings (AWGs), tunable lenses, optical switches, variable optical attenuators (VOAs), power taps. In particular, the realizations of various optical add/drop multiplexers and tunable dispersion compensators will be discussed. The integration techniques, the design architectures and the corresponding optical performances will be presented.

7942-23, Session 8
InP on SOI devices for optical communication and optical network on chip
J. Fédéli, B. Ben Bakir, Lab. d’Electronique de Technologie de l’Information (France)
For about ten years, we have been developing InP on Si devices under different projects focusing first on plasers then on semiconductor lasers. For aiming the integration on a CMOS circuit and for thermal issue, we relied on 3D/2D direct bonding of InP unpatterned materials. After the chemical removal of the InP substrate, the heterostructures lie on top of silicon waveguides of an SOI wafer with a separation of about 100nm. Different lasers or photodetectors have been achieved for off-chip optical communication and for intra-chip optical communication within an optical network. For high performance computing with high speed communication between cores, we developed InP microdisk lasers that are coupled to silicon waveguide and produced 100μW of optical power and that can be directly modulated up to 5G at different wavelengths. The optical network is based on wavelength selective circuits with ring resonators. InGaAs photodetectors are evanescently coupled to the silicon waveguide with an efficiency of 0.8A/W. The fabrication has been demonstrated at 200nm wafer scale in a microelectronics clean room for CMOS compatibility. For off-chip communication, silicon on InP evanescent laser have been realized with an innovative design where the cavity is defined in silicon and the gain localized in the OW of bonded InP hererostructure. The investigated devices operate at continuous wave regime with room temperature threshold current below 100 mA, the side mode suppression ratio is as high as 20dB, and the fiber-coupled output power is ~7mW. Direct modulation can be achieved with already 6G operation.

7942-24, Session 8
Optical signal processing with a network of semiconductor optical amplifiers in the context of photonic reservoir computing
K. T. Vandoorne, M. Fiers, D. Verstraeten, B. Schrauwen, J. Dambre, P. Bienstman, Univ. Gent (Belgium)
The combination of ever more sophisticated algorithms with increasing computational power has made several scientific breakthroughs possible in recent years. Certain classes of problems however, such as recognition and classification problems, have benefited less from this progress, because they require often a fundamentally different approach. The field of machine learning and neural networks has over the years been working on tackling this class of problems and in recent years the new concept of Reservoir Computing was introduced. Basically this is a new training approach to Recurrent Neural Networks which avoids many of the problems that traditionally have hampered the application of such neural networks with feedback. It has led to results comparable to the state-of-the-art for speech recognition, robot control and time series prediction.

Most implementations are in software. Dedicated photonic hardware would offer advantages in speed and power consumption, partly because of its inherent parallelism and unique nonlinear behavior. A photonic implementation also holds the promise of massively parallel information processing with low power and high speed. Therefore we proposed the use of a network of coupled Semiconductor Optical Amplifiers as a reservoir for reservoir computing. We have showed that, despite several limitations in comparison to classical software implementations, they can achieve comparable results on a benchmark isolated words recognition task. In this paper we will explore this concept further and highlight important parameters such as the delays in the network. We will also address fabrication tolerances, showing that they actually improve the robustness while the absolute performance decreases a bit.

7942-25, Session 8
Nd-doped waveguide amplifiers for heterogeneous integration in optical backplanes
F. Ay, J. Yang, Univ. Twente (Netherlands); T. Lamprecht, IBM Research GmbH (Switzerland); K. Wörhoff, S. M. Garcia-Blanco, A. Driessen, Univ. Twente (Netherlands); F. Horst, B. Offrein, IBM Research GmbH (Switzerland); M. Pollnau, Univ. Twente (Netherlands)
The optical amplifier performance of Nd3+-doped polymer and amorphous Al2O3 channel waveguides with single-mode and multi-mode behavior at 880 nm is compared. Internal net gain in the wavelength range of 665-930 nm is investigated under continuous-wave excitation near 800 nm. In polymers, a peak gain of 2.8 dB at 873 nm is obtained in a 1.9-cm-long waveguide with a Nd3+ concentration of 0.6 1020 cm-3 at
a launched pump power of 25 mW [1]. The small-signal gain measured in a 1-cm-long sample with a Nd3+ concentration of 1.03 \times 10^{20} \text{ cm}^{-3} is 2.0 dB/cm at 873 nm. In Al2O3, a peak gain of 1.57 dB/cm in a short and 3.0 dB in a 4.1-cm-long waveguide is obtained at 880 nm with a Nd3+ concentration of 0.65 \times 10^{20} \text{ cm}^{-3} [2]. Tapered multi-mode Nd3+-doped amplifiers are embedded into an optical backplane and a maximum 0.21 dB net gain has been demonstrated in a structure consisting of an Al2O3:Nd3+ amplifier placed between two passive polymer waveguides on an optical backplane. The gain can be further improved by increasing the pump power and improving the waveguide geometry, and the wavelength of amplification can be tuned by doping other rare-earth ions.


Integrated plasmonic systems for ultrasensitive biodetection
H. Altug, A. A. Yanik, R. Adato, S. Aksu, A. Artar, M. Huang, A. E. Cetin, Boston Univ. (United States)

Plasmonics, by localizing light to the sub-wavelength volumes and dramatically enhancing local fields, is enabling myriad of exciting possibilities in bio-detection field. In this talk, I will present integrated plasmonic systems for ultrasensitive infrared nano-spectroscopy and biodetection.

Infrared spectroscopy, which directly accesses vibrational fingerprints of the biomolecular/chemicals in mid-IR frequencies, is an important identification and analysis tool. Its low sensitivity, however, limits the technique in single molecule/monolayer studies. By engineering plasmonic nano-antenna arrays, we demonstrate an ultra-sensitive surface-enhanced spectroscopy with zepto-mole level sensitivities. Our arrays, supporting collective plasmonic resonances, give much strong near-field electromagnetic field which is achievable with individual antennas. Using such fields, we show 100,000-fold enhancements of amide band signatures of proteins and detect absorption signals from 145 proteins per antenna. In addition, we introduce a low-cost fabrication technique for high-throughput fabrication of engineered infrared plasmonic antenna arrays. The optical response of arrays fabricated by our method is comparable to that of the arrays fabricated by electron-beam lithography. We also show nanostencils can be reused multiple times to create series of nanoantenna arrays having identical optical responses.

Finally, we show merging of plasmonics and nanofluidics on nanohole array platform to overcome mass transport limitation. In a microfluidic channel, diffusive analyte transport to the biosensor surface severely limits the sensor performance. At low concentrations, this limitation causes impractically long detection times. Our device, manipulating light as well as transporting flow on the same platform through the nanohole, enables targeted analyte delivery and dramatically improves sensor response time.

Microfluidic manipulations with sub-cellular optical resolution
M. F. Yanik, Massachusetts Institute of Technology (United States)

We present various opto- and micro-fluidic technologies we developed for screening complex physiological processes in vivo such as neuronal regeneration and degeneration, organ development, and stem cell proliferation. These allow automated and rapid manipulation, orientation, and non-invasive immobilization of invertebrate and vertebrate animal models for sub-cellular resolution two-photon imaging and femtosecond-laser nanosurgery. Our technologies include microfluidic whole-animal incubation chambers for exposure of individual animals to compounds and sub-cellular time-lapse imaging of hundreds of animals on single chips. Our devices also allow delivery of compound libraries from standard multi-well plates to microfluidic chips, and rapid dispensing of screened animals into multi-well plates. These technologies allow a variety of highly sophisticated in vivo high-throughput compound and genetic screens: We performed the first in vivo screen for compounds enhancing neuronal regrowth after injury. We discovered highly potent compounds with a wide variety of cellular targets, such as cytoskeletal components, vesicle trafficking, and protein kinases that enhance neuronal regeneration.

Nano-plasmonic resonance integrated with optofluidics for biochemical sensing and identification
L. Pang, H. M. Chen, J. N. Ptasinski, P. Sun, Y. Fainman, Univ. of California, San Diego (United States)

Nano-Plasmonics possesses unique physical properties that enable localization of optical fields beyond the diffraction limit. These highly confined/nanoscale optical modes will enhance light/matter interactions in systems with free electrons in micro/nanoscale geometric structures. Metal-dielectric fluid interfaces can support surface plasmon polaritons (SPPs), which are electromagnetic modes interacting with free electron oscillations. For properly chosen parameters, the effective index of the SPP modes can be considerably higher than the index of the surrounding dielectric media and therefore localize the optical fields in a nano-scale volume near metals. In this presentation, we will describe our recent work on using optofluidic plasmonic chips for implementation of an optofluidic plasmonic sensor, demonstrating in situ, real-time, label-free detection of protein-protein interactions. We also present our novel metal-dielectric nanoresonator composites that can excite localized surface plasmon resonance (LSPR) in combination with SPP readout, enabling higher surface field localization and thereby, enhancing the surface detection sensitivity. In order to solve the long time challenging issue of overlapping molecule of interest onto LSPR to realize the maximal interaction cross-section, micro-nanofluidics integrated nanochip was developed and will be presented in detail. We employed electrokinetic forces to control and manipulate the nanoparticles onto the predefined positions. Simulations of the particle’s motion in the fluid will be also provided to show the validity of our approach. These functionalities are useful for various applications including military/homeland security applications, in vitro diagnostics, food and drug industry, proteomics, as well as environmental and process monitoring.

Molecular beam epitaxial growth of GaAs/AlGaAs multi quantum well on germanium substrate
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The growth of III-V device structures on Germanium (Ge) substrate offers opportunities from the perspective of integrating III-V optoelectronics with silicon (Si) microelectronics through the use of a Ge/graded Si1-xGeSi buffer layer. In this report we have addressed MBE growth of GaAs/AlGaAs multi quantum wells (MQW) grown on 6° off cut Ge substrate towards the (110) plane by deposition of a migration enhanced epitaxy (MEE) grown GaAs layer followed by a thin low-temperature (475oC) grown GaAs layer which are used to complement the GaAs/Ge interface as it suffers from antiphasedomain disorder due to the polar/nonpolar epitaxy and interdiffusion across the heterointerface. The thin low-temperature GaAs layer was grown in three steps and was annealed at 600°C after each pause. We believe the MEE layer along with this special annealing scheme effectively blocked the dislocations at the GaAs/Ge interface from propagating into the upper epitaxial layers. AFM exhibits a smooth surface with rms roughness ~0.16 nm, which proves the surface is defect free. XTEM images also confirm that the QWs are free from structural defects. The low-temperature PL spectra of the MQW sample shows six distinctly sharp peaks for the six QWs with a FWHM of 3meV to 19meV for all the QWs, which are comparable to a standard MQW sample grown on GaAs substrate. Moreover, the PL emission for the sample was observed up to 300K. The activation energy for the top-most QW was found to be ~235meV. Acknowledgement: DST India, SPN IITB.
Phase change characteristics of Ge2Sb2Te5 thin film for a self-holding optical gate switch

T. Toyosaki, Keio Univ. (Japan)

The fast and low power consumption optical switch is required for the photonic network. We proposed the optical gate switch using phase change material (PCM) and silicon waveguides. It is low power consumption because it consumes power only when a switch state changes. Furthermore, the chip size is very small due to the large refractive index change of PCM. We used Ge2Sb2Te5 (GST225) as PCM, whose complex refractive indices we measured were 4.4+0.098i for the amorphous state and 7.1+0.78i for the crystalline state, respectively.

At room temperature, PCM has the two different stable states, the crystalline state and the amorphous state. The PCM changes form the crystalline state to the amorphous state by heating over the melting temperature by laser irradiation. On the other hand it changes form the amorphous state to the crystalline state by heating above the crystallization temperature and below the melting temperature.

In this paper, the suitable peak power and width of the laser pulse for switching were experimentally studied. The GST225 film of 20-nm thick was deposited on the SOI (silicon on insulator) substrate. The optimized peak power and the pulse width were found to be 30 mW and 300 ns for crystallizing, and 80 mW and 180 ns for amorphizing, respectively.

The optical gate characteristics will also be presented at the conference.

Defect mediated detection of wavelengths around 1550nm in a ring resonant structure

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In recent years the development of monolithic waveguide detectors in SOI photonic circuits has been explored by a growing number of research groups [for example see 1, 2]. This approach is attractive due to the straightforward fabrication of the sub-bandgap responsive element. The competitive application of defect mediated devices to broadband, quasi-DC power monitoring has been proven [3] with a report of 0.001A/W/dB for a detector fabricated using a commercial facility. The use of defect mediated detection for other applications, particularly those requiring high responsivity and bandwidth, has been overshadowed somewhat by the high performance of Ge integrated on SOI [4] or hybrid III-V integration. Although there have been reports of defect mediated waveguide detectors with responsivity in excess of 1A/W and bandwidth >20GHz [5], the widespread adoption of the monolithic approach is still to be accepted, likely due to concerns over device footprint and corresponding bandwidth limitations. In this presentation we will outline recent results which combine defect mediated detectors in a ring resonant structure. Previous work form our group has shown the feasibility of defect mediated ring resonant sub-bandgap detection. Doylend et al. used optical lithography to fabricate ring resonant detectors in which boron implantation was used to introduce defects [6], whereas, Logan et al. utilized electron beam lithography and inert silicon ion implantation to create deep-levels to facilitate the detection process [7]. By exploiting the multiple-pass of the optical signal through the detector, we are able to significantly decrease the size of the detector structure while maintaining responsivities in excess of 0.1A/W. In such a geometry the detector’s bandwidth is no longer capacitance limited, while the leakage current is reduced to <0.2nA. The applicability for such devices in multiplexing applications will be discussed, as will their potential for integration with high speed modulation functionality.


7943-08, Session 3

Liquid core integrated ring resonator

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Optical ring resonators are an emerging sensing technology that has attracted a great deal of attention due to the possibility to obtain very high sensor sensitivity. In a ring resonator the light propagates for an effective length that is proportional to the light circulation cycles supported by the resonator. This results in an increased light-analyte interaction and thus a higher sensitivity. Solid core ring resonator based on the evanescent sensing has been demonstrated to be a very powerful tool for sensing application. However, in this case, the fluidics needs to be fabricated separately and then integrated with the ring through multiple complicated steps. Here we propose an optofluidic ring resonator based on liquid core antiresonant reflecting optical waveguides (ARROW’s). In this device the liquid waveguide used to realize the ring resonator is also used in order to deliver the sample under analysis resulting in an improved liquid-light interaction and the feasibility of the device. The waveguides have been realized to operate at the wavelength of 635nm and for a core refractive index of 1.33. The fabricated ring resonator has a total round-trip length of 174.4µm and a theoretical free spectral range (FSR) of 1.8nm. The spectral response of the ring resonator has been compared with the simulated one, obtained by performing a 2D-FDTD simulation of the device. From the measured spectrum we have estimated a FSR of 1.52µm around 640nm, in agreement with the numerical results. The extinction ratio measured from the spectrum is 3.42dB, and the quality factor is Q~740.

7943-10, Session 4

CMOS photonic crystal and slow light

T. Baba, Yokohama National Univ. (Japan)

In the last decade, SOI photonic crystals have been greatly improved with the advance in Si photonics. This presentation focuses on photonic crystal (PC) waveguides and slow light devices fabricated by using CMOS technology. No doubt, CMOS technology offers the state-of-the-art large-scale, uniform, productive, reproducible, integration of micro/nano devices even for photonics. Its structural resolution is slightly worse than that of e-beam technology, but the device quality is already on a satisfactory level for various applications. Its important merits are the easy integration of spotsize converters (SSC), heaters, and PIN structures. SSCs effectively reduce the fiber-to-fiber insertion loss from 40 dB when using lensed fibers to < 10 dB. This helps to demonstrate unique functions including large nonlinearity. There are still some technical difficulties in integrating air-bridge PC slabs and SSCs. However, they can be overcome by the reproducible multi-step masking and etching process of CMOS technology. Heaters are used as tuning and trimming elements in various functional devices. In comparison with that for Si wire waveguides, a low heating efficiency will be an issue to be improved in air-bridge PC devices. Silica-clad PC devices are worth developing for improving the low efficiency as well as chemical and chemical stability. PIN structures, of course, can be used as a phase shifter in MZI modulators. The low-dispersion slow light waveguide is effective for enhancing the phase shift and/or shortening the device. The PIN structure can also be used as fast and/or dynamically tuning element in the delay of slow light pulses.

7943-09, Session 3

Silicon photonic resonator integration with CMOS electronics

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Compatibility with high volume CMOS manufacturing makes silicon photonics an attractive approach for future processor-to-board, processor-to-process, and core-to-core interconnect. Integration of photonic and electronic parts remains a challenge and different approaches are appropriate based on the application. In this work we demonstrate two choices for integrating photonics with electronics in a final product including wire bonding the electronic chip to a photonics chip during post processing and manufacturing silicon photonics monolithically on the CMOS chip. In the first, a photonic chip is wire bonded to a 90nm node foundry chip containing an inverter chain. The silicon photonic device bonded to the 90nm chip is a disk resonator that can operate in standalone configuration at 10Gbps and 1Vpp. When bonded to the chip the system runs at 5Gbps with bit error rate (BER) below 10-12 using a 3.5V drive. The lower speed is not limited by the waveguide and connecting the shifted region with the electronic chip. The second demonstration is monolithic integration of silicon microdisks and microrings on chip with CMOS inverter chains, clocks and pseudo random bit sequence (PRBS) generators. The photonic parts directly integrated with CMOS and manufactured on Sandia’s 0.35µm Microelectronics Development Line can be driven with 3.5V at 1Gbps with BER below 10-12. Here the speed is limited by the integrated electronics manufactured at the 0.35µm node. This work demonstrates two photonic-electronic integration techniques for high-speed operation and the necessary steps to achieve integrated performance that matches the high speed in silicon photonics previously reported.
7943-12, Session 4

Reconfigurable bi-directional optical routing in photonic crystals enabled by silicon nanomembrane modules

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Wavelength-division multiplexing (WDM) is the transmission of many signals through a single communication channel using different wavelengths, each of which carries a separate, independent signal. We present and discuss a reconfigurable WDM based on slow-light, functioning as a bi-directional optical routing and processing network, consisting of photonic crystals designed as drop/add filters. The photonic crystal routing elements consist of two waveguides coupled through a resonant cavity. Photonic crystals offer the ability to achieve separation of many channels on a much smaller scale than their predecessors. Photonic crystals have led a challenging frontier of miniaturization and large scale integration of high-density optical interconnects, and with the aid of nanomembranes, optical routing networks can set a new standard for high-density optical interconnects.

7943-13, Session 4

Transformation of one-dimensional silicon photonic crystal into Fabry-Pérot resonator with tunable defect mode

T. S. Perova, Trinity College Dublin (Ireland); V. Tolmachev, Ioffe Physico-Technical Institute (Russian Federation); V. Melnikov, A. Baldycheva, Trinity College Dublin (Ireland)

For the last few years the attention of researchers has been focused on a new concept of microphotronics, namely the development of microphotronics in the middle and long-wave infrared spectral range, which is of particular importance for biochemical sensing, medicine, defense and security. Structures combining Silicon based Photonic Crystals (PCs) with Liquid Crystal (LC) materials and switchable elements based on them, are most suited for investigation due to their transparency in this range. The design, fabrication and characterization of optical device which was originally built as 1D PC based on microstructured Si and then was transformed to the Fabry-Pérot microresonator (FPR) by infiltration of LC E7 into the air channel is presented in this work. The reflection spectra, registered by means of polarized FTIR microspectroscopy in the range of spectra from 1.5 to 15 um, revealed a large number of stopbands (SBs) in this region as well as the defect modes within some of the SBs. It is shown that the alteration of liquid crystal alignment and consequently the refractive index value in the cavity by application of electric field from 0 V to 10 V results in the reversible tuning of the high-order resonance peaks up to Δ α / α = 5.2 %. The perspective targets of this work are the fabrication of the tunable polariser, tunable optical filter and a moderately fast light modulator, integrated into silicon chip as elements of silicon microphotonic for near-infrared (with submicron resonator dimensions) as well as for middle infrared range.

7943-14, Session 4

Design, fabrication, and optical characterization of multi-component photonic crystals for integrated Si microphotronics

A. Baldycheva, Trinity College Dublin (Ireland); V. Tolmachev, Ioffe Physico-Technical Institute (Russian Federation); T. S. Perova, Trinity College Dublin (Ireland); J. A. Zharova, E. Astrova, Ioffe Physico-Technical Institute (Russian Federation); K. Berwick, Dublin Institute of Technology (Ireland)

This study presents the latest results and discussion of possible applications of the optical elements based on new type of multi-component photonic crystals (PCs). Over the last years, multi-component PCs with various possible component configurations have been attracted particular interest, due to their intriguing optical properties over ordinary (two-component) PCs. The geometric parameters and refractive indices of the additional components introduced into ordinary Si based PCs enable the alteration of optical properties, thus offering a wide range of applications for multi-component PC in Si microphotonics and optical interconnects. In this work we focus on the design, fabrication and optical characterization of the high-contrast one-dimensional (1D) multi-component PC structures based on grooved Si (Si-Air PC) with additional regular component. The Gap Map approach and the Transfer Matrix Method were used in order to mathematically describe these three-component 1D PC structures. The manipulation of the optical contrast to a high degree of precision and, therefore, the Photonic Band Gap (PBG) modifications in both position and width has been achieved. Using a suggested approach, wide omni-directional PBGs have been obtained in original Si-Air periodic structure. We also describe different methods of fabrication of additional layers on the Si-based structures using various deposition techniques as well as alteration of the existing layers, formed on Si, by either wet etching or reactive ion etching. For the first time the experimental results for the high-contrast multi-component PCs with wide transmission bands are demonstrated in this study. By analogy with multilayer dielectric coatings the additional components in multi-component Si PCs can be treated as an antireflection layer. We have found that the introduction of the additional layers affects the properties of high-order PBGs, replacing them with transmission bands and creating regions of total transparency. Tuning the number, position and width of these regions of total transparency in Si PCs has been demonstrated using the Maps of Transparency. These maps constitute a unique design tool for infrared optical filters for Si based photonic integrated circuit.

We note that the approach suggested can also be applied to the design of any micro- and nanostructured semiconductor or dielectric materials for application across wide electromagnetic spectrum.

7943-15, Session 5

Engineering light at the sub-wavelength scale using silicon photonics

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Integrated optics research is increasingly focused on structures with length scales of several hundred nanometers or less - dimensions smaller than the wavelength of light. At the same time, semiconductor processing tools have become capable of wafer scale manufacturing of devices incorporating sub-wavelength features. Silicon dominates this area largely because of availability, and compatibility with established semiconductor fabrication methods. Consequently, complex optical devices may now require chip areas only a few hundred micrometers across. Power consumption in active devices can be greatly reduced. The optical properties depend to a much greater extent on the surface properties and surrounding cladding materials, thereby enabling the use of photonic wires as sensors. At the smallest length scales, diffraction no longer plays a role, and one can engineer the local optical constants simply by choosing the ratio and orientation of etched and unetched silicon regions. This digital approach to optical material design allows many different components on a chip to be fabricated simultaneously in one etch step. If such patterned structures are combined with appropriate cladding materials, it is also possible to create devices with optical properties not possible in silicon.

We will review the physics and design issues that come into play at these length scales. Examples from our work include molecular sensor arrays that combine photonic wire sensor elements integrated with grating couplers using sub-wavelength patterning, thermo-optic modulators with extremely low power consumption, and waveguide devices with tailored
optical properties that can only be achieved by manipulating material structures at sub-wavelength scales.

7943-16, Session 5

Rigorous characterization of silicon nanowires and nanophotonic devices

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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 and these recently have been receiving much attention. In this regard, silicon has been particularly attractive as the low-cost and mature CMOS fabrication technology widely used in the electronics industry can be exploited. The high index contrast of silicon allows light confinement in submicron size waveguides, along with the creation of very compact bends, to allow increased functionality of photonic integrated circuits. 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. The work done and reported reveals that the mode profile of a circular silicon nanowire is not circular and also has a strong axial field component. Arising from the results of the analysis, the characteristics of single mode operation, the vector field profiles, the modal ellipticity and the group velocity dispersion of both circular and planar silicon nanowires are presented. The modal birefringence of rectangular silicon nanowires and power density in low-index region of a slot-type waveguide and designs of compact silicon power splitters and polarization rotators will also be presented.

7943-17, Session 5

Reflection and transmission characteristics of silicon photonic wire Bragg gratings

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Silicon photonic wire Bragg gratings are highly attractive components for the realization of compact reflectors in integrated-on-chip sensor arrays. In this work, we optimized Bragg gratings for TM polarized light at 1550 nm center wavelength with respect to maximum reflectivity over a large wavelength range employing 3D FDTD simulations. Two different types of lateral grating modulation were studied: modulation with the grating width a) limited to, and b) exceeding the width of the photonic wire. The wavelength response was analyzed with a DFT algorithm for a Gaussian pulse source. The investigations resulted in grating structures providing a reflectivity of >70% over a wavelength range of 25 nm. The transmission and the radiation losses amount both to approximately 10 – 15% each.

In order to enable the experimental verification of the reflectivity two different approaches were employed. One uses a grating coupler in order to couple the light into and out of a photonic wire comprising the Bragg grating structure. A fiber circulator separates the light paths of the incoming and the reflected light. In the second approach a Y-branch separates the light paths directly on the chip. Corresponding samples of Bragg grating structures with lengths of ~10 μm were fabricated by means of e-beam lithography and RIE. The waveguides were covered with an SU-8 cladding layer. The measured reflection and transmission spectra match well with the simulations and demonstrate the good performance of the optimized Bragg grating reflector.

7943-18, Session 6

Backscattering in silicon photonic waveguides and circuits

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In the last years much attention has been devoted to mitigate the strong impact of surface roughness on the propagation loss of silicon optical waveguides. Today, silicon nanowires show losses as low as 1 dB/cm, largely fulfilling the requirements of many applications. However, surface roughness is also responsible for the generation of backscattering guided light, a phenomenon that, in our opinion, has not received a sufficient attention. As we show in this work, backscattering issues emerge dramatically in silicon waveguides, and more in general in high index contrast waveguides. A systematic experimental investigation on low-loss single mode silicon nanowires, with a sidewall roughness rms around 1-2 nm, show that a few hundreds of micrometers long waveguide exhibits a backscattering level that can hinder its exploitation in many applications.

The effect is typically stronger for TE polarization and is significantly enhanced inside optical cavities, such as microring resonators, where backscattering is coherently enhanced according to the square of the finesse of the resonator and can modify dramatically the spectral response of the resonators, even at moderate quality factors. We found general relationships relating backscattering to the geometrical and optical parameters of the waveguides, to polarization rotation effects, and to coupling with higher-order modes. On the basis of these results, design rules to mitigate backscattering effects are proposed.

The main statistical properties of roughness induced backscattering were also experimentally derived, these results enabling an accurate modeling of realistic waveguides and the evaluation of the backscattering impact in integrated devices and circuits.

7943-19, Session 6

Development of a 0.75 micron wavelength, all-silicon, CMOS-based optical communication system

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Si Avalanche based LEDs have been developed that effectively emit light at 1050 nm / μm 2 in the 450 -650nm regime. (Snyman et al, Japanese Journal Applied Physics, 2007; Snyman et al., Proc SPIE, 2008, 2009, 2010 ; Snyman et al., IEEE Journal of Quantum Electronics, June 2010). Correspondingly, small micro-dimensioned detectors with pW/ μm 2 sensitivity (for the same wavelengths ) can be realized also in CMOS integrated circuitry. Latest research results also show that specific Si CMOS Av LEDs can be developed that emit mainly in the 700-800nm regime.

A major stumbling block is however the development of effective waveguides in CMOS technology, since the emission spectrum of the Si LEDs lies mainly within the absorption band of silicon. Subsequent analyses showed that that both silicon nitride and Si ox-nitide offer good possibilities for development of such waveguides, utilizing either 0.2 to 2 micron trench-, or CMOS over-layer based technology.

Advanced optical simulation software (RSOF BeamPROP and RSOFT FULL WAVE) were subsequently used to design specific CMOS based waveguides operating at 750nm wavelength using CMOS materials and processing parameters.

The results show that effective single mode wave-guiding channel strips of 0.2 -1.5 micron wide, embedded in silicon oxide , can be realized with loss characteristics of below 0.5 dB.cm-1 and with dispersion characteristics (bandwidth-length product) of up to 100 Ghz-cm. Micro-bending, multi-plane coupling and chip edge coupling are possible. The analyses also show that waveguide edge coupling is possible on the
CMOS chip side or crevice interfaces. Adiabatic expansion techniques can be used to increase the effective coupling into adjacent positioned 10 um core optical fibres which are compatible to the same wavelength. First iteration experimental wave-guiding and signal detection between Si Av LED sources and optical detectors have already been realized. Aspects of the developed ideas have recently been extensively patented in the form of provisional RSA Patent Applications 2009/04162, 2009/04163, 2009/04509, 2009/04508, 2010/00200, 2010/02021, and three PCT patents filed by TUT, June 2010.

7943-20, Session 6
Patterned overlays
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The modifications to the optical properties of a waveguide coated with a patterned thin high dielectric overlay layer are examined. The asymmetric nature of the entire waveguide configuration makes it possible to keep the waveguide mode highly confined in the original waveguide while enhancing the evanescent wave–overlay interaction. A typical overlay layer may be a thin coating of silicon, this placed in contact with a surface diffused waveguide formed in a glass substrate. The silicon can be polycrystalline in the case that the grain boundaries are on the same order of dimension as the feature size. The overlay layer can be patterned into many different geometries such as a grating or photonic crystal. The enhanced extent of the evanescent field in the overlay magnifies the overlap effect on the guided light. This makes it possible to design optical waveguide devices that are directly optical fiber compatible and at the same time take advantage of the high dielectric contrast that exist between the silicon overlay and air. Gratings with high dielectric contrast provide the realization of features not normally present for a moderate index contrast for glass based integrated optics. The sensitivity of the guided light to variations in the refractive index, thickness, period, and length of patterned overlay are examined using Finite Difference Time Domain (FDTD) simulations. For various waveguide geometries, transmission and reflection spectrums are obtained from which active and passive optical device configurations are explored.

7943-21, Session 7
Fabrication of nanoscale photonic components in bulk silicon using ion irradiation
M. B. Breese, National Univ. of Singapore (Singapore)

We have recently developed a process based on ion irradiation in conjunction with electrochemical anodization to create a range of micro- and nano-scale photonic components in bulk silicon. This process is based on the use of high-energy beams of hydrogen or helium ions, either focused to a small spot or irradiating large areas through a surface mask, to selectively damage a silicon lattice. This damage acts as an electrical barrier during subsequent formation of porous silicon by anodization. Two key features to this process are the understanding of how to control the anodization process to produce nano-scale features and the ability to reduce the surface roughness to levels approaching 1 nm in order to minimize scattering losses. To this end, we have found a way to machine micrometer-thick layers with roughnesses of about 1 nm, resulting in ultra-low loss propagation losses of less than 1 dB/cm. This process has been used to fabricate a range of components such as low-loss single mode silicon waveguides, vertically stacked waveguides, three dimensional distributed Bragg reflectors, holographic surfaces, concave micro-mirrors and disk resonators.

7943-22, Session 7
Far-field approximation in two-dimensional slab-waveguides
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Far-field approximation for electromagnetic waves scattered from 3D objects has been extensively used in problems such as radars and antenna arrays. It is well-known that in the so called far-field zone, the electric and magnetic waves are perpendicular to each other and the propagation direction. Also, the surfaces of constant phase of partial wavelets generated by the volume elements constituting the object coincide locally when they reach an observation point in the far-field zone. In 2D cases such wave propagating in large thin slab waveguide, which is single mode in the direction perpendicular to the slab, we can never have the electric and magnetic waves perpendicular to each other and the propagation direction.

In this paper we will investigate the criteria for far-field approximation in a 2D problem, including the phase criterion. Using a silicon-lab as the platform, we will also compare these criteria with those of a 3D scattering problem for both sub-wavelength and large objects. The convergence of the exact solution, based on Hankel functions, and the far-field approximation will also be presented.

7943-23, Session 7
All optical broadband absorption modulation in submicron silicon waveguide
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We experimentally demonstrate an on-chip all-optical broadband modulation of light in submicron silicon waveguide based on linear free carriers’ absorption using side coupling configuration of a pump signal. This effect allows to directly attenuate the probe signal, without the need for a resonator or an interferometer. As a result, this modulation mechanism performs very similarly for broadband probe signals. We measured the attenuation of the probe as a function of the pump power and fit the result to a theoretical model. We demonstrate free carrier lifetime of ~3ns. We also show that the modulation effect is nearly constant over a broad wavelength range of 1460-1580 nm.

7943-24, Session 7
Pluggable compact optical connector for Si-photonics chip using MT-ferrule
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A pluggable compact optical connector between the single-mode optical fiber and the grating coupler in a Si-photonics chip has been prepared using a cost-effective MT-ferrule. The 12-channel MT-Ferrule with a dimension of 6.4 mm x 2.45 mm x 8.1 mm was processed to have a compact dimension of 6.4 mm x 2.45 mm x 1.5 mm. It can reduce the cost down to 1/30 of a commercial fiber-array-block unit. It has guide holes for passive plugging with another MT-Ferrule connected to the external light source. Small dimension and simple connection enabled a connector to be directly bonded to the Si-photonics chip, providing increased degree of freedom in designing of optical modules. The optical insertion loss of the connector showed constant values of ~1.80 dB for the wavelength range from 1520 nm to 1620 nm.

The assembled optical connector was directly bonded to the Si chip on which 12-channel waveguides were formed. Each waveguide has an etch depth of 120 nm, a width of 10 µm, and a length of 7.3 mm on a SOI wafer with a 220 nm-thick Si top layer and a 2 µm-thick SiO2 buried oxide layer. Grating couplers were formed at both ends of each
waveguide. An UV-curable epoxy adhesive, which has a refractive index of 1.51 at ~1550 nm, was used for the bonding of the connector to the Si chip. This thin cured epoxy layer at the interface between the fiber of a MT-Ferrule and the grating coupler enhanced the optical coupling efficiency. The coupling loss of the connector was 4.7 dB.

7943-25, Session 8  
Mid-infrared silicon photonics devices  
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Although the current focus of the silicon photonics research community is in the telecommunications wavelength range, the mid-infrared spectral region is interesting for several potential applications: bio-chemical sensing, environmental monitoring, medical sensing, industrial process control, free space communications, or military applications. Silicon is relatively low-loss from 1.2 to 8 μm and from 24 to 100 μm, and therefore silicon photonic circuits can be used in mid- and far-infrared wavelength ranges. Chip-scale integrated circuits for the mid-IR would offer higher performance, smaller size, lower power consumption and cost, and higher reliability. The major challenge in creating such circuits, is the design of passive and active mid-IR components that operate at satisfactory level at room temperature. In this paper we investigate several silicon based passive structures for mid-infrared wavelength region including silicon-on-insulator rib, ridge and strip waveguides, silicon on porous silicon waveguides, and silicon-on-sapphire waveguides. We also present characterisation of devices based on these waveguides.

7943-26, Session 8  
Light confinement and propagation characteristics in plasmonic gap waveguides on Si  
R. Salas-Montiel, S. Blaize, A. Bruyant, A. Apuzzo, G. Lerondel, Univ. de Technologie Troyes (France); C. Delacour, P. Grosse, J. Fedeli, A. Tchelnokov, Commissariat à l’Énergie Atomique (France)

Plasmonic waveguiding structures have the ability to confine and propagate light over short distances, typically less than a hundred micrometers. This short propagation length is the price that is paid for confining light to dimensions on the order of a hundred of nanometers. Surface plasmon gap waveguide (SPGW), waveguides that consist of a dielectric core bounded on either side by metallic walls, are among the plasmonic waveguiding structures that provides propagation lengths on the order of tens of micrometers while keeping the confinement on the order of hundred of nanometers for a light of wavelength of 1550 nm. With these scales in mind, several plasmonic devices can be proposed (e.g. wavelength multiplexers) and some of them have been already demonstrated such as Y junctions and directional couplers. Although the dimensions involved in such plasmonic structures are below the diffraction limit, large-scale optical characterization techniques, such as transmitted power, are still employed. In this contribution, we present an optical characterization technique for the study of the guided modes in plasmonic gap waveguiding structures that resolves subwavelength-scale features, as it is based on atomic force microscope (AFM) and on near field scattering optical microscope (NSOM) in guided detection. Under this configuration, we observe that the experimental NSOM signal is more sensitive to the optical near field component orthogonal to the surface of the waveguide (i.e. E-field component parallel to the AFM probe major axis), as confirmed by numerical simulations and scattering models. From the NSOM signal, we measured the plasmonic gap mode profile with a lateral resolution of about /7, and we deduced the real part of the effective index to 1.65 ± 0.10.

7943-27, Session 8  
Optical near field in silicon photonics  
R. Salas-Montiel, S. Blaize, A. Bruyant, A. Apuzzo, Z. Sedaghat, G. Lerondel, P. Royer, Univ. de Technologie Troyes (France)

Silicon-on-insulator (SOI) is today one of the most interesting silicon-based materials for photonics integration. This is because IR light can be confined and guided through waveguiding structures fabricated with microelectronics processes. The high index contrast of SOI waveguides allows the reduction of the dimensions in photonics devices thus increasing the integration of other optical functions in the same chip. Because of its excellent optical and electrical properties, the SOI is the ideal material for optoelectronic hybrid integration. Optical devices based on SOI have been fabricated and tested for the last decade by using far field optics. Alternatively, near-field scanning optical microscopes (NSOM) have the ability to reach unique optical resolution by converting the evanescent waves into radiation waves that can be detected by conventional far field optics. Thus, the aim of this paper is to show the most recent capabilities of the NSOM in a guided detection to probe SOI-based structures. By using this simple yet powerful configuration, we can observe the propagation of the light in Si-based devices and thus measure the propagation characteristics of the guided modes. In addition, we can measure the insertion and propagation losses as well as the mode profile inside the devices.

7943-28, Session 8  
Micro-cavities based on width modulated SOI waveguides  
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We have designed, fabricated and investigated one-dimensional (1D) micro-cavities in Silicon-on-Insulator (SOI) waveguides. The single mode waveguides are fabricated in a 220 nm silicon device layer. The 1D micro-cavities in Fabry-Perot structure consist of two mirror regions formed by a sinusoidal modulation of the waveguide width. The mirror regions are separated by a sub-micron spacer. The SOI photonic structures are produced in a CMOS environment using 248 nm DUV lithography. The waveguides as well as the width modulated mirror regions are designed using a single mask and are fabricated in a shallow trench process. The transmission spectra of these width modulated micro-cavities with different mirror reflectivities and cavity lengths are investigated. Q-factors of up to 855 could be observed at 1550 nm wavelength with an insertion loss of 3 dB.

The width modulated micro-cavities, including the mirror regions, have lengths of less than 20 microns and widths of maximum 450 nm. This small footprint cavities act as band pass filters and can be used as resonators for lasing or electro-optic modulation of light. The spectral transmission functions of the width modulated micro-cavities are simulated for different design parameters using the Finite-Difference-Time-Domain (FDTD) method. The simulations are compared with experimental results and further cavity designs are proposed.

7943-29, Session 9  
Integrated recirculating optical hybrid silicon buffers  
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Fully integrated hybrid silicon optical recirculating buffers with 12.8 ns hold time are presented. The devices are designed to buffer 40 byte packets at 40 Gb/s. Switching is achieved by a gate matrix switch consisting of hybrid silicon amplifiers. The devices are fabricated by bonding III-V quantum wells to patterned SOI samples. The waveguide in the delay is designed for low loss while the amplifiers are designed for high gain to overcome the loss in the delay. We have observed that amplifier processing resulted in substantial increases in passive waveguide loss. The increase was attributed to impurity diffusion and physical damage due to stress. A silicon nitride layer is shown to be an effective way to keep the passive loss from increasing during the III-V process.

Even though these devices use low loss waveguides, multiple amplifiers inside the delay are required to overcome the loss. Our simulations show that ASE accumulation inside the delay limits the number of recirculations because it degrades the BER and the eye diagram of the devices. Noise filtering techniques are shown to improve the BER and eye diagrams of the devices. We show simulations for noise filtering using saturable absorbers and optical band pass filters in the form of arrayed waveguide gratings.

7943-30, Session 9
Fast 100-channel wavelength selectors integrated on silicon
T. Aalto, M. Harjanne, M. Kapulainen, S. Ylinen, VTT Technical Research Ctr. of Finland (Finland); L. Mörl, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

We present the design, fabrication and characterisation of wavelength selectors integrated on silicon-on-insulator (SOI) chips. The devices are able to select one 10 Gb/s wavelength channel among 100 wavelength channels, representing an aggregate input data rate of 1 Tb/s. Wavelength selection is based on two key components integrated successively one after another. First, the 100 wavelengths are demultiplexed to four output waveguides with an arrayed waveguide grating (AWG) implemented with 4 µm thick SOI waveguides. Then a semiconductor optical amplifier (SOA) array hybrid integrated behind the AWG amplifies the ten wavelength channels that propagate in one of the four output waveguides. The rest of the wavelengths are blocked by the other nine SOA's that are in the off state. Another AWG then redistributes the passed wavelength into individual output waveguides and another SOA array allows only one of these wavelengths to pass through. To improve the extinction ratio a third AWG-SOA-array pair was added to one implemented layout. The sub-ns response time of the SOAs enables much faster wavelength selection that what can be achieved with thermo-optic or micromechanic devices.

The wavelength selector device includes a hybrid integrated photodiode to make it a complete receiver unit in a terabit communication system. The device has been developed for a space application where it is planned to form one output port in a 100x100 optical packet switch on board a satellite.

7943-31, Session 9
Progress in waveguide-integrated germanium avalanche photodetectors
S. Assefa, F. Xia, Y. A. Vlasov, IBM Thomas J. Watson Research Ctr. (United States)

Avalanche photodiodes (APD) integrated with silicon waveguides are attractive for optical interconnect applications due to their ability to detect low-power optical signals. For CMOS-integrated optical interconnects, the APD has to be compatible with CMOS process, have compact footprint, operate at CMOS-compatible voltages, and providing high avalanche gain at high bandwidth. This talk will discuss the recent progress in high-speed Ge APD monolithically integrated into front-end CMOS [1, 2]. Unlike previous demonstrations which utilize a Ge layer for absorption and a Si layer for multiplication [3], this APD utilizes the Ge layer both for absorption and multiplication. The gain and bandwidth of the APD was characterized by performing small signal RF measurements. Bandwidth exceeding 35GHz was measured at a bias voltage of around 3V. Gain of 10dB was obtained for the same voltage. The noise factor measured at high gain is below the calculated value for kff=0.2, indicating that the APD has low noise performance even at high avalanche gain. Furthermore, the open eye-diagrams measured at 40Gbps for 10dB gain confirm that the APD has low noise while operating at high speed.


7943-32, Session 10
Design of SOI wavelength filter based on multiple MMs structures
Y. Hu, F. Y. Gardes, Univ. of Surrey (United Kingdom); R. M. Jenkins, E. D. Finlayson, QinetiQ Ltd. (United Kingdom); G. Z. Mashanovich, G. T. Reed, Univ. of Surrey (United Kingdom)

SOI based MMs prove to be versatile photonic structures for optical power splitting/combining, directional coupling, wavelength multiplexing/demultiplexing, etc. Such a structure benefits from relative ease of fabrication, low sensitivity to fabrication error and low temperature dependence. Whilst the majority of previous designs and optimisations investigated single MMs, there is significant potential to combine MMs within a single device for the realisation of improved device performance. We have designed and simulated a wavelength filter device consisting of a series of MMs with different lengths. The bandwidth, free spectrum range, and extinction ratio can be controlled by changing the MM's width and length. We have optimized our design to achieve a >3dB bandwidth of 5nm, a free spectral range of 60nm, and an extinction ratio of >20dB. Such a device can be used for high performance coarse wavelength filtering. The whole structure can fit into a 200umx300um area.

Temperature sensitivity and fabrication error sensitivity of the designed structures were also investigated.

7943-33, Session 10
Integrated optical phased array based large angle beam steering system fabricated on silicon-on-insulator
D. N. Kwong, A. Hosseini, Y. Zhang, R. T. Chen, The Univ. of Texas at Austin (United States)

In this paper, we present a highly compact silicon nano-membrane based optical phased array fabricated using conventional CMOS processing on silicon-on-insulator that provides for over 10 degrees of beam steering in a silicon slab at α=1.55µm using transverse-electrical polarized light. A low loss 1-to-12 multi-mode interference (MMI) optical beam splitter with high uniformity is used to provide inputs to the optical phased array. Using an unequally spaced waveguide array permits us to relax the half-wavelength spacing requirement for large angle beam steering, thereby avoiding the optical coupling between adjacent waveguides and reducing the side-lobe-level of the array radiation pattern. S-bend waveguides convert the equally spaced MMI output to the unequally spaced wave guide array, while passively equalizing the phases of each array element to compensate for the MMI output phase profile. Independently controllable thin film metal heaters are used to achieve phase shifting using the strong thermo-optic response of silicon. Heat-insulating air
grooves minimize thermal crosstalk, while also achieving fast response time and low power consumption.

7943-34, Session 11

Polarization dispersion compensated waveguide grating on silicon

J. He, Zhejiang Univ. (China)

Silicon waveguide grating devices are important components for WDM based optical interconnect. For practical applications in multi-wavelength receivers and routers, the waveguide grating, which commonly takes the form of arrayed waveguide grating (AWG) or echelle grating, must be polarization insensitive. While many techniques for polarization dispersion compensation exist in widely used silica-based AWGs, the techniques applicable to silicon waveguide gratings are limited. This paper will review polarization dispersion compensation techniques for waveguide gratings and present latest results on recently proposed approach using angled star-couplers in AWGs. It effectively combines an AWG with an echelle grating without introducing any additional fabrication step, and is particularly suitable for the silicon platform.

7943-35, Session 11

Low energy silicon on insulator ion implanted gratings for optical wafer scale testing

R. Loiacono, G. T. Reed, R. M. Gwilliam, G. Z. Mashanovich, Univ. of Surrey (United Kingdom); R. Feldesh, Numonyx Israel (Israel); R. Jones, Intel Corp. (United States)

Silicon photonics shows tremendous potential for the development of next generation of ultra fast telecommunication, tera-scale computing, and integrated sensing applications. One of the challenges that must be addressed when integrating a “photonic layer” onto a silicon microelectronic circuit is the development of a wafer scale optical testing technique, similar to that employed today in integrated electronics industrial manufacturing. This represents a critical step for the advancement of silicon photonics to large scale production with reduced costs. In this work we propose the fabrication and testing of ion implanted gratings is sub micrometer SOI waveguides, which could be applied to the implementation of optical wafer scale testing strategies. An extinction ratio up to 30dB has been demonstrated for ion implanted Bragg gratings fabricated by low energy implants in submicron SOI rib waveguides with lengths up to 1mm. Furthermore, the possibility of employing the proposed implanted gratings for an optical wafer scale testing scheme is discussed in this work.

7943-37, Session 12

Towards integrated photonic quantum technologies with fiber-integrated single photon emitters

O. Benson, T. Schröder, A. Schell, T. Alchele, G. Kewes, M. Barth, Humboldt-Univ. zu Berlin (Germany)

Future quantum technologies based on photons will benefit from on-chip waveguide quantum circuits. These on-chip circuits have been proven to reliably perform linear quantum operations [1]. Single photons that were used for these operations were produced by spontaneous parametric down-conversion in an external setup. Coupling from the down-conversion source to the on chip network was realized by optical fibers. A future goal will be to integrate a single photon source directly onto the chip. Besides single photons from down-conversion processes single photons from single photon emitters such as single color centers in nanodiamonds are well suited for this purpose. Some of the color centers like the nitrogen vacancy (N-V) center or Ni-related color centers have been proven to have a stable and bright emission at room temperature [2]. However, so far integration of these nanomitters has not been shown and miniaturization of the source-chip system has not been achieved. Here we demonstrate that the complexity of the system can be reduced if fiber integrated quantum emitters can be used to provide the single photons necessary to perform quantum operations. The direct near-field coupling of a single N-V center in a nanodiamond to the modes of a photonic crystal fiber is shown. Collection efficiency reaches that of an air objective with a numerical aperture of n=0.85. Direct coupling out of the fiber to the on chip waveguides would allow improved performance, miniaturization, and scalability.

[1] Politi et al., SCIENCE, 320, 647

7943-38, Session 12

Spintronics using Si

H. Dery, P. Li, Univ. of Rochester (United States)

Silicon is an ideal material choice for spintronics devices due to its relatively long spin relaxation time and mature technology. In spite of recent important progress in spin injection into silicon [1,2], there are no parameter-free methods to accurately determine the degree of spin polarization of electrons in silicon. This missing link is established with a theory that provides concise relations between the degrees of spin polarization and measured circular polarization for each of the dominant phonon-assisted optical transitions [3]. Knowing the theoretical circular polarization values of complete spin polarization and comparing them with measured values are imperative in determining the actual spin polarization in silicon. These values are also instrumental in extracting the spin relaxation time or the spin injection efficiency across ferromagnet/silicon interfaces.

By invoking symmetry arguments, we first provide concise selection rules for each of the phonon-assisted optical transitions in unstrained bulk silicon. Then, these rules help in analyzing the polarized luminescence spectrum calculated by a comprehensive rigid-ion model. The effects of spin-orbit coupling and doping are studied in detail. It is shown that an opposite behavior of longitudinal and transverse optical phonon-assisted transitions is responsible to recent experimental results of spin injection into silicon [2].

A future goal will be to integrate a single photon source directly onto the chip. Besides single photons from down-conversion processes single photons from single photon emitters such as single color centers in nanodiamonds are well suited for this purpose. Some of the color centers like the nitrogen vacancy (N-V) center or Ni-related color centers have been proven to have a stable and bright emission at room temperature [2]. However, so far integration of these nanomitters has not been shown and miniaturization of the source-chip system has not been achieved. Here we demonstrate that the complexity of the system can be reduced if fiber integrated quantum emitters can be used to provide the single photons necessary to perform quantum operations. The direct near-field coupling of a single N-V center in a nanodiamond to the modes of a photonic crystal fiber is shown. Collection efficiency reaches that of an air objective with a numerical aperture of n=0.85. Direct coupling out of the fiber to the on chip waveguides would allow improved performance, miniaturization, and scalability.

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7943-39, Session 12

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The theory sets a basis for future studies of the circular polarization in silicon due to strain (splitting the valleys and hole states), no-phonon and multi-phonon-assisted optical transitions. The theory also sets a basis for studying spin injection into silicon based nanostructures (e.g., SiGe
polarized.

0.6 dB gain has been determined with both pump and probe being TE white light source as probe signal. With 35 mW pump power, around

Stimulated Raman amplification measurement is carried out with a SLED output peak at 1253 nm is also observed with around 35 mW pump.

power. A temperature dependence of Raman frequency shift of about

relationship between spontaneous Raman output power and pump

of around 90 pW is obtained by around 22 mW pump. The stimulated

spectrum is measured as around 100 GHz. Maximum Raman output

corresponding to a Raman shift of 15.6 THz, while the FWHM of Raman

analyzer. The first order Raman peak is measured at around 1441.4 nm

Nd:YAP laser at 1340.6 nm with 7 GHz FWHM spectral width is used as

mode from the device edge. In this study, we have overcome these
difficulties and report the experimental observation and measurement of

the polarized electroluminescence (EL) from an edge-emission Si based- 

OLED with a Sm/Au or Sm/Ag cathode. Light collected from the OLED edge comes from the scattering of the SPP at the device boundary. This experiment shows that such Si-OLED is potentially an electrically excited SPP source on a silicon chip for optical interconnect based on SPPs.

Surface Plasmon Polaritons (SPPs) play an important role. The emitters in close proximity to the thin cathode metal efficiently (up to 40%) couple their radiation energy into SPP mode in the interface of the metal cathode and the organic material. For the surface (top or bottom) emission OLEDs, this is considered as an energy loss channel, which substantially limits the surface light outcoupling efficiency. On the other hand, an OLED is in fact an electrically excited SPP source if we collect light from its edge. The about 100 nm organic film sandwiched between a metallic cathode and anode is too thin to support photonic mode but can easily support the excited SPP mode, which contribute to the edge emission. If the SPPs contribution is high sufficiently, we can predict that light from the device edge is partially polarized, even purely polarized in transverse magnetic (TM) mode due to the TM nature of SPPs; however, there are some experimental difficulties in direct observation of the SPP mode from the device edge. In this study, we have overcome these difficulties and report the experimental observation and measurement of the polarized electroluminescence (EL) from an edge-emission Si-based-OLED with a Sm/Au or Sm/Ag cathode. Light collected from the OLED edge comes from the scattering of the SPP at the device boundary. This experiment shows that such Si-OLED is potentially an electrically excited SPP source on a silicon chip for optical interconnect based on SPPs.

Spontaneous and stimulated Raman scattering in planar silicon waveguides

S. Wang, S. Meister, S. Mahdi, B. Franke, A. Al-Saadi, Technische Univ. Berlin (Germany); L. Zimmermann, H. H. Richter, D. Stolarek, IHP GmbH (Germany); V. Lisinetskii, S. K. Schrader, Technische Fachhochschule Wildau (Germany); H. Eichler, Technische Univ. Berlin (Germany)

Raman scattering in planar silicon on insulator (SOI) waveguides with 2 microm width, 220 nm height and 2 cm length is investigated. A cw Nd:YAP laser at 1340.6 nm with 7 GHz FWHM spectral width is used as the pump source. A lensed fiber of 2.5 microm focus diameter is used to couple the pump laser into the waveguide. The coupling efficiency is estimated to be around 10%. Spontaneous Raman scattering is observed with as low as 2.5 mW pump power inside the waveguide. The spontaneous Raman spectrum is measured by an optical spectrum analyzer. The first order Raman peak is measured at around 1441.4 nm corresponding to a Raman shift of 15.6 THz, while the FWHM of Raman spectrum is measured as around 100 GHz. Maximum Raman output of around 90 pW is obtained by around 22 mW pump. The stimulated Raman gain coefficient is estimated as around 56 cm/GW from the relationship between spontaneous Raman output power and pump power. A temperature dependence of Raman frequency shift of about 0.6 GHz/K is measured. The spontaneous anti-Stokes Raman scattering output peak at 1253 nm is also observed with around 35 mW pump. Stimulated Raman amplification measurement is carried out with a SLED white light source as probe signal. With 35 mW pump power, around 0.6 dB gain has been determined with both pump and probe being TE polarized.

Silicon optical modulators have gone through a period of rapid development in recent years, with many devices now achieving data rates of 10 and even 40Gbit/s. The next era will inevitably see some commercialisation and integration of devices with other photonic and electronic components. In order for this to be viable, a high device yield is required and therefore process tolerance induced performance variations should be mitigated. Self-aligned fabrication steps have been successfully employed in the CMOS industry for many years to eliminate feature alignment errors for such reasons. The majority of high speed silicon optical modulators reported to date are based upon carrier depletion in a reverse biased pn diode and require the positioning of the pn junction within the optical waveguide. In this work we present a design of a high speed silicon optical modulator which uses a self aligned process to form the pn junction thus eliminating performance variations which can result from variations in its position. The device is designed through the use of optical and electrical modelling to target data transmission at rates up to 40Gbit/s. Experimental results from a first fabrication batch targeting 10Gbit/s have demonstrated that a 25dB static extinction ratio is achievable with only a 3V reverse bias applied over a 3.5mm phase shifter as well as data transmission at 10Gbit/s with a 7dB modulation depth. The results from further device modelling have demonstrated an enhanced performance through optimisation of the design, with 40Gbit/s modulation targeted in future fabrication runs.
A compact depletion mode silicon modulator based on a photonic hybrid-lattice mode-gap resonator

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The photonic crystal (PC) electro-optic (EO) modulator is optically based on a hybrid-lattice mode-gap (HLMG) resonator, which is designed to introduce a photonic bandgap (PBG) misalignment by sandwiching a rectangular lattice of holes (PC2) with hexagonal lattices (PC1) on a silicon thin film. From 3D FDTD simulations, the resultant optimized resonator with transitional lattices between PC1 and PC2 provides Gaussian-like spatial mode variation, and therefore strong optical confinement and enhanced EO sensitivity as $Q/V=7700$ ($\mu$m$^3$). More importantly, the aligned periods of holes in the cavity centre (PC2) can effectively reduce electrical scattering by the insulator holes and serve as a high speed carrier movement channel for free carrier based EO modulation. Here, 3D physically-based modeling is used for the first time to predict carrier distribution and I-V response of a PC-embedded diode by solving the Poisson's and continuity equations in a 3D temperature-dependent dielectric-insulator-conductor environment. A 2.26 times higher static carrier level is detected in the HLMG resonator than in a double heterostructure cavity for the same bias voltage. Dynamically, the speed of the device reaches 238 GHz due to the combination of the high EO sensitivity resonance medium and breakdown delay based depletion mode operation. The negligible leakage current also results in an ultra-low DC energy consumption of 26.6 fJ per bit, which minimizes substrate temperature fluctuation from localized heat generation, and is therefore suitable for realizing green photonics in high density photonic integrated circuits. The device characterization is in progress and supported by Singapore's A*Star SERC grant (0921010049).

40 Gb/s high-speed silicon modulator for TE and TM polarisation

F. Y. Gardes, D. J. Thomson, G. T. Reed, Univ. of Surrey (United Kingdom)

The workhorse of future high speed short reach interconnect technology will be the optical modulator. These devices in silicon have experienced dramatic improvements over the last 6 years and the modulation bandwidth has increased from a few tens of MHz to over 30 GHz. 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 an extinction ratio above 5dB and working for both polarisation is of utmost importance. Here we describe an approach based on the fabrication of a novel self aligned pn junction structure embedded in a silicon waveguide with an active length in the millimetre range that can produce high-speed optical phase modulation whilst retaining a high extinction ratio. This all-silicon optical modulator uses a CMOS compatible fabrication and demonstrates high data rate transmission with a large extinction ratio for both TE and TM polarisations. This technology is not only compatible with conventional complementary MOS (CMOS) processing, but is also intended to facilitate a high yield, reliable fabrication process.

SiGe metallized stub and plasmonic gap mode electro-absorption modulators

R. Thomas, Z. Ikonice, R. W. Kelsall, Univ. of Leeds (United Kingdom)

Metal-coated stubs in planar plasmonic waveguides act as high quality resonators, coupled to the underlying waveguide. The transmission depends strongly on the stub quality factor and on detuning from resonance, which can be controlled by varying the absorption coefficient of the stub filling. The effect is of interest for electroabsorption modulators (EAMs) for integrated photonics, since the sub-wavelength device size offers low power operation and high switching speeds. We investigate the prospects of incorporating plasmonic stub modulators on a conventional SOI platform, with electro-absorption achieved via QCSE in Ge/SiGe MQWs or Ge quantum dots in silicon matrix. Practical design features necessary for electrical biasing of the stub (e.g. insulating layers or gaps) are considered. Such modifications have a considerable influence on the optical performance. For a 5 nm oxide layer with permittivity of 2.5 on the sides of the stub, a modulation depth of 6.6 dB and insertion loss of 7.2 dB are predicted for the second-order lateral mode regime operation, with Ge/SiGe MQW filling that has a realistic value of on/off absorption ratio of 5. Comparison is then made with an alternative class of plasmonic EAMs based on metal-gap-dielectric structures, relying on the sensitivity of the gap plasmon mode losses near the mode cutoff to the precise refractive index profile, which can be changed via free carrier accumulation. These devices offer reduced insertion losses and, in contrast to the stub structures, their insertion loss and modulation depth scale with device length.
drops to 52K at 120K. The temperature dependence of the radiative current density is much weaker than threshold current density (Jth), which indicates that the non-radiative process increases superlinearly with increasing temperature. From the measured Jth and its radiative component we found that non-radiative processes are becoming more dominant at higher temperature in these lasers and contribute to ~45% of the Jth at 120K. The application of hydrostatic pressure shows that the Jth increases with pressure much faster than radiative current, suggesting the presence of a carrier leakage path in these devices. The pressure co-efficient for the band gap of the device is measured to be ~6.1 meV/kbar and Jth for the devices increased by ~30% up to 7 kbar at 120K. Further prognosis for room temperature lasing on silicon with this approach will be discussed in more depth at the conference.

7943-32, Session 14

Electrically pumped diode lasers on silicon substrates based on Ga(NAsP)/GaP multi-quantum well heterostructures
S. Rogowsky, R. Ostendorf, G. Kaufel, W. Pietzchen, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); S. Liebich, K. Volz, W. Stolz, M. Zimprich, Philipps-Univ. Marburg (Germany); B. Kunert, NASP III/V GmbH (Germany)

The monolithic integration of optoelectronic devices, including efficient light emitters such as laser diodes, into conventional Si-based devices and circuits is a challenging task. This is mainly due to the indirect electronic bandgap of silicon which makes it a poor light-emitter. One promising approach to overcome this drawback is the growth of direct bandgap III/V compound semiconductor material, like the dilute nitride Ga(NAsP)-material system, on silicon substrate. This material system can be grown lattice matched on silicon, which allows to avoid misfit dislocations detrimental to the performance of laser diodes.

In this work we report on electrically pumped diode lasers based on a Ga(NAsP) multi-quantum well (MQW) active region. The lasers have been grown by metal organic vapour phase epitaxy (MOVPE) pseudomorphically on Si and, for reference purposes, GaP. The lateral structure of the devices was fabricated using a multiple mask layer processing sequence.

By inductively coupled plasma (ICP) etching, ridge-waveguides with different lengths and widths were fabricated. On Si-substrate an additional ICP etching step was developed in order to produce etched facets. Electrically pumping of the quantum wells was achieved by applying top p- and lateral n-contacts.

Electro-optical characterization of the ridge-waveguide lasers was performed at room temperature in pulsed and for the low current regime also in cw-operation. Additional optical waveguide analysis was performed. The results show distinct light emission at 975 nm being consistent with photo-luminescence measurements.

7943-46, Session 14

Hybrid silicon ring laser
D. Liang, M. Fiorentino, Hewlett-Packard Labs. (United States); J. E. Bowers, Univ. of California, Santa Barbara (United States); R. G. Beausoleil, Hewlett-Packard Labs. (United States)

Hybrid silicon platform provides a solution to integrate active components (lasers, amplifiers, photodetectors, etc.) with passive ones on the same silicon substrate, which can be used for building an optical interconnect system. Owing to the advantages in footprint, power consumption, and high-speed modulation, hybrid silicon microring lasers have been demonstrated as a potential candidate for on-chip silicon source. In this talk we review the progress to improve the performance of recently demonstrated compact microring lasers with ring diameters of 25 and 50 microns. Approaches to enhance optical mode and electron-hole recombination, which result in threshold reduction and efficiency improvement, and reduce device thermal impedance, which improves device thermal performance are discussed. Design tradeoff and concerns are included. Up to 5 GHz 3 dB bandwidth is shown in direct modulation experiment, while 10 GHz is projected theoretically if device heating is negligible. Power consumption from the perspective of p/J/bit is analyzed. A picture of future microring-based optical transceiver is unfolded at the end.

7943-47, Session 14

Self-organized InAs quantum dot tube lasers and integrated optoelectronics on Si
Z. Mi, P. Bianucci, F. Li, Z. Tian, V. Veerasubramanian, A. G. Kirk, D. V. Plant, McGill Univ. (Canada); P. J. Poole, National Research Council Canada (Canada)

High performance 1.3 - 1.55 µm micro- and nanoscale lasers, that can be monolithically integrated with Si waveguides and modulators are in demand for the emerging chip-level optical communications. Such high performance devices can be potentially realized using rolled-up quantum dot tube cavities, which are formed when a coherently strained quantum dot heterostructure is selectively released from the host substrate. Compared to conventional optical microcavities, they can be fabricated using standard photolithography process and can exhibit epitaxially smooth surface, directional emission and controlled polarization. In this context, we have investigated the molecular beam epitaxial growth, fabrication and characterization of both 1.3 µm InAs/GaAs and 1.55 µm InAs/InP quantum dot tube devices. We have demonstrated 1.2-1.3 µm InAs/GaAs quantum dot tube lasers, with an ultra-low threshold of 4 µW at room temperature. In addition, we have achieved strong 1.55 µm coherent emission from InAs/InP quantum dot tubes. We have further demonstrated that the 3-dimensionally confined optical modes can be precisely tailored by using either a bottle-like surface geometry or by embedding a microbelt at the tube inner surface. With the use of substrate-on-substrate and fiber taper assisted transfer processes, such novel photonic devices can be achieved on Si or any other platform. Work is currently in progress to demonstrate electrically injected 1.3 and 1.55 µm self-organized quantum dot tube lasers by employing a novel lateral p-i-n junction design. The achievement of such nanoscale lasers on Si, as well as their monolithic integration with Si-based waveguides and modulators will be presented.

7943-48, Poster Session

Effects of substrate temperature on SiO2 films deposited by PECVD
S. Gao, L. Jie, S. Ping, Shandong Univ. (China)

Depositing silica films by plasma enhanced chemical deposition (PECVD) is promising. However in the growth of silica films using PECVD, impurity elements are inevitable. Therefore how to reduce impurity elements is a problem which needs an urgent solution. In this work, we present the results of silica films which are deposited by PECVD on GaAs substrates of different substrate temperatures. The films are analyzed by X-ray Photoelectron Spectroscopy (XPS). XPS results demonstrates that the content of impurity elements in the product of this reaction with a higher substrate temperature is much lower than it is with a lower substrate temperature and the ratio of silicon and oxygen of the reaction product is nearly 1:2. And the refractive index of films rises with the increase of substrate temperature. These facts indicate that increasing substrate temperature is an effective way to promote the quality of deposited silica films.
7943-49, Poster Session

**PECVD grown silicon dioxide film process optimization**

S. Ping, L. Jie, S. Gao, Shandong Univ. (China)

SiO2 films have been widely applied in the production of electronic devices, integrated devices, optical thin film devices, sensors because of their desirable properties, such as good insulation, high light transmittance, strong corrosion resistance, good dielectric properties, etc. Amorphous silicon dioxide was fabricated by plasma enhanced chemical deposition on GaAs substrate. The thickness and refractive index are obtained by optical transmittance of the film, which are measured by ellipsometer. The SiO2 thin film growth rate remained basically unchanged over time, but its refractive index gradually increased and become stable after 4 min. The reaction chamber pressure, which makes the SiO2 thin film growth rate getting the peak, should be about 800mTor. The pressure and the refractive index are anti-related; we should reduce the pressure of the reaction chamber in the premise of ensuring the reaction rate. The enormous changes of the gas flow rate do not have huge impact to the response rate. However, the refractive index of SiO2 thin film changed greatly when the SiH4 flow increased the refractive index of the thin films is highest when the ratio of SiH4/N2O is 200:20.

7943-50, Poster Session

**Variation of optical properties by the crystalline phase transition of polycrystalline silicon**

I. Hidenori, K. Tomohiro, H. Yamada, Tohoku Univ. (Japan)

Silicon waveguide optical circuits are a good candidate to achieve on-chip optical interconnects for future generation microprocessors since very small size and low power consumption optical circuits can be realized using CMOS compatible fabrication processes. From a practical point of view, polycrystalline silicon is attractive because of its ease of deposition on almost any substrate. This advantage allows us to realize multi-level or three-dimensional integration of optical circuits. We focus our research on the variation in optical properties caused by the crystalline phase transition of polycrystalline silicon.

Here, we report the change in the refractive index of polycrystalline silicon due to the crystalline phase transition. First, we deposited amorphous silicon on a thermally oxidized silicon wafer by PE-CVD. Next, the sample was annealed for 30 to 90 min at 900 °C in a nitrogen atmosphere, transforming the amorphous silicon into polycrystalline silicon. Finally, the refractive index was measured using the prism coupler technique.

We obtained refractive indices of 3.37, 3.40 and 3.43 for the polycrystalline silicon samples annealed for 30 min, 60 min, and 90 min respectively. Comparing the measured refractive index of amorphous silicon as 3.27, we found that the refractive index of polycrystalline silicon changes about 0.1 by crystallization and it increases monotonically with annealing time.

7943-51, Poster Session

**Si photonic-wire waveguide ring filters for wavelength tunable lasers**

K. Suzuki, K. Tomohiro, H. Yamada, Tohoku Univ. (Japan)

Small size and low power consumption wavelength tunable lasers are a key device for improving the performance and expanding the possibilities of optical communication networks. Therefore, several types of wavelength tunable lasers have been proposed. Especially, tunable lasers based on photonic waveguide ring resonator filters and semiconductor optical amplifiers are studied by many institutions, for their simple structure and suitability for mass production. We investigate about tunable laser filters based on silicon photonic wire waveguide ring resonators. Si photonic wire waveguide contributes to the reduction of power consumption and size of the filter, because of the high thermo-optic efficiency and small bending radius of Si waveguides. The filter structure consists of two Si photonic wire waveguide ring resonators. By designing their free spectral range slightly different, we can obtain an extinction ratio between the main peak and the side peaks, which enables us to select only the main peak. We analyzed the ring resonator filters using the Fabry-Perot (FP) approximation. We confirmed that the FP approximation is in good agreement with the experimental results. Finally, we analyzed the proposed filter as a possible structure for the design of a tunable laser filter with wide tuning range and narrow laser spectral linewidth, required for WDM and coherent communication systems.

7943-52, Poster Session

**Design and demonstration of a polarized light-emitting structure based on omni-directional porous silicon waveguide**

K. Hwang, Y. Park, H. Jeon, Seoul National Univ. (Korea, Republic of)

The polarization control of light generated in the light-emitting devices is one of the important research areas. Based on the fundamental physics of one-dimensional photonic crystals (1D-PCs), we anticipate some unique polarization characteristics to occur in a specially designed multilayered waveguide structure, in which a low refractive index central guiding layer is sandwiched between two 1D-PC reflectors. When designed properly, the 1D-PC reflectors become omni-directional in reflection for TE-polarized light only, not for TM-polarized light. As a consequence, the multilayered waveguide structure can guide the TE-polarized light, whereas the TM-polarized light leaks out through the claddings. Here we realized such a polarization-controlled waveguide structure using porous silicon (PSi). The in-situ controllability of refractive-index and film thickness makes the PSi very useful in fabricating 1D-PCs such as DBR mirrors, Fabry-Perot filters, etc. The light-emitting nature of highly porous PSi may facilitate experimental investigations of the fabricated structures. We optically pumped the device and examined the polarization characteristics of the light emitting through the edge of device. We found that the edge emission is strongly TE-polarized, consistent with the theoretical predictions. Furthermore, the TE-polarized edge emission is only over the frequency range in which the 1D-PC reflectors are omni-directional. Consequently, the edge emission spectrum is severely changed from that of PSI itself. Finite-difference time-domain simulation results also confirm the polarization properties of the waveguide structure. This multilayered waveguide structure can be utilized as a waveguide polarizer or as a polarized light-emitting device.

7943-53, Poster Session

**Investigation of optical properties of two-dimensional photonic crystals by means of the scattering matrix method**

S. A. Dyakov, T. S. Perova, Trinity College Dublin (Ireland); E. Astrova, Ioffe Physico-Technical Institute (Russian Federation); S. G. Tikhodeev, N. A. Gippius, A. M. Prokhorov General Physics Institute (Russian Federation)

The scattering matrix (S-matrix) method [1] was used to simulate the reflection, transmission and absorption spectra of two-dimensional (2D) photonic crystals (PCS) made of silicon. This method was developed by Tikhodeev et al. [1] based on a generalization of the method proposed by Whitaker and Culshaw [2], to model the properties of multilayered 1D and 2D patterned PCS’s with frequency dispersive constituent materials. To calculate the optical properties of the PCS’s we split the system into
layers, homogeneous along z-direction, and solve Maxwell's equation for each layer via decomposition into partial plane waves. Then for each layer we construct the material matrices and a total S-matrix of the structure. Knowledge of the S-matrix enables us to calculate the optical spectra and the spatial distribution of the electromagnetic field for the structure under consideration.

2D PCs were fabricated by photo-electrochemical etching of (100) Si [3]. The polarised light reflection and transmission spectra of fabricated structures were investigated experimentally by means of FTIR microspectroscopy. A very good agreement between the experimental and the simulated reflection spectra was demonstrated for both TM and TE polarisations of the incident light.

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7944-01, Session 1

Low power thermal tuning of SOI-CMOS photonic structures
I. N. Shubin, X. Zheng, H. D. Thacker, J. Yao, G. Li, A. V. Krishnamoorthy, J. E. Cunningham, Oracle (United States); T. Pinguet, A. Mekis, Luxtera (United States); B. Guenin, Oracle (United States)

Silicon photonic circuits have shaped up into a compelling technology offering performance and energy boost to the computing, signal processing or communication systems. Ring waveguide resonating structures with high quality factors are the key components servicing such circuits. We demonstrate a highly efficient spectral tunability of the microphotonic ring structures manufactured in commercial 130 nm SOI CMOS technology. Our rings are fitted with dedicated heaters and integrated with silicon micro-machined features. Optimized layout and structure of the devices result in their maximized thermal impedance and increased efficiency of the thermal tuning.

7944-02, Session 1

Low power photonics components for optical interconnects
P. Dong, R. Shafiiha, D. Feng, M. Asghari, Kotura, Inc. (United States)

Silicon-based optical interconnects are expected to provide high bandwidth and low power consumption for chip-level communication, due to their electronics integration capability, proven manufacturing record and price volume curve. In order to compete with electrical interconnects, the power budget is projected to sub-pJ per bit for an optical link in chip to chip communication. Such low power consumption poses significant challenges to the optical components to be used. In this talk, we review several low power photonics components developed at Kotura for DARPA’s Ultraperformance Nanophotonic Interchip Communications (UNIC) program. These components include high-speed silicon microring modulators, wavelength (de)multiplexers using silicon cascaded microrings, low power low-electro-optic silicon switches, low loss silicon routing waveguides, and low capacitance Germanium photodetectors. Our microring modulators require a power consumption of ~10 fJ per bit with a drive voltage of 1 V. Silicon routing waveguides have a propagation loss < 0.3 dB/cm, enabling a propagation length of a few tens of centimeter. The Germanium photo detectors can have a low device capacitance of a few fF, a high responsivity up to 1.1 A/W and a few tens of centimeter. We demonstrate that Ge/SiGe QWs can be selectively grown onto silicon substrates with an oxide mask. Optimized growth conditions yield high quality epitaxy with very high selectivity and minimal loading effect. To prevent the lateral growth from the exposed sidewall of the SOI waveguide during the selective epitaxy, a thin insulating layer is proposed to be inserted in between the SOI waveguide section and the selectively grown Ge/SiGe QW section. Through finite-difference time-domain (FDTD) method simulation, we demonstrate that coupling efficiency between the SOI waveguide and Ge QW waveguide increases as the thickness of the insulating layer decreases. For a 10 nm thin SiO2 layer, the insertion loss can be as low as 0.09dB. We also implemented an approach to reliably fabricate this very thin SiO2 on the sidewall of the SOI waveguide without sacrificing the crystal quality of the selective epitaxy growth window through a dual-layer process.

7944-03, Session 1

Ge/SiGe quantum well waveguide modulator integrated with silicon-on-insulator waveguide
S. Ren, Y. Rong, T. I. Kamins, J. S. Harris, Jr., D. A. B. Miller, Stanford Univ. (United States); P. Dong, S. Liao, Kotura, Inc. (United States)

The Quantum-Confined Stark effect (QCSE) in germanium (Ge) quantum well structures opens up a way to realize electrical to optical conversion in a low energy, low cost, high speed, high density, and CMOS compatible fashion. However, due to the background absorption from the indirect band gap, passive Ge QW waveguides would have too high a loss for signal routing purposes. On the other hand, silicon-on-insulator (SOI) waveguides show very low loss and high density. Here, we will present an approach to integrate Ge/SiGe quantum well modulators into the SOI waveguide platform to leverage the advantages of both. We demonstrate that Ge/SiGe QWs can be selectively grown onto silicon substrates with an oxide mask. Optimized growth conditions yield high quality epitaxy with very high selectivity and minimal loading effect. To prevent the lateral growth from the exposed sidewall of the SOI waveguide during the selective epitaxy, a thin insulating layer is proposed to be inserted in between the SOI waveguide section and the selectively grown Ge/SiGe QW section. Through finite-difference time-domain (FDTD) method simulation, we demonstrate that coupling efficiency between the SOI waveguide and Ge QW waveguide increases as the thickness of the insulating layer decreases. For a 10 nm thin SiO2 layer, the insertion loss can be as low as 0.09dB. We also implemented an approach to reliably fabricate this very thin SiO2 on the sidewall of the SOI waveguide without sacrificing the crystal quality of the selective epitaxy growth window through a dual-layer process.

7944-04, Session 1

Grating coupler based optical proximity coupling for scalable computing systems
J. Yao, X. Zheng, G. Li, I. N. Shubin, Y. Luo, H. D. Thacker, Oracle (United States); A. Mekis, T. Pinguet, Luxtera (United States); K. Raj, J. E. Cunningham, A. V. Krishnamoorthy, Oracle (United States)

Scaling multiple-core computing systems interconnects has been drawing great deal of interest to meet the ever-increasing bandwidth and computational demands generated by the commercial and military applications. Silicon photonics is deemed as a promising enabling solution attributed to its bandwidth, density, and latency advantages. To leverage its advantages and provide scalable capability to the interconnects of high performance, many-chip computing systems, optical proximity coupler is one of the critical enablers. Chip-to-chip, layer-to-layer optical proximity couplers with low loss, large bandwidth, small footprint and integration compatibility are highly desirable, but also remarkably challenging to achieve.

In this paper, we have designed and demonstrated grating coupler based optical proximity coupling for high performance intra/inter chip interconnects. A set of simulation models using Finite Difference Time Domain (FDTD) method are developed to design the grating coupler parameters. Compared to reflecting mirror based optical proximity coupling fabricated using Si micro-machining and metal coating, this approach avoids 3-dimensional waveguide tapers, and is fully CMOS compatible. Low cost can be easily achieved leveraging existing CMOS fabrication infrastructures.

We discuss the design, modeling, and simulation methodology in details, and present the simulated performance results. 3dB loss and more than 55nm bandwidth can be achieved according to the simulation results. We further report the experimental results of the fabricated optical proximity couplers using a commercial 130nm SOI CMOS process. The experimental results are compared with simulated modeling results in various conditions. In addition, the integration potentials, further improvements and future applications are discussed.

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7944-05, Session 2

**Evaluation of graded index glass waveguides for board-level WDM optical chip-to-chip communications**

J. Schrage, C-LAB (Germany) and Siemens AG (Germany); O. Stuebbe, C-LAB (Germany) and Univ. Paderborn (Germany); L. Brusberg, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); Y. Soenmez, C-LAB (Germany) and Univ. Paderborn (Germany); H. Schroeder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); R. Schuhmann, Univ. Paderborn (Germany)

A Proof-of-Concept for a multi-channel WDM board-level optical communications link is under development. This paper is focusing on theoretical and experimental evaluation of thin-glass based graded index optical waveguides with regard to low loss in the 1310nm regime, preserving light polarization and guiding single mode. Results from characterization (material attenuation, refractive index profiles, coupling efficiency between the glass waveguides and fibers) will be reported. Waveguide modes are determined theoretically from the measured refractive index profiles. Towards improvement of the robustness of the coupling efficiency against misalignments, investigations on the use of tapered waveguide structures will be presented too.

7944-06, Session 2

**Next generation optical interconnection technology; high performance photonics polymers for optical waveguide fabrication and evaluation**

O. Sugihara, T. Kaino, Tohoku Univ. (Japan)

Polymer optical waveguides are key components for board level optical interconnection. In this paper high performance photonics polymers and polymer optical waveguides for next generation optical interconnection are presented.

7944-07, Session 2

**PCB with fully integrated optical interconnects**

G. Langer, Austria Technologie & Systemtechnik AG (Austria); V. Satzinger, V. Schmidt, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); G. Schmid, W. R. Leeb, Technische Univ. Wien (Austria)

The increasing demand for miniaturization and design flexibility of polymer optical waveguides integrated into electrical printed circuit boards (PCB) calls for new coupling and integration concepts. We report on an innovative method for the coupling of optical waveguides to electro-optical components and for the integration of the entire optical link into the PCB. The electro-optical components are attached to the PCB and embedded into an optical material. A focused femtosecond laser beam stimulates a two photon absorption effect in the optical material and locally increases the refractive index of the material. In this way waveguide cores can be realized and the embedded components are optically connected. This approach does not only allow a precise alignment of the waveguide end faces to the components but also offers a truly 3-dimensional routing capability of the waveguides.

Using this technology we could show butt-coupling and mirror-coupling interface solutions realized in several demonstrators. We could also realize demonstrator boards with fully integrated driver and preamplifier components, which show very low power consumption. Furthermore, demonstrators with 3-dimensional optical interconnects will be presented.

7944-08, Session 2

**Optical loss characterization of polymer waveguides on halogen and halogen free FR-4 substrates**

B. W. Swatowski, C. T. Middlebrook, K. Walczak, M. C. Roggemann, Michigan Technological Univ. (United States)

Glass resin epoxy FR-4 is used as a lamination layer in printed circuit board applications. Chemicals such as bromine or other halogens are introduced into the FR-4 layer to serve as a flame retardant. During the photolithography and temperature cycling process these halogens elements diffuse into the optical polymer structures residing on the FR-4 substrate. The introduction of these elements into the polymers alters the optical absorption properties of the waveguides. In order to optimize an overall link budget for an optical communication channel the absorption loss of the waveguides must be well known and minimized. Research and characterization has been performed to ascertain the impact of the use of halogen vs. halogen free FR-4 circuit boards. An analysis of waveguide structures with a fixed core dimension of 50x50 µm was done to characterize the effects of the Halogen FR-4. The thickness of the cladding layer, the thermal cycling times, and the maximum curing temperatures were varied in order to determine the relationships between these processes and the penetration depth of halogen diffusion into the cladding layer. The performance of the optical polymer waveguides was subjected to index of refraction measurements, optical analysis at 850 nm in order to measure the specific optical attenuation, and Bit-Error-Rate Testing (BERT) at speeds up to 10 Gb/s. Eye diagrams are presented in order to provide a measure and visual representation of the optical communication channel. Mitigation techniques and methods are also explored for situations where Halogen FR-4 boards must be utilized.

7944-09, Session 3

**20 Gbps optical link with high efficiency 1060 nm VCSEL**

J. B. Héroux, M. Tokunari, S. Nakagawa, IBM Japan, Ltd. (Japan)

Recent advances in the development of low power GaAs-based VCSEL devices with InGaAs quantum wells are promising for optical interconnect applications in high performance computers. Not only is the strain in the wells advantageous to decrease the threshold current and increase the modulation efficiency of the lasers, but a long operating wavelength in the 1 µm range, as opposed to 850 nm as used in legacy systems, allows to obtain a higher responsivity on the receiver side using InP-based InGaAs photo-diodes. The GaAs and InP substrates are also transparent to obtain a higher responsivity on the receiver side using InP-based InGaAs photo-diodes. The GaAs and InP substrates are also transparent at a long wavelength, which enhances system design flexibility. In this work, we present measurement results of a high speed, low power single channel optical link operating at 1060 nm. The link is composed of VCSEL devices fabricated and provided by Furukawa Electric Co. Ltd. and low cost OM2 fibers. Clear eye openings are observed at 20 Gbps with a 2 mA DC bias. A modulation voltage of 150 mV-p-p results in a -4.1 dBm OMA at the fiber output in a back to back configuration, with 0.19 unit amplitude eye opening and 32 ps total jitter at a 10E-12 bit error ratio. The insertion of a 100 m OM2 fiber causes negligible signal degradation due to the fact that the properties of the fiber (dispersion, attenuation) are better at this wavelength than at 850 nm. In the next phase of this project a compact, low power CMOS laser driver will be integrated to the system. A transmitter power consumption well below 2 mW/Gbps is expected.
Hybrid-integrated silicon photonic bridge chips for ultralow energy inter-chip communications

H. D. Thacker, I. N. Shubin, Y. Luo, J. Costa, J. Lexau, X. Zheng, G. Li, J. Yao, R. Ho, Oracle (United States); T. Pinguet, Luxtera (United States); M. Asghari, Kotura, Inc. (United States); K. Raj, J. G. Mitchell, A. V. Krishnamoorthy, J. E. Cunningham, Oracle (United States)

Hybrid integration is a practical approach for combining best-of-breed silicon photonic components and CMOS VLSI chips. Such integrated bridge-chips may be used in transmitter/receiver arrays or as communication physical layer elements in a multi-chip computing node. To maximize the performance advantages of the optimized components in a hybrid assembly, we have developed an ultralow parasitic scalable chip-to-chip interconnect (<100mOhm/bump, <25fF/bump). These I/Os, consisting of an under-bump-metalization and a microsolder bump may be scaled for wafer-level processing. The chips are attached by flip-chip bonding in diving board configurations to allow access for optical I/Os. We present the microsolder technology and the integration challenges and solutions for hybrids using surface-normal or edge-coupling optical I/Os.

Previously, we reported the performance results from Si-photonic hybrids, which combined 130nm SOI-CMOS photonic chips and SOI-photonic chips to 90nm bulk CMOS circuits. At 5Gb/s, Tx and Rx bridge-chips achieved ultralow-energy performance of 320fJ/bit and 690fJ/bit, respectively. The integration of these devices is summarized. We also present the integration of the next generation of photonic bridge-chips, comprising of scaled photonic devices attached to 45nm bulk CMOS ICs. For the new generation of hybrids, being tested at higher datarates, we have scaled the microsolder by roughly 20% to further lower parasitics.

In this work, the VLSI and photonic chips were received post-dicing, so microsolder fabrication needed to be performed at the chip-scale. To overcome this inefficient process, we devised methods for batch-fabrication of the I/Os on a multichip of chips from different technology platforms; these techniques are detailed.

Thin glass based packaging and photonic single-mode waveguide integration by ion-exchange technology on board and module level

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The field of photonic integrated circuits is rapidly growing with strong potential for intra and interchip optical interconnects in data and telecom applications. The O/E integration into the chip and the applied single-mode waveguide structures characterize high integration (small feature size) and high bandwidth density (wavelength multiplexing). Beside ultra-short reach interconnects long-haul single-mode glass fibers build the global telecon network since two decades. A hybrid packaging platform providing 3D optical single-mode 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 single-mode waveguides for fiber-to-chip and chip-to-chip links. 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 single mode waveguide circuits, optical mirrors and lenses providing an 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 adopted planar waveguide process based on ion-exchange technology is very suitable for high-volume manufacturing. The modeling of the ion-exchange process and the optical propagation is described in detail for thin glass substrates. An extensive characterization of all basic circuit elements like straight and curved waveguides, couplers and crosses proves the low attenuation of the optical circuit elements.

A concept for the assembly and alignment of arrayed microelectronic and micro-optical systems for optical multi-gigabit communication

F. Merchán, K. Brenner, Ruprecht-Karls-Univ. Heidelberg (Germany)

In the first part of this contribution we present a concept for the fabrication, assembly and alignment of a multichannel micro optical-coupler and arrayed microelectronic devices placed on a PCB. This concept is based on a micro optical-coupler that integrates several optical sub-systems in a monolithic substrate in order to simplify adjustment processes. The optical-coupler is fabricated by plastic replication of a metal master with the negative shape of the coupler. For the fabrication on the PCB, only one alignment step is necessary. By placing markers on the PCB it is possible to position the coupler over the VCSEL or photodiode array. The placement and connections between the electronic devices on the PCB are taken into account in the design of the coupler. The mechanical assemblies for populating PCBs with electronic devices have an accuracy of a few micrometers. Using these techniques an optimal position of the coupler relative to the VCSEL or photodiode array can be found. In the second part we examine with the help of simulations the effect of misalignment, tilt, increased roughness or dust on the optical surfaces and possible differences between the optical fibers like irregularities on the end-surfaces. Bitrates of 120 Gbps in a 12-channel system can be reached using this coupler with commercial electronic devices. Applications for this system are active optical cables and ultra wide-band board to board communication systems. A FPGA-board for the test of this concept is in the design phase and will be referenced.

Packaging technology enabling flexible optical interconnections

E. Bosman, G. Van Steenberge, B. Van Hoe, J. Missinne, S. Kalathirimekkad, P. Van Daele, Univ. Gent (Belgium)

This paper reports on the latest trends and results on the integration of optical and opto-electronic devices and interconnections inside flexible carrier materials. The use of flexible carriers and materials for optical communication purposes opens a world of opportunities due to the advantages of mechanical bendability. Electrical circuits on flexible substrates are a very fast growing segment in electronics, but opto-electronics and optics should be able to follow these upcoming trends. This paper presents the results of 5 years of research on this topic. Highly flexible and reliable opto-electronic packages are realized by embedding ultra thin opto-electronic devices into a layer build-up of consecutive spin coated layers. A technology has been developed to thin down commercially available Vertical Cavity Surface Emitting lasers and photodiodes to a thickness of only 20 μm without any chance in functionality or characteristics. An embedding process is presented to embed the thin devices in a layer of SU-8 material. Back-contact heat sinks and electrical interconnections from and towards the embedded components are fabricated within the process. Mechanical support layers are applied at both sides of the SU8-layer to obtain high strength and flexibility of the package. Next to the active components, also optical waveguides and optical out-of-plane coupling structures are integrated inside the layer stack, resulting in complete VCSEL-to-PD links with low
total optical losses (~6dB) and high resistance to heat cycling (~40 °C to 125 °C) and moisture exposure (1000h at 85 °C at 85% relative humidity).

7944-14, Session 4

Transfer and characterization of silicon nanomembrane based photonic devices on flexible polyimide substrate

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The flexible electronic and photonic devices have attracted a lot of attention in past decade because of their potentially wide applications. A general method to fabricate silicon nanomembrane devices involves two steps. At first, a nanomembrane on top of a sacrificial layer is patterned. In the next step, the nanomembrane is released from the SOI wafer by selectively etching the sacrificial layer. The released nanomembrane weakly bonds to the substrate via Van der Waals forces and is peeled up from the silicon handle wafer with a temporary elastomeric substrate. Then, this intermediate substrate is brought into conformal contact with the final substrate so that the silicon nanomembrane device can be transferred to the flexible substrate due to the different adhesive properties of the materials. Through this method, a lot of exciting approaches have been taken in flexible electronics. However, the progress in flexible photonic device is still limited to surface-normal devices such as photonic crystal filter and light emitting diodes (LED).

In this paper, we report the transfer and characterization of in-plane silicon nanomembrane based photonic devices on flexible polyimide film. Compared with electronic devices and surface normal optical devices, the in-plane photonic devices have high requirements on transfer precision because any shifting can affect the performance of devices. Therefore, the use of a supporting layer is explored to protect the device during the transfer process. With the supporting layer, different types of photonic devices are successfully transferred and tested.

7944-15, Session 4

Autonomous and dynamic reconfigurable waveguide for optical interconnection with large shift-tolerance

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In order to realize a dynamic reconfiguration technique that automatically switches configurations and functions of an optical device, we need a technique to control freely the connections of light inside and between devices without needing submicron-level alignments. In this study, we investigate the behavior of dynamic index gratings with nanoscale reversible self-organization in Sn2P2S6 crystals that we have newly developed so as to realize an autonomous and dynamic reconfigurable optical waveguide by externally controlling its motions with light and examine its basic properties. Experimental results showed autonomous and dynamic reconfigurations of the optical waveguide formed in a Sb doped Sn2P2S6 crystal with a 4mm thickness for variations of an incident light position. We have successfully reconfigured the waveguide by a self-organization based on a photorefractive effect without cutting time series signals flowing through the waveguide, for variations of an incident light position long as approximately 2000 m. Furthermore, we have recognized tolerance up to around 0.2 degrees for incidence angles in the experiment. This technique allows us to connect light freely without needing spatial adjustments in a nanostructured optical waveguide seen in photonic crystal fibers. Moreover, it is a technique that can be applied to dynamic connections between optical fibers and integrated waveguides accompanied with time variations of spatial modes. We also verified a possibility of removable and replaceable optical connection by utilizing large shift-tolerance of the autonomous and dynamic reconfigurable waveguide.

7944-16, Session 4

Inter-channel crosstalk analysis for W-shaped and graded-index core polymer optical waveguides with ray tracing method

H. Hsu, K. Shitanda, T. Ishigure, Keio Univ. (Japan)

We fabricate multichannel and multimode graded-index (GI) core polymer optical waveguides which feature the low-loss, high bandwidth, and low inter-channel crosstalk. According to our previous study, the waveguide (50 μm in core radius and pitch between two core center is 150 μm) performs 12.5 Gbps data rate per channel and ~30 dB crosstalk value. This satisfies the requirement for high bandwidth and flexible installation such as on-board interconnection in high-performance computers. Though multimode waveguides have a large tolerance in the misalignment between light sources and photo detectors, mode conversion (inter-modal energy transfer among the propagation modes) and modal noise have been a problem in multimode waveguide based data communication systems. Thus, in this paper, we investigate the relationship among mode conversion, propagation loss, and inter-channel crosstalk in multimode parallel polymer optical waveguides. It has generally been considered that the inter-channel crosstalk is dominated by mode conversion, which originates from irregular structures on the core-cladding boundary and the light scattering loss inherent to the core polymer. In order to address these problems more specifically, we fabricate some more featured waveguides and establish theoretical analysis with self-developed algorithm based on ray tracing method. We show the experimental results of our newly-developed W-shaped index core waveguides, which is capable of reducing the inter-channel crosstalk significantly even compared to GI-core waveguides. Then we apply the ray-trace simulation to verify how the W-shaped index core works by showing the ray trajectories and calculating the length dependence of the near field patterns (NFPs) and crosstalk values. Furthermore, with this algorithm, we visually and numerically compare the performance between the conventional step-index (SI) core waveguides and our graded-index type counterparts. These theoretical and experimental investigations prove that W-shaped and GI-core waveguides have high potential to be used in high-speed and high-density optical interconnections.

7944-17, Session 5

300 Gb/s bidirectional fiber-coupled optical transceiver module based on 24 TX + 24 RX “holey” CMOS IC


A novel, compact 48-channel optical transceiver module has been designed and fabricated based on a “holey” Optochip - a single-chip CMOS transceiver IC with 24 receiver and 24 laser driver circuits each with a corresponding through-substrate optical via (hole). The holes enable 24-channel 850-nm VCSEL and photodiode arrays to be directly flip-chip soldered to the CMOS IC to maximize high-speed performance and facilitate direct fiber-coupling to a standard 4 x 12 MMF array. The Optochips were packaged into complete modules by flip-chip soldering to high-density, high-speed organic carriers. High-speed characterization of all 48-channels showed good performance up to 12.5 Gb/s/ch providing a 300 Gb/s bidirectional aggregate data rate.
High density active optical cable: from a new concept to a prototype

D. Wohlfeld, F. Lemke, H. Froening, Schenck, U. Bruening, Ruprecht-Karls-Univ. Heidelberg (Germany)

Evolution in high performance computing (HPC) leads to increasing demands on bandwidth, connectivity and flexibility. A promising concept solving most appearing problems are Active Optical Cables (AOC).

Optimization and development of AOC solutions requires enhancements concerning different technology barriers.

Area and volume occupied by connectors is of special interest within HPC networks due to common design standards giving height restrictions and providing limited edge space for connectors. A 3D-torus for example requires 6 connections per node, ideally placed at the edge of a PCI standard sized card. This led to the development of a 12x AOC for the mini-HT connector creating the densest AOC available.

In order to integrated electrical optical conversion into a module not higher than 3 mm, a new concept of coupling fibers to VCSEL or photodiodes had to be developed. This unique concept is based on a direct replication process of an integrated fiber coupler consisting of a 90° light deflection and focusing mirror, a fiber guiding structure, and a fiber funnel. The integrated fiber coupler is directly replicated on top of active components, reducing the distance between active components and fibers to a minimum, thus providing a highly efficient light coupling.

As AOC prototype multi-chip-modules (MCM) including the complete electrical to optical conversion for send and receive connected by two 12x fiber ribbons have been developed.

The paper will present the integrated fiber coupling technique and also design and measurement data of the prototype.

Silicon nanophotonics for optical interconnects and applications

R. T. Chen, The Univ. of Texas at Austin (United States)

No abstract available

Group velocity independent coupling into slow light photonic crystal waveguide on silicon nanophotonics integrated circuits

C. Lin, The Univ. of Texas at Austin (United States); X. A. Wang, Omega Optics, Inc. (United States); R. T. Chen, The Univ. of Texas at Austin (United States)

No abstract available

Novel organic-inorganic hybrid materials for optical interconnects

T. Sato, Nissan Chemical Industries, Ltd. (Japan)

Optical materials in the optical circuit board are required to overcome soldering process. In detail, the material should not have absorption and shape changes after several tens of seconds heating at around 250 °C. For such application field, we have developed a novel organic-inorganic hybrid material having a high thermal stability and low absorption at telecom wavelength.

The material is designed to UV and/or Thermal curable resin, and soluble to popular organic solvents. We fabricated a rigid optical waveguides on a SiO2/Si wafers by UV lithography. The size of waveguide was 40um in width, 30um in height, and 7cm in length. Optical attenuation of the waveguide measured by the cut back method was 0.1dB/cm at 850nm, 0.29dB/cm at 1310nm, and 0.45dB/cm at 1550nm. These values are good low attenuation for the Near-IR optical communication.

The 5% weight loss temperature of the UV cured material was 380 °C. In addition, the material is having a high refractive index of n=1.60 at 633nm and a low curing shrinkage of 4.7%. We have demonstrated to fabricate a bulk body sample by UV curing, and obtained high uniformity cured materials with 5mm-thick and 1cm-diameter.

From these properties, the developed organic-inorganic material is expected to be beneficial for the optical interconnection such as micro lenses and optical packages.

Direct fabrication of optical elements by photoinduced processes on sol-gel materials

O. Soppera, Univ. de Haute Alsace (France)

The sol-gel process is one of the most attractive routes for the fabrication of optical elements due to the control of the material composition and structural properties in a wide range, low-cost, and abilities to deal with substrates of large area and/or complex shape.

Today, the challenges are mainly relative to the development of new processes and associated materials for achieving easy generation of complex optical devices.

In this context, photoactivable sol-gel materials are of primary interest. Indeed, the photochemical pathway allows a direct writing of the optical element avoiding the recourse to complex and time-consuming etching or any additional steps.

To illustrate this trend, we will focus here on two new strategies that combine the sol-gel chemistry with photochemical processes for the design and fabrication of optical elements.

The first technique is aimed at implementing optical elements in complex systems (optical systems, light sources, etc...) by self-guiding photopolymerization. The idea is to use the light source or the optical fibre on which the optical device has to be implemented to trigger the crosslinking reaction. Microlenses and optical waveguides obtained by this process are thus perfectly aligned at the microscale. This process was adapted to hybrid sol-gel materials.

The second part will deal with the possibility of obtaining inorganic optical micro and nanostructures by direct irradiation using wavelengths in the Deep-UV range (193 nm). ZrO2 and TiO2 gratings were obtained by adapting the sol-gel chemistry with high-energy photons. The recourse to deep-UV wavelength allows exciting new photoinduced processes that can be used to crosslink the sol-gel layer.

In both cases, the goal is to obtain micro or nanostructures with specific optical properties by relatively simple processes.
By two tones of photoresist (PR), positive and negative, only one method, called the boundary-confined method, was proposed and demonstrated. Poor uniformity and low lens height. A new MLA fabrication method, using thermal reflow processes, cause micro lenses merge together easily due to the non-uniformity after the thermal reflow process. Traditional photo resist PR is stopped by the boundary; uniformity is improved without tight thermal dose constrains. Meanwhile, micro lenses with a large height are achievable due to “no cling” effect. The method has advantages, not only for large area MLAs but also for a microlens that require precision diameter or positioning. Besides, we replicate MLAs with the optical polymer to verify some optical specifications. Both the fabrication and replication are straightforward and reliable. Our results show that the microlens is approximately a hemispherical profile. The gap between microlenses with 48 μm diameter in hexagonal arrangement is 2 um and the height of microlens is 22 um.

Self-organization of optical Z-connections in three-dimensional optical circuits simulated by the finite difference time domain method

T. Yoshimura, K. Wakabayashi, Tokyo Univ. of Technology (Japan)

To reduce efforts for optical assembly with micron/submicron accuracy, we developed the reflective self-organized lightwave network (R-SOLNET). In R-SOLNET, optical devices with wavelength filters on their core facets are placed in a photo-polymer. Write beams from some of the devices and reflected write beams from the wavelength filters of the other devices overlap. In the overlap regions, the refractive index of the photo-polymer increases, pulling the write beams to the wavelength filter locations (the “pulling water” effect). By self-focusing, self-aligned optical waveguides are formed between the optical devices. It is expected that R-SOLNET is useful to construct optical-Z-connections in three-dimensional optical circuits. In the present work, we simulated self-organization of optical Z-connections utilizing R-SOLNET by the finite difference time domain method.

We considered simulation models of optical Z-connections with vertical waveguides of R-SOLNET. A 2-um-thick core with a 45 deg. total internal reflection (TIR) mirror is on a 0.5-um-thick under clad layer to form an optical waveguide film. Two optical waveguide films are stacked with a 10-um gap filled with a photo-polymer. Refractive index of the photo-polymer varies from 1.5 to 1.7 with write beam exposure. Wavelengths of write beams and probe beams are 650 nm and 850 nm, respectively. From the simulation, it was found that the “pulling water” effect is induced even when ~1-um displacement exists between the two optical waveguide films and the coupling efficiency increases from 30% to 60% by depositing perfect conductor on the mirror surface.

Modeling of a tunable refractive lens based on liquid crystals

L. Li, L. Shi, D. Bryant, Kent State Univ. (United States); D. Duston, eVision, LLC (United States); P. J. Bos, Kent State Univ. (United States)

We propose an innovative design and fabrication method for a tunable refractive lens based on liquid crystals. The lens has 204 rings of transparent ITO conductor with an inter-ring resistor network. The width of each electrode is calculated to have maximum phase change between any pair of electrodes of about 1/8 . The radius of the central electrode d is about 250 μm, and the width of the outermost electrode is 12 μm, the gap between any 2 adjacent electrodes is 3 μm. Totally, the active area is about 4.7 mm in radius, and our lens has a thickness of 25 μm, filled with a LC material of a large birefringence.

Through a via in a SiO2 layer deposited on the ITO pattern, we run metal interconnects with polymer waveguides, much higher data rate and low inter-channel crosstalk in polymer optical waveguides with GI cores due to the optical confinement effect of the GI-core. Hence, the channel density could be increased for GI multiple-core waveguides. In this paper, we successfully fabricate a polymer waveguide with GI cores directly on a substrate utilizing the soft-lithography method or a dispenser. We experimentally confirm that near parabolic refractive index profiles are formed in the parallel cores with 40 um x 40 um size at 75-um pitch in a length of 20 cm. We also use a copolymer for forming the GI profile, and then, confirm the high-temperature stability of the parabolic index profile compared to the one formed with a doped polymer. Finally, we discuss about the crosstalk property of the fabricated waveguides.
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is calculated by our simulation, taking into account the details of the electrode structure and the properties of the LC material used.

To characterize the optical performance: we use a Mach Zehnder interferometer to obtain the actual phase profile across the lens aperture; and a beam scan device to quantify the spot profile of a collimated beam at the focal plane. An eye chart image is also taken. In the talk, the results from a lens system that can vary its power continuously from 0 to 2 diopters will be discussed.

7944-28, Session 7

Micro-optics packaging and integration for high power diode laser beam combining
Y. G. Soskind, David H. Pollock Consultants, Inc. (United States)

High power diode laser beam combining using micro-optics components is emerging as a cost-effective technique of producing high power laser output from a small-sized laser packages. Packaging of micro-optics lenses and lens arrays that are matched to lithographically fabricated diode laser waveguides provides a practical approach for combining multiple field distributions into a single high output power beam. The beam combining is often associated with additional output beam shaping that is tailored to a specific photonic application which the laser is intended for, such as surface treatment or microfabrication, photomedicine, laser pumping, or remote spectroscopy.

It is shown that packaging imperfections and components’ misalignments during the packaging phase influence the output laser beam spatial characteristics and produce specific beam distortions. Micro-optics design optimized for packaging and integration reduces the beam distortions caused by the packaging imperfections, such as post-bonding shifts and lens-induced aberrations. Another role of optical design optimization and tolerance analysis is in providing a deterministic approach of distinguishing specific misalignment effects based on the observed distortions of the beam distributions. This, in turn, is used to develop appropriate compensation techniques that can be applied to improve the quality of the combined beam output during the fabrication process.

7944-01, Session 8

Free-space-wave add/drop multiplexing for WDM optical-interconnect system in package
S. Ura, Kyoto Institute of Technology (Japan); K. Kintaka, National Institute of Advanced Industrial Science and Technology (Japan)

No abstract available

7944-02, Session 8

Three-dimensional crossbar interconnection using planar-integrated free-space optics and digital mirror-device(TM)
U. Lohmann, J. Jahns, Univ. of Hagen (Germany); S. Limmer, D. Fey, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

We consider the implementation of a dynamic crossbar interconnect using planar-integrated free-space optics (PIFSO) and a digital mirror-device(TM) (DMD). Because of the 3D nature of free-space optics, this approach is able to solve geometrical problems with crossings of the signal paths that occur in waveguide optical and electrical interconnection, especially for large number of connections. The DMD device allows one to route the signals dynamically. Due to the large number of individual mirror elements in the DMD, different optical path configurations are possible, thus offering the chance for optimizing the network configuration. The optimization is achieved by using an evolutionary algorithm for finding best values for a skewless parallel interconnection. Here, we present results of the optimization and experimental examples for the use of the PIFSO/DMD-setup.

7944-29, Session 8

Photonic switching for reliable nanoscale three-dimensional integrated network-on-chips
I. B. Djordjevic, The Univ. of Arizona (United States)

As the multi-core architecture is becoming a prevailing high-performance chip design approach, power efficiency, limited bandwidth and low reliability have been recognized as major communication bottlenecks for on-chip networks (NOCs). To simultaneously tackle the above problems, we propose a three-dimensional integrated (3D) photonic NOC architecture. This architecture is composed of the following layers: (i) the multi-core processor layer that host multiple heterogeneous processing cores together with corresponding local memories and network interfaces, (ii) multiple 3D memory layers that provide the bulk of on-chip memory, and (iii) photonic NOC layer. The photonic NOC layer is based on the optical cross-point switches (OXSs) implemented using active vertical coupler (AVC) structures. The use of this photonic NOC layer will provide ample bandwidth at reduced latencies along with high reliability. Moreover, the photonic NOC approach is able to significantly reduce the overall power consumption. This is possible as power is consumed only when the photonic switching cell is ON. This idea was inspired by recent advances in CMOS photonics, and by development of large-scale photonic integrated circuits (PICs). While recent photonic NOCs are based on ring resonators our approach employs AVCs at the switching crossconnects. The proposed AVC-based switching technique is less lossy and, more importantly, insensitive to temperature when compared to similar devices such as micro-ring resonators. The basic photonic layer NOC building blocks include: (a) the OXS employing AVC structures, (b) DFB lasers/VCSELs, (c) Mach-Zehnder silicon optical modulators, (d) SiGe photodetectors, (e) arrayed waveguide grating in silicon to perform wavelength multiplexing/demultiplexing, and (f) silicon waveguides.

7944-30, Session 8

Low-power high-speed SerDes with new dynamic latch and flip-flop for optical interconnect in 180 nm CMOS technology
J. Sangirov, A. I. Ukaegbu, T. Lee, M. H. Cho, H. Park, KAIST (Korea, Republic of)

A low power high-speed serializer/deserializer (SerDes) has been designed using new dynamic D-latch for the optical link in multipoint-to-multipoint data transmission architecture. As the SerDes is one of key components of serial communication architecture for high-speed optical interconnect. The power consumption of SerDes has been considered as major issue and it has been a step forward to reducing its power consumption for a low-power optical interconnection design. Using dynamic circuits like D-latches and flip-flops can give full advantages for reliable performance of a circuit, and circuit techniques for high speed circuit design. The SerDes uses a system clock and its phases to multiplex data to the serial link which avoids the need for a phase-locked-loop-based high frequency clock generation used in serializing parallel data as in conventional SerDes design. The multiplexed link combined with the de-serializing clock is used as a reference signal for de-serialization. Signal latency has been evaluated for the synchronization of the de-serializing clock with data signal. The analog-type high-speed SerDes has been designed in 0.18 μm Si-CMOS technology. The overall SerDes circuit uses less than 28 percent of transistor ratio and Serializer occupies 50% less area, compared to original work. The SerDes has a core chip size of 480 x 790 μm2. The SerDes operates well up to 10 Gbps data rate and the power consumption is 49.3 mW at 1.8 V and it is 30 % less power than previous work.
Devices and architectures for large scale integrated silicon photonics circuits
R. G. Beausoleil, A. Farao, D. Fattal, M. Fiorentino, Z. Peng, C. M. Santori, Hewlett-Packard Labs. (United States)

Silicon photonics, with its promise of large scale integration and low cost, is poised to revolutionize data links at scales ranging from the chip to the datacenter. Many groups have introduced DWDM nanophotonics architectures based on silicon photonic. Here we focus in particular two architectures based on microring resonator modulators and detectors: an on-chip interconnect for a many-core processor (Corona) and a high-radix photonic switch for an exascale datacenter network (HyperX).

The stringent requirements that these applications place on the photonic circuit performance require a careful optimization of the devices’ design and fabrication strategies of large scale integrated circuits. The key technological constraints stem from the need to use DWDM to fulfill bandwidth requirements. DWDM requires modulation, multiplexing, and demultiplexing of sources with closely spaced frequencies. Ring resonators are well suited for DWDM applications but present a series of challenges because the difficulties in controlling their performance parameters such as the resonant frequency, quality factor, and extinction ratio. For example, while it is possible to actively control the resonant frequency (e.g. by temperature tuning) the amount of tuning necessary has a large impact of the system power consumption. Fabrication parameters also affect other properties of the rings such as the extinction ratio that have a large impact on the design of the integrated electronic-photonic circuit. We will present our efforts to study the effect of fabrication variations on the ring parameters and the effect of these variations on system performance as well as ways to mitigate these effects.

CMOS compatible waveguides for all-optical signal processing
D. J. Moss, The Univ. of Sydney (Australia)

All-optical signal processing chips provide the promise of cheaper, faster and more energy efficient operation that will complement and enhance electronic integrated circuits for both telecom and computing applications. The challenge is to realize these in a platform compatible with CMOS technology, and in devices with linear and nonlinear optical characteristics good enough to achieve low power operation. I will review our results of the past year on nonlinear optics in a CMOS compatible platform, including four-wave mixing, supercontinuum generation, parametric gain and time-lens imaging.

Pure silicon - high performance: advanced optical receivers in standard silicon BiCMOS technologies
K. Schneider-Hornstein, Technische Univ. Wien (Austria); R. Swoboda, A3PICs Electronics Development GmbH (Austria); B. Goll, H. K. Zimmermann, Technische Univ. Wien (Austria)

We present the state of the art of integrated silicon photodetectors and circuits by concentrating on the progress in the last decade. Especially three highlights of own work will be presented in more detail.

In this paper a vertical pin-photodiode in a 0.8µm BiCMOS technology, consisting of an n-buried cathode, an n-epi layer, and a p+ anode will be discussed. The measured responsivities for different wavelengths were 0.26A/W @ 850nm and 0.36A/W @ 660nm, respectively. Really outstanding is the reached speed of the photodiodes, the -3dB cut-off frequencies of these 50x50µm² diodes were depending on the reverse bias voltage up to 2.1GHz @850nm light, and up to 3GHz @660nm light.

This high performance photodiode allows the competition of pure silicon optoelectronic integrated circuits (OEICs) even with GaAs OEICs. A silicon OEIC reaches at 2.5Gb/s [1] a higher sensitivity than a GaAs OEIC [2]. It also consumes less power and a remarkable smaller chip area. Highly parallel integration of optical receivers enables also extremely high data rates via parallel optical receivers. A new OEIC consisting of 45 parallel channels with a data rate of 3Gb/s @850nm each allows an overall data rate of 135Gb/s.


High-speed CMOS optical communication using silicon light emitters
P. J. Venter, Univ. of Pretoria (South Africa); M. E. Goosen, INSiAVA (Pty) Ltd. (South Africa); M. du Plessis, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa); I. J. Nell, Univ. of Pretoria (South Africa); A. W. Bogalecki, P. Radermeyer, INSiAVA (Pty) Ltd. (South Africa)

Silicon forms the backbone of most modern integrated circuits, with CMOS representative in circuits ranging from cellphones to mainframe CPUs. Optical communication between chips is a long desired functionality promising to solve a number of interconnect related bottleonecks. The marriage between CMOS and optics therefore presents a lucrative combination supported by numerous research efforts in this field. However, an efficient silicon light source still represents the missing link to ensure the feasibility of commercial silicon photonics.

In this paper, we discuss our recent advances towards a complete silicon optical communication solution. We prove that transmission of baseband data at multiples of megabits per second rates are possible using improved silicon light sources in a completely native standard CMOS process with no post processing. Techniques for improving the internal and external quantum efficiency of silicon light emitters are used to enhance the emission of sources operating on the principle of avalanche electroluminescence. The CMOS die is aligned to a fibre end and directly modulated with driver circuitry. The signal is transmitted to a silicon APD module where subsequent amplification and filtering results in a detectable electrical signal. Signal detectability is proven through eye diagram measurements.

The results show an improvement of more than tenfold over some of our previous results and is also the fastest optical communication from standard CMOS light sources. As the devices are not operating at their intrinsic switching speed limit, we believe that even higher transmission rates are possible with complete integration of all components in CMOS.
The device was designed using the beam propagation method (BPM) module from Rsoft. The non-uniform array design was used in the single OPA layer to enable large angle beam steering in one-dimension. The first OPA layer was fabricated on SOI wafer. The device was patterned using electronic beam lithography system with NEB-31A3 negative resist and the pattern was transferred to silicon layer using reactive ion etching (RIE). A 1-µm silicon dioxide layer was deposited on the device as top cladding. Afterwards, the metallic heater and the wire-bonding pads were fabricated on top of the silicon dioxide layer using electronic beam lithography system with ZEP520A positive resist and a lift-off process.

After the first OPA layer was fabricated, a 5-µm silicon dioxide layer was deposited on the first OPA layer and the surface was planarized by chemical mechanical polishing (CMP). A 250nm-thick single-crystal silicon layer was attached to the surface as the second device layer. The second OPA layer was fabricated using the same process of fabricating the first OPA layer. After all, an extra photolithography step opened windows for the wire-bonding pads on the first OPA layer. The final device was wire-bonded to a chip carrier and its performance was measured.

7944-35, Poster Session

Group velocity independent coupling into slow light photonic crystal waveguide

C. Lin, The Univ. of Texas at Austin (United States); X. A. Wang, S. Chakravarty, Omega Optics, Inc. (United States); B. Lee, W. Lai, R. T. Chen, The Univ. of Texas at Austin (United States)

Slow light in photonic crystal waveguide can significantly enhance the light-matter interaction, which is a promising approach toward building ultra-compact photonic devices. To take advantage of the slow light effect, it is crucial to efficiently couple light between photonic crystal waveguide and external optical circuit. It has been shown that good coupling to photonic crystal waveguide can be obtained by proper termination of photonic crystal lattice. However, the coupling efficiency depends strongly on the group velocity of light and it degrades rapidly as light slows down near the bandedge due to the increasing group velocity mismatch between strip and photonic crystal waveguide. This issue can be addressed by designing a photonic crystal taper with gradually decreased width of line defect waveguide, in which the group velocity of light slows down period by period when light enters the photonic crystal waveguide. Two dimension finite difference time domain (FDTD) simulation shows good coupling efficiency can be maintained, regardless of the group velocity of light, until the mode cutoff by photonic bandgap using only eight periods of photonic crystal taper. Oscillation of coupling efficiency in the defect guided mode spectrum can also be reduced due to better-matched optical interfaces. Compared to photonic crystal waveguide without photonic crystal taper, measurement result shows 10dB improvement in coupling efficiency with 7dB lower fluctuation. Coupling to slow light mode near the bandedge is enhanced by 17.5dB. The measurement result shows excellent agreement with 2D FDTD simulation.

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Optoelectronic Interconnects and Component Integration XI

The effect on Strehl ratio from thickness variations in liquid crystal diffractive lenses

L. Lu, L. Shi, Kent State Univ. (United States); D. Duston, eVision, LLC (United States); P. J. Bos, Kent State Univ. (United States)

We analyzed a design of a liquid crystals diffractive lens for the effect of thickness variations and operations at wavelengths other than the designed wavelength. As shown in Fig. 1, this diffractive lens contains 20 resets, with the focal Length around 1 meter; optical phase difference (OPD) is 1 wavelength; liquid crystal cell gap is 3 µm and radius of the lens is around 4.5 mm. Our mathematical analysis was performed using numerical calculations that take into account the details of electrode structure and the physical properties of the liquid crystal material. The calculations proceeded by: finding the equi-potential field within the cell and the exact liquid crystal director configuration; then the near field optical phase profile; and finally the optical spot profile resulting from an input Gaussian beam at normal incidence. We show that thickness variation is a critical factor to the Strehl ratio of the diffractive lens in Fig. 2. The diffractive lens performs very well for different incident wavelengths with high strehl ratio and high efficiency, but it has a variation of focal length due to changes of incident wavelengths.

The diffractive lens is comparable to a refractive lens. Efficiency and Strehl ratio is compared with a refractive lens with the same aperture and focal length. Results are also matched with those calculated by analysis equations of a Gaussian beam transformation by a lens. Applications of the lens in color camera systems will be discussed.

7944-36, Poster Session

Polymeric waveguide array with 45 degree slopes fabricated by bottom side tilted exposure

X. Lin, X. Dou, The Univ. of Texas at Austin (United States); X. Wang, Omega Optics, Inc. (United States); R. T. Chen, The Univ. of Texas at Austin (United States)

This paper presented a novel fabrication process of a SU8 pre-mold with 45 degree slope for vertically coupling purpose. The key step of the process included a bottom side tilted exposure of SU8 photo resist. First, we transferred the pattern from the mask to a glass substrate. After applying 50µm SU8 resist on top of it, the tilted back side exposure was employed. The whole setup was immersed in DI water and UV beam was shined vertically. By placing the sample upside down and tilting it by 58.7°, the beam went through from the bottom of the glass substrate and directed into top side SU8 with 45° to form the surface. This method was able to guarantee no-gap contact between the mask pattern and the photo resist when exposing. We also compared different effects with top side and bottom side exposure. It was obvious that exposing from the bottom side could help avoid the tailing effect when performing the tilted exposure. Also, it helped to reduce the process complexity since no external forces were needed to ensure the best contact. The SEM pictures showed high quality tilted surface. After achieving the SU8 pre-mold, the reversed PDMS mold was then fabricated on top of it. The PDMS mold was used to imprint the cladding layer of the waveguide array. After metal deposition, core filling and top cladding layer coating, the final polymeric waveguide array device was achieved. The 850nm laser beam from VCSEL was modulated to 10G signals and vertically coupled into the waveguide array. The eye diagrams revealed high Q factor when transmitting signals along these waveguide array.
Mid-IR quantum cascade lasers as an enabling technology for a new generation of chemical analyzers for liquids

B. Lendl, M. Brandstetter, Technische Univ. Wien (Austria); W. Ritter, QuantaRed Technologie GmbH (Austria)

Technology and working principle of a QCL based analyzer for measuring oil-in-water is shown. The analyzer uses a solvent extraction step using cyclohexane followed by the determination of the extracted hydrocarbons in the cyclic solvent by QCL spectroscopy. Due to the high spectral power density of the used QCLs, it is possible to quantify the extracted oil by focusing on the region of the C-H deformation vibrations. Portability, a large dynamic range (0.5 - 2000 ppm), high precision (< 4 %) and the use of the environmental friendly solvent cyclohexane are the key advantages of this new method for oil-in-water.

Isotopic N2O analysis using quantum cascade lasers

E. R. Crosson, Picarro Inc. (United States); D. Balslev-Clausen, Univ. of Copenhagen (Denmark)

This work presents the first continuous in-field measurements, with a standalone MIR-WS-CRDS instrument. The presented instrument is based entirely on thermo electrically cooled technology, enabling the system to be run unattended for extended periods of time. The light source is a Mode-Hop-Free Quantum Cascade Laser centered at 4.55 µm, with a narrow line width and power exceeding 100 mW, operating at room temperature. A fast low noise TE cooled MCT detector is used to record the ~10 µs optical decay from the ring-down cavity, which provide an effective absorption path length of numerous kilometers. Ambient atmospheric gas samples may be introduced directly into the instrument achieving a N2O concentration precision < 0.1 ppbv, in only few seconds of data acquisition time while the isotopologues 15N and 18O of N2O are analyzed at < 1 precision within 30 sec.

MIR-WS-CRDS provides possible enhanced sensitivity to several species of molecules, (CO2, CH4, NO, NO2, isotopologues are a few e.g.) and can be combined with various sample preparation systems, to study substances not being on gas form. In this work N2O is being addressed, as this is a potent greenhouse gas, which is increasing in atmospheric concentration by 0.25%/yr, and is still not fully understood. Although the sensitivity is not as good as IRMS (± 0.1 ?), MIR-WS-CRDS has the vantage of being easy to use and is able to directly distinguish the isotopomers of N2O which is not possible with conventional IRMS.

Narrow linewidth quantum cascade lasers as ultra-sensitive probes of molecules

S. Bartalini, S. Borri, P. Cancio Pastor, I. Galli, G. Giusfredi, D. Mazzotti, European Lab. for Non-linear Spectroscopy (Italy); P. de Natale, Istituto Nazionale di Ottica Applicata (Italy)

Recently, we have demonstrated that the “intrinsic” linewidth of Quantum Cascade Lasers (QCLs) can go beyond the radiative lifetime of the upper level [1]. This represents the first demonstration of a sub-radiative linewidth for any laser. The intrinsic linewidth of a QCL can be as narrow as hundreds Hz, paving new ways for ultra-sensitive and precise harnessing and detection of molecules. We are working towards full exploitation of such intrinsic properties by designing appropriate phase-lock loops and enhancement-cavities for interaction with molecules. Combination with optical-frequency-comb-synthesizers and appropriate spectroscopic techniques, like saturated-cavity-ringdown-SCAR [2] or polarization spectroscopy [3] can provide unprecedented sensitivity and frequency accuracy for molecular detection.


Quantum cascade laser sensors for online gas chromatography

S. Wu, A. Deev, Y. Tang, California Institute of Technology (United States)

Firstly, we report the progress in stabilizing Quantum Cascade (QC) lasers to Whispering Gallery Mode of a CaF2 spherical resonator. The stabilized QC laser will a much narrower instantaneous linewidth and able to scan over several GHz. Secondly, we report that hollow waveguide (HWG) with 1mm Inside Diameter could maintain a vacuum under 40Torr over 1 meter length with regular capillary GC flow rate, thus giving a Doppler Limited linewidth inside the HWG with QC lasers. We further elaborate that saturated absorption could be carried out inside the HWG with restricted capillary flow and stabilized QC laser.

Amplitude modulation and stabilisation of QC lasers

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Technological applications using quantum cascade (QC) lasers could largely benefit from the building of compact devices with new functionalities enabling their amplitude and phase modulation at high frequencies with low injected power. By implementing electrical feedback these functionalities could also be used to stabilise the frequency of the lasers with metrological precision.

To this end we have developed a three terminal device with integrated functionalities for mid-infrared wavelengths (5 - 10 µm), allowing the electrical control of the QCL complex refractive index. We have also demonstrated (i) that metallic waveguides embedding QC lasers are ideal for high frequency modulation (up to 50GHz) and (ii) a laser system able to actively stabilize the frequency and the phase of a 2.7 THz quantum cascade laser to an optical frequency comb based on a commercial, modelocked, erbium-doped fibre laser. For THz lasers line-width of 1Hz has been measured opening the possibility for new detection scheme in this frequency range.

The aim of this presentation is to shine light on the physical properties of the Quantum cascade lasers that differ fundamentally from those of diode lasers. Our recent studies on their modulation and stabilisation properties show new opportunities for applications.
7945-08, Session 2

**latest progress in high power vcsels**

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Vertical external cavity surface emitting lasers (VECSELs) have captured the interest of high-brightness semiconductor researchers, primarily due to their simplicity in design, power scalability, and "open cavity architecture," wherein it is simple to integrate nonlinear elements into the cavity. Through direct emission and indirect (frequency-converted) means, wavelengths from the UV through to the mid-wave infrared regimes have been demonstrated, increasing the suitability of the VECSEL platform for multiple applications. This presentation will outline recent progresses in VECSELs, measurements, novel cavities, and potential applications for these lasers.

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7945-09, Session 2

**GaSb and InP-based VCSELs at 2.3 μm emission wavelength for tunable diode laser spectroscopy of carbon monoxide**

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We present long-wavelength buried tunnel junction (BTJ) VCSELs for emission wavelengths well beyond 2 μm. Two different device concepts have been realized utilizing either GaSb- or InP-based materials. The InP-VCSEL is based on the well-proven BTJ-design which has been available for the wavelengths up to 2.3 μm just recently. To extend this range up to emission wavelengths around 2.3 μm, a main focus is set on the optimization of the active region. In this context, we use a graded and heavily strained quantum well design in conjunction with optimized growth conditions. The photoluminescence and x-ray characterization shows a very good material quality. At room-temperature, such VCSELs exhibit around 0.5 mW of output power with single-mode emission at 2.3 μm representing the longest wavelength that has been achieved with InP-based interband lasers so far. Opposite to these VCSELs, the GaSb-based devices utilize an epitaxial back mirror and a dielectric output mirror while the basic BTJ-principle is maintained. Using mature antimony material, the active region reveals excellent gain characteristics at 2.3 μm. Singlemode VCSELs show room temperature threshold currents around 1 mA and output powers of 0.7 mW, respectively. Both laser types have been implemented in a tunable diode laser spectroscopy (TDLs) setup to evaluate their capability for sensing of carbon monoxide. Using an absorption path length of only 40 cm, concentration measurements down to a few ppm have been successfully demonstrated.

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7945-10, Session 2

**High finesse external cavity VCSELs: from very low noise lasers to dual frequency lasers**

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Low noise-level optical sources are required for numerous applications such as microwave photonics, fiber-optic sensing and time/frequency references distribution. In this paper, we present how inserting a semiconductor active medium into a centimeter high-Q external cavity is a simple way to obtain a shot-noise-limited laser source over a very wide frequency bandwidth. This approach ensures, with a compact design, a sufficiently long photon lifetime to reach the oscillation-relaxation-free class-A regime. This concept has been illustrated by inserting a ¼ VCSEL in an external cavity including an etalon filter. A very low relative intensity noise has been observed (-156dB/Hz over the 100 MHz -18 GHz bandwidth) and is at the shot noise limit, thanks to class-A regime operation. The optimization, in terms of noise, is shown to be a trade-off between the cavity length and the laser mode filtering. The transition between the class-B and class-A dynamical behaviors is directly observed by continuously controlling the photon lifetime is a sub-millimetric to a centimetric cavity length. It’s proven that the transition occurs progressively, without any discontinuity. Based on the same laser architecture, tunable dual frequency oscillation is demonstrated by reducing the polarized eigenstates overlap in the gain medium. The class-A dynamics of such a laser, free of relaxation oscillations, enables to suppress the electrical phase noise in excess, usually observed in the vicinity of the beat note and thus appears as a laser source of choice to be used in atomic clocks.

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7945-11, Session 2

**Integrated Terahertz pulse generation and amplification in quantum cascade lasers**

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Terahertz (THz) pulse generation from quantum well systems using bandgap transitions has been extensively studied where electrons from the valence band are injected on ultrafast time scales into the confined conduction subbands. This can result in coherent charge oscillations between two confined subbands, Bloch oscillations or accelerated carriers through miniband transport. This leads to a time-varying polarisation that can generate electromagnetic radiation in the THz range. Since a THz quantum cascade laser (QCL) consists of a series of quantum wells and its operation based on intersubband transitions, it could act as the non-linear medium to generate, as well as amplify, THz pulses. This would enable direct injection of the THz pulses into the amplifying region of the QCL. We demonstrate that THz pulses can be directly generated by the THz QCL by illuminating the QCL facet with a femtosecond near-infrared laser. Photogenerated electrons are excited into the QCL conduction band, producing THz pulses that are amplified by the narrowband gain of the QCL. By comparing bandstructure calculations and electrical characteristics, the origin of the generated THz pulse is shown to be a result of charge acceleration within the QCL miniband. The contribution of charge oscillations between the confined subbands will also be presented. This scheme has the potential to inject THz pulses into waveguide structures with sub-wavelength dimensions (i.e. double metal waveguides), as well as efficiently integrating the generation and amplification of THz pulses.

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7945-12, Session 2

**High power 1D and 2D photonic crystal distributed feedback quantum cascade lasers**

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For many practical applications that need bright sources of mid-infrared radiation, single mode operation and good beam quality are also required. Quantum cascade lasers are prominent candidates as
compact sources of mid-infrared radiation capable of delivering very high power both CW and under pulsed operation. While 1D photonic crystal distributed feedback structures can be used to get single mode operation from quantum cascade lasers with narrow ridge widths, novel 2D photonic crystal cavity designs can be used to improve spectral and spatial purity of broad area quantum cascade lasers. In this paper, we demonstrate high power, spatially and spectrally pure operation at room temperature from narrow ridge and broad area quantum cascade lasers with buried 1D and 2D photonic crystal structures. Single mode continuous wave emission at \( \lambda = 4.8 \mu m \) up to 400 mW in epi-up configuration at room temperature was observed from a 12 \( \mu m \) wide 3 mm long distributed feedback quantum cascade laser with buried 1D gratings. High peak powers up to 34 W was obtained from a 3mm long 400 \( \mu m \) wide 2D photonic crystal distributed feedback laser at room temperature under pulsed operation. The M2 figure of merit was as low as 2.5 and emission spectrum had a dominating single mode at \( \lambda = 4.36 \mu m \).

7945-13, Session 3

The progress of QD laser in the near IR wavelength region

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Demand on high quality and new contents in optical internet still requires continuous development of advanced optical components in the point of low cost and high performance. The use of quantum dot structure in the active region of semiconductor optical devices have shown superior high carrier dynamic and temperature less sensitive properties by some research groups.
A 1.5 m QD laser on the InP(100) substrate will be demonstrated in detail with the brief review of new achievements of QD optical devices in the near IR wavelength range. Enhanced temperature stability of Fabry-Perot QD laser will be reported compare to the CW laser. Also, 100bps direct modulation speed demonstrated with the moderate side mode suppression in the DFB QD laser. Static approach for the reproducible formation of quantum dot in the MOCVD and MBE system also will be introduced in this talk.

Finally, fundamental question about “The use of commercial QD optical devices can be realized?” will be discussed. “If yes, When?”

7945-14, Session 3

DFB lasers for sensing applications in the 3.0-3.5 um wavelength range

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Mid infrared laser sources experience a growing demand due to their excellent potential of use in diverse fields of applications, including for example medical, military or industrial process control [1-3]. The fact that many technologically relevant gas species have their strongest absorption lines in the MIR region makes Tunable Diode Laser Spectroscopy (TDLS) a powerful means of monitoring such gases. Especially the detection and monitoring of hydrocarbons play an important role in a wide range of industrial and environmental applications, including for example industrial process control of aliphatic hydrocarbons like acetylene, propane or propene [4]. By using the fundamental transitions instead of presently used overtones different hydrocarbons can be more easily distinguished and the sensitivity can be increased by several orders of magnitude. With strong absorption bands of several important hydrocarbons located in the 3.0 - 3.5 \( \mu m \) wavelength range, laser sources with application-grade performance are an essential prerequisite for novel TDLS sensor systems. Two approaches in the GaSb material system currently appear particular suited to obtain laser emission in the wavelength range of interest: type-I quantum well lasers using quinary AlGaInAsSb material and type-II interband cascade (IC) lasers [5-6].
For sensing applications monomode emitting devices are of particular importance. In this contribution, we will present DFB laser sources in the 3.0 - 3.5 \( \mu m \) wavelength range based on type-I quantum well material as well as type-II IC material. Based on the characteristic waveguide design of the respective underlying material, different DFB concepts are employed: Lateral metal gratings as well as deeply etched sidewall gratings defined in conjunction with an etched ridge waveguide structure were used to achieve single mode emission. Using these overgrowth-free device concepts, DFB operation with excellent performance figures has been achieved, qualifying the novel devices for TDLS applications of hydrocarbons.

Figure 1 shows an exemplary DFB device under continuous wave operation emitting at around 3.35 \( \mu m \). This DFB device was fabricated based on a type-I QW structure with an active region constituted of GaInAsSb/AlGaInAsSb. The quinary barrier material offers the possibility to adjust independently both conduction and valence band offsets which allows to improve hole confinement in the quantum wells compared to classical structures made from quaternary AlGaAsSb barriers.

References:

7945-15, Session 3

Circuit, antenna-based, and photonic crystal terahertz quantum cascade lasers

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In the Terahertz, MBE-grown structures have demonstrated record low frequency operation, down to 1.27THz. Taking advantage of the tight confinement provided by the metal-metal waveguide, we also have explored third order photonic wire lasers as well as photonic crystal quantum cascade lasers. In a further development, LC resonator cavities enable us to explore the coupling between transport and photon emission in the regime of very subwavelength emitters, as the ratio of volume over lambda cube is much below unity.

7945-16, Session 3

All photonic crystal DFBs for laser arrays


Planar quasi 2D photonic crystals (PhC) are of tremendous interest for integrated optics applications1. In the last years, several possible laser cavities have been proposed in that prospect2. In this paper, we review our work on 2D photonic crystal second order DFB lasers. All PhC 2nd order DFB lasers exhibit a natural single mode behavior extremely interesting for arrays realization3. We have shown that an affine deformation of the photonic crystal allows the fabrication of closely
spaced arrays of DFB lasers. Experimental demonstration of such arrays is done using GaAs based membranes with InGaAs quantum wells emitting around 980 nm. We show that using a combination of waveguide and photonic crystal array deformations, arrays of optically pumped single mode DFB lasers with controlled wavelength spacing and high Q values of 500 000 can be realized. We also demonstrate that such an optimized design lowers the laser sensitivity to optical reinjection. Potential extension of this scheme will be discussed, altogether with potential for electrical pumping implementation.


7945-17, Session 3

The InAs/GaSb/InSb short-period superlattice: an active zone for mid-IR lasers

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There is still a lack of semiconductor lasers operating in the 3 - 3.5 µm wavelength range of the mid-IR for photonic sensor applications. The "type-II broken gap", also called type-III, band alignment at the InAs - GaSb interface allows tailoring the effective bandgap of InAs/GaSb superlattices (SLs) from the mid- to the long- IR range. Wavelength below 4 µm can be reached with very thin layers only, i.e. with short-period SLs (SPSLs).

In this work, we have investigated the potential of this SPSL for laser emission. Gain calculations indicate that the important parameters are the SPSL average composition, period, thickness and the waveguide dimensions. Controlled insertion of InSb layers within the SL allows playing with the strain and band-offsets and gives additional flexibility. A typical active zone is based on the 1.2nm InAs /1.8nm GaSb /0.7 nm InSb SPSL which shows the level of control which is required.

Transmission electron microscopy reveals

We have then studied the growth by molecular-beam epitaxy and electronic properties of such SPSLs. Transmission electron microscopy and X-ray diffraction reveal a high structural perfection of the samples. Bright PL is achieved at room temperature in the whole wavelength range. The PL lineshape depends strongly on the number of periods in the SPSL in agreement with the SPSL band structure. Finally, broad-area laser diodes have been fabricated which operate in pulsed regime at room temperature. Typical threshold current densities are close to 0.7 kA/cm² @ 2.9 µm and close to 2kA/cm² @ 3.3 µm. CW operation is achieved at temperatures > 200 K. Optimization is underway toward CW operation at room temperature.

Part of this work has been funded by the French National Research Agency (ANR) in the frame of its program in Nanosciences and Nanotechnologies (MIRNANO project n° ANR-08-NANO-053).

7945-18, Session 3

Modulation cancellation method for laser spectroscopy

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Several applications of analytical spectroscopy require the determination of the deviation of the ratio of intensities of two absorption peaks with respect to the ratio in the reference sample or for the reference conditions. Two examples of such applications include the characterization of the isotopic composition and temperature measurements. To address these topics, we have developed a novel spectroscopic technique (MOCAM). The idea of MOCAM is that the powers and modulation phases of two lasers resonant with two selected absorption lines are adjusted in such a way that the signal detected from the reference sample is zero. Then the signal from the analyzed sample will be directly proportional to the deviation of the absorption line strength ratio from the reference ratio in the selected optical configuration. Spectroscopic measurements of small temperature differences in an acetylene/N2 gas mixture will be reported. We use quartz enhanced photoacoustic spectroscopy (QEPAS) as a detection technique.

To determine small temperature changes, two spectroscopic transitions originating at lower states with different energies were probed. We demonstrated detection of temperature changes with a sensitivity of ≈24 mK in 17 s, in close agreement with an estimated value of ≈9 mK, based on the optical power delivered to spectrophones, the respective acetylene line intensities, a QEPAS sensitivity of 5 - 10-9 cm-1/WHz1/2 and bandwidth of 1 Hz [1].


7945-19, Session 3

Acetylene measurement using quantum cascade lasers at 14μm

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Monitoring of acetylene (C2H2) concentration is important for many chemical processes. Industrial trace gas measurements are usually performed using gas chromatography (GC) analyzers which have time constants of several minutes. Optical analyzers are expected to yield faster response times at lower maintenance costs. We investigated the use of quantum cascade laser (QCL) spectroscopy in the 14µm range for a sensitive and fast specific detection of C2H2. This spectral range is favorable to avoid spectral interferences by other components which could be present in typical raw process gases. For these purpose new DFB QCLs were developed and their spectral properties were investigated. Performance characteristics determined with a laboratory setup of a new QCL gas analyzer for low concentrations will be presented.

7945-20, Session 3

Real time ammonia detection in exhaled human breath using a distributed feedback quantum cascade laser based sensor

R. Lewicki, A. A. Kosterev, D. M. Thomazy, Rice Univ. (United States); T. H. Risby, The Johns Hopkins Univ. (United States); S. Solga, T. Schwartz, St. Luke’s Hospital (United States); F. K. Tittel, Rice Univ. (United States)

The development and performance of a cw, TE-cooled DFB quantum cascade laser based sensor for quantitative measurements of ammonia (NH3) concentrations present in exhaled breath 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 ammonia concentration levels in exhaled breath a fast, non-invasive diagnostic method for treatment of patients with liver and kidney...
The NH3 concentration measurements are performed with a 2f wavelength modulation quartz enhanced photoacoustic spectroscopy (QEPAS) technique [1], 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 Hamamatsu air-cooled DFB-QCL was operated at 17.5 degrees Celsius, targeting the NH3 absorption line at 967.35 cm⁻¹ (~10.34 µm), with ~20 mW of optical power. The sensor includes a reference cell, filled with a mixture of 2000 ppmv NH3 and N2 at 130 Torr, which is used for line-locking. A minimum detection limit (1σ) for the line locked NH3 sensor is ~10 ppbv with a 1 sec update time of the control electronics. This NH3 sensor, packaged in a 12 x 14 x 10 housing, will be clinically tested at St. Luke’s Hospital in Bethlehem, PA.

References

Low power consumption lasers for next generation miniature optical spectrometers for trace gas analysis

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Tunable laser spectrometers are important class of instruments considered for a number of upcoming planetary space missions. Laser spectrometers in the 3.0-3.5 µm wavelength range are particularly important for detection of methane and its isotopes as a method of investigating potential signatures of past life on planets and lunar bodies; and detection of acid gases like HCl, HCN, and HF for astronaut life support systems. In this paper we report on our progress developing high wall-plug efficiency type-I quantum-well GaSb-based diode lasers operating at room temperatures in the spectral region of 3.0-3.5 µm. These lasers will enable miniature, low-power consumption laser spectrometers for environmental monitoring and detection.

7945-23, Session 4

Process analytical applications in the mid-infrared

S. H. Lundqvist, P. Kluczynski, Siemens Laser Analytics AB (Sweden)

We will present work on tunable diode laser spectroscopy of hydrocarbons in the 3 micron wavelength region using novel GaSb DFB lasers. A number of suitable process analytical applications especially in ethylene and propylene manufacturing have been investigated. Detection of acetylene impurities in ethylene in a gas matrix typical of a hydrogenating reactor has been performed. The performance for detection of acetylene impurities in pure ethylene using a TDLS sensor was better than 18 ppm·m for a response time of 3 seconds. Experience from in-situ measurements of hydrocarbons in an industrial environment using a cross duct instrument will also be presented.

Faraday rotation spectroscopy of nitrogen dioxide based on a widely tunable external cavity quantum cascade laser

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Faraday Rotation Spectroscopy (FRS) is a well established technique for the sensitive and selective detection of paramagnetic molecules such as O2, NO or NO2 [1] due to the insensitivity to non-paramagnetic interfering molecules such as H2O and CO2. Performance details of a FRS based sensor for NO2 detection employing an external cavity quantum cascade laser (EC-QCL) will be reported for the first time. The tunable EC-QCL operates mode-hop free between 1600 cm⁻¹ and 1650 cm⁻¹ and enables targeting the optimum 441 < 440 Q-branch NO2 transition at 1613.2 cm⁻¹ with an optical power of ~130mW. When an AC magnetic field is applied to a 44 cm long NO2 cell, placed between two nearly crossed MgF2 Rochon polarizers, the polarization of the linear polarized laser beam is rotated. This rotation of the polarization axis is proportional to the NO2 concentration and can be determined by a Peltier-cooled detector located after the second polarizer. For long-term continuous measurements a second sensor branch consisting of a Peltier-cooled detector and a reference cell filled with 0.2 % NO2 in N2 at 25 Torr is used to lock the laser to the targeted line. A minimum detection sensitivity of the FRS sensor of 2 ppbv (1σ) was obtained for a 1 sec lock-in time constant for optimum FRS parameters.

References:
7945-25, Session 4

Stand-off explosive detection on surfaces using multispectral MIR imaging

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We present a system for the stand-off and contactless detection of solid explosive traces and precursors on surfaces. The system consists of a widely tuneable mid-infrared laser and an uncooled thermal imaging camera. The external cavity quantum cascade laser illuminates the surface of a distant object at different characteristic wavelengths. In synchronisation with the camera a hyperspectral data cube of the backscattered radiation is generated allowing a multivariate analysis of the scene. We demonstrate how multidimensional image processing is used in order to fast and sensitively detect traces of hazardous substances such as trinitrotoluene (TNT) or pentaerythritol tetranitrate (PETN). The software classifier is trained to effectively suppress false alarms. Experiments are performed on real world like surfaces such as standard car paint, polyacrylic cloth or jeans fabric. Measurements of concentration series in the range of µg/cm² corresponding to amounts that are transmitted by finger prints show the sensitivity of the system. The presented work has been realised within the joint research project IRLDEX supported by the German Ministry for Education and Research (BMBF).

7945-27, Session 4

Recent advances in resonant optothermalacoustic detection

J. H. Doty III, A. A. Kosterev, F. K. Tittel, Rice Univ. (United States)

Optothermal detection is a spectroscopic technique where the energy input into a gas or other media caused by absorption of optical radiation is measured directly by means of a thermal detector [1-3]. A fraction of the absorbed energy is transported to the thermal detector by heat conduction or molecular diffusion. In this work a conventional thermal sensor was replaced by a quartz tuning fork (QTF), and the optical power input into the gas was modulated at the QTF resonant frequency. We call this approach “resonant optothermalacoustic detection”, or ROTADE. The same experimental setup can be used to conduct a closely related technique, quartz enhanced photoacoustic spectroscopy (QEPAS) [4]. QEPAS relies on energy transfer from the initially excited molecular vibrational state to the translational degrees of freedom. In some cases this process is too slow to follow the modulation required for QEPAS. In other cases, the resonant energy transfer can result in vibrational excitation of nitrogen, which relaxes very slowly. ROTADE, on the other hand, detects the energy delivered by molecules even if this energy is still in the form of vibrational excitation. The molecules will then release their energy to the QTF upon collision with its surface. Experimental investigations of ROTADE and its comparison with QEPAS were performed in pure CO2 and 0.5% acetylene in N2 using near-infrared diode lasers. A fiber collimator and a refocusing lens were used to focus the laser to a ~15 µm diameter waist. Its position was scanned in the QTF plane using a 3D translation stage with computer-controlled actuators. Different QTF’s were used to compare the effect of modulation frequency on the ROTADE signal.

References:

7945-28, Session 4

compact portable QEPAS multi-gas sensor

L. Dong, A. Kosterev, D. Thomazy, F. K. Tittel, Rice Univ. (United States)

The quartz-enhanced photoacoustic spectroscopy (QEPAS) is based on a novel approach to photoacoustic detection which employs a quartz tuning fork (QTF) as a resonant acoustic transducer. This approach allows the analysis of gas samples –1 mm3 in volume, results in immunity to environmental acoustic noise, and the QEPAS detection module size matches the size of telecommunications diode lasers so that the sensor can be very compact. Design and performance details of a portable QEPAS multi-gas sensor using near infrared laser diodes will be reported. The sensor is specifically designed to detect and quantify concentrations of carbon monoxide (CO), hydrogen cyanide (HCN), hydrogen chloride (HCl), and carbon dioxide (CO2) in ambient air. It can operate autonomously or interact with another device (such as a computer) via a RS232 serial port. The sensor incorporates rechargeable batteries and can operate on batteries for >8 hours. Furthermore, the sensor was designed to quantify trace concentrations in the ambient atmosphere and is equipped with a fan which ensures efficient gas exchange between the ambient air and the internal sensor case volume. The HCN, CO2, and HCl measurement channels are based on cw telecommunication-style packaged, fiber-coupled lasers, the CO channel uses a can-packaged laser as an excitation source. Trace gas detection limits (1 s averaging time) of 7.74 ppm at 4288.29cm−1 for CO, 450ppb at 8539.11 cm−1 for HCN, 1.48 ppm at 5739.26 cm−1 for HCl and 97ppm at 8361.25 cm−1 for CO2 have been demonstrated.

7945-29, Session 4

Compact spectroscopic sensor for air quality monitoring in spacecrafts

B. Scherer, H. Hamid, Fraunhofer-Institut für Physikalische Messtechnik (Germany); S. Forouhar, Jet Propulsion Lab. (United States); J. Rosskopf, Vertilas GmbH (Germany)

The air quality of any manned spacecraft needs to be continuously monitored in order to safeguard the health of the crew. Any accidental release of harmful gaseous contaminants or malfunction in the air revitalization system have to be detected as fast and reliable as possible to provide enough time for the crew to react.

For this application there is a need for a fast, reliable, compact and low-power gas sensor, which is able to detect harmful trace gases in very small concentrations as well as oxygen to monitor the air revitalization system. According to possible scenarios in manned spacecrafts, the sensor has to be operated in a wide pressure range between 8 and 15 psi, needs a fast response time of less than 2 s and a maintenance-free operation time of more than 10 years. In this paper, a sensor system based on tunable diode laser spectroscopy is presented, which is able to detect three important gases: two harmful trace gases, carbon monoxide and hydrogen chloride, as well as oxygen. Its design is optimized to offer maximum sensitivity at minimum sensor dimensions. The use of vertical-cavity surface-emitting lasers with threshold currents below 5 mA reduces the power consumption to a minimum. A calibration-free measurement method is presented, which is only based on molecule specific constants which are available from the molecular data base HITRAN. With this technique, there is no need for a recalibration of the sensor which is the basis for long maintenance-free operation times.
7945-30, Session 4

Engineering intersubband population inversion with dilute nitrides

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The first demonstration of intersubband lasing without inversion has been realized by exploiting the nonparabolicity of the conduction subbands and local population inversion near k=0 even though the lowest subband may have larger global occupation [1].

Later on, also exploiting bandstructure engineering, valence-band-based designs have been proposed [2,3] and more recently a mechanism combining bandnonparabolicity with a k-space filtering for hole intervalence transitions in quantum wells has been introduced [4].

In this paper we investigate the possibility of interconduction band without inversion by engineering the conduction band effective masses in dilute nitride structures [5] so that the upper lasing subband has an effective mass considerably smaller than the lower lasing subband that could not be obtained in usual III-V materials. This analysis is the first step towards possible far infrared dilute nitride based quantum cascade lasers that could benefit from the gain without inversion effect to operate at higher temperatures.

References


7945-31, Session 5

Monolithic focal plane arrays for terahertz active spectroscopic imaging: an experimental study

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The detectors have been illuminated by QCLs and compared in terms of their performances (noise equivalent power, response time), requirements (illuminator power, operating temperature), fabrication process, readout circuit and material costs.

7945-32, Session 5

Bound terahertz waves on meta-surfaces and active metamaterials

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Meta-surfaces are artificial, very thin materials that are composed of plasmonic unit cells with sub-wavelength dimensions. By the design of the above structures it is possible to tailor the dispersion relation and the electromagnetic behavior of both bound waves along such artificial surfaces and the near field of oscillating fields close to the surface in general. By this means, meta-surfaces are very promising candidates for the specific design of plasmonic detectors with high sensitivity. In this presentation, we discuss the propagation of bound magneto-inductive waves along a meta-surface that consists of metallic split-ring resonators and demonstrate the applicability of specifically designed meta-surfaces as very sensitive terahertz plasmonic near-field detectors. As a second topic, we discuss the coupling of the plasmonic subwavelength structures of a meta-surface to an active gain medium. A detailed understanding of the coupling mechanisms between metals and gain media is of crucial importance when it comes to the design of active, loss-compensated metamaterials at high frequencies. We show that the resonant coupling between the plasmonic structures and a resonant (Lorentz) gain medium can result in an electromagnetic behavior that is very similar to electromagnetically induced transparency. Furthermore, we discuss the dynamical behavior of the coupled system and the influence of the net gain on its stability.

7945-33, Session 5

Intersubband impact ionization in THz QWIPs: shaping band structure reorganizations to design novel detectors

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In this paper phase transitions and instabilities in THz QWIPs will be studied. At low temperature, a current phase transition occurs when the voltage reaches a threshold where a quantum well can be depleted by efficient impact ionization. This depletion induces an enhancement of the local electric field and results in a barrier breakdown at the contact, which dramatically increases the current injection in the device. Hysteresis is observed between these two states of the system. It is crucial to understand the physics of the electronic transport in this device in order to be able to design very sensitive THz detectors, working at the edge of the phase transition. In this paper, we describe in detail the electronic transport, and show how a full calculation of the transport (including the calculation of impact ionization and electronic capture in the wells) leads to the full I(V) curve, despite its very sophisticated shape. Thanks to this modeling, the design of very efficient THz detectors will be discussed.
Phonon and polaron enhanced IR-THz photodetectors

H. C. Liu, C. Song, Z. R. Wasilewski, M. Buchanan, National Research Council Canada (Canada)

Polar optical phonons exist in all polar semiconductors which are used for almost all quantum structure infrared photodetectors. The transverse optical phonons are directly optical active; whereas the longitudinal ones couple strongly with electrons. The coupled mode excitation of electron and phonon in solids is referred to as a polaron. In the past, polarons have been mostly a pure physics phenomenon. Here we investigate the active use of phonons and polarons for realizing new optoelectronics devices. We present an application of the concept to photodetection in the infrared-terahertz spectrum. The ability to design a phonon or polaron is the first step in making use of them. We show this by a model system employing the electron intersubband excitation in quantum wells coupled with phonon modes. This results in a photodetector with a high response at the selected wavelength.

GaN for THz sources

M. Marso, Univ. du Luxembourg (Luxembourg)

We investigate two different approaches to generate THz radiation by the use of GaN. One method is heterodyne photomixing, a compact and inexpensive approach to generate continuous electromagnetic radiation in the terahertz range, with tunable frequency. It uses two lasers with slightly different wavelengths that illuminate an ultrafast photoconductor. The interference of both laser beams generates a beat frequency of the illumination intensity in the terahertz range. One drawback of the conventionally used LT GaAs as ultrafast photoconductor material is the relatively low THz power in the nW to pW range. The aim of our work is to increase the output power by replacing the LT GaAs with GaN. This semiconductor is rather known as basic material for blue LEDs and lasers, but it has also remarkable electrical and thermal properties that allow higher laser power and bias voltage. A more conventional, electronic approach to generate THz radiation consists in the fabrication of an oscillator circuit based on ultrafast transistors, e.g. High Electron Mobility Transistors based on InGaAs. These circuits can be designed up to about 100 GHz oscillation frequency. The THz region is achieved by frequency multipliers, e.g. realized by very small-sized Schottky diodes. However, each multiplier stage considerable reduces the output power. In this field we investigate GaN based transistor devices to profit from the much better power performance of this material, compared to classical semiconductors. In summary, GaN turns out to be a promising material in the field of THz generation.

Terahertz emission from Mg-doped a-plane InN

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We report terahertz emission from magnesium doped a-plane indium nitride (a-InN:Mg) films with different background carrier density, relative to the Mg-doped InN films grown along the c-axis (c-InN:Mg). Due to its high electron affinity, as-grown InN film is typically n-type and it has extremely high background carrier density, which causes much weaker THz emission than that from other semiconductors, such as InAs. The background carrier density of Mg-doped InN can be widely changed by adjusting the Mg doping level. For c-InN:Mg, terahertz emission is dramatically enhanced (∼500 times) than that of undoped c-InN as the background carrier density decreases to a critical value of 1×10^18 cm^−3, which is due to the reduced screening of the photo-Dember field at the lower carrier density. For a-InN, however, intense terahertz emission (∼400 times) than that of undoped c-InN) is observed for both undoped and Mg-doped a-InN and the enhancement is weakly dependent on the background carrier density. The primary terahertz radiation mechanism of the a-plane InN film is found to be due to the acceleration of photoexcited carriers under the polarization-induced in-plane electric field perpendicular to the a-axis, which effectively enhances the geometrical coupling of the radiation out of semiconductor. The weak dependence of terahertz radiation on the background carrier density for a-InN shows that in-plane surface field induced-terahertz emission is not affected by the background carrier density. Small, but apparent azimuthal angle dependence of terahertz emission is also observed for a-InN, indicating the additional contribution of nonlinear optical processes on terahertz emission.

Subpicosecond Sub-terahertz soliton laser based on a C-MOS compatible integrated microring resonator

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Subpicosecond ultrafast optical clocks with repetition rates of hundreds of GHz are of considerable interest, motivated by their application to optical time-division multiplexing (OTDM) telecommunication networks that are rapidly evolving to extremely high bit rates, and by their potential applications to wavelength division multiplexed systems that exploit supercontinuum spectral slicing. High repetition rate, transform limited, pulse trains can be spontaneously generated from passively modelocked fiber ring lasers incorporating a nonlinear Kerr element, a band limited amplifier, and an anomalous dispersive element. When a high finesse filter (HFF) is added “intracavity”, the repetition rate is stabilized to the free spectral range (FSR) of the HFF. This technique is known as dissipative four wave mixing (DFWM).

Here, we demonstrate a sub-picosecond passively modelocked laser based on a CMOS compatible integrated micro-ring resonator with a repetition rate of 200GHz. Our approach involves a novel configuration that embeds the ring resonator directly inside a fiber-optic ring laser cavity. It operates through dissipative FWM in the highly nonlinear ring resonator, allowing the resonator to play the role of both the nonlinear element and the HFF.
nanostructures has recently been reported. In this paper, we approached in a structural way to obtain the energy coupling by SP as well as the carrier injection. We fabricated a high efficient blue light emitting diode by implementing a partially etched p-GaN and Ag nanostructure in the roughened top layer to realize simultaneous improvement of light extraction and internal quantum efficiency. After the growth of a blue light emitting diode structure, the p-GaN layer was roughened by inductive coupled plasma etching and the Ag nanostructures were formed on it. This structure showed a drastic enhancement in photoluminescence (PL) and electroluminescence intensity and the degree of enhancement was found to depend on the morphology of Ag nanostructures. Secondly, we investigated the localized surface plasmon (LSP) coupling behaviors by Ag/SiO2 core/shell nanoparticles (NPs) in InGaAs/InGaN based LED. The Ag/SiO2 NPs exhibited the extinction spectra at 475 nm and suitable for LSP coupling to blue emission. As evident of LSP coupling, the PL intensity of Ag/SiO2-NPs-coated sample was enhanced by 50 %. Also, the spontaneous emission rate increased 1.5 times after the Ag/SiO2-NPs coating. From time-resolved PL measurements, a faster decay time of Ag/SiO2-NPs-coated sample indicates that the enhanced luminescence intensity was attributed to the energy transfer from MQWs to Ag/SiO2 NPs by LSP coupling.

7945-39, Session 6
Infrared plasmonic detectors
N. Pére-Laperne, S. S. Collin, F. Pardo, J. Pelouard, Ctr. National de la Recherche Scientifique (France)

Since 2002, plasmonics has demonstrated the ability to enhance performances of photodetectors at a resonant wavelength. Absorption in a photodetector can reach 100% using nanophotonic plasmonic array. Plasmonic devices are confining light at the interface metal/dielectric, as a consequence, detection volume is smaller (100 to 1000 times) than in usual photodetectors leading to a decrease in dark current of infrared photodetectors and therefore a higher working temperature. The second consequence of a short detection volume is a higher collection efficiency of photocarriers as the transit time is smaller than the lifetime. We are working on the enhancement of different quantum infrared detectors using plasmonic array. Both theoretical and experimental results will be presented.

7945-40, Session 6
Surface plasmons polaritons for optical circuitry
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Surface plasmons polaritons are electromagnetic waves that propagate along the surface of a conductor. Surface plasmons photonics is a promising candidate to satisfy the constraints of miniaturisation of optical devices which could be relevant for optical interconnects.

Material to be presented in this lecture will be based on results of European projects devoted to plasmonic circuitry: FP6 NoE Plasmonicdevices (2004-2008), FP6 STREP Plasmonics (2006-2010) and the FP7 STREP Platon (Merging Plasmonic and Silicon Photonics Technology towards Tb/s routing in optical interconnects, 2010-2012). This contribution will review progresses in dielectric loaded surface plasmon waveguides as well as the recently suggested hybrid technology merging plasmonic and silicon photonics on a single board. Recent achievements of basic optical functionalities useful for surface plasmon launching, routing, switching, compensation of losses by optical pumping will be detailed.

An appealing feature of plasmonic circuitry is that it enables to carry optical signals and electric currents through the same thin metal circuitry, thereby opening the perspectives of technical combinations to insert electrically driven devices on the same circuitry on which light is propagating. Also the possibility of in-line power monitoring is an interesting example of recycling the intrinsic surface plasmon losses in order to monitor signal flow without destroying the signal itself. In-line power monitoring may be coupled with standard thermo-optical processes useful for switching or modulation operations.
NSOM illumination combined with apertureless monitoring of plasmons has significant potential for investigating plasmonic structures.

7945-43, Session 6

Optimization of plasmonic nanostructures

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We perform finite difference time domain (FDTD) simulations to find the electric field intensity at the center of a cluster of plasmonic nanoparticles irradiated by a planewave source. An iterative optimization algorithm is used to maximize the electric field intensity. Non-symmetric and non-intuitive optimized configurations that cannot be derived from straightforward human logic are obtained as a result of this optimization. The optimized electric field intensity is found to increase monotonically with the number of nanoparticles in the cluster. To fabricate plasmonic nanostructures with nm separation experimentally, we have employed a novel technique using angle evaporation. The plasmonic activity of these nanostructures is evaluated both experimentally and theoretically using surface enhanced Raman spectroscopy (SERS) measurements and FDTD simulations, respectively. We also investigate the photocatalytic performance of TiO$_2$ films enhanced by plasmonic Au nanoparticles, which can induce increased amounts of charge in the TiO$_2$ films. Depositing strongly plasmonic nanoparticles on a strongly catalytic TiO$_2$, we observed enhanced photocatalytic splitting of water as well as decomposition of methyl orange under visible light illumination. FDTD simulations of these plasmonic films based on their high resolution transmission electron microscope images, yield enhancement factors consistent with our experimental observations.

7945-44, Session 7

Cubic III-nitrides: potential photonic materials

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Cubic (zincblende) III-nitrides are the potential photonic materials which will extend the usefulness of III-nitrides beyond the hexagonal (wurtzite) ones. Especially, charge separation within a quantum well of hexagonal III-nitrides due to the strong internal electric field, which leads to a significant reduction of light-emission efficiency, is totally avoided with cubic III-nitride structures. In the growth of cubic III-nitride films, however, the major issue is the undesired inclusion of the hexagonal phase which degrades the whole film quality. It is known that the hexagonal phase tends to be generated through the stacking faults on the (111) facets which happen to occur by thermal roughening of the substrate surface. In our study, c-GaN on GaAs, c-GaN and c-AlGaN on MgO, and c-InN and c-InGaN on YSZ have been grown by MOVPE or MBE, and structural and optical characterizations have been widely done.

7945-45, Session 7

Optical properties of narrow-bandgap dilute nitrides

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The InAsN alloy is a narrow-bandgap semiconducting material which is potentially useful for infrared optical devices. As in other III-V-N type alloys such as GaAsN and GaPN, InAsN has a large bandgap bowing which gives a significant bandgap reduction with N incorporation. The observation of the bandgap reduction of InAsN films, however, is hindered by the Burstein-Moss (B-M) effect due to the high electron concentration associated with N incorporation. We have demonstrated the observation of bandgap bowing by utilizing the quantum well structure that suppresses the B-M effect due to the step-like functional form of the two-dimensional density of states. In this report, we will show the optical properties of InAsN thin films, quantum wells and quantum dots grown by MOVPE as well as RF-plasma-assisted MBE.

7945-47, Session 7

Paving the way to high-quality indium nitride: the effects of pressurized reactor

T. Matsuoka, Y. Liu, Tohoku Univ. (Japan) and CREST (Japan); T. Kimura, Y. Zhang, K. Prasertsuk, Tohoku Univ. (Japan); R. Katayama, Tohoku Univ. (Japan) and CREST (Japan)

Nitride-semiconductor light-emitting-devices such as blue, green, and white LEDs, and 400nm-wavelength LDs have been commercially available since 1993. The active layers in all these devices consist of InGaN, whose indium composition is designed for the wavelength of the emitted light. In this paper, the MOVPE growth and the phase separation of InGaN is reviewed. The current status of the InN research as an ultimate material of InGaN is also introduced.

Usually, hydrogen has been used as a carrier gas in the vapor phase epitaxy of all materials including GaN. However, the carrier gas for the growth of the nitride semiconductors including indium was invented in 1999 because of the extremely high equilibrium vapor pressure of nitrogen between solid and gas phases. To suppress this nitrogen vapor pressure, the growth temperature $T_g$ was also investigated. The flow rate ratio of ammonia gas as a nitrogen source to trimethylindium as an indium source ($V/I$) was optimized. As a result, the strong blue photoluminescence was obtained at room temperature by using 800 °C of $T_g$ and 16000 of $V/I$ in 1999. The almost same values as these ones have been widely used like magic numbers in the mass-production. The phase separation in InGaN is also described.

InN remains as a mysterious material. Still now, its properties including the band-gap energy are not clear because its high PN hampers the growth of high quality InN. The present status of InN research is also introduced.

7945-48, Session 7

Effects of substrate quality and orientation on the characteristics of III-nitride resonant tunneling diodes

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The resonant tunneling diodes (RTDs) are one way of generating reliable room temperature (RT) negative differential resistance (NDR) - that may be employed in generating high frequency (up to terahertz) waves enabling many applications such as ultra speed wireless communications, spectroscopy, and imaging.

III-nitrides offer unique advantages in RTD performance thanks to high peak electron velocity, saturation velocity, and thermal stability. Due to large conduction band discontinuity of AlN/GaN (i.e. ~2.1 eV), double barrier GaN-based RTDs are expected to have high peak-to-valley ratio (P/V) and NDR even at RT. However, high lattice mismatch of conventional substrates such as sapphire has hindered the development of these quantum devices. Requirement for high quality material, precise control over angstrom-scale active layer thicknesses, and abrupt interface are the biggest issues needs to be addressed for III-nitride-based quantum device technology. Foremost, the lattice mismatch should be reduced or eliminated by using proper templates on sapphire or homoepitaxial growth on freestanding substrates, respectively.

In this study we report the effect of different templates (AlN, GaN, and LNO) on NDR characteristics of AlGaN/GaN double barrier RTDs grown on conventional sapphire substrate using metal-organic chemical vapor deposition(MOCVD). In addition, we employ c-plane(polar) and
m-plane (non-polar) freestanding GaN substrates for MOCVD growth of AlGaN/GaN double barrier RTDs. Our results reveal that the stability of NDR in III-nitride RTDs can be increased by proper substrate selection and active layer design. We discuss the future prospects of III-nitride based quantum devices.

7945-49, Session 8

Control of characteristic performance by patterned structure in light-emitting diodes

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Various types of nano-to-micron scale patterned structure have been employed into nitride light-emitting diodes (LEDs) in order to investigate the characteristic performance of LED. The patterned structure was fabricated on top of the LED epitaxial structure or was embedded between epitaxial layer and sapphire substrate. It turned out that the patterned structure affected to the LED performances in terms of internal strain, light distribution and anisotropic increase of light extraction as well as increase of external quantum efficiency. Figure 1 shows the anisotropic increase of the light extraction by the AlN nano patterned template formed on sapphire substrate. The increase of light extraction in upward direction is higher than that in downward direction because of the index matching of AlN patterned structure.

Figure 1. Anisotropic increase of light extraction by the AlN nano patterned template.

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7945-50, Session 8

Efficiency enhancement of light-emitting diodes based on regularly patterned GaN nanocolumn growth and coalescence overgrowth


Emission enhancement results of blue and green-emitting InGaN/GaN quantum well and light-emitting diode (LED) structures based on GaN nanocolumn (NC) growth and coalescence overgrowth are presented [1]. Significant enhancements (up to ~100 % output intensity increase in a blue LED) are demonstrated [2]. For LED application, the threading dislocation (TD) density reduction in an overgrown GaN template can more effectively enhance the emission efficiency of a blue LED, when compared with a green LED.

Meanwhile, TD evolution during patterned GaN NC growth and coalescence overgrowth with metalorganic chemical vapor deposition is studied based on the comparisons of NC and coalescence overgrowth samples of different NC cross-section diameters and spacing sizes [3]. From the measurement results of depth-dependent X-ray diffraction and cross-section transmission electron microscopy, it is found that the TD density in an NC template on a patterned hole size for NC growth. Also, the TD formation at the beginning of coalescence overgrowth is related to the NC spacing size. Although the TD density and the occupied hole size for NC growth. Also, the TD formation at the beginning of coalescence overgrowth is related to the NC spacing size. Among the overgrowth samples of different NC diameters and spacing sizes with a fixed NC diameter/spacing ratio, the one with the smallest size and spacing leads to the lowest TD density, the largest lateral domain size, and the highest photoluminescence efficiency. Also, the optical and crystal qualities at}

the surfaces of all the overgrowth samples are superior to those of a GaN template.

References:

7945-51, Session 8

III-Nitride semiconductors for intersubband devices

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The extension of intersubband (ISB) optoelectronics towards the near infrared spectral region is interesting for the development of ultrastable photonic devices for optical telecommunication networks, as well as for application in a variety of chemical and biological sensors. Thanks to their large conduction band offset and subpicosecond ISB scattering rates, III-nitride heterostructures are excellent candidates for high-speed unipolar devices relying on the quantum confinement of electrons. In this talk, we will present the latest achievements in terms of molecular-beam epitaxial growth and characterization of GaN/AlN unipolar devices operating in the near infrared.

On the other hand, there is an interest to push the operation of ISB nitride devices to longer wavelengths, namely to mid-infrared as well as to the THz frequency range. Indeed, the large GaN LO-phonon energy (92 meV) opens prospects for intersubband (ISB) lasers and detectors at IR wavelengths inaccessible to other III-V semiconductors due to Reststrahlen absorption. We have experimentally demonstrated that the mid-IR domain can be covered by GaN/AlGaN with proper QW design. In this contribution, we analyze the effect of Si doping on the ISB absorption. The intersubband absorption is strongly blue shifted by many-body effects like exchange interaction and depolarization shift. The magnitude of the ISB energy shift due to many-body effects is comparable to the predicted e1-e2 transition, so that it cannot be treated as a perturbation. With the presented evidence, many-body effects become a critical parameter for design of nitride-based ISB structures operating at longer wavelengths, and all the theoretical calculations of devices for the far infrared should be accordingly revised.

7945-52, Session 8

Structural characterization of III-nitride materials and devices

D. J. Smith, L. Zhou, Arizona State Univ. (United States); T. D. Moustakas, The Boston Univ. Photonics Ctr. (United States)

Electron microscopy provides a wide range of techniques for structural characterization of nanophotonic materials and devices. High-resolution electron microscopy (defect identification and strain field analysis), Z-contrast imaging in the scanning transmission electron microscope (cation distribution), convergent-beam electron diffraction (local lattice parameter), and electron holography (internal electric field), provide powerful complementary approaches for characterizing the often
competing effects of growth conditions and compositional differences. These various TEM techniques have been used separately or in tandem in our recent investigations of the growth of III-nitride heterostructures and nanostructures, where lattice mismatch, compositional inhomogeneities and phase separation are all important considerations that affect the structural quality of the final material and/or device. Representative applications chosen to illustrate the prospects and some of the problems for microstructural characterization of nanophotonic materials will include the following examples:
- Relaxed InN quantum dots [1];
- Deep-UV-emitting AlGaN quantum wells, with high internal quantum efficiencies [2];
- Near-UV light-emitting diodes based on InN/GaN quantum wells [3];
- Blue-green LEDs based on GaN quantum-dot superlattices [4].

7945-53, Session 8
GaN as a detector of α-particles and neutrons
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GaN is a wide-bandgap III-V material that has certain potential advantages as a radiation detector over such classical detector materials as Ge, Si, GaAs. These potential advantages stem from robust operation at above room temperature due to high bandgap of 3.4 eV and from a high radiation hardness coming from very strong crystal bond in GaN. Of course, the crystalline quality of GaN is still much inferior compared to the crystalline quality of more established semiconductors. Also, only epitaxial material can be presently grown with low concentration of residual donors and deep traps. However, in niche applications, such as -particles detection or spectrometry and dosimetry of thermal neutrons GaN can successfully compete against its more traditional counterparts. In this talk we’ll show that present day epitaxial growth technologies allow to fabricate GaN films with thickness of 4-12 µm and residual donor concentration below 1014 cm-3 thus covering the range of typical -particles with energies from 1.48 MeV (products of neutron interaction with 10B) to 5.2-5.5 MeV (products of radioactive decay of 239Pu and 241Am). The studied -particles detectors were simple Ni Schottky diodes prepared either on undoped MOCVD grown material on on both conventional sapphire and low dislocation density free-standing c- and m-plane GaN substrates. Leakage current, gain, and capacitor-voltage measurements, spectral response and quantum efficiency were performed on single detectors.

As a result, measurements revealed dark current densities of 1.5x10^-7 A/cm2 at 100K and J = 0.33A/cm2 at 200K for Vbias =-50mV, while the measured R0A product reaches 1x10^6 Ohm.cm2 at 77K. Analysis of dark current characteristics shows that the diode is diffusion limited above 140K and generation-recombination limited below 140K. These results obtained on asymmetric SL photodiode are compared with equivalent MWIR symmetric InAs(8MLs)/GaSb(8MLs) SL devices.

7945-54, Session 8
Advances in UV sensitive visible blind GaN-based APDs
M. P. Ulmer, R. P. McClintock, M. Razeghi, Northwestern Univ. (United States)

In this paper, we review the current state-of-the-art in our process in making visible-blind APDs based on GaN. We av he grown our material on on both conventional sapphire and low dislocation density free-standing c- and m-plane GaN substrates. Leakage current, gain, and single photon detection efficiency (SPDE) of these APDs will be compared.

The spectral response and Geiger-mode photon counting performance of UV APDs are studied under low photon fluxes. Single photon detection capabilities with over 30% has demonstrated. We show how with pulse height discrimination the Geiger-mode operation conditions can be optimized for enhanced SPDE.

7945-55, Session 9
Asymmetric InAs/GaSb superlattice pin photodiode to improve temperature operation
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A mid-wavelength infrared (MWIR) asymmetric InAs/GaSb superlattice pin photodiode was fabricated by MBE on p-type GaSb substrate and characterized as a function of temperature. The SL structure was made of 7.5 InAs monolayers (MLs) and 3.5 GaSb MLs, for a total thickness of 1 µm and exhibits at 80K a cut-off wavelength of 5.5µm.

A set of electro-optical characterizations including dark current, capacitance-voltage measurements, spectral response and quantum efficiency were performed on single detectors.

As a result, measurements revealed 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 1x10^6 Ohm.cm2 at 77K. Analysis of dark current characteristics shows that the diode is diffusion limited above 140K and generation-recombination limited below 140K. These results obtained on asymmetric SL photodiode are compared with equivalent MWIR symmetric InAs(8MLs)/GaSb(8MLs) SL devices.

7945-56, Session 9
Room temperature photocurrent response of split-off band infrared detectors with a graded barrier
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Split-off band detectors have been developed for high operating temperatures but require reductions in dark current. One possible approach is to develop a photovoltaic type split-off band detector. Photovoltaic operation is possible when an asymmetric band structure makes it easier for excited carriers to travel in one direction than in the other leading to a built-in potential. In the work presented, the asymmetry which shows a good promise for GaN as an -particle or thermal neutrons detector for operation in harsh environment. The work at IRM and IPC was supported by a grant from ICTS (grant #3870).


In this paper, we report our work on the integration of GaSb-based active devices onto SOI passive waveguide circuits to improve the system performance. This technology based on high refractive index contrast waveguides, enabling processing is compatible with CMOS processes. Hence, integration of GaSb active devices onto SOI passive waveguide circuits, on the other hand, is a well established field of metamaterials. Not only might these new materials present us a lead to such a device. The way we are approaching this is via the new front of a broadband detector. There are many avenues of research that we are investigating how nanostructured metal surfaces can produce plasmon-enhanced fields to improve detectivity of a detector material placed directly below the metal surface. We are also investigating a wavelength-tunable detector scheme that involves a coupled double quantum well structure with a thin middle barrier between the two wells. The photocurrent from this structure will be swept out with a lateral bias. Another form of wavelength tunability is to have a tunable filter in front of a broadband detector. There are many avenues of research that lead to such a device. The way we are approaching this is via the new field of non-equilibrium device results.

7945-57, Session 9
Enhancing the performance of infrared detectors for space applications
D. A. Cardimona, D. Huang, M. Landau, C. P. Morath, B. P. Feller, Air Force Research Lab. (United States)

At the Air Force Research Laboratory's Space Vehicles Directorate, we are investigating how nanostructured metal surfaces can produce plasmon-enhanced fields to improve detectivity of a detector material placed directly below the metal surface. We are also investigating a wavelength-tunable detector scheme that involves a coupled double quantum well structure with a thin middle barrier between the two wells. The photocurrent from this structure will be swept out with a lateral bias. Another form of wavelength tunability is to have a tunable filter in front of a broadband detector. There are many avenues of research that lead to such a device. The way we are approaching this is via the new field of non-equilibrium device results.

7945-58, Session 10
Heterogeneous GaSb/SOI mid-infrared photonic integrated circuits for spectroscopic applications
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Mid-infrared spectroscopy has gained significant importance in recent years as a detection technique for materials whose absorption spectra appear in this spectral region. Traditionally, spectroscopic system consists of bulky equipments which are difficult to handle and incur high cost. An integrated spectroscopic system, on the other hand, eliminates all these disadvantages. The development of GaSb-based active devices offer improved mid-infrared light sources and detectors for such integrated systems. Silicon photonics, based on Silicon-on-Insulator (SOI) waveguide circuits, on the other hand, is a well established technology based on high refractive index contrast waveguides, enabling ultra-compact passive integrated photonic circuits. Moreover, SOI processing is compatible with CMOS processes. Hence, integration of GaSb active devices onto SOI passive waveguide circuits would potentially allow highly compact spectroscopic systems with flexibility in passive devices design to improve the system performance. This approach has great potential for several applications, e.g. an implantable glucose sensor and gas sensing devices. In this paper, we report our work on the integration of GaSb-based epitaxy and SOI waveguide circuits. The realization of heterogeneous integration is based on a bonding process using the polymer divinylsiloxane-benzocyclobutene (DVS-BCB) as a bonding agent. The bonding process is performed by transferring the epitaxial layer to an SOI wafer through a die-to-wafer bonding process. With this approach, a bonding layer of 150 nm thickness is achievable. We also report our results on the integration of waveguide-based GaSb p-i-n photodetectors coupled to SOI waveguide circuits based on evanescent coupling, which show a responsivity higher than 0.4A/W. The design of active and passive structures and the overall fabrication process will also be discussed.

7945-59, Session 10
VLWIR high operating temperature non-equilibrium photovoltaic HgCdTe devices
S. Velicu, C. H. Grein, EPIR Technologies, Inc. (United States); A. Itsuno, J. D. Phillips, Univ. of Michigan (United States)

A nearly universal goal for infrared photon detection systems is to increase their operating temperature without sacrificing performance. For high quality HgCdTe photovoltaic infrared detectors at elevated temperatures, the low-doped absorber layer becomes intrinsic, carrier concentrations are high and Auger processes typically dominate the dark current. Device designs have been proposed to suppress Auger processes in the absorber by placing it between exclusion and extraction junctions under reverse bias. In this work, we analyze the non-equilibrium operation of mid-wavelength infrared (MWIR), long wavelength infrared (LWIR) and very long wavelength infrared (VLWIR) HgCdTe devices and identify the performance improvements (operation temperature, responsivity, detectivity) expected when Auger suppression occurs. We identify critical structure design (exclusion, absorber and extraction layer thicknesses and compositions), material (absorber dopant concentration and minority carrier lifetime) and device (passivation, annealing) requirements that must be satisfied for optimal performance characteristics from MWIR, LWIR and VLWIR non-equilibrium devices. We will also describe our experimental work to realize the non-equilibrium structure and device requirements, with an emphasis on the molecular beam epitaxy growth of MWIR, LWIR and VLWIR structures having absorber layers with low dopant densities and high minority carrier lifetimes. We will present an analysis and comparison of our theoretical and experimental non-equilibrium device results.
In this talk, we report the molecular beam epitaxial growth of Type II superlattice focal plane array infrared detectors.

One of the great advantages of Type II InAs/GaSb superlattice over other competing technologies for the third generation infrared imagers is the number of defective pixel on the matrix detector. Sources for pixel outages are manifold and might be caused by the dislocation in the substrate, the epitaxial growth process or by imperfections during the focal plane array fabrication process. The goal is to grow defect-free epitaxial layers on a dislocation free large area GaSb substrate. Permanent improvement of the substrate quality and the development of techniques to monitor the substrate quality are of particular importance. To examine the crystalline quality of 3° and 4°GaSb substrates, synchrotron white beam X-ray topography (SWBXT) was employed. In a comparative defect study of different 3° GaSb and 4° GaSb substrates, a significant reduction of the dislocation density caused by improvements in bulk crystal growth has been obtained. Optical characterization techniques for defect characterization after MBE growth are employed to correlate epitaxially grown defects with the detector performance after hybridization with the read-out integrated circuit.

Defect density reduction in InAs/GaSb type II superlattice focal plane array infrared detectors

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InAs/GaSb short-period superlattices (SL) have proven their large potential for high performance focal plane array infrared detectors. Lots of interest is focused on the development of short-period InAs/GaSb SLs for mono- and bi-spectral infrared detectors between 3 - 30 μm. InAs/GaSb short-period superlattices can be fabricated with up to 1000 periods in the intrinsic region without revealing diffusion limited behavior. This enables the fabrication of InAs/GaSb SL camera systems with very high responsivity, comparable to state of the art CdHgTe and InSb detectors. The material system is also well suited for the fabrication of dual-color mid-wavelength infrared InAs/GaSb SL camera systems. These systems exhibit high quantum efficiency and offer simultaneous and spatially coincident detection in both spectral channels.

An essential point for the performance of two-dimensional focal plane infrared detectors in camera systems is the number of defective pixel on the matrix detector. Sources for pixel outages are manifold and might be caused by the dislocation in the substrate, the epitaxial growth process or by imperfections during the focal plane array fabrication process. The goal is to grow defect-free epitaxial layers on a dislocation free large area GaSb substrate. Permanent improvement of the substrate quality and the development of techniques to monitor the substrate quality are of particular importance. To examine the crystalline quality of 3° and 4°GaSb substrates, synchrotron white beam X-ray topography (SWBXT) was employed. In a comparative defect study of different 3° GaSb and 4° GaSb substrates, a significant reduction of the dislocation density caused by improvements in bulk crystal growth has been obtained. Optical characterization techniques for defect characterization after MBE growth are employed to correlate epitaxially grown defects with the detector performance after hybridization with the read-out integrated circuit.

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High-performance long wavelength superlattice infrared detectors


The nearly lattice-matched InAs/GaSb/AISb (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 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 on our recent efforts in achieving state-of-the-art performance in antimonide superlattice based infrared photodetectors. Specifically, we report a 10 um cutoff superlattice device based on a complementary barrier infrared detector (CBIRD) design. The detector, without anti-reflection coating or passivation, exhibits a responsivity of 1.5A/W and a dark current density of 1e-5 A/cm² at 77K under 0.2V bias. It reaches 300K background limited infrared photodetector (BLIP) operation at 87K. In addition, we discuss the noise and gain characteristics of high-performance SL photodetectors. Direct measurements of the noise spectra of high performance SL heterodiodes at different operational conditions reveal the absence of intrinsic 1/f noise in these structures, but shows that an additional frequency-dependent noise can be generated by side-wall leakage current. These results advance our understanding of SL photodiode operation and are essential for improving the design and fabrication of state-of-the-art SL heterostructures.

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7945-65, Session 11
Lateral diffusion of minority carriers in InAsSb-based nBn detectors
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Photodetectors operating in the mid-wave infrared (MWIR, 3-5um) region of the IR spectrum are of high demand for a variety of applications. The technologies currently dominating this wavelength range are mercury cadmium telluride (MCT) and InSb photodetectors. MCT detectors are characterized by low operation temperatures due to a low electron effective mass resulting in excessive leakage current. InSb detectors are limited to cryogenic operation temperatures as well. InAsSb is a good candidate for the development of room temperature MWIR photodetectors due to a reduced Auger recombination rate compared with HgCdTe alloys. In addition, InAsSb offers other advantages such as better stability over large areas, high electron and hole mobilities, and commercial availability of high quality and low cost substrates. InAsSb MWIR detectors with the nBn design have lower dark current due to eliminated Shockley-Read-Hall generation-recombination current and reduced surface leakage current. However, the major problem associated with the nBn design is the lateral diffusion of minority carriers which defines the device dimensions.

We report on the investigation of lateral diffusion of minority carriers in nBn InAsSb photodetectors. Diffusion lengths (DL) were extracted from temperature dependent I-V measurements. The behavior of DL as a function of applied bias, temperature, and composition of the barrier layer was investigated. The obtained results suggest that lateral diffusion of minority carriers is not the limiting factor for nBn InAsSb MWIR detector performance at high temperatures (>200K). The detector with AlAs0.15b0.8 barrier has demonstrated values of DL as low as 7um (Vb = 0.85V) at 240K.

7945-66, Session 11
Gamma-ray irradiation effects on InAs/GaSb-based nBn IR detector

IR detectors that are operated in a space environment are subjected to trapped protons yet they are required to have very low noise performance. Conventional mercury cadmium telluride (MCT)-based detectors have been shown to perform well in space environments, when properly passivated. However, the inherent manufacturing difficulties associated with the growth of MCT has resulted in a research thrust in alternative detector architectures specifically type-II Strained Layer Superlattice (SLS) infrared detectors. Theory predicts that SLS-based detector technologies have the potential of offering several advantages over MCT detectors including lower dark currents and higher operating temperatures. Experimentally it has been found that conventional p-on-n or n-on-p SLS detectors have large dark current densities. An emerging detector technology referred to as an nBn utilizes a uni-polar barrier design to reduce dark currents to an acceptable level.

Little work has been done to characterize nBn IR detectors tolerance to total ionizing dose (TID) and proton radiation. The nBn IR detector under test is composed of an InAs/GaSb SLS absorber (n) and contacts (n) with AlxGa1-xSb barrier (B) grown by solid source molecular beam epitaxy. Both proton induced surface and bulk radiation effects for the nBn IR detector will be characterized in this paper.

7945-67, Session 11
Pixel isolation of low dark-current large-format InAs/GaSb superlattice complementary barrier infrared detector focal plane arrays with high fill factor

Low dark current and high fill factor are two crucial characteristics for the realization of the InAs/GaSb superlattice technology as third generation focal plane arrays. Recent development proved high performance results for the complementary barrier infrared detector (CBIRD) design, and a high-quality etch technique is required to minimize surface leakage currents. We report on a n-CBIRD with 10.3 um cutoff, exhibiting a responsivity of 1.7 A/W and dark current density of 1x10^-5 A/cm² at 77K under 0.2 V bias, without AR coating and without passivation. Results from four different mesa isolation techniques are compared on single element diodes: chemical wet etch using C4H6O6:H3PO4:H2O2:H2O, BC13/Ar inductive coupled plasma (ICP), CH4/H2/Ar ICP, and CH4/H2/BC13/C12/Ar ICP. The CH4/H2/BC13/C12/Ar etched structures yielded more than 2.5 times improvement in dark current density and near-vertical sidewalls. Using this etching technique, we implement a 1k x 1k p-CBIRD array with 11 um cutoff. Operating at 80K, the array yielded a 81% fill factor with 98% operability and performance results of 21% quantum efficiency, 53 mK NEDT, and NEI of 6.9x10^13 photons/sec-cm².

7945-68, Session 12
Vertical transport in InAs/GaSb superlattices: model results and relation to in-plane transport
F. Szmulowicz, Univ. of Dayton Research Institute (United States); G. J. Brown, Air Force Research Lab. (United States)

Operation of InAs/GaSb superlattice-based devices requires efficient transport of carriers perpendicular to superlattice layers by drift and/or diffusion. While transverse mobility measurements are performed routinely, vertical transport measurements are difficult and nonstandard, so that very little is known about their value and dependence on material quality, which is important in device modeling. In such a situation,
model calculations can help fill the void. In this work, we model both the horizontal and vertical electron transport in InAs/GaSb superlattices qua superlattices, not quantum wells, as in Gold's model or its extensions. We solve the respective Boltzmann equations in the relaxation time approximation, using the interface roughness scattering as the dominant mobility-limiting mechanism. We derive a universal relation that the vertical relaxation rates are always smaller than horizontal relaxation rates; hence vertical mobilities are generally smaller than horizontal mobilities. We calculate vertical and horizontal mobilities as a function of superlattice parameters such as layer widths, the correlation length of interface roughness, and the Fermi energy. In general, the vertical mobilities track the behavior of the horizontal mobilities but can differ greatly, depending on superlattice parameters. The calculated ratios of the vertical to horizontal mobilities can be used to estimate vertical mobilities from measurements of horizontal mobilities.

7945-69, Session 12
Barrier engineered superlattice and quantum dot detectors for HOT operation
J. Shao, T. E. Vandervelde, A. V. Barve, W. Jang, A. Stintz, S. Krishna, Ctr. for High Technology Materials, Univ. of New Mexico (United States)

There is an increased emphasis on obtaining higher operating temperature (HOT) detectors as a part of the third generation detector development. 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, 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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7945-70, Session 12
Progress in Sb-based type II superlattice infrared detector technology and minority carrier lifetime study
S. Bandara, M. Z. Tidrow, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

Type-II Superlattice detector (T2SL) technology for IR detection has progressed significantly, demonstrating experimentally potential as a strong candidate for future high-performance IR sensors. This paper will discuss recent improvements in device design such as the inclusion of wide-gap based p-n junctions and optimization of the doping profile in the active layer of the detector. In addition, advances in device processing, specifically in dry-etch techniques, have culminated detector arrays with nearly vertical mesa walls. Despite recent progress, current T2SL detector performance appears to be limited by the shorter minority carrier lifetime associated with the generation-recombination process. This paper will analyze T2SL's quantum efficiency and dark current based on various aspects of the device such as diffusion, generation-recombination and tunneling, and dependence on the minority carrier lifetime of T2SL detector material. This analysis will allow us to predict the detector performance as a function of minority carrier lifetime and possible improvements resulting from T2SL's flexible bandgap-engineered growth capability. The paper will also present experimental measurements of minority carrier lifetime of T2SL detectors.

7945-71, Session 12
Modified type-II superlattices for long wavelength infrared applications
Y. Chen, SVT Associates, Inc. (United States)

Long wavelength infrared (LWIR) photo detectors and detector focal plane arrays are in high demand for various applications such as remote sensing, environmental monitoring, and spectrometry. The performance of type II InAs/GaSb superlattice (SL) has been improved considerably [2-7] since it was first proposed for IR detection in 1987 [1]. However, the detectivities of LWIR type II SL photo diodes are still at least one order of magnitude lower than theoretically predicted values [8,9], indicating there is still room to improve their performance.

Here we report a new modification on SL structure that substantially improves the overall performance of SL photo detectors including extended cutoff wavelength and improved specific detectivity. Both our experimental data and theoretical analysis show that InSb thickness can be used to adjust band structure and cutoff wavelength much more effectively than that of InAs, GaSb, AlSb, or any combination thereof. In our modified SL design, a thicker InSb layer was used to extend the cutoff wavelength and a thin compressively-strained wider bandgap layer was inserted to balance the strain of the thicker InSb layer. The presence of 2MLs of the wider bandgap material which differs from the more common AlSb variety will help to reduce dark current and sidewall leakage as it serves as a barrier for both electrons and holes in SLs. The detectivities of 2.6e11, 5.5e10, and 2.1e10cmHz1/2/W have been achieved for the modified SL diodes with cutoff wavelength of 14.1, 18.2, and 23.3 micron, respectively, at 83K. Details of the material growth, device fabrication and characterization will be presented.

References

7945-72, Session 12
Effect of the oxide-semiconductor interface on the passivation of hybrid type-II superlattice long-wave infrared photodiodes
J. A. Nolde, U.S. Naval Research Lab. (United States); R. Stine, Nova Research, Inc. (United States); E. M. Jackson, C. L.
While type-II superlattice (T2SL) LWIR photodiodes continue to show gains in performance relative to those using HgCdTe, successful T2SL-based focal plane array (FPA) technology will require the development of effective passivation of exposed surfaces in pixel-sized mesa diodes. For FPA pixel pitches of 30 microns and less, surface leakage can readily dominate bulk dark current, and even well behaved surfaces degrade severely during hybridization, in which epoxy is used to stabilize the hybrid for substrate removal. Passivation approaches that have been reported to date, however, have been inconsistent, have worked poorly on FPAs, and have offered little understanding of underlying material issues.

Here we investigate the relationship between the thickness and composition of the native oxide at the T2SL-SiO2 interface and the diode performance in terms of sidewall resistivity. Device performance is compared between samples with untreated surfaces, those in which the native oxides have been removed at various intervals prior to SiO2 deposition, and samples in which oxide growth was promoted by ozone exposure with and without a prior oxide strip. InAs- and GaSb-capped pieces were processed in an identical manner and studied using X-ray photoelectron spectroscopy (XPS). From these spectra, the composition and thickness of the native oxides just prior to SiO2 deposition is determined, complementing the electrical characterization of devices. Correlation of performance and surface composition is presented.

Quantitative analysis of formation and thermal stability of oxide phases between SiO2 and InSb

J. Lee, S. Park, J. Kim, C. Yang, S. Kim, C. Seok, J. Park, E. Yoon, Seoul National Univ. (Korea, Republic of)

SiO2 has received great attentions as a promising candidate for the active layer of infrared photodetectors due to the band gap well matched to the detection of 3–5 μm infrared (IR) wavelength and high electron mobility (106 cm2/Vs at 77 K). In the fabrication of InSb photodetectors, passivation to suppress dark currents is the key process and intensive studies were conducted to deposit the high quality passivation layers on InSb. Silicon dioxide (SiO2), silicon nitride (Si3N4), anodic oxide have been investigated as passivation layers and silicon oxide is generally used in recent InSb detector fabrication technology due to its better interface properties than other candidates. However, even in SiO2, indium oxide and antimony oxide formation at SiO2-InSb interface has been a problem and these oxides prevent the further improvement of interface properties. Also, the mechanisms of the formation of interface phases are still not fully understood. In this study, we report the quantitative analysis of indium and antimony oxide at SiO2/InSb interface formed at various growth temperatures during plasma enhanced chemical vapor deposition and subsequent heat treatments. 30 nm-thick SiO2 layers were deposited on InSb at 120, 160, 200, 240 and 300 °C, and analyzed by X-ray photoelectron spectroscopy (XPS). With increasing deposition temperature, contents of indium and antimony oxides were also increased due to the enhanced diffusion. In addition, the sample deposited at 120 °C was annealed at 300 °C for 10 and 30 min and the contents of interfacial oxides were analyzed. Thermodynamic stability and the resulting interfacial solid-state reactions and its effect on the interfacial states will be discussed in detail.

7945-40, Session 13

Leveraging electric and magnetic dipole transitions for active nanophotonic devices

R. Zia, Brown Univ. (United States)

In this talk, we will explore the device implications of controlling the strong magnetic dipole transitions in Lanthanide ions (such as the 1550nm line in trivalent Erbium). For decades, Lanthanide ions have served as important light emitters in a range of optical technologies from lighting and displays to solid-state lasers and telecom fiber amplifiers. Recently, our lab has explored a number of optical techniques to selectively enhance both electric and magnetic dipole transitions. In experimental studies, we have demonstrated strong (> 4X) Purcell enhancement of magnetic dipole emission and broad (>100nm) spectral tuning using trivalent Europium. Building on this work, we will discuss new device designs that can be enabled through control of such magnetic transitions. Specifically, we will explain how the differing symmetry of magnetic dipole emitters can open a new degree of design freedom for active nanophotonic devices.

Potential of carbon nanotubes films for infrared bolometers

C. Koechlin, S. B. Maine, ONERA (France) and Ctr. National de la Recherche Scientifique (France); S. Maine, C. Koechlin, R. Haidar, B. Tretout, J. Jaeck, ONERA (France); N. Pére-Laperne, J. Pelouard, Ctr. National de la Recherche Scientifique (France)

The use of uncooled (i.e. low cost) detectors for infrared imaging (3-12 microns) has been the subject of research and development for many decades. Among them the resistive bolometer (basically, a photoresistor) is widespread in commercial applications such as drivers or aircraft aid, fire-fighting, night vision... These light sensors are however still plunged by their relatively low performances (sensitivity, spectral range, response time), and there is a need for new materials and/or architectures for increasing the potential, while maintaining their low cost.

In this context, CNT-film based devices appear as a promising solution, since they exhibit a wide-range absorption in the infrared (from 3 microns to 300 microns, due to the excitation of free carriers), a strong bolometric behaviour (that we identified as a fluctuation induced tunneling through the inter-tube junctions) and good thermo-mechanical properties. Besides the influence of the CNT type (Semiconductor and metal) has been investigated on both absorption and bolometric behaviors.

We thus developed the technological building blocks (film deposition and etching, electrical contacting on micrometer-scale suspended CNT ribbons) for the realization of large, uniform, and reproducible matrix of SWCNT-film infrared-bolometers. We obtain state-of-the art results for electrical characteristics (specific contact resistance and resistivity dispersion), and demonstrate the first photoresponse to mid IR radiation.

Electrical and optical characteristics of CNT-film based devices based on suspended CNT films will be discussed


7945-41, Session 13

Spontaneous emission of light in nanostructured disordered media

R. Carminati, Ecole Supérieure de Physique et de Chimie
Patterns with PS-b-PMMA block copolymer on various substrates and their applications

M. M. Alam, Y. Lee, W. Jung, Kookmin Univ. (Korea, Republic of)

High density arrays of nanostructures over large area can be formed by self-assembly of block copolymers on a variety of substrates such as silica deposited silicon wafer, glass, GaN, PET etc. This block copolymer thin film, such that the domains are oriented perpendicularly to the substrate, is particularly useful for the formation of templates for patterns. The degradation and elimination of the minor component transforms the material into an array of nanopores to form some patterned template that offer potential benefits in a number of applications. The morphology of the polymer surface is strongly dependent on the thickness of the polymer layer. Moreover it is necessary to control the size and shape in order to get the desired properties. Spin coating followed by baking the polymer solution onto the substrate self assembles the components of the polymer. PS and PMMA have significantly different photodegradation properties. Exposure to ultraviolet radiation degrades the PMMA (polymethyl methacrylate) chain that can be removed by rinsing in acetic acid giving patterned holes. But the small size of hole limits the template to several applications. This problem can be solved by sonicating the sample in different solution in different steps which gives fingerprint pattern or sometimes patterns with PS cylindrical domains with large interstitial spaces. Moreover the interstitial space depends on the composition of the polymer solution. Deposition of gold on patterned glass gives linked gold pattern which can be used as transparent conducting electrode. As well as, the patterns can be used to fabricate memory devices which have controlled metallic nanoparticle/polymer composite layers. The creation of regular, nanoscale structures will offer potential benefits in a number of applications.

Advances in nano-enabled GaN photonic devices

P. A. Shields, C. Liu, W. N. Wang, D. W. E. Allsopp, F. Causa, Univ. of Bath (United Kingdom)

In this work, the results are presented of a nanorod LED array. If the lateral size of the nanorods is small enough, it is possible to achieve a degree of lateral confinement. If the nanorods are ordered into a suitable photonic lattice, then this will reduce the lateral spontaneous emission and enhance emission along the vertical axis via the Purcell effect. Additionally there is a degree of dislocation filtering that can occur [1]. However, one potential drawback of this device is the large free surface that borders the multi-quantum well active region. Nevertheless, it has been shown that the surface recombination in the nitride materials is the lowest of all III-V semiconductors.

Results of SEM, PL, EL, and far field pattern are presented to compare the progressive effect of using photo-assisted electroless and wet etching [2]. It can be seen that over time the photo-assisted electroless method clearly delineates the active MQW region, possibly as a result of the different etch rate of InGaN. Alternatively, a purely chemical etching method was used. With a narrowing of the nanorods, there is a progressive blue shift of the photoluminescence peak. The optical image of the emission shows that there are well-defined lines of enhanced light propagation that match the symmetry of the nanorod array, thus showing there is a photonic crystal effect.

The authors acknowledge support from the European Union under FP 6 contract No 017481 (N2T2) and from the UK Technology Strategy Board of the emission shows that there are well-defined lines of enhanced light propagation that can be attributed to near-field interactions and/or to collective interactions in the multiple scattering regime. In view of imaging applications, we show that decay rate (or fluorescence lifetime) fluctuations could be used as a sensitive local probe at the nanoscale in a complex medium or material. In the multiple scattering regime, we show that the probability of observing a decrease of the decay rate (increase of the fluorescence lifetime) is substantial. It originates from a reduction of the LDOS due to collective interactions and interferences. We also show that a fundamental relationship exists between the averaged LDOS and the extinction mean free path, both quantities being connected by dispersion relations and a frequency sum rule. These results suggest novel approaches for the design of disordered photonic materials with specific properties.

References


Quantum-dot-based nano-pillar light emitting diodes

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Colloidal compound quantum dots (QDs) have recently been introduced to the white light emitting diode (LED) technology as a new family of phosphor materials with many superior properties, such as sharp exciton absorption features, extremely high luminescence efficiency (~90-95%), and size-tunable emission color spanning the entire visible spectrum [1,2,3]. Recently, Achermann et al. observed 13% color conversion efficiency in an electrically pumped LED using non-radiative energy transfer between an InGaN/GaN quantum well (QW) and a monolayer of CdSe/ZnS QDs [4]. But it is still difficult to address the conflict between the need for close proximity of the QW and QDs and the use of sufficiently thick contact layer with a low resistance for LED operation. In this study, we fabricated an InGaN based nano-pillar LED structure with colloidal QD phosphors deposited in between the nano-pillars, creating side-wall coupling between QD phosphors and InGaN MQW emitters. The InGaN/GaN MQW LED nano-pillars were fabricated by the inductively coupled plasma (ICP) etching using self-assembled indium tin oxide (ITO) nanodots as the etching mask. By controlling the size of ITO nanodots and the ICP etching time, nano-pillars with a height of 500 nm and diameters ranging between 100nm and 500nm can be fabricated successfully. A layer of CdSe/CdS core/shell QDs were spin-coated over the nano-pillar LED sample and subsequently annealed at a 100°C to remove the solvent.

Time-resolved photoluminescence (TRPL) studies and power dependent TRPL studies for InGaN nano-pillar LED structure with and without colloidal QD coating clearly showed the existence of MOQW-to-QDs non-radiative energy transfer, which provides an additional relaxation channel.
for MQW excitations. In addition, highly efficient QD-phosphor based electrically pumped nano-pillar LEDs will be presented. The authors in SCNU acknowledges support by the World Class University (WCU) program at Sunchon National University and by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MEST) (No. 2009-0080313).


7945-80, Session 14

Flexible nanogenerators for self-powered touch and light sensor applications

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Nanopiezotronics is an emerging area of nanotechnology with a variety of applications that include piezoelectric field-effect transistors and diodes, self-powered nanogenerators and biosystems, and wireless nano/biosensors. By utilizing coupled piezoelectric and semiconducting characteristics of ZnO, it is possible for ZnO nanowires, nanorods or nanotubes to generate rectifying current and potential under external mechanical energies such as body movement (handling, winding, pushing, and bending) and muscle stretching, vibrations (acoustic and ultrasonic waves), and hydraulic forces (body fluid and blood flow). In the conference, as the first issue, I will present fully transparent, flexible, rollable nanogenerators that are operated by external mechanical forces. ZnO nanorod-based nanogenerators with a PdAu, ITO, CNT, and graphene top electrodes gave output current densities of approximately 1-10 µA/cm2 at a load of 0.9 kgf. Transparent flexible (TF) nanogenerators are greatly promising for realization of TF self-powered touch sensors. As the second talk, a naturally hybrid architecture of a piezoelectric nanogenerator and a photodetector will be presented. The hybrid power generator enables excellent piezoelectric scavenging performance of up to ~1 W/cm2 in an independent operation mode. In addition, under normal visible light (room light) illumination (~1 mW/cm2), the output voltage of the hybrid architecture is enhanced by a factor of 2.6 by integrating the contribution made by piezoelectric generator, which is able to drive a ZnO or CdS based ultraviolet or visible light nanosensor, revealing its great potential towards building up self-powered nano sensor systems.

7945-81, Session 14

Luminescence quenching and enhancement dynamics in composites of CdSe/ZnS quantum dots and gold nanoparticles

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The mechanisms of quenching and enhancement phenomena for CdSe/ ZnS core/shell quantum dots (QDs) and gold nanoparticles (Au NPs) in layer-by-layer structures as well as in aqueous solution have been investigated. Different sizes of QDs and different excitation wavelengths were used to elucidate the quenching and enhancement mechanisms. To excite various sizes of QDs with emission wavelengths from 545 to 619 nm, different excitation wavelengths are used, allowing us to excite non-resonantly and resonantly with surface plasmon absorption peak of Au NPs. Based on detailed analysis of experimental results, e.g., relative PL excitation and time-resolved PL spectra, we found that the quenching and enhancement phenomena are affected by interplay of Förster resonant energy transfer and surface plasmon enhancement processes of Au NPs on QDs, which depend on different conditions such as the excitation energy, spectral overlap between QDs emission and Au NPs absorption, and the located positions of QDs with respect to Au NPs. Our results can provide better understanding in the interaction between QDs and Au NPs both in layer-by-layer and in aqueous solution, which are useful for practical photonic and biological applications.

7945-82, Session 14

Optical nano-antennas: a new approach for optical imaging and detection

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During the past few years, the field of optical nano-Antennas has experienced extensive growth in activity and has been receiving much focus and attention, primarily due to their possible applications in telecommunications, field enhancement, sensing and solar energy harvesting. A Rectenna (Rectifying antenna) is composed of an antenna connected to a rectifying component (e.g. a diode), which enable direct conversion of electromagnetic energy to direct electrical current. The concept, originally proposed in Raytheon during the 60s, was aiming at achieving highly efficient power transfer and indeed, power conversion efficiencies exceeding 80% have been demonstrated in RF frequencies. An attempt to push this concept to the optical domain encounters two primary hurdles: the fabrication of extremely small structures and realizing very high bandwidth (10-1000 THz) diodes. Employing state-of-the-art nano-fabrication tools and extremely high-mobility carbon nano-tubes for the rectification diode, we believe it is possible to realize a rectenna operating at the far to near IR bands and maybe even at the visible band as well. Nano-antenna array operating at telecom wavelength are demonstrated experimentally and their spectral properties are studied in detail exhibiting excellent agreement with the theoretical analysis. Applications in the field of imaging and telecommunications will be presented and discussed.

7945-83, Session 14

Dielectric optical waveguides using periodic layers of metamaterials and dielectrics

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A stack of alternating layers of dielectrics with positive refractive index and metamaterials with negative refractive index can be tuned to a vanishing average refractive index and shows a ‘zero-bandgap’ condition different from the conventional Bragg characteristics [1]. We can design photonic sensors for measuring pressure or strain and/or temperature using such a stack [2]. In this paper we explore the possibility of incorporating a stack of zero band-gap in a stripped-cladding fiber-optic evanescent field sensor. The stack is put around the stripped cladding area as the new cladding. The refractive index of the stack determines the output optical field. We determine how the physical parameters affecting the permeability and permittivity of the metamaterial change the output intensity of the fiber optic sensor. We explore how practical sensors can be developed with this device.

References

Energy transfer driven optoelectronics of semiconductor nanocrystals for energy efficiency
H. V. Demir, Bilkent Univ. (Turkey) and Nanyang Technological Univ. (Singapore)
Semiconductor colloidal nanocrystal quantum dots enable light generation and light harvesting at extended spectral ranges using both radiative and nonradiative energy transfer. In this talk, as emerging technologies enabled by green nanophotonics, we will present our recent research results on light-emitting diodes (LEDs) integrated with quantum dot nanophosphors including those enhanced with nonradiative energy transfer for energy efficiency, and photovoltaic (PV) nanocrystal scintillators hybridized on solar cells for spectral enhancement as well as light harvesting based on nonradiative energy transfer. For energy efficiency in nanophotonics, we will showcase and discuss nanocrystal integrated LEDs for ultraefficient, high-quality solid-state lighting. In our energy transfer enhanced LEDs, we use custom-design assemblies of core/shell heteronanocrystals with a bandgap gradient to recycle the trapped excitons. Here we will present the design, fabrication, integration and characterization of these nanocrystal integrated light emitting diodes. In this talk, for light harvesting, we will present semiconductor nanocrystal based PV scintillators integrated on solar cells to enhance photovoltaic device parameters including spectral responsivity, short circuit current, fill factor, and solar conversion efficiency. We will discuss and show that such nanocrystal scintillators provide the ability to extend the photovoltaic activity towards shorter wavelengths. We will also present light harvesting of these colloidal quantum dots to nonradiatively transfer their excitonic excitation energy. We will further demonstrate substantial lifetime modifications of these quantum dots via nonradiative energy transfer. Such energy transfer driven optoelectronics of semiconductor nanocrystals hold great promise for energy efficiency in light generation and light harvesting. (This work is supported by NRF RF, EU FP7 Nanophotonics4Energy NoE, ESF EURYI, and TUBITAK109E002-1009E004.)

Manufacturing and optical properties of band gap graded ZnCdO nanostructures
A. Y. Kuznetsov, V. V., M. Trunk, T. Zhang, A. Y. Azarov, A. Galeckas, Univ. of Oslo (Norway)
Oxide semiconductors in general and ZnO-based semiconductors in particular have attracted much of attention on behalf of unique properties having promising applications in advanced electronic and optoelectronic devices. For example, realizing novel band-to-band absorbers made of reasonably cheap materials is a challenge in photovoltaics and - highlighting just one of ZnO potentials - band gap engineering in ZnO-based materials can actually answer this challenge. Indeed, alloying ZnO with CdO results in a gradual band gap shrinking in the range of 3.3-1.8 eV as a function of Cd content. Moreover, pure ZnO may be readily synthesized in various forms of nanowires (NWs) and manufacturing of ZnCdO NWs having a graded concentration/bandgap is interesting to research too. In the frame of this work we are making a systematic effort to manufacture and study ZnCdO, synthesizing high quality crystalline samples using metal organic vapor phase epitaxy and targeting both multilayer (ML) and NW structures. The fundamental result reached so far is in realization of graded ZnCdO ML nanostructures as well their characterization employing a variety of methods. As an example, please find two diagrams below illustrating (a) - photoluminescence measurements and (b) - chemical composition depth profiling in typical ML nanostructures (note, Cd content in panel (b) is deduced from Rutherford backscattering spectroscopy results).

Development of chipscale chalcogenide glass based infrared chemical sensors
J. Hu, Univ. of Delaware (United States); J. D. Musgraves, Clemson Univ. (United States); N. Carlie, Clemson Univ. (Albania); B. Zdyrko, I. Luzinov, Clemson Univ. (United States); A. M. Agarwal, Massachusetts Institute of Technology (United States); K. Richardson, Clemson Univ. (United States); L. C. Kimerling, Massachusetts Institute of Technology (United States)
In this talk, we will review the design, processing, and characterization of novel planar infrared chemical sensors. Chalcogenide glasses are identified as the material of choice for sensing given their wide infrared transparency as well as almost unlimited capacity for composition alloying and property tailoring. We show that high-Q chalcogenide glass micro-disk optical resonant cavities can operate in several sensing modes where different molecular species are detected using distinctive yet complementary mechanisms. As a consequence, molecules can be sensed with improved detection sensitivity and specificity. We further illustrate that resonant cavities can also serve as an ideal device platform for cavity-enhanced opto-mechanical interactions, which potentially enables multi-functional molecular manipulation and detection.

Photonic sensors for explosive detection
U. Willer, Clausthal Univ. of Technology (Germany); R. Orghici, P. Lützow, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); W. Schade, Technische Univ. Clausthal (Germany) and Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)
The detection of improvised explosive devices (IEDs) in conflict areas as well as the threat posed on common welfare by terrorist attempts increasingly became focal points of interest in recent years. Novel photonic sensor devices applying photoacoustics and evanescent field spectroscopy in combination with silicon photonics and nano-dimensional waveguides combined with the use of miniaturized lasers such as microchip- and quantum cascade lasers reveal entirely new possibilities for in-situ and real-time diagnostics. Such approaches enable extreme sensitive detection of low-vapor pressure explosives, e.g. TNT (Trinitrotoluene), which is highly toxic and carcinogenic. The detection of this explosive is very difficult due to its extreme low vapor pressure, resulting in concentrations at low ppb levels. Specially engineered receptor films (triphenylene-based ketals) accumulate selectively TNT molecules which are detected very sensitively by evanescent field effects. This opens new possibilities for miniaturized photonic sensor devices, e.g. for applications on robotic platforms. A second photonic sensor device is developed applying photoacoustic spectroscopy. Instead of a conventional photoacoustic cell a simple quartz tuning fork is used as sensor element. Miniaturized laser technology in combination with silicon photonics and fiber optics enables engineering a smart handheld sensor, e.g. for the detection of TATP (tri-acetone tri-peroxide). Impulsive femtosecond laser excitation as new approach for selective multi-species excitation in combination with photoacoustic spectroscopy is also discussed.

Differential spectral imaging with gold nanorod light scattering labels
L. T. Perelman, L. Qiu, E. Vitkin, L. Guo, E. B. Hanlon, I. Itzkian, Harvard Univ. (United States)
Gold nanorods can be used as extremely bright labels for differential
Experimental results on CNT nanostructures will be presented. We will discuss optical and electronic properties that show the feasibility for IR detection. Critical technologies being developed include carbon nanostructure growth, characterization, and spectral properties. The nano-bolometer for MWIR and LWIR bands is under development. The critical technologies provide next generation high performance, high frame rate, and uncooled infrared detectors and arrays. We will discuss detector concepts that will be discussed in this paper. We will discuss recent modeling efforts and the experimental work under way for next generation carbon nanostructures for IR detection. The path forward to demonstrate enhanced IR sensitivity and larger arrays will be discussed.

7945-89, Session 16
Single photon emission from nitrogen delta-doped semiconductors
H. Yaguchi, Saitama Univ. (Japan)

Single-photon emitters are expected to play a key role in the field of quantum information technology, such as quantum cryptography. Isolated isoelectronic traps in semiconductors are promising candidates for single-photon emitters because sharp emission lines with well-defined wavelengths are readily obtained. In this paper, we report single photon emission from individual isoelectronic traps in nitrogen delta-doped semiconductors. We have found there is a remarkable difference in the polarization properties of luminescence for various planes of substrates, and successfully obtained unpolarized single photons by utilized (111) substrate, which are desirable for the application to quantum cryptography.

7945-90, Session 16
Single photon image discrimination
J. C. Howell, C. Broadbent, G. A. Howland, Univ. of Rochester (United States)

In a generalization of 2 state quantum state discrimination, we consider the notion of quantum image state discrimination. Heralded entangled photons pass through amplitude masks. Optical correlators are then used to distinguish both orthogonal and nonorthogonal images in a single measurement event.

7945-91, Session 16
Growth and characterization of low density droplet GaAs quantum dots for single photon sources
S. K. Ha, J. D. Song, J. Y. Lim, Nano Convergence Devices Ctr. (Korea, Republic of); S. Bounouar, F. Donatini, L. S. Dang, J. Poizat, Institut NEEL (France); J. S. Kim, Yeungnam Univ. (Korea, Republic of); W. J. Choi, I. K. Han, J. I. Lee, Nano Convergence Devices Ctr. (Korea, Republic of)

The quantum dot (QD) material systems are promising zero dimensional nanostructures for single photon source devices. We have grown GaAs/AlGaAs QD samples by droplet molecular beam epitaxy (MBE), and rapid thermal annealing (RTA) process is applied to the samples to improve QD emission properties. The droplet epitaxy has advantages over the conventional Stranski-Krastanov (S-K) method in single photon source application. Firstly, GaAs can be selected as QD material with emission wavelength of around 700 nm which is within the optimal detection range of silicon based detector so that highly sensitive and cost effective photon detection is possible. Moreover, the surface density of QDs can be designed to be low to make it more convenient to isolate single QDs, and the surface density level of just a few QDs per μm2 is reproducibly achieved. The cathodo-luminescence (CL) and photo-luminescence (PL) measurements were used to characterize individual QDs. We have identified exciton and biexciton emission peaks from power dependent and time-resolved PL measurements. From CL measurement, the spatial and spectral position of each active QD was found which can be used to fabricate photonic crystal (PC) resonator optimized for each specific QD. The characteristics of single photon emission enhanced by the Purcell effect from QD coupled with PC cavity will be investigated. Also, a novel and rapid nano-patternning technique was developed and demonstrated. In this method, an additional droplet GaAs QD layer grown on top of...
sample is transformed to self-aggregated GaAs cluster layer during RTA process. Each cluster behaves as a small mask which can protect QDs from wet etching to form mesa structure. The decreased etch rate of clusters may be attributed to the formation of protective layer of GaO or GaN on the clusters from ambient gas (N2) during RTA process.

7945-92, Session 16

A solid state ultrabright source of entangled photon pairs


A single semiconductor quantum dot (QD) is a promising system to achieve a solid-state source of single photons or of entangled photon pairs. The main advantage of QD based sources over attenuated classical sources is the possibility to generate exactly one photon for each excitation pulse. However, to be of practical value for quantum cryptography or quantum computing, one needs to efficiently extract and collect the photons emitted by the QD. Controlling the radiative lifetime of a QD in the weak coupling regime (Purcell effect) is a way to make sure that the photons emitted by the QD are funnelled into a cavity mode.

We have fabricated an ultrabright source of entangled photon pairs by deterministically coupling a single QD to a photonic molecule[1]. Polarization independent Purcell effect ensures efficient extraction of each photon of the pair as well as improved fidelity. With a 10 MHz rate of collected polarization entangled photon pairs, corresponding to 0.12 pairs per excitation pulse, the present source is one order of magnitude brighter than any previously existing source.


7945-93, Session 16

Semiconductor integrated sources of quantum light at room temperature

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In the last few years considerable effort has been devoted to the miniaturization of quantum information technology on semiconductor chips including micro-traps for ions and atoms, and quantum-dot based sources of entangled photons. In addition, recent developments in quantum information theory have roused a growing interest in ‘generalized’ states of frequency correlation. Parametric generation in semiconductor waveguides allows room-temperature operation and high emission directivity in the telecom range. In this context, AlGaAs benefits from both high nonlinear susceptibility and a well-mastered growth technique, opening the way to the fabrication of integrated devices. Different geometries of phase matching can be used depending on the researched properties of the two-photon state. We will present our recent results on a microcavity-based source in which a transverse pump beam generates two counterpropagating, orthogonally polarized signal and idler guided photons. The indistinguishability of the photons of a pair is demonstrated via a Hong-Ou-Mandel experiment showing a visibility of 85%. Several features of the device for quantum information applications are discussed, such as the direct generation of polarization-entangled Bell states or the controlled generation of frequency correlated, anticorrelated and uncorrelated two photon states via a proper choice of the spatial and spectral pump beam profile. We will also discuss other phase matching geometries, such as the modal phase matching, leading to an electrically pumped laser diode emitting photon pairs through intracavity parametric fluorescence.

7945-94, Session 16

Ultra-low-noise high-speed single-photon detection using a sinusoidally gated InGaAs/InP avalanche photodiode

N. Namekata, S. Inoue, Nihon Univ. (Japan)

Single-photon detector (SPD) in near infrared is the most important component for the quantum communication technologies, as well as sensing applications that require the measurement of very weak light fields. A practical solution for the near infrared SPD is a gated InGaAs/InP avalanche photodiode (APD), especially a sinusoidally gated InGaAs/InP APD (SG-APD). The SG-APD has a high detection efficiency (DE). Moreover, the SPD can be operated at multi-gigahertz repetition frequency with low afterpulsing probability. However, their dark count probability (DC; 10^-5–10^-6) has been much higher than that (~10^-9) of a superconducting single-photon detector (SSPD). It is challenging to realize that the semiconductor-based SPD has DC comparable with that of the SSPD. The current SSPD has the signal-to-noise ratio (DE/DC) in the order of 10^6. As regards the SG-APD, the DE can be increased to 10%, and therefore the DC must be reduced to less than 10^-7.

Here, we report the performances of the SG-APD operated in a low temperature regime (223 – 183 K), in which the Pd can be reduced, while the afterpulse noise is increased. We investigated whether the SG-APD could achieve low dark count and afterpulsing probabilities, simultaneously, in the low temperature regime. At the operating temperature of 183 K, the DC can be reduced to 2.6×10^-7 with DE of 10% at 1550 nm. Thus the signal-to-noise ratio reaches 4.10^5. Furthermore, the afterpulsing probability is limited to only 3%. The performances of the SG-APD considerably approach those of the SSPD.

7945-95, Session 17

Compact detection module based on InGaAs/InP SPADs for near-infrared single-photon counting up to 1.7 μm

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Nowadays, state-of-the-art InGaAs/InP Single Photon Avalanche Diodes (SPADs) can be successfully employed in many demanding applications that require to detect single photons in the 1 - 1.7 μm wavelength range. However, in order to exploit at best such detectors, it is mandatory to operate them in optimized working conditions, by means of dedicated electronics. Moreover, InGaAs/InP detectors can indeed pioneer much broader application fields (from biotechnologies to physics, from communications to integrated circuit testing) only if the associated circuity provides very good overall performance and can be easily tailored for each specific application. We present design and experimental characterization of a high-performance compact electronic detection module able to operate at best InGaAs/InP SPADs. The module contains a pulse generator for gating the detector, a front-end circuit for avalanche sensing, a fast circuity for detector quenching and resetting, a counting electronics, and some sub-circuits for signal conditioning. The pulse generator is able to turn-on or off the detector with sub-nanosecond transitions and with user selectable pulse amplitude, time-duration, and repetition rate. The fast quenching circuit efficiently reduces the amount of charge carriers flowing through the device, thus minimizing the afterpulsing effect, hence the dark-counting rate, while low time-jitter front-end electronics detects avalanche pulses with high timing precision. The avalanche pulses counter and the ancillary electronics complete the module. Finally, we describe experimental measurements that prove the state-of-the-art performance, both on the bench and on-field applications.
Single-photon detection in time-of-flight-depth imaging and quantum key distribution

G. S. Buller, R. J. Collins, G. J. Clarke, N. J. Krichel, A. McCarthy, R. E. Warburton, F. Izdebski, R. H. Hadfield, Heriot-Watt Univ. (United Kingdom)

Single photon detectors play an increasing role in emerging application areas in quantum communication and low-light level depth imaging. The single-photon detector characteristics have a telling impact in system performance, and this presentation will examine the role of single-photon detectors in these important application areas. We will discuss the experimental system performance of GHz-clocked quantum key distribution systems focussing on issues of quantum bit error rate, net bit rate and transmission distance with different detector structures, concentrating on single-photon avalanche diode detectors, but also examining superconducting nanowire-based structures. The quantum key distribution system is designed to be environmentally robust and an examination of long-term system operation will be presented. The role of detector performance in photon-counting time-of-flight three-dimensional imaging will also be discussed. We will describe an existing experimental testbed system designed for kilometre ranging, and recent experimental results from field trials. The presentation will investigate the key trade-offs in data acquisition time, optical power levels and maximum range. In both examples, experimental demonstrations will be presented to explore future perspectives and design goals.

SPAD electronics for high-speed quantum communications

J. C. Bienfang, A. Restelli, A. Migdall, National Institute of Standards and Technology (United States)

We discuss high-speed electronics that support the use of single-photon avalanche diodes (SPADs) in gigahertz single-photon communications systems. For InGaAs/InP SPADs, recent work has demonstrated reduced afterpulsing and count rates approaching 500 MHz can be achieved with gigahertz periodic-gating techniques designed to minimize the total avalanche charge to less than 100 fC. We show that one such technique based on detecting the difference between adjacent gate signals can obscure current flowing in adjacent gates, an effect that is akin to afterpulsing and that can limit the maximum useful count rate of the detection system. To establish a connection between afterpulsing in the high-speed gating regime and that observed with more conventional techniques, we present measurements of afterpulse probabilities in an InGaAs SPAD, using the traditional double-gate technique, for recovery times from 150 ns down to 6.4 ns with sub-nanosecond gate pulses and total charge flows of about 50 fC, which are comparable to those observed in high-speed gating schemes. For Si SPADs, we demonstrate the benefits of improved timing electronics that enhance the temporal resolution of Si SPADS used in a free-space quantum key distribution (QKD) system operating in the GHz regime. We show that the effects of count-rate fluctuations induced by daytime turbulent scintillation are significantly reduced, benefitting the performance of the QKD system. Finally, we discuss the design and development of FPGA-based time-tagging electronics suitable for high-resolution, high-count-rate detectors.

Advanced single photon counting instrumentation for SPADs

A. Tosi, A. Dalla Mora, Politecnico di Milano (Italy); A. Della Frera, Micro Photon Devices S.r.l. (Italy); F. Acerbi, A. Bahgat Shehata, F. Zappa, Politecnico di Milano (Italy)

In order to acquire faint optical signals at the single-photon level, Single-Photon Avalanche Diodes (SPADs) are exploited thanks to their extreme performance. For many demanding applications, there is a growing need to operate such detectors with advanced instrumentation, specifically designed for efficiently exploiting the best performances in terms of sensitivity, timing resolution, fast-gating capabilities, etc. To this purpose we designed, tested and employed an ultra-fast pulse generator, a fast gated-counter and a wide-band delayer.

The pulse generator is designed for gating SPADs with ultra-fast transition times (less than 100 ps), when it is needed to avoid unwanted photons that either precede or follow the useful signal. It can be easily integrated into many experimental setups since it can work either with internal or external trigger, it has programmable gate width (200 ps - 500 ns), voltage pulse amplitude (2 - 8.5 V) and repetition rate (40 Hz - 133 MHz).

The gated counter acquires photons in well-defined time windows, programmable from 100 ps up to 10 ns. When operating with short windows, it can replace expensive timing boards since it can acquire burst of single-photons at up to 100 Mcounts/s.

Finally, a very flexible and handy wide-band delayer can provide programmable delays, ranging from 25 ps up to 6.4 ns with 25 ps step. The bandwidth is 1 GHz and it can be used to synchronize various signals (in any standard) for many different experimental setup conditions. All the described instruments are remote controlled via USB connection.

Planar silicon SPADs with improved photon detection efficiency

A. Gulinatti, F. Panzeri, I. Rech, Politecnico di Milano (Italy); P. Maccagnani, Consiglio Nazionale delle Ricerche (Italy); M. Ghioni, S. D. Cova, Politecnico di Milano (Italy)

Remarkable advances in semiconductor technology as long as improvements in device design resulted in today’s Silicon Single Photon Avalanche Diodes (SPADs) that are widely used in many demanding applications thanks to their excellent performance. However a lot of work is still be done in order to simultaneously meet three requirements crucial in a large number of applications, i.e. high Photon Detection Efficiency (PDE), good timing resolution and suitability for the fabrication of arrays. Currently available devices can be essentially divided in two categories: thin and thick SPADs. While the formers are characterized by an excellent timing resolution (<35ps), the reduced thickness of the absorption layer strongly limits their PDE for wavelengths higher than 800nm. Conversely, thick SPADs achieve good PDE even in the near infrared range, but at the expense of a severe worsening in timing resolution. Moreover, their fabrication technology is inherently non-planar, impairing the fabrication of arrays of detectors.

In this paper we will report on our advances on the design and fabrication of a new planar SPAD capable of overcoming the limitations outlined above. While a 10µm thick epitaxial layer allows for the absorption of a significant fraction of photons even at the longer wavelengths, a proper electric field design limits the breakdown voltage value and the timing jitter; biased guard rings are also included to prevent edge breakdown. Preliminary results show that the new devices can attain a PDE as high as 30% at a wavelength of 800nm, while keeping photon detection jitter below 100ps.
Controlling light emission in nanostructures

A. Scherer, S. Walawalkar, A. Homyk, California Institute of Technology (United States)

The technology to fabricate sub-10nm structures has enabled us to define light emitting devices with interesting new properties, and allowed us to control the emission of photons with geometry and the introduction of strain. Here we show our efforts to explore the opportunities as we shrink the sizes of light-emitting devices down to 2 nm.

Plasmonic, semiconductor, and dielectric building blocks for nanophotonics

M. L. Brongersma, Geballe Lab. for Advanced Materials, Stanford Univ. (United States)

Metamaterials and nanophotonic devices are most commonly constructed from metallic (i.e. plasmonic) nanostructures. However, recent research has begun to also exploit the optical resonances of high-permittivity semiconductor and dielectric nanostructures to realize similar optical functionalities. In this talk, I will illustrate the use of plasmonic, semiconductor, and dielectric nanostructures in a variety of applications (nanoscale and thermal sources, high-speed modulators, and detectors) and discuss their relative strengths and weaknesses.

Acoustic metamaterials based on the homogenization of periodic scatterers

J. Sanchez-Dehesa, D. Torrent, Univ. Politécnica de Valencia (Spain)

A review of the recent advances on the topic of acoustic metamaterials based on the homogenization of periodic arrangements of sonic scatterers will be presented. Particular emphasis will be given in the application of these structures for acoustic cloaking and other acoustic devices like gradient index sonic lenses and radial sonic crystals. Also, we will report experiments demonstrating the physical realization of cylindrical mass anisotropy.

Bibliography

of photonic crystal cavities in GaInP slab waveguides containing InP quantum dots. We measure quality factors in excess of 7,500 and demonstrate for the first time semiconductor quantum dots coupled to photonic crystal cavity modes operating in the visible spectrum. Using time resolved micro-photoluminescence we demonstrate full control over the spontaneous emission rate of the quantum dots. By controlling the sample temperature the exciton emission is tuned into resonance with the fundamental cavity mode, reducing the exciton lifetime by a factor of ~8. The dependence of the lifetime on the energy detuning between the quantum dot and the cavity mode reflects the spectral linewidth of the cavity mode, confirming that the spontaneous emission rate is due to the Purcell effect.

InP quantum dots embedded in GaInP provide an alternative to the more established InAs/GaAs system and have the significant advantage of emitting in the red spectral range, where the detection efficiency of commercial silicon photodetectors is highest. This work is demonstrated in power dependent measurements, where we observe a ten times higher count rate at saturation from InP quantum dots compared with InAs quantum dots. This makes InP quantum dots an attractive proposition for implementation in optical quantum information processing and free space quantum communication applications.

7946-08, Session 2

Photonic crystal cavities for efficient thermophotovoltaics: exceeding Planck’s free-space energy transfer rate

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Thermophotovoltaic (TPV) systems, including solar photovoltaic cells, suffer from low over-all conversion efficiency relative to the cost of fabrication except when relatively high operating temperatures are used. Spectral compression in TPV devices using photonic crystals (PhCs) has been studied extensively as a way to eliminate the spectral mismatch between the emitter and the photovoltaic cell. However, even if perfect spectral compression could be achieved, Planck’s blackbody radiation law still limits how much energy can be extracted from the emitter. Overcoming this limit is critical to pushing the efficiency of solar photovoltaic devices beyond the Shockley-Queisser limit for a single-junction photovoltaic.

While evanescent energy transfer has gained much recent interest, the major drawbacks in those scenarios are not only the extremely challenging separation distances at which such coupling takes place from an engineering point of view, but also that at such distances the receiving PV cell would be heated excessively and thus experience a rapid decline in conversion efficiency. In this work, we theoretically demonstrate energy transfer between two resonantly coupled PhC cavities that exceeds Planck’s free-space limit, using simulations of a system of 1D PhC cavities calculated with the finite-difference time-domain technique. We will discuss how these results can be extended to 3D PCs, the remaining design hurdles to be overcome, and possible schemes for integrating PhC nanostructures with current photovoltaic technology.

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7946-09, Session 3

Diamond nanophotonics and quantum optics

M. Loncar, T. M. Babinec, B. M. Hausmann, J. T. Choy, Y. Zhang, Q. Quan, Harvard Univ. (United States)

Nitrogen-Vacancy (NV) color centers in diamond have emerged as promising solid-state platform for realization of scalable systems for quantum information processing. Here we present nanoscale optical devices that engineer optical properties of NV centers. In particular, we describe a bright, room temperature, source of single photons based on diamond nanowires embedded with NV centers. NV centers were defined using ion-implantation of nitrogen in ultra-pure diamond substrates. We also describe the integration of NVs with other nanophotonics devices, including metallic nanostructures and photonic crystal nanocavities, in order to further increase photon production rate and collection efficiency of emitted photons.

7946-10, Session 3

Nonlinear optics in photonic crystal nanocavities: from light sources to quantum photonic interfaces

J. Vuckovic, K. Rivoire, S. Buckley, A. Majumdar, G. Shambat, Stanford Univ. (United States)

We have been developing photonic interfaces between infrared and visible wavelength ranges, by employing enhanced nonlinear optical processes in photonic crystal cavities in GaP or GaAs. This is critical for a variety of applications, including building IR detectors on silicon platform, light sources at wavelengths that are difficult to access with existing lasers, and photonic quantum interfaces between the fiber-optic networks and quantum emitters.

7946-11, Session 3

Silicon membrane photonic crystal microcavities for the mid-infrared

R. Shankar, I. Bulu, M. Loncar, Harvard Univ. (United States)

The mid-infrared wavelength range (2-20 µm) has a wide range of applications, including trace gas sensing, thermal imaging, chemical bond spectroscopy, and free-space communications. However, it is a very underdeveloped range in terms of passive photonic elements, despite the recent commercial availability of stable, high-power, room-temperature laser sources, in the form of quantum cascade lasers (QCLs), and photodetectors. In order to make on-chip platforms for mid-infrared wavelengths, we need waveguides, resonators, splitters, etc. Silicon is an ideal candidate material for these photonic elements, having low losses (less than 2 dB/cm) for wavelengths between 1.2-8 µm, and also allows us to capitalize on the extensive nano and micro-fabrication capabilities available for silicon, as well as electronics compatibility. Here, we present the design, fabrication, and experimental characterization of photonic crystal microcavities on a Si membrane platform. L3 photonic crystal cavities with resonances centered around 4.4 µm were designed using finite difference time domain software, with theoretical quality factors of about 5x10^3. E-beam lithography and reactive ion etching were used to define the structures in the silicon device layer of a 500-nm thick silicon-on-insulator (SOI) wafer, and then a HF undercut was performed to remove the insulator layer and produce air bridged photonic crystal cavity structures. Resonant scattering techniques were used to characterize these cavities, with measured quality factors of around 2x10^4. This represents the first demonstration of mid-infrared photonic crystal cavities in silicon, enabling a wide range of cavity-based on-chip applications, especially in trace gas sensing.
Optical cavity is one of the most used fundamental structures for many applications, such as in lasers, in studies of cavity quantum electrodynamics (QED), and in opto-mechanical phenomena. The basic requirements for the cavity used in all these studies are high quality factor (Q) and small mode volume. The coupling strength between the optical mode and an atom (in cavity QED), a gain medium (in a laser) or a mechanical resonator (in a opto-mechanical resonator) is also a big concern. In this paper we report a realization of small volume optical cavity mode with high Q. A prominent feature of the structure is that most of the mode volume stands in the free space and is readily accessible by particles or other structures, while in many of the current on-chip cavities (photonic crystal or micro-ring resonator based) only an evanescent tail of the field is accessible. A much stronger coupling between the particle and our optical cavity mode can be expected, which is important in applications such as cavity QED, optical tweezers, etc. The structure is composed of two identical groups of dielectric grooves. The dielectric grooves in each group are of the same thickness and are placed in the same plane, but with the lateral positions and widths determined through a stochastic optimization process using Q or Q/V as a fitness function. Cavities of Q~600,000 and mode sizes smaller than the free space wavelength can be designed, as we will discuss in details in the paper.

Optical microcavities clad by transparent conductive oxides

O. Senlik, L. Tang, P. Tor-ngern, T. Yoshie, Duke Univ. (United States)

Optical microcavities are building blocks of various nanophotonic devices such as microlasers, optical modulators, optical switches, single photon sources and optical sensors in consequence of their high quality (Q) factors, smaller mode volumes and fewer optical modes. Considering practicality and on-chip integration of these devices, it is required to integrate metal electrodes in these cavities for current injection and electric field applications. Conventional metals used as electrodes such as gold and silver deteriorate the Q factors due to their large absorption coefficients. In the past current injection microcavity designs, indirect current injection approach is used to save the resonance at the expense of low thermal conductance, high electrical resistivity and large leakage current.

In our work, we propose direct current injection approach by using transparent conductive oxide (TCO) materials as electrodes. Since the imaginary part of the permittivity of TCO materials such as indium tin oxides (ITO) is small, it is possible to preserve high resonator Q factors and implement direct current injection that alleviates the complexities mentioned above. Four types of optical microcavities - microdisk, 1-D photonic crystal nanobeam, 2-D photonic crystal slab and 3-D photonic crystal clad by planar ITO are designed and analyzed by both perturbation theory and 3D FDTD analysis. It is confirmed that Q factors obtained by both methods agree well and they are sufficiently high for lasing action. The developed perturbation theory analysis is a powerful tool to predict the Q factor of absorptive microcavities and reduces computational cost. The developed high-Q microcavities would be useful for many compact optoelectronic devices such as microlasers, modulators, switches, logic gates, photodiodes, and single photon sources.

Theory of nanophotonic light trapping for solar cell applications

S. Fan, Z. Yu, A. Raman, Stanford Univ. (United States)

We present a theory to understand the fundamental limit of light trapping enhancement in solar cells. We show that the conventional limit for absorption enhancement can be overcome, over broad bandwidth and over all angles, through nanophotonic light confinement.

Finite difference simulation of thermally tuned hexagonal photonic crystals

S. R. Newman, R. C. Gauthier, Carleton Univ. (Canada)

Thermal tuning of hexagonal photonic crystals by absorption of laser energy is examined through finite difference numerical simulation. The photonic crystals are patterned in the device layer of the silicon on insulator (SOI) platform. The thermal equation which include contributions from laser absorption gain, conduction loss, and radiation loss, are combined to obtain a heat balance equation. This governing equation is modeled using a thermodynamic finite difference computation engine. To ensure the stability of the thermal model within the transient regime the velocity of heat propagation is calculated and included as aCourant factor controlling the coarseness of the discretization grid and time step interval. The thermal distribution obtained from the numerical simulation, combined with the thermo-optic effect, can be used to alter the initial dielectric distribution of the device layer. The integration of the change in refractive index into the existing dielectric enables the thermal effects to be included into a standard optical finite difference time domain (FDTD) engine. Through the implementation of the optical and thermal simulation tools, the laser thermal tuning of the band gaps and localized states of hexagonal photonic crystals will be explored. The temperature dependence of the central wavelength and quality factor of the localized states will be calculated and used in the design of active photonic crystal based filter device configurations.

Modeling of the topological surface states in 2D photonic crystals

N. Malkova, G. W. Bryant, National Institute of Standards and Technology (United States)

There is a fast growing interest in topological surface states in photonic crystals. The characteristic feature of the topological surface states is in their gap-less band spectrum which inhibits back scattering, allowing a dissipation-less propagation of the photons trapped on the surface which makes the topological surface states very attractive for many applications. In this paper we model the topological surface states in 2D photonic crystals. We study the square lattice of the Si rods embedded in vacuum or in air. The lattice is doped by the s-type and p-type defects periodically arranged. Using the tight-binding model we show first that such a complex lattice can support the topological surface states. We next demonstrate these surface state using Finite Difference Time Domain technique and investigate their transport characteristics.

Band structure properties of mixed photonic crystals arranged in digital alloy format

J. Lee, D. Kim, H. Jeon, Seoul National Univ. (Korea, Republic of)
We have investigated band structure properties of photonic crystal (PC) digital alloys, which are semi-disordered mixed PCs. PC superlattices have been studied previously in the optical regime, but digital alloys, or short-period superlattices, have not been explored yet due to the difficulty in preparing such structures. We have realized PC digital alloys that operate in the microwave regime and studied their photonic properties. The PC digital alloys are prepared by alternately stacking two kinds of PC sub-systems; each composed of either alumina or silica spheres of equal diameter of 5 mm. Because they are configured in superlattices, the PC digital alloys possess an additional periodicity in the [111] direction. We varied the superlattice periodicity and examined the band gap properties of the PC digital alloys. When the superlattice period is short, PC digital alloys behave similarly to the random alloys of the same mixing composition as far as their band gap properties are concerned. As the superlattice period increases, however, additional mini band gaps appear. We also calculated band structures of the PC digital alloys using three-dimensional plane wave expansion method. In order to obtain the exact photonic band structures of the PC digital alloys, we used the actual unit cells of digital alloys (rather than the conventional unit cell of diamond lattice) in the super-cell calculations. Calculated band structures indeed exhibited the additional mini band gaps, their spectral positions in agreement with the experimental observations. The results confirm the analogy between the photonic and electronic crystals.

Theoretical analysis of the order to disorder phase transition in random photonic crystals
S. Hamada, Keio Univ. (Japan); S. Takeda, Keio Univ. (Japan) and Ecole Centrale de Lyon (France); P. Viktorovitch, Ecole Centrale de Lyon (France); M. Terakawa, M. Obara, Keio Univ. (Japan)

We present the effect of structural randomness introduction into ordered photonic crystals on the behavior of Bloch-mode and defect modes. In order to induce strong localization of optical waves in nanostructures, there are two kinds of schemes: to utilize the defect mode in photonic crystals and Anderson localization modes in random structures. Recently, the intermediate state between the two above structures has been remarkably noticed. Despite its potential advantage, however, the modal characteristic of this merged structure, random photonic crystals, has not been revealed systematically yet. Our aim is to figure out the appropriate degree of randomness to induce highly localized modes. We investigate an impulse response of the random photonic crystals by using 2-dimensional FDTD method. We array air holes with triangular lattice shape into silicon-substrate-based materials, and set a defect area in the center. The randomness is introduced into the structure by randomly dislocating the positions of the air holes. After the impulse illumination, we acquire the temporal evolution of the electric amplitudes over the system. By employing DFT on the sampled signals, we achieve the frequency spectrum and Q factors of the modes. We confirmed the optical “phase transition” of the system: with the increase of the randomness, the propagating Bloch-modes become localized and achieve higher Q factors. Slight spectrum shifts are also confirmed. The confinement efficiency of optical waves in the photonic crystals is greatly improved as well.

Colloidal co-assembly route to large-area high-quality photonic crystals
J. Aizenberg, B. Hatton, L. Mishchenko, Harvard Univ. (United States)

Whereas considerable interest exists in self-assembly of well-ordered, porous “inverse opal” structures for optical, electronic, and (bio)chemical applications, uncontrolled defect formation has limited the scale-up and practicality of such approaches. Here we demonstrate a new method for assembling highly ordered, crack-free inverse opal films over a centimeter scale. Multilayered composite colloidal crystal films have been generated via evaporative deposition of polymeric colloidal spheres suspended within a hydrolyzed silicate sol-gel precursor solution. The co-assembly of a sacrificial colloidal template with a matrix material avoids the need for liquid infiltration into the preassembled colloidal crystal and minimizes the associated cracking and inhomogeneities of the resulting inverse opal films. We demonstrate that this co-assembly approach allows the fabrication of hierarchical structures not achievable by conventional methods, such as multilayered films and deposition onto patterned or curved surfaces, and can be transformed into various materials that retain the morphology and order of the original films. We show that colloidal co-assembly is available for a range of organometallic sol-gel and polymer matrix precursors, and represents a simple, low-cost, scalable method for generating high-quality, chemically tailorable inverse opal films for optical applications.

Electrically-driven emission from 3D photonic crystal devices formed by selective area MOVPE
P. V. Braun, E. C. Nelson, Frederick Seitz Materials Research Lab. (United States) and Univ. of Illinois at Urbana-Champaign (United States); K. P. Bassett, Univ. of Illinois at Urbana-Champaign (United States); X. Li, Beckman Institute for Advanced Science and Technology (United States) and Univ. of Illinois at Urbana-Champaign (United States)

Photonic crystals provide unprecedented control over light emission, absorption and propagation, which has led to the proposal of a large variety of optoelectronic devices. Three-dimensional photonic crystal devices with electronic functionality have remained elusive, as fabrication of three-dimensional, nanostructured materials remains complex. Numerous techniques have been demonstrated to fabricate 3D photonic crystals, including colloidal crystallization [1, 2], phase mask and multibeam interference lithography [3, 4], direct laser writing [5], photolithography [6, 7] and wafer bonding [8]. Most of these techniques result in amorphous or polycrystalline material which does not possess the required electronic properties for application in optoelectronics. There are a number of elegant techniques which make use of single crystal semiconductor substrates [7-9], however they tend to require elaborate, slow processing, are limited in what photonic crystal structures may be created, and have not demonstrated electrical functionality. In this work we demonstrate a method of forming 3D photonic crystals from single crystal III-V semiconductors by metal-organic vapor phase epitaxy (MOVPE). We employ a template-based fabrication method and grow semiconductor material to fill the structure using a form of selective area epitaxy. The epitaxial growth process (originating at the substrate, in contrast to conformal growth) is much the same as the growth of planar III-V devices in that light emitting layers (e.g. quantum wells), cladding layers, electrically doped layers, etc may all be grown in a single process. Thus the layers of an optoelectronic device may be defined by the MOVPE growth parameters while the photonic crystal structure is simultaneously imparted to the material using the 3D template. To demonstrate the potential of this technique we have fabricated vertically emitting LED’s with embedded InGaAs QW’s. The fundamental behaviors of this growth technique will be discussed, including prevention of polycrystalline nucleation, doping and fabrication of light-emitting heterostructures. Finally, possible future directions in photonic crystal research using 3D selective area epitaxy will also be discussed.

References
7.946-21, Session 5

Woodpile photonic crystal of various crystal orientations

L. Tang, S. Su, T. Yoshiie, Duke Univ. (United States)

Three-dimensional (3D) photonic crystal is a unique platform that molds light in a 3D space via three-dimensional Bragg reflection. Recent progress in 3D photonic crystal fabrication enables one to achieve high quality factor in 3D nanocavities experimentally. However, the layer-by-layer method produces woodpile photonic crystals with (001) surface plane only where z direction is along woodpile layer stacking. The development of photonic crystal with diverse crystal orientations would enhance the functionality of 3D integrated optics and benefit research on surface Bloch modes. In this study, we fabricate woodpile photonic crystals with a variety of crystal orientations and surfaces, including (110), (001), (100) and (010). The first method studied is the two-top etching technique, with which 2D patterns are defined on a semiconductor wafer surface and the etchings are made along and -<101> directions. The fabricated woodpile has (110) and (001) photonic crystal surfaces. This method can be modified so that woodpiles with arbitrary surface in (m0n) plane are defined via etching toward and -<m0n> directions where m and n are integers. The second method is the one-top, one-side method that defines one pattern on a wafer surface and the other on a wafer side facet. The etching direction is vertical to each surface plane. The method is applied to create silicon and GaAs woodpiles with (100) and (010) surface planes.

7.946-22, Session 5

On the physics of the darkest material: 3D mesh-like nanostructure

S. Lin, Rensselaer Polytechnic Institute (United States); M. Hsieh, National Taiwan Normal Univ. (Taiwan)

We describe, here, a random network of vertically aligned carbon-nanotube (VA-CNT) structure that minimizes optical reflection to less than 5 x 10^-4 - the lowest ever been reported. We further show that, in an extremely random regime, optical reflectance of our VA-CNT is nearly dispersion-independent and does not follow the well-known wavelength scaling behaviours. We will attempt to describe the physical origin of this surprising discovery and make connection to the nature of 3D nano-network. We will further illustrate a nearly perfect blackbody radiation from such a 3D photonic nanostructure.

7.946-23, Session 6

Flatland metamaterials with graphene

A. Vakil, N. Engheta, Univ. of Pennsylvania (United States)

Graphene, a single layer of carbon atoms, possesses an optical conductivity function that depends on the temperature, frequency, charged particle scattering, and the chemical potential. By varying the chemical potential through electric field biasing, one can tune the graphene conductivity. We show, through a series of theoretical studies involving numerical simulations, that inhomogeneous, nonuniform distribution of conductivity across a single sheet of graphene may help us manipulate, redirect and/or scatter surface-plasmon polariton (SPP) along the surface of the graphene. The manipulation and tailoring of SPP on the graphene provides the possibility of ‘flatland’ metamaterials and transformation optics at the IR wavelengths. We theoretically explore the possibility of having waveguiding, scattering, and lensing phenomena on this ‘zero-thickness’ platform, phenomena that could give rise to ‘zero-thickness’ optical edge wave, waveguides within waveguides, and waveguide splitters and combiners all within a single sheet of graphene. In this talk, we will present some of our results on this topic.

7.946-24, Session 6

Transforming light with tunable and active metamaterials

V. M. Shalaev, A. V. Kildishev, S. Xiao, V. P. Drachev, X. Ni, G. Nai, Z. Jacob, J. Kim, A. Boltasseva, E. E. Narimanov, Purdue Univ. (United States)

Loss-free and active metamaterials can enable a new powerful paradigm of engineering space for light with transformation optics, leading to a family of new applications ranging from a planar hyperlens to optical black hole and to new quantum-optical devices. The recent progress in this field will be reviewed.

7.946-25, Session 6

3D invisibility cloaks at optical frequencies

T. Ergin, N. Stenger, Karlsruhe Institute of Technology (Germany); J. C. Halimeh, Max-Planck-Institute for Quantum Optics (Germany) and Ludwig-Maximilians-Univ. (Germany); M. Wegener, Karlsruhe Institute of Technology (Germany)

In this contribution, we review our latest work on three-dimensional cloaking utilizing the “carpet cloak” (or “ground-plane cloak”) scheme. Here, a bump in a metallic carpet is rendered invisible to an observer by adding a nanostructured metamaterial cloak on top. As a result, the observer again sees a flat metal mirror. In our case, the metamaterial consists of a polymeric woodpile photonic crystal that is used in the long-wave limit. The filling fraction of the woodpile is changed locally to give rise to a tailored refractive-index distribution. This distribution is derived in the framework of transformation optics using quasiconformal mapping. We characterize the three-dimensional cloak by optical bright-field and dark-field microscopy using unpolarized light from an incandescent lamp. A cone of light with a full opening angle of 60 degrees in three dimensions is sampled. We observe a bandwidth of nearly one octave at optical wavelengths. Furthermore, we provide numerical ray-tracing calculations which simulate the complete experimental setup within ray optics and the carpet cloak within the effective-medium limit. We find good qualitative agreement between experimental results and calculations. Ongoing work in our group aims at bringing the three-dimensional carpet cloak even into the visible regime.

7.946-26, Session 6

Coupling in complex plasmonic nanostructures and metamaterials

H. W. Giessen, Univ. Stuttgart (Germany)

No abstract available

7.946-27, Session 7

Broadband circular polarizer formed by stacked plasmonic metasurfaces

A. Alu, Y. Zhao, The Univ. of Texas at Austin (United States)

Control and detection of the polarization state of light is fundamental in several optical and photonic applications, and it is one of the relevant functionalities that distinguish the human vision system (which cannot
detect polarization information) from several other biological species. Although linear polarizers are quite easily realized, and they may work over broad range of frequencies, detection of circular polarization is more challenging, since it is inherently based on phase detection, and it may be usually performed over a limited range of frequencies using classic quarter-wave plate technology. However, biological species can detect circular polarization information over much broader bandwidths and they are able to use this information for orientation, signaling and defense. It would be relevant to develop analogous functionalities in a man-made photonic system.

Recent ideas involving plasmonic metamaterials have been put forward to enhance the overall bandwidth of operation of quarter-wave plates. However, the currently proposed metamaterial geometries are inherently complex to realize and are difficultly scalable beyond the near-infrared frequencies. Here, we show how by properly stacking lithographically printed plasmonic metasurfaces with simple patterns may provide large extinction ratios for the detection of circular polarization, combined with broadband operation and simplicity of design and realization. In our talk, we will discuss in detail the physical modeling of this novel metamaterial geometry, the fundamental advantages and ultimate limitations of this approach, and we will discuss the exciting possibilities that such geometries may provide in realistic configurations.

7946-28, Session 7
Enhanced transmission through deep subwavelength apertures using metamaterials
E. Özbay, Bilkent Univ. (Turkey)

We obtained high transmission enhancement factors through a subwavelength aperture by placing connected split ring resonators in the vicinity of the aperture. We experimentally show higher than 70000-fold extraordinary transmission through a deep subwavelength aperture with an electrical size of l/31-1/12 (width/length), in terms of the operational wavelength.

7946-29, Session 7
Controlling ultrafast light with dispersive metamaterials
D. P. Brown, UES, Inc. (United States); A. M. Urban, Air Force Research Lab. (United States)

Because metamaterials possess strong resonances, a strong group delay dispersion (GDD) is also possible, which is an important parameter for ultrafast laser pulses. A metamaterial design was optimized to create a large GDD near a central wavelength of 810nm. Then a multiphoton intrapulse interference phase scan (MiIPS) technique was used to measure the GDD directly over the bandwidth of an ultrafast laser. We found GDD values were an order of magnitude larger than for dispersive optical glass three orders of magnitude thicker. Near a wavelength of 810nm the GDD was about -2000fs2 for our design that was one micron thick. A 3mm thick piece of Schott N-SF5 glass only had a GDD of about 500fs2, which is consistent with a Cauchy model for this type of glass. Finally, we explored ways that dispersive metamaterials can shape an ultrafast pulse of light shorter than 20fs. Large dispersion values spread a short pulse, and large negative dispersion values can compress a long pulse if the nonlinear phase in the pulse matches the GDD in the material. In our metamaterial some oscillations existed in the GDD properties that caused non-trivial changes to our ultrafast pulses.

7946-30, Session 7
Inverting scattered fields for sub-wavelength resolution using negative index materials
M. A. Fiddy, The Univ. of North Carolina at Charlotte (United States); Y. Zhang, Nanyang Technological Univ. (Singapore)

Pendry’s paper (PRL 85 p3966) in 2000 indicated that negative refraction would provide infinite resolution in principle, if a negative index metamaterial could be made that was virtually lossless and its index approached precisely $n = -1$. To achieve sub-wavelength resolution in practice, Pendry’s perfect lens may need rather thin objects located extremely close to the negative index material and losses greatly affect performance; we present a model for what high spatial frequency information can be obtained. We assume the object has finite thickness and expect multiple scattering and coupling between evanescent and propagating waves will occur inside it. The field scattered by an object can is only well approximated by the product of the incident wave with a transmission function (the first Born approximation) for very weak scatterers. This is an increasingly poor approximation as the dimensions of the scattering features constituting the object reduce in size and become subwavelength in nature. Subwavelength resolution imaging therefore has two significant problems. The first is to determine the relationship between the field in the object domain and the scatterer one wishes to image. The second is to understand how to make measurements in the image domain from which the structure of the object can be computed. This classic inverse problem is exacerbated by the interaction of a detector with the strongly resonant negative index lens and the associated surface waves that penetrate and overlay parts of the image domain. We present a procedure for recovering subwavelength index fluctuations from measured data.

7946-31, Session 7
Infrared metamaterial design using derivative-free numerical optimization

In this work, we characterize optical metamaterials with full-field electromagnetic (FDTD) simulations and convert the output to scalar valued objective functions. Evolution of the device design is then cast as a minimization problem in parameter space, which we address using gradient descent and a derivative-free, nonlinear mesh adaptive search technique. We apply these numerical optimization methods, in combination with full-field electromagnetic simulations, to tailor the broadband spectral response of metamaterials to have predetermined resonances. This technique is used to design split-ring resonator “notch filters”, with narrow pass bands across the near to mid infrared spectrum. The results of both search techniques are compared and the derivative-free technique is found to be a more robust and efficient search algorithm. The tunability of the corresponding line width at the pass band as well as percent change in reflectivity are analyzed and the results are compared with those from traditional parameter sweeps. Optimized designs are presented which have a 45% change in reflectivity at the pass band and corresponding line widths of ~90 meV.

7946-32, Session 8
Low loss and broadband hollow-core photonic crystal fibers
F. A. Benabid, Y. Wang, Univ. of Bath (United Kingdom)

We report on the latest developments on hollow-core photonic crystal fibers that ensure both low optical transmission loss and ultra-broad optical bandwidth.
Novel aspects of pulse propagation in photonic crystal fibers
S. P. Stark, A. V. Podlipensky, P. S. Russell, Max-Planck Institute for the Science of Light (Germany)

In this talk we summarize our latest results on pulse propagation in solid-core silica-air photonic-crystal fibers (PCFs). These fibers confine light by means of a hexagonal array of hollow channels (a photonic crystal cladding) surrounding a solid glass core [1]. They have high designability, and can be tailored to have unusual linear [2] and nonlinear properties [3,4]. For example, they can exhibit two closely lying zero-dispersion wavelengths (ZDWs) in the visible spectral range [5]. We will discuss the various pulse propagation regimes that arise at different wavelengths within the anomalous dispersion region. Broad spectra form at low threshold power, with high conversion efficiencies into the UV and near-IR spectral ranges. For certain input conditions, inter-solitons collisions occur, which can additionally enhance the energy conversion.

In contrast, the highly nonlinear interaction between intense light and the core material can be used to modify the temporal characteristics of the optical field [6]. We demonstrate the synthesis of a train of sub-50 fs pulses, generated by an uncompensated chirp during pulse breakup. The temporal spacing between these pulses can be tuned by varying the input power, at repetition rates in the THz.

The photonic crystal cladding prevents interactions between the guided light and the surrounding environment, enabling the realization of robust, axially-varying PCFs [7]. Influenced by a continuous change of linear and nonlinear properties, unexpected processes emerge. We show that by an appropriate cascading of mechanisms, the blue spectral edge of a broad-band supercontinuum can be extended into the deep-UV. In addition, solitons respond strongly to a changing dispersion landscape, transferring energy to dispersive waves in the UV and IR.


Selective filling of metals into photonic crystal fibers
R. Spittel, A. Schwuchow, S. Brückner, K. Schuster, J. Kobelke, H. Bartelt, Institut für Photonische Technologien e.V. (Germany)

We report on our work on the selective filling of single holes of various photonic crystal fibers (PCFs) with metals (e.g. gold). To prepare the fibers, we have applied a combination of selective hole blocking technique with UV-adhesive and subsequent hole collapsing in a filament furnace. By using a high pressure cell with pressures of almost 200 bar and temperatures of over 1100°C we could achieve filling lengths of several centimeters for hole diameters in the sub-micron scale. This means the so processed fibers contain metal wires with aspect ratios greater than 100,000.

We analyzed the fiber samples with respect to their transmission spectra and polarization dependent coupling between the fundamental fiber mode and the first higher order surface plasmon polaritons. Furthermore, the measured near field patterns will confirm the coupling of the light power from the fiber core to the metal surface at the phase matching points. We also studied the influence of the temperature on these resonance wavelengths.

Finally, the experimental results are compared with semi-analytical calculations of a perfect cylindrical gold wire embedded in fused silica and full vectorial finite element simulations of the real wire with an elliptical cross section. The simulations and experiments show that maximum coupling in a non-perforated fiber (no grating) occurs for the surface plasmon plasmon of order m=2.

Improved laser damage threshold for chalcogenide glasses through surface microstructuring
J. Sanghera, U.S. Naval Research Lab. (United States); C. Florea, Global Defense Technology & Systems, Inc. (United States); L. Busse, B. Shaw, I. Aggarwal, U.S. Naval Research Lab. (United States); D. Hobbs, J. Nole, TelAztec LLC (United States)

We demonstrate improved laser damage threshold of chalcogenide glasses with microstructured surfaces as compared to chalcogenide glasses provided with traditional antireflection coatings. The surface microstructuring is used to reduce Fresnel losses over large bandwidths in As2S3 and As2Se3 glasses and fibers. The treated surfaces show almost of factor of two of improvement in the laser damage threshold when compared with traditional antireflection coatings.

One of the major issues for high power laser in the infrared is the lack of suitable antireflection coatings. In particular, fabrication of traditional antireflective coatings is problematic for chalcogenide glasses since they cannot be subjected to the high temperatures required for deposition. An alternative approach is to build a gradient index microstructure on the interface. These microstructures are often referred to as “motheye” surface structures [1]. Artificially produced structures have been demonstrated extensively in the last few years for many materials and through a variety of techniques [2,3], and it has been shown that they have higher resistance to damage from high-intensity laser illumination, for example [4].

While most of the work has been directed to bulk optics, little has been done in terms of creating similar structures directly onto the fiber ends. Most of the work has been focused on obtaining surface-enhanced fiber sensors [5] with approaches based on nanoimprinting of additive layers to the fiber end [6]. In this paper we demonstrate that glasses and fibers with microstructured ends have increased laser damage threshold compared to traditional coatings.

References
7946-36, Session 9

Bi-layer photonic crystal for optomechanics
M. Notomi, NTT Basic Research Labs. (Japan)

No abstract available

7946-37, Session 9

Photonic crystals for high efficiency LEDs
E. Matioli, Univ. of California, Santa Barbara (United States)

No abstract available

7946-38, Session 9

Optically reconfigurable photonic crystal nanobeam filter and modulator
P. B. Deotare, Y. Zhang, Q. Quan, I. Frank, Harvard School of Engineering and Applied Sciences (United States); R. Elic, Cornell Univ. (United States); M. Loncar, Harvard School of Engineering and Applied Sciences (United States)

Photonic crystal cavities with high quality factors (Q) have been of much interest in the recent past due to their potential applications in optoelectronics, sensing, and optomechanics. We present optically reconfigurable integrated photonic crystal nanobeam cavities that have continuous tunable optical modes operating near 1550 nm. Tuning is achieved by actuating the nanobeams using optical force by pumping outside the bandgap of the nanobeam photonic crystal. The devices were fabricated on a SOI substrate and were tested by coupling a tunable CW laser using a tapered lensed fiber. The supermodes of the coupled nanobeam cavities are highly dispersive to the lateral gap between the nanobeams. This gap can be varied by changing the power in the optical pump. Using attractive or repulsive optical force, the cavity resonance can be either blue or red shifted. Applying the same tuning principal, we can use the pump to modulate the probe signal. We have been able to successfully design and fabricate high-Q nanobeam cavities with 100nm spacing between them. We show 60pm of static tuning and have been able to modulate the probe at 97MHz, which is limited by the mechanical response of the nanobeams.

7946-39, Session 9

Photonic crystal waveguide based sensors
M. Askari, S. Yegnanarayan, A. Adibi, Georgia Institute of Technology (United States)

Waveguide-based sensors allow independent control over sensitivity and dynamic range, which is not possible in resonance-based sensors. In this paper, we present a refractive index sensor based on using photonic crystal waveguides (PCWs) in an unbalanced Mach-Zehnder interferometer configuration. In this configuration, the dynamic range of the sensor is determined by the path difference between the two arms and the sensitivity is controlled by the length of the PCW. We show that by using PCWs we can get a factor of six improvement in sensitivity over a ridge waveguide-based sensor. This enhanced sensitivity is achieved due to reduced group velocity in a PCW. By reducing the loss at low group velocities the sensitivity can be further improved.

7946-40, Session 10

Surface acoustic wave band gap in semi-infinite medium with locally resonant two-dimensional phononic structure
A. Khelif, CNRS-Georgia Tech Lorraine (France); Y. Achaoui, Institut FEMTO-ST (France)

In this work, we show a new band gap material for surface acoustic waves composed of an array of nickel pillars on a lithium niobate substrate surface. Such medium affect the classical surface acoustic waves and exhibit two different kinds of band gaps. The first frequency gap based on the local resonance of each pillar is several times lower than that is expected from Bragg interferences. Besides, the entire pillars interact together to give rise to a high frequency gap as in an usual phononic crystal. The sample have been characterized both electrically and optically and the numerical simulations have been performed in order to understand the physics behind using the Finite Element Method.

7946-41, Session 10

Functional microfabricated phononic crystal structures for communications and sensing signal processing applications
S. Mohammadi, A. Adibi, Georgia Institute of Technology (United States)

Phononic crystals (PnCs) are artificially-made structures that show interesting phenomena such as phononic band gaps (PnBGs) which are ranges of frequencies in which mechanical vibration (or phonons) are not allowed to propagate. Recently, there has been a growing interest in micro/nano-fabricated PnC structures that can operate at very high frequencies (VHF) and above for wireless communications and sensing applications. Energy confinement in three and two dimensions in the form of resonators and waveguides, as well as achieving functionalities such as multiplexing and demultiplexing, are of great interest for signal processing applications in wireless communications and sensing applications. PnC structures with PnBGs can provide an adiabatic and adaptable platform for implementing such functionalities with high performance.

In this presentation we report the design, fabrication, and characterization of a set of CMOS-compatible VHF resonators, waveguides, multi/multiplexer and demultiplexers, and filters based on the PnBG of a PnC structure fabricated in silicon (Si). It is shown that signals can be excited using high-Q PnC resonators and multiplexed into a single waveguide that supports their propagation and can be demultiplexed after conception of a pre-determined delay. Filters with high quality factors also made by coupling PnC resonators through the PnC structure.

The PnCs are made of an array of void holes etched into a Si slab due to its unique advantages. The void holes are etched in a 15 µm-thick Si slab and the spacing between the centers of the closest holes is also 15 µm. The diameter of the holes is 12.5 µm. Such a PnC structure has a large complete PnBG in the frequency window of 117 MHz < f < 149 MHz, which is appropriate for wide-band applications. We have used a thin (~1 um) stack of transducer made by sandwiching a piezoelectric layer between two metallic electrodes to excite and detect the acoustic signals.

7946-42, Session 10

Is there really a sound line limit for surface waves in phononic crystals?
S. Benchabane, Institut Femto-ST (France); A. Khelif, CNRS-Georgia Tech Lorraine (France); V. Laude, Institut Femto-ST (France)
When phononic crystal were first introduced in the early 1990’s, their ability to prohibit acoustic wave propagation was first demonstrated for bulk waves. Since then, it has been shown that these artificial materials offer unprecedented ways of steering the course of any type of elastic waves, bulk or guided. A series of works has then focused on investigating the effects these artificial materials could have on already confined surface-guided waves, an interest clearly driven by the prominent position surface acoustic waves and their combination with piezoelectric solids occupy in the vast field of wireless telecommunication systems. Theoretical reports stated that complete surface wave band gaps could be obtained in perfect 2D structures. Experimental demonstrations did not live up to one’s expectations, though: significant energy loss was observed for frequencies supposedly lying above the bandgap and coupling of the acoustic energy to the bulk substrate was blamed. The radiation of these modes located above a sound line -- defined by the dispersion relation of the bulk mode with the lowest velocity -- seemed to cast a genuine stumbling block on the development of phononic structures relying on surface waves. Yet, if losses are unavoidable there, configurations do exist that can make them acceptable. We hence present in this paper some of the works reported on piezoelectric phononic crystals for surface waves. We will focus more closely on recent theoretical and experimental results that show, through the simulation, fabrication and characterization of a hypersonic phononic crystal, not only that bandgaps can be obtained at near-GHz frequencies, but also that a clear transmission of the signal can be observed even for modes lying within the sound cone.

7946-43, Session 10
Time-resolved two-dimensional imaging of GHz surface acoustic waves in 1D and 2D phononic crystals and devices based on them
O. Matsuda, Hokkaido Univ. (Japan); I. A. Veres, Univ. of Stratchlyde (United Kingdom); O. B. Wright, Hokkaido Univ. (Japan)
Ultrashort light pulses of temporal width in the sub-picosecond regime can generate and detect high frequency acoustic waves in solids or liquids. The method involves the optical pump-probe technique, and has been widely used to study elastic properties and sample structure using the excitation of longitudinal or shear acoustic waves. The combination of the pump-probe technique, two-dimensional scanning of the probe light spot position over the sample surface, and optical interferometry allows one to follow the spatiotemporal evolution of GHz surface acoustic wave (SAW) fields. This time-resolved two-dimensional imaging of SAW is also very useful for investigating elastic and structural properties. We have applied this SAW imaging method to the study of the acoustic properties of 1D and 2D phononic crystals and devices based on them, such as phononic crystal waveguides. By taking temporal and spatial Fourier transforms of the spatio-temporal acoustic field data, the acoustic dispersion relations and, in particular, phononic band gaps are revealed. The results are compared with numerical simulations based on the finite-element method. This research forms a basis for the efficient evaluation of phononic structures based on the phononic crystals. The talk will, in particular, review our recent results in this field.

7946-44, Session 11
Plasmo-photonic nanopillar array for large-area surface-enhanced Raman scattering sensor
Vertical Si nanopillar arrays of different predetermined diameters, etch-to-etch separation (gap) and height were overcoated with thin layers of Ag and Au for use as SERS substrates. The arrays were fabricated by e-beam lithography and reactive ion etching. Such arrays feature uniform plasmonic field distributions over large areas that can be reproduced inexpensively via nanoimprint lithography. However, the fabrication of these systems is at a developmental stage and extensive work is needed in order to fully understand their capabilities as well as the mechanisms that govern their behavior. For instance, while it is relatively well known that increasing the diameter of plasmonic structures leads to a red-shift in the surface plasmon resonance (SPR) condition and therefore the optimal SERS wavelength, it is unclear what the response of partially coated core-shell pillar arrays would be for increasing diameter, or what influence diffraction has upon the SERS enhancement and SPR position. Here we present a systematic study that monitored varying parameters such as array geometry (circles/ squares), nanopillar diameter/ width and pillar-to-pillar gap (20nm-200nm) as a function of incident laser wavelength (457nm, 514nm, 532nm, 633nm and 785nm). The results are compared to COMSOL MultiPhysics computational package simulations and suggest that the SPR condition is not only influenced by the dielectric constant of the pillar core, but that multiple SPR conditions are induced that are separated from one another, not only in wavelength, but also spatially. These results offer valuable insight into the optimization of nanopillar structures in order to obtain more efficient plasmonic-based sensors.

7946-45, Session 11
Planar metallic nanostructures in a waveguide for sensing applications
M. Roussey, Q. Tan, A. Cosentino, H. Herzig, Ecole Polytechnique Fédérale de Lausanne (Switzerland)
The challenge for the integration of optical devices has motivated many research groups. Since the last decade nano-photonics appears as a potential solution thanks to nano-structures, such as photonic crystals, plasmonic or surface wave devices. The interest in nano optical objects is due to their high sensitivity to small variations of their environment. In particular a modification of the geometry or the refractive index surrounding the structure can modify drastically the spectral response of the device. The objective is to measure the variation of the refractive index of an analyte deposited on the structure. Moreover, thanks to the small size of the nano-sensor, an array of them can be created to perform parallel measurements for higher precision or multi-wavelength systems. We present the study of an array of slot waveguide cavities. The sensor structure is composed of a thin layer of gold (20nm thick) deposited on an optical waveguide. The layer is nano-patterned using e-beam lithography in order to perform an array of grooves (30nm width) with a period of 500nm. Finite Difference Time Domain (FDTD) simulations have shown the presence of a dip in the transmission spectrum of the structure, which can be shifted when the refractive index of the medium above and in the structure changes. The sensitivity of the nano-device is around 800nm/ RIU (refractive index unit).
We shall present here the theoretical optimization of the geometrical parameters, the different crucial fabrication steps and the first characterizations of the device.

7946-46, Session 11
InGaAsP photonic crystal slot nanobeam waveguides for refractive index sensing
B. Wang, M. A. Dündar, R. Nötzel, F. Karouta, Technische Univ. Eindhoven (Netherlands); S. He, Joint Research Ctr. of Photonics (China); R. W. van der Heijden, Technische Univ. Eindhoven (Netherlands)
We investigate InGaAsP photonic crystal slot nanobeam slow light waveguides with embedded InAs quantum dots consisting of two parallel suspended beams separated by a small gap, each patterned with a one-
ZnSe nanowires can be used as biological labels for harmonic generation microscopy (harmonophores), since they exhibit intense and anisotropic nonlinear optical effects. The orientation dependencies of linear polarization of the laser with respect to the NW axis on the second and third harmonic generation, as well as multiphoton fluorescence are described in ZnSe semiconductor nanowires (NWs). The mismatch of dielectric constants between ZnSe NWs and their environment governs the particularly intense second harmonic generation (SHG), though the highly symmetrical crystal lattice does not allow bulk SHG. The optical electric field intensity inside illuminated nanowires dramatically depends on their orientation relative to the exciting light polarization due to depolarization effects, resulting in a giant angular dependency of all the aforementioned optical phenomena. Individual ZnSe nanowires were imaged using a multicontrast nonlinear laser scanning microscope coupled to a femtosecond Yb:KGW laser with a repetition rate of 14 MHz and 1030 nm wavelength. Angular dependencies of nonlinear phenomena based on the orientation of laser polarization with respect to the NWs showed that a maximum signal occurred when the laser polarization was parallel to the NW. The influence of the relative dielectric constant between the NWs and their environment was demonstrated, in agreement with the theory. The relative amplitudes of the angular dependencies were also significantly influenced by nanowire bending and nonuniformity, revealing dominance of this effect in the anisotropy measurements of nonlinear optical signals.
Optical anisotropy is an inherent property of columnar dielectric films, such as those fabricated by Glancing Angle Deposition technique. This process utilizes physical vapor deposition combined with computer-controlled substrate motion to finely tune the direction of column growth and vital morphological parameters such as column cross-section and inter-columnar spacing. Control over the anisotropic properties of the porous film provides an opportunity to design polarization selective photonic devices and films with improved band-gap properties. Anisotropic defects in multilayer films also result in a polarization-sensitive position of resonant transmission modes.

We employed the finite-difference time-domain and frequency-domain methods to theoretically analyze and design columnar films with unique band-gap properties. The following morphologies were considered:

(i) s-shaped columnar films with polarization dependent band-gap position and width. Using numerical simulations we have shown that the competitive effect of different sources of anisotropy can be used to engineer photonic band gaps with strong selectivity to linearly polarized light;

(ii) vertical post films with a rugate refractive index profile. Due to the optical anisotropy of the vertical post film the band gap position has a reduced dependence on the angle of light incidence, leading to an omnidirectional reflection of light;

(iii) splitting of the resonant mode in rugate thin films with an anisotropic defect has been studied for various defect morphologies.

Optical devices were fabricated using titanium dioxide because it has good transparency in the visible range of the optical spectrum and a large refractive index. Experimental results were compared to simulations in order to verify the designs and understand the limitations of the fabrication process.

7946-70, Poster Session

**Femtosecond laser-ultrasonic investigation of plasmonic fields on embedded interface**

H. Chen, Y. Wen, C. Tsai, National Taiwan Univ. (Taiwan); K. Lee, P. Wei, Academia Sinica (Taiwan); J. Sheu, National Cheng Kung Univ. (Taiwan); C. Sun, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

We demonstrate a new approach to observe the surface plasmon field on the embedded interface by using femtosecond laser ultrasonics. The study was performed on a 1D nanoslit array deposited on a GaN thin film. A 590nm-period gold nanoslit array with a 70nm slit-width and a 70nm film thickness was designed according to a commercial simulation. In this nanoslit array, surface plasmon resonance was expected to be excited on the embedded metal/GaN interface under 720nm wavelength of normal incident light. Different optical probe signals were observed when the femtosecond laser ultrasonic pulse propagated through the metal film and metal nanoslits. By analyzing the shape and temporal response of the induced acousto-optical signals, our femtosecond laser-ultrasonic study directly reveals the plasmonic field distribution optically excited on the embedded metal/GaN interface for the first time, while the measured 150 nm penetration depth of the plasmonic field into the substrate agrees well with the theoretical expectation. Our study also indicates that a 1D nanoslit array could be a sensitive detector for nanoacoustic pulses through surface plasmon resonance. In this presentation, we will not only present the physical mechanisms on how to observe the plasmonic fields excited on the embedded interface through laser ultrasonics, but also compare the experimental finding with the numerical simulations.

7946-71, Poster Session

**Experimental demonstration of deep subwavelength waveguiding and focusing with designer surface plasmonic waveguides**

W. Zhao, O. Eldaiki, R. Yang, Z. Lu, Rochester Institute of Technology (United States)

Some important applications of surface plasmons in the THz regime have been limited where deep subwavelength optical devices are a critical technique, due to the large transverse mode size (~100 and ~1000 in the THz and microwave regimes, respectively) in the frequency regime far below plasma frequency (in the ultraviolet regime for most metals).

Here we experimentally demonstrate focusing and guiding electromagnetic (EM) waves in a designer surface plasmonic 3D waveguide, which is a row of rectangular rods (each metal rod, length l=6.35 mm, width w=6.35 mm, and height h=19.05 mm; period d=12.7 mm) patterned on an aluminum slab. The maximum of the mode size can be mapped in the middle plane of two neighboring rods. The mode size slightly varies with different frequencies and minimizes at 0.04° by 0.03° at 2.25 GHz.

Moreover, due to the tight binding of surface waves, the decrease of the waveguide width does not significantly affect the dispersion of the guided modes. This fact enables the mode tapering in the transverse direction from a wide waveguide into deep subwavelength waveguide with high efficiency. To this end, we fabricated a tapered DSP waveguide as the input is the uniform DSP waveguide. The waveguide is tapered from 203 mm to 6.35 mm within the distance of 216 mm. From the experimental results, as the EM waves propagate in the taper, the mode size becomes smaller and smaller with the intensity gradually increasing, and eventually EM waves are coupled into the deep subwavelength mode.

7946-72, Poster Session

**Nanostructured metal-insulator-metal resonators for high-resolution color filtering and spectral imaging**

T. Xu, Y. Wu, L. J. Guo, Univ. of Michigan (United States)

With the miniaturization of integrated devices, current research on imaging sensors focuses on novel designs aiming at high efficiency, low power consumption and slim dimension, which poses great challenges to the traditional colorant-based filtering and prism-based spectral splitting techniques. In this context, surface plasmon-based nanostructures are attractive due to their small dimensions and the ability of efficient light manipulation. Here we show that, by selective conversion between the free-space waves and spatially confined modes in plasmonic nano-resonators formed by the subwavelength metal-insulator-metal (MIM) stack arrays, the transmission spectra through such arrays can be well controlled by using simple design rules. High efficiency color filters made by these plasmonic resonators capable of transmitting arbitrary colors with absolute transmission over 50% can be achieved. By combining MIM stack arrays of different pitch, arbitrary nano- to micrometer-scale color patterns can be obtained. At present, this lateral dimension is 1-2 orders of magnitude smaller than the best high-definition color filters currently available. Furthermore, the thickness of these plasmonic filters is about one order of magnitude thinner than the conventional colorant, which is very attractive to the design of ultrathin panel display devices. Besides the small dimensions, the nature of strong polarization dependence of plasmonic resonators can potentially benefit the LCD displays by eliminating the need of a separate polarizer layer. These artificial nanostructures provide an approach for high spatial resolution color filtering and spectral imaging with extremely compact device architectures.
7946-73, Poster Session

Supported gold plasmonic dimers in total internal reflection microscopy and spectroscopy: effects of evanescent field distribution

C. Wang, S. Yang, H. Chen, S. Gwo, National Tsing Hua Univ. (Taiwan)

Plasmonic dimers represent the simplest and most fundamental structure for studying plasmon coupling phenomena. Recently, antibonding and bonding coupling modes (plasmon polarizations oriented perpendicular to dimer axis, i.e. transverse coupling) of supported octahedral gold nanocrystal dimers (side length: 150 nm, immobilized onto ITO-coated silica substrate) had been directly observed by total internal reflection (TIR) microscopy and spectroscopy using the p-polarized incident light with the wavevector perpendicular and parallel to the dimer axis, respectively [1]. The experimental results were in agreement with the plasmon hybridization model (m = ±1) proposed by Nordlander and coworkers [2].

However, when the s-polarized incident light is used to excite dimers in TIR microscopy and spectroscopy with the wavevector perpendicular to the dimer axis (longitudinal coupling), the plasmon resonance energy blue shifts (665 nm to 25 nm). In this case, it is inconsistent with the predicted red shift of the plasmon hybridization model (m = 0) [2]. In this study, we use the finite-difference time-domain (FDTD) method [3] to understand this phenomenon. We find out that the evanescent field distribution generated by TIR results in this blue shift.

In our simulations, we set up gold nanoparticles with a octahedral shape (side length: 150 nm) and simplify the ITO-coated silica substrate by SiO2 substrate. We use three kinds of excitation geometries: TIR scattering, dark-field scattering, and free-space scattering. The TIR scattering utilizes the evanescent field generated by TIR to excite the dimer. The dark field scattering (incident wave propagating along the surface of substrate, and only the scattering wave from nanoparticles can be detected by using the total-field/scattered-field technique [3]) utilizes a homogeneous plane wave to excite dimer. The free-space scattering utilizes a homogeneous plane wave to excite dimer without the presence of a substrate.

Using the FDTD method, we could obtain the same results as the experimental study by TIR scattering spectroscopy. The plasmon resonance energy blue shifts (665 nm to 25 nm) with decreasing separations from 125 nm to 25 nm. However, we observe a red shift in dark field scattering and free space scattering simulations. This results confirm the evanescent field distribution strongly influence the plasmon coupling modes for the case of relatively large nanocrystal dimers supported on the substrate.

References:

7946-75, Poster Session

Computational analysis of the effects of gain material inclusion in engineered nanostructures

J. Duan, General Dynamics Information Technology (United States); R. Pachter, Air Force Research Lab. (United States)

Compensation for the loss in optical metamaterials by introducing gain media has been suggested by Ramakrishna and Pendry (Phys. Rev. B, 2003). Although progress was made in this area experimentally, analysis of the effects of gain material inclusion for various engineered nanostructures to mitigate loss has not been systematically carried out. In this work, we analyze engineered nanostructures, such as the so-called fishnet, single split resonators, and nanowire assemblies, with gain material inclusions, by applying finite-difference-time-domain simulations. Detailed results on the permittivity and permeability will be discussed in detail.

7946-76, Poster Session

Enhancement and suppression of transmission in 2D-periodic arrays of nanoslits

M. A. Vincenti, D. de Ceglia, The AEgis Technologies Group, Inc. (United States); M. Scalora, U.S. Army Aviation and Missile Command (United States); R. Marani, V. Marrocco, M. Grande, G. Morea, A. D'Orazio, Politecnico di Bari (Italy)

We investigate the transmission properties of 3D arrays of sub-wavelength slits on gold films having a 2D periodicity, describing the interaction effects of cavity modes resonating in the slits with surface plasmon modes. The role of all geometrical parameters of the 2D-periodic pattern, namely length and width of the slits, thickness of the metal layer and periodicity in both directions, will be highlighted, and polarization and angle dependance of the spectral response of the structure will be analyzed. Form and air filling factors of the grating will be also considered as parameters to reach full control on the transmission spectrum. The main transmission features of a simple 1D-periodic array of slits can be easily observed in structures having a 2D-periodicity. In particular, a strong inhibition of transmission occurs when the impinging plane wave-vector, added to the grating lattice wave-vector, matches the surface plasmon wave-vector of the unperturbed air-gold interface. This phenomenon favors the opening of a plasmonic band gap, where a transmission suppression band is induced by the simultaneous coupling and back-radiation of the unperturbed surface plasmon. Two highly resonating modes, resulting from the hybridization of Fabry-Pérot-like
fabricated in a photosensitive polymer. spacer layer between gratings. Using the two-layer phase mask and the structure. We also fabricate the two-layer phase mask by placing a maximum bandgap of 27% was found in the optimal photonic crystal 21% of the middle bandgap is found between band 4 and band 5 while microscope glass slide inserted into the beam. A maximum bandgap of gallium nitride nanocolon samples, using the finite-difference time-domain method. In the simulation, the radius of columns is 50 nm and the filling fraction of those is 0.4, and they are placed randomly inside a finite area and embedded in vacuum. To realize strong localization in such a finite size system, the radius, the filling fraction, and the frequency of light must be properly tuned. For investigating the frequency dependence, we have assessed the localization characteristics using different parameters, those are diffusion length, autocorrelation function, and decay time constant of light energy within the system. We show these results are consistent with each other, and we find that some localization strength peaks occur in the frequency domain. We conclude that the frequency characteristics because of wave interference due to Bragg-like diffraction. Furthermore, we show a single parameter scaling of the decay time constant as a function of ratio between the localization length and the system size, and then we have succeeded in obtaining frequency dependence of localization length.

7946-78, Poster Session
Investigation of the nonlinear optical response from arrays of Au bowtie nanoantennas
K. D. Ko, A. Kumar, K. H. Fung, G. L. Liu, N. X. Fang, K. C. Toussaint, Jr., Univ. of Illinois at Urbana-Champaign (United States)

We demonstrate that the optical response of a single gold bowtie nano-antenna (BNA) can be favorably modified to increase the local intensity by a factor of 10² in the feed gap region when a periodic array of BNAs are used. We use the periodicity of the arrays as an additional degree of freedom in manipulating the optical response and investigate the behavior of the resultant nonlinear emission, which include second harmonic generation (SHG), two-photon photoluminescence (TPPL), and an additional photoluminescence that cannot be attributed to a single multiphoton process. We discuss the effects of the array with respect to the nonlinear emission and also find that the considerable field enhancement of our antenna system leads to a broadband continuum with spectral response that is highly controllable. Resonantly excited arrays of BNAs are shown to exhibit a remarkably uniform emission over 250 nm of the visible spectrum. In addition, our analysis suggests that high field enhancements, as well as resonance matching, may not be the only preconditions for enhanced nonlinear emission. To our knowledge, this is the first report of implementing optical antennas in an array to favorably augment its optical response.

7946-79, Poster Session
Simulation of photonic bandgaps in real holographically formed 3D photonic crystals and holographic fabrication
Y. Lin, K. Ohlinger, F. Torres, The Univ. of Texas-Pan American (United States); D. Xu, K. Chen, Univ. of Pittsburgh (United States)

This conference paper presents a photonic bandgap simulation for real holographic 3D photonic crystals instead of optimal photonic crystal structures. The holographic photonic crystals are formed through five-beam interference generated by single optical elements: one is the two-layer phase mask and the other is the top-cut four-side prism. The photonic bandgap depends on the relative phase difference among the interfering beams. The phase of the two side beams from the two-layer mask is intrinsically controlled by the separation distance between two orthogonally oriented gratings however the phase of one side beam from the prism is externally controlled through a rotation of a thin piece of microscope glass slide inserted into the beam. A maximum bandgap of 21% of the middle bandgap is found between band 4 and band 5 while a maximum bandgap of 27% was found in the optimal photonic crystal structure. We also fabricate the two-layer phase mask by placing a spacer layer between gratings. Using the two-layer phase mask and the top-cut four-side prism, photonic crystal templates are holographically fabricated in a photosensitive polymer.

7946-81, Poster Session
Anderson localization of light in a random configuration of semiconductor nanocolumns
Y. Inose, Sophia Univ. (Japan) and CREST, Japan Science and Technology Agency (Japan); M. Sakai, Univ. of Yamanashi (Japan); K. Ema, A. Kikuchi, K. Kishino, T. Ohtsuki, Sophia Univ. (Japan)

In the two-dimensional random system composed of a disordered array of a dielectric cylindrical column ensemble, Anderson localization of light is possible. However, detailed studies for the phenomenon are much more difficult than those for photonic crystal. As a result, the light localization effect is not well understood. To obtain parametrical dependence of the localization characteristics, we have simulated temporal diffusion of light in a random system adopting parameters of gallium nitride nanocolon samples, using the finite-difference time-domain method. In the simulation, the radius of columns is 50 nm and the filling fraction of those is 0.4, and they are placed randomly inside a finite area and embedded in vacuum. To realize strong localization in such a finite size system, the radius, the filling fraction, and the frequency of light must be properly tuned. For investigating the frequency dependence, we have assessed the localization characteristics using different parameters, those are diffusion length, autocorrelation function, and decay time constant of light energy within the system. We show these results are consistent with each other, and we find that some localization strength peaks occur in the frequency domain. We conclude that the frequency characteristics because of wave interference due to Bragg-like diffraction. Furthermore, we show a single parameter scaling of the decay time constant as a function of ratio between the localization length and the system size, and then we have succeeded in obtaining frequency dependence of localization length.

7946-82, Poster Session
Precise permittivity measurement technique for low dimensionality structures
L. Arnaud, S. Blaize, A. Bruyant, M. Kazan, G. Lérondel, P. Royer, Univ. de Technologie Troyes (France)

We present a new technique for the measurement of the electric permittivity of nanostructures. This far field characterization technique uses measurable quantities which are independent of the properties of the substrate. This specificity allows a slight variation of the nanostructure properties to impact directly on the measured signal, and makes the technique insensible to uncertainties of the substrate characterization, which in case of a nanostructure on substrate may have a greater influence on most optical properties than the total contribution of the nanostructure under study itself. An easy to implement experimental mounting using simple optical elements is proposed. In combination with ready to use analytics formulae coming from electromagnetics modeling, it allows a direct spectral characterization of the permittivity of the nanostructure. The proposed technique is particularly suited for the study of confinement permittivity modifications due to reduction of dimensionality, for which the very low volume of material under study generally leads to badly conditioned problem with traditional techniques such as ellipsometry or reflectometry.

7946-49, Session 12
Optical manipulation using surface plasmons and silicon micro-ring resonators
K. B. Crozier, Harvard Univ. (United States)
A new class of plasmonic crystals: the eigen modes, field enhancement, and applications

M. Iwanaga, National Institute for Materials Science (Japan)

We report a new class of plasmonic crystals, which have eigen modes of coupled electric and magnetic fields. Enhanced electric field induces and couples with rotary magnetic field in a plasmonic crystal; in contrast, enhanced magnetic field is associated with rotary electric field in another plasmonic crystal. The composite plasmonic modes are realized as local plasmonic modes in stacked complementary metallic nano-structures.

The subwavelength insights on the electromagnetic (EM) dynamics have been obtained by the precise numerical calculations using finite element method. The field enhancement has been also evaluated and was found to be controllable on the ratio of electric and magnetic components. The nano-structures are good and new candidates for enhanced near-field EM field engineering.

Moreover each of the two EM-coupled modes was shown to be the representative mode derived directly from one of Maxwell equations. Experimental evidence is in excellent agreement with the resultant optical properties of local plasmons such as enhanced and strongly polarization-selective transmission.

The compensative results on the new class of plasmonic crystals will be presented at Photonic West.

Efficient coupling to plasmonic nanoresonators using on-chip Silicon Nitride integrated photonic structures

M. Chamanzar, S. Yegnanarayanan, E. Shah Hosseini, A. Adibi, Georgia Institute of Technology (United States)

We demonstrate a hybrid integrated photonic-plasmonic platform in which photonic guided modes are used to efficiently excite localized surface plasmon resonances (LSPR) of plasmonic nanoparticles. Efficient coupling of light to the LSPR modes of plasmonic nanoresonators in the visible and the near-infrared range of the spectrum is demonstrated by tight integration of plasmonic nanoparticles on silicon nitride (SiN) waveguides and microresonators. It is shown that by integrating gold nanoparticles with SiN microresonators, we can achieve high coupling efficiencies (>45%), resulting in large field enhancements. We will discuss the design, fabrication, and characterization of the hybrid platform which consists of gold nanoparticles integrated with SiN waveguides and microresonators.

Engineering aperiodic order in nanoplasmic devices: past, present, and future opportunities

L. Dal Negro, Boston Univ. (United States)

The study of light-matter interaction in deterministic media without translational invariance offers an almost unexplored potential for the creation and manipulation of highly confined optical fields. Unlike conventional photonic/plasmonic structures, Deterministic Aperiodic Nano Structures (DANS) possess unique light localization and transport properties defined by the iteration of simple mathematical rules encoding a fascinating complexity. Interestingly, DANS share distinctive physical properties with both periodic media, i.e. the formation of well-defined energy gaps, and disordered random media, a dense spectrum of localized eigenstates with large field enhancement distributed over large frequency spectra. In this talk, I will review the conceptual development, the design principles and the device applications of DANS in the context of nanophotonics and nanoplasmics. Tailoring multiple light scattering and electromagnetic coupling in metallic and silicon-based nanostructures without spatial periodicity provides a novel technological
approach for the creation of a new class of optical devices ideally suited to achieve broadband field localization and enhancement of light-matter coupling at the nanoscale. Specifically, I will discuss sub-wavelength field confinement, multiple light scattering and optical resonances in photonic-plasmonic coupled aperiodic systems. Based on the unique optical properties of DANS systems, I will demonstrate their potential for the engineering of on-chip optical devices including bio-chemical sensors (based on colorimetric and inelastic light scattering), multi-frequency light-emitters, pseudo-random lasers, polarization-based optical readers, nonlinear switches and thin-film solar cells.

7946-55, Session 13
Quantifying multipolar light emission
R. Zia, Brown Univ. (United States)

Although it is often assumed that light-matter interactions are dominated by electric dipole transitions, higher-order multipoles play a critical role in many optical devices. For example, the dipole-forbidden transitions of Lanthanide ions serve as light emitters in a range of technologies from lighting and displays to solid-state lasers and telecom fiber amplifiers. While these ions are known to support a number of strong magnetic dipole transitions throughout the visible and near-infrared regime, the magnetic contributions to many important transitions (such as the 1550nm line of trivalent Erbium) have not been fully characterized.

In this talk, we will present a momentum- and energy-resolved spectroscopy technique that can readily quantify multipolar emission processes in structured optical environments. This method exploits natural self-interference effects to distinguish between electric and magnetic transitions of the same order. Using a microscope-coupled imaging spectrograph, we will experimentally explore the angular emission of Lanthanide ions near reflective interfaces. The obtained frequency-resolved momentum images contain a wealth of information that enable the direct quantification of degenerate electric and magnetic transitions.

7946-56, Session 13
Study of plasmonic nanoprisms via apertureless near-field scanning optical microscopy
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To study nano-scale optical local-field phenomena, an apertureless near-field scanning optical microscope (aNSOM) is an important tool. Herein, an aNSOM has been developed and is utilized for observing the local surface plasmon resonance, wave propagation, and nano-antenna enhancement of nanoprisms. The developed aNSOM based on a commercial atomic force microscope is integrated with homodyne and heterodyne interferometric techniques to detect the near-field amplitude and phase of nanostructures. With the help of mechanical system designs, different direction illuminations and detections for different applications can be achieved.

7946-57, Session 13
Phonon confinement effects in nanowires revealed by scanning near-field optical microscopy: theory and experiment
A. Bruyant, M. Kazan, Z. Sedaghat, S. Blaize, Univ. de Technologie Troyes (France); N. Rochat, N. Chevalier, Commissariat à l’Énergie Atomique (France); P. Morin, STMicroelectronics (France); J. Vaillant, P. Royer, Univ. de Technologie Troyes (France)

While the electronic confinement in very small nanostructures (< 5nm) and its impact on the dielectric function is the object of intensive researches, the influence of phonon confinement on optical properties is often disregarded. However, in a recent theoretical study, we have quantitatively predicted a strong modification of the infrared dielectric function induced by phonon confinement in large crystalline nanostructures (<100nm). On the other hand, scattering-type near field optical microscopy has proved its ability to recover the chemical fingerprint of materials at a nanometer scale due to the intrinsic sensitivity of the technique to the local dielectric function. We have developed and employed this highly resolved technique to demonstrate the dramatic influence of phonon confinement on the infra-red optical properties of tungsten nanowires.

The obtained experimental results are clearly corroborated by a complete simulation taking into account the phonon confinement and the description of the undertaken near-field experiment. In this coupled model, the modification of the permittivity is precisely evaluated through an elastic medium theory, while the near-field experiment is reproduced with a full 3D electromagnetic simulation. The effect of phonon confinement on other microelectronic materials such as silicon is discussed in detail. The proposed approach bridges an important gap in the description of phonon-photon interactions occurring in material engineered at a deca-nanometer scale.

7946-58, Session 14
Single particle photocatalysis: towards solar-fuels with non-linear optics and plasmonics
J. A. Dionne, Stanford University (United States)

Nanocrystal photocatalysts enable a variety of important processes, ranging from water electrolysis for solar fuel generation to water purification and environmental cleanup. In all applications, the efficiency of catalysis is directly determined by the quantity of photogenerated charges and the rate of charge transfer. These quantities are difficult to determine in ensemble measurements, where nanoparticle heterogeneity conceals many important and interesting structure-dependent catalytic properties. Here, using single-particle spectroscopy, we directly observe the quantity and rate of charge transfer events in individual nanoparticles that catalyze the generation of hydrogen from water - an important half-reaction for solar-fuel production. The catalysts consist of a 2 nm CdSe core embedded in a 60-nm-long CdS rod. Visible light is absorbed by the rod, creating electron wavefunctions that are delocalized throughout the rod and hole wavefunctions that are localized in the core. The catalyst is tipped with a small (1-2nm) metallic nanoparticle, which acts as an electron sink to host the hydrogen evolution reaction. Using a combination of far-field optical microscopy and single-particle electrical measurements, we explore fluence- and bias-dependent single-particle photoluminescence. We find that individual catalysts are characterized by strong optical and electrical non-linearities, with features indicative of the quantized electronic structure of these particles. Our measurements allow for determination of the rates of photocatalytic charge transfer, the number of charges transferred, and the barrier height between the semiconducting rod and metallic tip. We also observe bias-dependent photoluminescence oscillations, an optical analogue of Coulomb blockade indicative of discrete charge transfer events. This talk will highlight the interesting quantum physics of hydrogen-evolving nanoparticles and discuss prospects for enhanced solar-fuel photocatalysis through nonlinear optics and plasmonics.
Infrared spoof plasmons on nanomembranes: physics and applications

G. Shvets, The Univ. of Texas at Austin (United States); A. Khanikaev, The Univ. of Texas at Austin (United States) and Macquarie Univ. (Australia); S. H. Mousavi, B. Neuner III, The Univ. of Texas at Austin (United States)

Highly confined “spoof” surface plasmon-like (SSP) modes are theoretically predicted to exist in a perforated metal film coated with a thin dielectric layer. Strong confinement of the modes is achieved due to the additional waveguiding by the layer. Spectral characteristics, field distribution, and lifetime of these SSPs are tunable by the holes’ shape and geometry. SSPs exist both above and below the light line, enabling two different classes of applications: to “perfect” far-field absorption and to efficient emission into guided modes. It is shown experimentally that these plasmon-like modes can turn thin weakly-absorbing semiconductor films into “perfect” absorbers.

High-throughput engineering of infrared plasmonic nanoantenna arrays with nanostencil lithography

S. Aksu, A. A. Yanik, R. Adato, A. Artar, M. Huang, H. Altug, Boston Univ. (United States)

In this talk, we will present a novel fabrication approach for low-cost and high-throughput fabrication of engineered infrared plasmonic nanorod antenna arrays with Nanostencil Lithography (NSL). Our approach, relying on direct deposition of materials through a pre-patterned mask, allows fabrication of nanoplasmonic devices without using operationally slow and expensive electron/ion-beam lithography tools. Our spectral measurements and electron microscopy images faithfully confirm the feasibility of NSL technique for large area patterning of nanorod antenna arrays with optical qualities achievable by electron-beam lithography. In addition, we show nanostencils can be reused repeatedly to fabricate same nanorod antenna arrays with identical optical responses reliably. This unique advantage is leading a way to high-throughput replication of the optimized nanoparticle arrays. In addition to its high-throughput capability, we demonstrate this technique has the flexibility and the resolution to create complex plasmonic nanostructures on the substrates that are difficult to work with e-beam and ion-beam lithography tools. NSL is a resist free process thus allows the transfer of the nanopatterns to any planar substrate whether it is conductive, insulating or magnetic. This fabrication technique is general and can be adapted to fabricate various engineered plasmonic devices with variety of geometries and arrangements. As we will present, NSL also offers the flexibility and the resolution to engineer nanoantenna arrays for excitation of collective plasmonic resonances (2). These excitations, by enabling spectrally narrow far-field resonances and enhanced near-field intensities, are highly suitable for ultrasensitive vibrational nanospectroscopy (3).

References:

Multipolar nonlinear optics with metallic nanoparticles


Nanoscience and nanotechnology have focused a wide interest in the past decades on noble metal nanostructures in view of the unique optical properties offered by the surface plasmon resonances (SPR). The understanding of the nonlinear processes at play in plasmonic nanostructures is therefore focussing a growing interest especially in the case of second harmonic generation (SHG), the process whereby two photons at the fundamental frequency are converted into a single photon at the harmonic frequency.

The SHG response from centrosymmetric gold or silver spherical nanoparticles is forbidden in the dipolar approximation for symmetry reasons. Therefore, a correct description of this nonlinear optical response must be developed beyond the electric dipole approximation. We show that the SHG response from these particles is truly multipolar and discuss how this strong selection rule may be overcome: through the local breaking of the centrosymmetry at the surface and through the retardation effects arising from the spatial variation of the electric fields over the particle (non-local sources). The discrimination of these two kinds of contributions is a long-standing problem we address here using polarization resolved measurements.

Nanoplasmonic photonic crystal phytoliths


Evidence is emerging that silica-containing single cell micro-organisms (diatoms) exhibit optical properties reminiscent of photonic crystals. These properties appear to arise from light interactions with the intricate periodic patterns of micro- and nano-pores that exist within the diatom frustules and girdle bands. Coscinodiscus Walesii and pennenate Nitzschia Closterium were cultured from pure colonies in sterile aqueous nutrient media. Diatoms were harvested and freed of organic components by acid hydrolysis. Not unexpectedly, Finite Difference Time Domain (FDTD) calculations reveal that patterns in native disc shaped C. Walesii and the pennate Nitzschia Closterium do not exhibit a band gap in the range of optical frequencies explored. The diatoms can nevertheless be used to template patterns of nanoplasmonic particles to confer more complex and interesting photonic crystal properties. Selective templating of silver and gold in the pores can be achieved by differential wetting/dewetting of poly(4-vinylpyridine) containing bound metal ions, followed by chemical reduction to yield nanoplasmonic particles. Alternatively, diatoms can be decorated with metal nanoparticles by selective binding to chemically grafted alkoxysilanes functionalized with mercapto alkanes and amines. The nanoplasmonic diatoms exhibit strong surface enhanced Raman scattering from chemisorbed p-mercaptoproline with rastered confocal laser excitation. Nanoplasmonic diatom frustules were characterized by optical, transmission electron and confocal Raman microscopy. Near and far-field micro-optical responses of the nanoplasmonic phytoliths were characterized by standard methods. Dewetting of evaporated silver and magnetic elements on the diatoms offers ways to fabricate new kinds of periodic metal nanostructures over different length scales based on the photonic phytolith templates. FDTD calculations suggest electromagnetic field responses different from those exhibited by periodic nano-hole arrays machined in metal films.
7946-64, Session 15

Observation of full plasmonic stop bands in fractal structures

N. Yasrebi, S. Khorasani, B. Rashidian, Sharif Univ. of Technology (Iran, Islamic Republic of)

In the last year's meeting we reported a novel approach [1] for stabilization of numerical calculation of plasmonic propagation band structure. This method enables us to precisely obtain the propagation modes of periodically patterned two-dimensional conducting sheets, with arbitrarily high order of spatial harmonic content. Following the above contribution [1], we here present successful construction of a periodic fractal structure based on the combination of square array of wires and the space-filling Hilbert curves, leading to very large plasmonic gaps in the propagation spectrum. Possible applications will be discussed.


7946-65, Session 15

Mapping of surface plasmon polaritons on nanostructured thin films using cathodoluminescence imaging

A. Kumar, K. H. Fung, N. X. Fang, Univ. of Illinois at Urbana-Champaign (United States)

We report investigations on mapping of surface plasmon polaritons (SPPs) on nanostructured thin films using electron-beam excitation. Because the incident electrons can provide wide range of momentum matching, this approach has the ability to excite SPPs all the way up to the flat-band region of dispersion curve—a region not normally accessible using optical excitation. For film thicknesses comparable to skin depths, the dispersion curve shows a large flat region providing opportunities to excite SPPs with very large wave-vectors that are critical for most sub-wavelength optical devices.

To map the SPPs, we fabricated square cavities of thin Ag films using electron-beam lithography. The two-dimensional confinement of SPPs on nanostructured films showed standing wave patterns that were imaged using cathodoluminescence (CL) imaging spectroscopy. These standing wave patterns showed a strong dependence on film thickness, with a higher SPP wave vector excitation probability for thinner films. For a 15 nm Ag film on silicon oxide substrate, SPP wavelengths as small as 200 nm were mapped.

The electron-beam excitation was modeled using a newly developed time-domain approach. In these FDTD based simulations electron beam was modeled as a series of dipoles with a temporal phase delay based on electron beam velocity. Excellent matching with experimental results was observed. Our investigations provide important understanding of light-matter interaction at nanoscale that has applications in various areas including photonics, optoelectronics, chemical and biological sensing, and next generation optical communication.

7946-66, Session 15

Description and characterization of the complex modes in a linear chain of noble metal nanospheres

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In this paper, we analyze complex modes in a linear chain of metallic nanospheres by using the dispersion diagrams for both longitudinal and transverse (with respect to the array axis) polarization states. In this analysis, we consider both lossless and lossy nanoparticles. The novelty of our approach is that we are able to describe single mode evolution. As a result, our dispersion relationship diagram is now composed by the superposition and interaction of all the different modes in the one dimensional array. Indeed, we are able to track the evolution of all the modes varying frequency. We model each nanoparticle to act as an electric dipole, by adopting the single dipole approximation, and we compute the complex zeroes of the homogeneous equation characterizing the field in the periodic structure. We employ Ewald method to achieve rapid convergence of the periodic Green’s function, which can be analytically continued in the spectral domain. We provide full characterization of the modes in terms of their direction of propagation (forward/backward), in terms of guidance and radiation properties (bounded/leaky), in terms of the position of the wavenumber on the Riemann sheet (proper/improper), and also in terms of their actual physical excitation in the structure by a source or defect in proximity of the array layer (physical or non physical modes). In this way we are capable of identifying the subset of physical modes that are allowed in the array as well as the set of non physical ones. Understanding the modes excitable in this kind of structures is essential for possible applications in which the linear chain can be employed, from near-field enhancement to innovative sensors.
Cavity quantum electrodynamics studies with site-controlled InGaAs quantum dots integrated into high quality microcavities

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Semiconductor quantum dots (QDs) are fascinating nanoscopic structures for photonics and future quantum information technology. Even though tremendous progress has been achieved in understanding the properties of QDs and integrating them into microcavities, microdisks or photonic crystals, the random position of self-organized QDs inhibits a large scale fabrication. Thus a great challenge regarding the integration of QDs into devices like single photon sources or electron memory modules is the precise control of the position of the QDs. Recently several groups succeeded in the growth of site-controlled QDs and their integration into microcavities, but a complete characterization of the intrinsic parameters of these dots is still missing.

In this work we present the growth of site-controlled InGaAs QDs and their integration into high quality microcavities for cavity quantum electrodynamics (cQED) experiments. Our technology platform allows for a deterministic fabrication of photonic devices based on single quantum dots and provides an alignment precision better than 50 nm. Besides the technology, we will address the optical quality of the QDs which can be determined by means of time resolved photoluminescence. By detecting the decay rate of the QD emission as a function of the distance between the QDs and the GaAs-air interface we extracted a quantum efficiency of 50% and an oscillator strength of 10 for the excitonic transition of site-controlled QDs. Finally, we will present cQED interaction effects between site-controlled QDs and the photonic modes of high quality microcavities in the weak coupling regime and single photon emission from the coupled system.

Control of the electronic structure of single site-controlled InAs/InP quantum dots via intermixing

K. Mnaymneh, D. Dalacu, P. Poole, J. Lapointe, R. L. Williams, National Research Council Canada (Canada)

Controlling the emission spectra of single quantum dots is important to creating scalable devices for quantum information processing. Ideally, one would like to fabricate an array of single quantum dots at specified positions and with a specified electronic structure. Controlling the electronic structure entails control of the size, shape, and composition of the dot, and is typically determined through epitaxial growth conditions. Here we explore intermixing-induced modifications to the physical structure of quantum dots as a means to control the ground state energy, biexciton binding energy, and anisotropic exchange splitting.

The samples used are single site-controlled InAs/InP quantum dots grown via a directed self-assembly process, as shown in figure 1. As-P intermixing is achieved through rapid thermal annealing (RTA) at 750°C in N2. Figure 2 shows a dot’s spectral lines before and after an RTA process. One can clearly see that the RTA process blueshifts the energy levels of a dot by around 30 meV.

The results show that this leads to a reduction of \( \omega_{\text{Rabi}} \) and, interestingly, the system remains in the strong coupling regime although the double peak cannot be spectrally resolved. In related experiments we have investigated the mechanism responsible for coupling of off resonant quantum dots to the cavity mode.[4,5,6]

We also report measurements performed on a system consisting of two spatially separated self-assembled InGaAs quantum dots strongly coupled to a single optical nanocavity mode [3]. Due to their different size and compositional profiles, the two quantum dots exhibit markedly different DC Stark shifts. This allows us to tune them into mutual resonance with each other and a high Q photonic crystal nanocavity mode as a bias voltage is varied. Photoluminescence measurements show a characteristic triple peak during the double anti-crossing, which is a clear signature of a coherently coupled system of three quantum states. We fit the entire set of emission spectra of the coupled system to theory and are able to investigate the coupling between the two quantum dots via the cavity mode, and the coupling between the two quantum dots when they are detuned from the cavity mode. We suggest that the resulting quantum V-system may be advantageous due to incoherent losses from the cavity mode can be avoided.

Experiments performed by Arne Laucht, Michael Kaniber, Soren Stobe and Thomas Guenther, theory by Jose Villas Boas, Ulrich Hohenester and Fabrice Laussy. We acknowledge financial support of the DFG via SFB 631 B3, the Nanosystems Initiative Munich and the European Union via SOLID and the Marie Curie scheme.

References

an unbounded regime. Figure 4 shows that the s-p splitting is getting smaller. This is indicative of a larger dot with a weaker potential. The intermixing is increasing the size of the dot and hence weakening the confining potential.

Figure 1: Single quantum dot. Figure 2: RTA effect on spectrum. Figure 3: Binding energy compare. Figure 4: s-p shell compare.

REFERENCES

7947-04, Session 2

Artificial atom lasers: lasing oscillation in a single quantum dot-photonic crystal nanocavity strongly coupled system

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One of the most ultimate goals for researchers in the field of the semiconductor lasers is to realize ultra-small lasers consisting of an optical cavity with the size of a wavelength of light and a single (artificial) atom. Since a single atom laser using a single trapped gas atom was demonstrated by advanced atom optics[1], various efforts have been devoted toward realization of such single emitter laser in solid-state materials. Combination of a single semiconductor quantum dot (QD)[2] with a semiconductor photonics crystal nanocavity is one of the best candidates for this purpose.

In the strong coupling regime, reversible exchange of a single quantum between a single quantum dot and the nanocavity is well-preserved. Vacuum Rabi oscillation—the coherent exchange of a single quantum between a single QD and an optical cavity—and highly efficient cavity-QED lasers have both been reported.[3] The coexistence of vacuum Rabi oscillation and laser oscillation seems to be contradictory, but it has recently been predicted theoretically that the strong-coupling effect could be sustained in laser oscillation.[4]

We have demonstrated the onset of lasing in the strong-coupling regime of a single quantum dot-photonic crystal nanocavity system. A high-quality semiconductor optical nanocavity and strong single QD-field coupling enabled the onset of lasing while maintaining the fragile coherent exchange of quanta. The onset of lasing in the strong coupling regime is observed in solid-state material for the first time.[5] These results show a clear achievement of the lasing oscillation in a single artificial atom nanolaser.

7947-06, Session 2

Coherent coupling of the excitonic states in a single quantum dot

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We show how a large vertical electric field can be used to linearly change the fine-structure splitting of a single InAs/GaAs quantum dot by over 100 micro-eV.

Our dots emits at a wavelength of 940nm and are embedded in a heterostructure that leads to strong confinement of both types of carriers in the dot. Thus electric fields of up to 500 kV/cm can be applied, without degradation of the emission. This represents an order-of magnitude increase in the field that can be applied over previous reports and allows Stark shifts of 25 milli-eV to be observed.

We find the two fine-structure split exciton states have slightly different permanent dipole moments, ensuring that they move together at a fixed rate, which is the same for all dots in the ensemble. In each single dot an avoided crossing is observed, where the magnitude of the splitting reaches a minimum value. The magnitude of this anti-crossing varies considerably from dot-to-dot, with smaller values occurring more frequently. In one particular dot with a minimum splitting of 1.8 micro-eV we are able to observe polarisation-entangled photon pair emission with continuous-wave excitation (fidelity 71%) and pulsed excitation (fidelity 64%).
Capture delay and modulation bandwidth in a quantum dot laser

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The carrier injection into a quantum-confined active region of semiconductor lasers is an indirect process - carriers are first injected into the reservoir (optical confinement layer (OCL)) and then captured into the active region. Reservoir-mediated injection adversely affects the laser operating characteristics - the threshold current is increased and more temperature-sensitive, and the output optical power is decreased. Due to a transport delay across the OCL and a capture delay from the OCL into the active region, the bandwidth of direct modulation of the output power by injection current is also reduced. In this work, we study the effect of non-instantaneous capture of carriers from the OCL into quantum dots (QDs) on the dynamic properties of a QD laser. The small-signal analysis of rate equations is used for free carriers in the OCL, confined carriers in QDs, and photons. The maximum modulation bandwidth and the optimum dc component of the injection current density, at which it is attained, are calculated as functions of the cross-section of carrier capture into a QD. Closed-form analytical expressions are obtained for the maximum modulation bandwidth and the optimum dc injection current density in the limiting cases of fast and slow capture into QDs. Our analysis provides a basis for optimizing the QD laser design for high-speed applications.

Fabrication of the CdSeTe alloy and CdSeTe/ZnS core-shell quantum dots

J. Zhu, Nanjing Univ. (China)

The novel properties of Quantum dots (QDs), such as improved brightness, narrow and symmetric emission spectra, resistance against photobleaching, and multicolor light emission, have opened new possibilities for ultrasensitive chemical analysis and cellular imaging. Firstly, we report the preparation of high-quality near-infrared (NIR) emitting CdSeTe QDs in an aqueous medium using L-cysteine as the stabilizer following a facile one-pot refluxing route. By changing the growth time and/or composition, the fluorescence emission of the QDs could be tuned from the visible to NIR region. The as-prepared CdSeTe QDs have excellent water solubility, stability and high quantum yield (QY), and can used as a selective fluorescent Cu2+ probe with low detection limit. Moreover, the proposed sensing system has been applied for the determination of Cu2+ in vegetable samples and the recovery test was satisfactory. The fluorescence of the QDs was sensitive to hydrogen peroxide (H2O2), which was used for the sensitive determination of glucose and cholesterol. All these results show that the prepared CdSeTe QDs with NIR emission have great potential applications for biosensing. We also reported the fabrication of water dispersed CdSeTe/ZnS core-shell (CS) QDs. The prepared CS QDs not only possess high QY, but also exhibit excellent photostability and favorable biocompatibility. Moreover, the CS QDs showed a high electrogenerated chemiluminescence (ECL) signal. All of these showed their potential applications in cell imaging and biosensing with high sensitivity. We greatly appreciate the support of the National Natural Science Foundation of China (20635020) and National Basic Research Program of China (Grant 2006CB933201).

Single colloidal quantum dots as sources of single photons for quantum cryptography

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Single colloidal quantum dots (QDs) are increasingly exploited as triggered sources of single photons for quantum cryptography. Here we report on single photon sources (SPS) based on colloidal quantum dots, whose size, shape and optical properties can be finely tuned by wet chemistry approach.

The optical properties of different colloidal nanocrystals, such as dots, rods and dot in rods and their use as single photon sources will be first discussed. Among those, CdSe/CdS dot-in-rods (DR) are very promising nanostructures for polarization-resolved single photon sources. Techniques for isolation and positioning of single QDs, a major issue for the fabrication of single photon sources, and various approaches for the embedding of single nanocrystals inside microcavities are also presented. The insertion of single colloidal QDs in quantum confined optical systems allows one to improve their overall optical properties and performances in terms of efficiency, directionality, life time and polarization control.

Finally the electrical pumping of colloidal nanocrystals light emitting devices and of NC-based single photon sources is reviewed.

Probing oxygen consumption in epileptic brain slices with QDs-based FRET sensors

C. Zhang, M. Xiao, Nanjing Univ. (China); J. Xu, J. Ingram, S. J. Schiff, The Pennsylvania State Univ. (United States)

Brain represents only 2% of the body weight and receives 20% of total body consumption. Increased states of neuronal activity elicit profound effects on oxygen metabolism throughout the brain. This principal is the basis for many indirect optical imaging techniques that monitor such changes, yet the relationship between molecular O2 and neuronal activity still remains unclear, which has been limited by the lack of a real-time, quantitative, and biocompatible sensor. Coupling oxygen metabolism with neuronal activity has relied on many indirect techniques (positron emission tomography, functional magnetic resonance imaging, etc) that are restricted in spatiotemporal resolution to monitor fast [O2] dynamics with single cell resolution. To design a sensor suited for fast response times, greater functionality, and allow quantitative measurements, here we applied a strategy of fluorescence resonance energy transfer to excite an oxygen sensitive dye (OSD) with donor CdSe/CdS nanocrystal quantum dots embed in polymer matrix. The NQDs we have chosen due to their luminescence insensitivity to O2, but their emission peak at 595 nm provides perfect spectral overlap right at absorption peak of OSD. This design neglects direct excitation and subsequent bleaching of the OSD, creating an optimized ratiometric sensor with 3–4 fold imaging lifetimes compared to organic dyes. This sensor allows us to image the spatial temporal dynamic of oxygen consumption over hippocampal slices during the initiation, propagation, and termination of pathological seizure like events for the first time.
Developing coherent coding with colloidal quantum dot-based two photon lasers
J. Xu, The Pennsylvania State Univ. (United States) and Univ. of Shanghai for Science and Technology (China); G. You, C. Xie, The Pennsylvania State Univ. (United States); F. Wu, S. Zhuang, Univ. of Shanghai for Science and Technology (China); C. Zhang, The Pennsylvania State Univ. (United States); Y. A. Wang, Ocean NanoTech (United States)

We report in this conference our effort to develop high-efficiency two-photon lasers based on the microbeads doped with colloidal quantum dots (QDs) toward their applications in coherent-optical coding. Efficiency and stability of the two-photon nanolasers were studied for their potential applications in coherent optical coding. We have obtained stable, high-efficiency and low-threshold QD lasering materials and QD-doped microbead lasers exhibiting dual lasing wavelengths which could take key roles in biological barcode sensing and many other applications. The research work represents an important step toward developing coherent optical barcode with two-photon lasers for high-accuracy and high-throughput analysis of biological molecules.

Photothermal lens spectrometry of metallic nanoparticle colloids
A. Marcano, F. Delima, S. Haynes, Y. Markushin, C. R. Sabanayagam, N. Melicheki, Delaware State Univ. (United States)

We report on photothermal lens experiments of metallic nanoparticles water solutions. We use an optimized pump-probe mode-mismatched photothermal lens scheme where the pump beam is focused and the probe beam is collimated. Under this condition the Z-scan signature of the signal exhibits a single peak that bears information about linear and nonlinear absorption and photothermal parameters of the sample. Using this scheme we show that metallic nanoparticles colloids exhibit nonlinear absorption effects related to attraction or repulsion forces that result from the interaction of the electromagnetic radiation with the surface plasmon induced on the nanoparticles. These forces induce spatial gradients of concentration that affects the local absorption values. We have performed photothermal lens spectrometry experiments on gold, silver and iron oxide nanoparticle colloids using second harmonic (400 nm) from a 140-fs near-infrared radiation of a Ti-Sapphire laser. The type and sign of the interaction depend on the value of the plasmon resonance and concentration. Under concentration values below 1 ppm, gold and iron oxide nanoparticle show a double peak structure that is associated to the presence of attraction forces generated by the light pump wave. For concentrations above 1 ppm the effect is reduced. Silver nanoparticles show a peak-hole structure which is associated to the presence of repulsive forces. We calibrate the experiment using the linear absorption values of the samples obtaining their corresponding nonlinear absorption coefficients.

Exciton states in quantum tetrapods
K. Sakoda, National Institute for Materials Science (Japan) and Univ. of Tsukuba (Japan)

Quantum tetrapods have been attracting much interest because of their unique structure, peculiar self-assembly process, and unique electronic states [1]. Particularly the symmetry of their electronic wave functions is expected to be much different from that of quantum dots, which may result in a different selection rule of optical transition for example. Although one-particle electronic states, that is, confined electron and hole states have been studies theoretically [2], confined exciton states do not seem to be studied in detail yet.

In this paper, I present a detailed calculation on the confined exciton states of tetrapods based on single-band effective-mass approximation for both conduction and valence bands and rigorous diagonalization of configuration interaction Hamiltonian taking into consideration the Coulomb interaction between electron and hole. The selection rule is examined by both group-theoretical consideration and numerical calculation of optical transition dipole moments. Numerical results on absorption and emission spectra are also given. Numerical calculation is motivated for the first time theoretical calculation for tetrapod that consists of a zinc blende core and four symmetric wurtzite arms. Quantum tetrapods of the core/shell type are discussed briefly.

References

Catalyst-free growth and characterization of III-AsSb nanowires by MOCVD
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Nanowires provide a bottom-up approach for semiconductor fabrication to serve as building blocks for nano-sized structures and devices with designed dimensions and properties at desired locations. Among III-V semiconductors, antimony compounds are attractive for mid-infrared and electronic applications due to their small bandgaps and high carrier mobilities. In this study, we report successful growths of GaAsSb and InAsSb nanowires on nanopatterned substrates by metal-organic chemical vapor deposition in the catalyst-free growth mode. The material, optical, and electrical properties of these nanowires are characterized and analyzed.

Majority of nanowires are formed in the vapor-liquid-solid growth mode, where metal particles (usually Au) serve as catalysts. Wide choices of material combinations are available for nanowires and substrates even when they are highly lattice mismatched, and the nanowire growth temperatures are generally lower than the comparable epitaxial growths. A different approach is to grow nanowires on patterned substrates in the catalyst-free growth mode. Vertically aligned, highly faceted nanowire arrays with high aspect ratios and densities are available on designed patterns through electron beam lithography. The catalyst-free growth mode avoids possible reactor contamination and introduction of deep level traps through the incorporation of foreign metal catalytical particles, and offers possibility for simpler integration platforms through lateral overgrowth and device lithography registration marks.

We have demonstrated the formation of vertically aligned, highly faceted GaAsSb and InAsSb nanowire arrays on SiO2-masked GaAs and InAs (111)B substrates, respectively. Through transmission electron microscopy, the densities of stack faults and twin plans are observed to reduce dramatically with increased Sb composition. Red shifts in photoluminescence are also observed with Sb incorporation. The electrical properties of these nanowires are characterized by two techniques. The surface-state density, doping concentration and carrier dynamics can be derived from the current-voltage measurement by direct probing of free-standing nanowires with a Au-coated conducting atomic force microscope tip. At the same time, the blanket-deposition of transparent-conducting indium-tin oxide layer over the nanowire array provides the benefit of combined optical and electrical characterizations.
The combination of III-V semiconductor-based optoelectronics with silicon technology is recently attracting practical interest for the realization of photonic devices integrated with complementary metal oxide semiconductor structures. We propose as promising nanostructures for the realization of visible light emitting diodes a new concept of GaP-based self-catalyzed core/shell nano-wires (NWs). Two samples were grown by metal-organic chemical vapour deposition on silicon substrates and consist of a GaP core covered by either a single or a double GaInP shell. Their optical properties are investigated by photoluminescence (PL) and time resolved PL (TRPL) at 10 K. PL spectra for both examined structures exhibit two separated features: one main peak at 575 nm (660 nm) related to the emission from the single (double) core/shell heterostructure and one common peak at 760 nm associated with the well known surface states. The carrier dynamics are investigated by using the second harmonic of a femtosecond Ti: Sapphire laser as excitation source and a streak camera as detection system. Measured emission decay time of the main emission is 0.43 ns for the single heterostructure and 0.6 ns for the double heterostructure. Moreover, the double core/shell structure exhibits the same emission dynamics for both GaInP shell and surface states, which is evidence of close correlation between the capture processes of the two features, and may indicate carrier exchange between the states. NW passivation enhances the main emission peak and significantly reduces surface states related emission. The influence of passivation on the carrier dynamics will be further discussed in the presentation.

7947-16, Session 4

Silicon Nanowire Optical Waveguide (SNOW): achieving high optical confinement in nanowire structures
M. Khorasaninejad, S. S. Saini, Univ. of Waterloo (Canada)

Recently, semiconductor nanowires have attracted considerable research interest as a building block for nanophotonic and electronic devices. This considerable attention is owing to the fact that the fundamental physical properties of the nanowires can be altered with regard to that of bulk material. This opens an opportunity to improve the performance of various devices. There have been several works using single nanowire as an optical waveguide. However, one main disadvantage of this is the lack of optical confinement especially when the diameter of nanowire is sub hundred nanometers required to take advantage of quantum confinement. The low confinement factor results in the fact that though the intrinsic properties of nanowires increase, the overall device performance is not greatly enhanced. In addition, due to the small size of these kinds of optical waveguides, the coupling efficiency is a potential issue. In this paper, we propose a novel optical waveguide consisting of arrays of silicon nanowires in close proximity. We show that such a structure can guide an optical mode provided the electric field is polarized along the length of the nanowires. This polarization is of interest as the enhanced optical interactions in nanowires are mostly observed in this polarization which is not usable in a single nanowire waveguide. On the other hand, high radiation losses are observed if the electric field is polarized in the transverse direction to the nanowires. Further, such guidance can happen even if the nanowires are arranged randomly. We calculate the optical radiation loss for different structures using Finite Difference Time Domain (FDTD) method. We also show that the fraction nanowire region can be approximated using an effective index method. The advantage of the proposed waveguide structure is that it allows for increased optical confinement while using the enhanced optical interactions of nanowire structures. This allows for many various applications to be developed. While our analysis is done on silicon nanowires, the proposed structures can be extended to other materials also.
Antimony-based quantum dot memories
D. Bimberg, A. Marent, T. Nowozin, Technische Univ. Berlin (Germany)

No abstract available

GaSb/GaAs quantum dots with type-II band alignments prepared by molecular beam epitaxy for device applications
S. Lin, Academia Sinica (Taiwan) and National ChiaoTung Univ. (Taiwan) and Institute of Optoelectronic Sciences, National Taiwan Ocean Univ. (Taiwan); C. Tseng, W. Lin, National Tsing Hua Univ. (Taiwan); S. Chen, Academia Sinica (Taiwan)

Compared with traditional In(Ga)As/GaAs quantum dots (QDs) with type-I band alignments, GaSb/GaAs QDs with type-II band alignments have provided an alternate choice for bandgap engineering of optical devices. However, the difficulty of achieving defect-free As/Sb interfaces for the GaSb/GaAs QDs is usually encountered during molecular beam epitaxy (MBE) growth. In this case, inferior optical characteristics are obtained for the GaSb QDs such that its application in optical devices would become less possible. In this report, the formation of GaSb quantum rings (QRs) is observed for the embedded GaSb QDs without long Sb soaking time after QD growth. By intentionally exposing the uncapped GaSb QDs to the As irradiation, increasing QR number is observed with increasing As irradiation time. The results suggest that As-for-Sb exchange is the main mechanism responsible for the QR formation after GaAs layer growth. With extended Sb soaking time after QD growth, the GaSb QDs can be well preserved after the GaAs capping layer growth. It is also observed that with increasing Sb soaking time after GaSb QD growth, the photoluminescence (PL) intensity of the GaSb QDs would be greatly enhanced. By inserting the GaSb QDs into a GaAs PIN structure, a room-temperature operation light-emitting diode with intense emitting intensities is fabricated. The linear dependence of electro-luminescence intensities over the third root of injection currents has confirmed the luminescence to be from the type-II QD structures. Quantum-dot infrared photodetectors (QDIPs) and memory devices based on the GaSb QDs have also been demonstrated.

Dense lying GaSb quantum dots on GaAs by Stranski-Krastanov growth
T. H. Loebert, D. Hoffmann, H. Fouckhardt, Technische Univ. Kaiserslautern (Germany)

GaSb quantum dots (QDs) have been grown on GaAs in the Stranski-Krastanov (SK) mode. By variation of the Sb/Ga (V/III) flux ratio, the growth temperature, and the nominal coverage the QD dimensions and optoelectronic characteristics can be tuned. The samples have been grown in a V/III ratio range between 0.45/1 and 1.50/1, a temperature range between 480 and 560°C and a nominal coverage between 2 and 6 monolayers (MLs), commonly not used before by other research groups. These modifications of the growth process enable dense lying dots with a density up to 9.6·10^10 cm^-2 and a diameter and height of 20 nm and 3 nm, respectively. The photoluminescence (PL) spectra reveal only one peak for each QD sample. The spectral position of the PL peak can be varied in a wide range between 0.850 and 1.170 µm by precise control of the growth parameters. Also to raise PL intensity and as a preparation for QD lasers up to 10 layers of GaSb QDs were grown on GaAs wafer. On one hand the barrier thickness - from 5 up to 50 nm thick - between each layer has a major influence on the PL intensity. On the other hand with varying growth parameters the emission wavelength of the PL peak can be shifted for the stack of QD layers. Moreover by changing these parameters during the growth of one stack with 10 QD layers two or more PL peaks can be achieved.

High resolution photocurrent spectroscopy and imaging of sub-surface InAs quantum dots by atomic force microscopy
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Engineering quantum optical devices requires knowledge of the electronic structure and distribution of the quantum dots, however, there are only few methods that allow for non-destructive imaging of sub-surface nanostructures with high spatial and spectral resolution. Photoconductive atomic force microscopy (pcAFM) is a sensitive, high-resolution method that derives from conductive AFM but measures the current under illumination, i.e. the photocurrent generated in a material. pcAFM allows simultaneous measurements of topography and photocurrent as well as the detection of photoactive sub-surface structures, such as buried InAs QDs. We have used this technique to obtain photocurrent images and spectroscopic results of buried InAs QDs embedded in a GaAs Schottky-i-n architecture at room temperature and under ambient conditions.

Performing local spectroscopic measurements at the position of the sub-surface InAs QDs, we were able to resolve transitions between three different sets of electron and hole states. Photocurrent maps showed variations of the wetting layer thickness and provided information on the location and distribution of QDs. Simultaneous imaging of several QDs was realised under illumination of the sample at the wetting layer wavelength and InAs QDs were shown to form clusters surrounded by InAs depleted regions. Image resolution was determined by the number of scanning steps and the extent of the current collection region underneath the tip, determined by the typical distances charge carriers travel laterally in the near-surface region. Image contrast correlated with the concentration of the photoactive material as well as with the local photoconductive properties of the sample.

Real time metrology of self assembled quantum dots by reflection high energy electron diffraction
A. Freundlich, C. Rajapaksha, Univ. of Houston (United States)

The ability to control and reproduce desired structural properties of quantum dots (QD’s) during growth is critical for the performance of QD optoelectronic and electronic devices. So far quantitative investigations of QD’s has been mostly limited to post growth microscopic (STM, AFM, TEM) and X-ray diffraction analysis which require non standard growth geometries and are complex to implement.

Reflection high energy electron diffraction (RHEED) is a powerful non intrusive technique which is applied in situ to provide real time structure evolution during thin film growth in epitaxy (MBE, CBE, LPVPE) and is routinely used to monitor the onset of 2D-3D transition (dot formation) during growth of self assembled dots. It has been also shown that the average facet orientation and dot coverage density could be extracted real time from the evolution of RHEED patterns during growth. However, a method to extract the average size of self assembled QD’s during growth, necessary for a full in situ metrology was still lacking.

Recently, by an analysis based on atomistic strain distribution in dots and kinematic diffraction theory, we have predicted that quantum dot heights can be directly extracted from RHEED intensity profiles along the chevron tails. Here we report the experimental evidence on the existence of periodic RHEED intensity fringes along chevron tails and demonstrate the possibility of monitoring real time and during the growth the evolution of the average dot size in the archetype InAs/GaAs material system.
Different approaches have been used in the past few years to extend the emission wavelength of InAs/GaAs quantum dots (QD). The main goal behind this is to obtain GaAs-based QD light emitting devices working in the 1.3-1.55 µm range, which would benefit from both the advantages of QD properties and GaAs substrates. In this work, we show how the height, strain and QD/capping layer band offsets can be controllably tuned by using a thin GaAs(Sb)(N) capping layer, allowing to reach emission in the 1.3-1.55 µm region. LEDs and laser diodes based on this approach are demon-strated and their main characteristics analyzed. Several GaAs(Sb)(N)-capped InAs QD samples with different Sb and N contents were grown by Molecular Beam Epitaxy, and their structural and optical properties studied by cross-sectional scan-nanng tunneling microscopy, transmission electron microscopy and photoluminescence (PL). Besides the expected reduction in the QD strain and the transition to a type-II band alignment at high Sb contents (~ 16 %), we find that the QD height can be controlled through the amount of Sb in the capping layer due to reduced In-Ga intermixing during the capping process. On the other hand, GaAsN capping layers strongly reduces the QD conduction band offset inducing also a PL red shift but preserving the band alignment. The longest wavelengths are achieved with simultaneous presence of both Sb and N in a 5 nm thick capping layer. Neverthe-less, in this case the PL spectra are degraded compared to the case of the counterpart ternary alloys.

Surface states in negative-band-gap slabs

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Nanostructures made from negative bulk bang gap materials such as HgTe have attracted a great deal of interest recently. A key feature of negative band gap nanostructures is that the transport of the surface electrons must be gapless, so-called, topological surface states. A key feature of topological surface states is that the transport of the surface electrons must be dissipation-less. These properties of the surface states are very attractive for applications in quantum computing and spintronics.

In this work we investigate the origin of the surface states which appear in the negative gap semiconductors like HgTe. Three types of electronic band structure of slabs are studied. We study the electronic band structure of slabs using tight-binding approach. The surface layers of slabs are passivated to remove dangling bonds.

For thin slabs, the passivating potential brings the cation-back-bond inside the bulk conduction band which is the inverted light hole band that originate from anion p-states. Mismatch of the character of the back bond band and bulk conduction band has striking consequences. With increasing slab thickness the confined conduction bands push out the cation-back-bond band. At the zone center, it forms resonant surface states inside the inverted band gap. Away from the zone center, the surface band are inside one or two branches of the surface states. The resonant surface states at the zone center saturate to the some levels inside the inverted band gap which depend both on the type of the surface and on the passivating potential. The surface states can be formed only when the passivating potential reaches some threshold value determined by overlapping between a positive band gap of the surface layers and a negative band gap of the interior layers of the slabs. The surface states found do not have any characteristic topological properties: they are neither gapless nor dissipation-less. We conclude that the surface states of the passivated HgTe slabs originate from the cation-back-bond band and they must be classified as intrinsic surface states of inverted gap materials.
Size dependent surface energy of silicon nanoclusters in SiO2 determined from the thermal evolution of their size distribution using a combination of X-TEM and Raman

I. F. Crowe, The Univ. of Manchester (United Kingdom); O. Hulko, A. P. Knights, McMaster Univ. (Canada); M. P. Halsall, The Univ. of Manchester (United Kingdom); R. M. Gwilliam, Univ. of Surrey (United Kingdom)

The broad distribution of silicon nanocluster sizes embedded in oxide films strongly influences their opto-electronic properties. Controlling the size distribution in ion implanted films using rapid thermal processing and monitoring it using cross-sectional imaging microscopy provides a deeper understanding of the formation dynamics and the ability to engineer materials for a wide range of applications. These include display and lighting technologies and improved efficiency multi-junction solar cells.

Furthermore, by invoking a phonon confinement model (PCM), which includes the measured size distributions as well as a size dependent stress, we can accurately replicate the line-shape of the measured Raman spectra associated with the Si-Si bond formation on an ordered length scale in samples prepared on Al2O3 substrates. Using the Laplace-Young relation and the stress, we obtain an incidental estimate of the silicon surface energy, which approaches the literature value for bulk Si as the cluster size increases.

Surface enhanced Raman radiation of crystal violet dye with a SiO2 buffer

T. Liu, I. Jiang, W. Hung, C. Kuo, National Sun Yat-Sen Univ. (Taiwan)

Surface enhanced Raman radiation of crystal violet dye has been studied by modulating the localized surface plasmon effect of silver nanoparticles. In the experiment, a buffer layer of silicon dioxide (SiO2) was established between crystal violet dye and silver nanoparticles. With a probe of laser beam of 532 nm in wavelength, it was found that the intensity of the Raman scattering significantly depended on the thickness of SiO2 layer. A maximum Raman-radiation intensity occurred with a 10nm-thick SiO2 layer. The experimental observation shows a possible modulation of surface enhanced Raman radiation by a proper dielectric buffer.

Synthesis of well-aligned and high density nanopore arrays with the assistance of ultrasonic

Y. Ting, Far East Univ. (Taiwan); S. Shy, National Nano Device Labs. (Taiwan)

Highly ordered and high density nanopore arrays of anodic aluminum oxide template was prepared by a two-step anodization method and with the assistance of ultrasonic. Well-aligned nanopore arrays were obtained perpendicular to the surface of aluminum. The first step anodization was carried out under 0.4 M oxalic acid for one hour, and the anodized film was removed by chemical etching, than the sample was anodized again for 40 minute under the same conditions as the first anodization and with ultrasonic. The results of aluminum oxide films were characterized by scanning electron microscopy, and the microstructure of the anodic aluminum oxide membrane indicating that the nanochannel arrays prepared with the assistance of ultrasonic are better than those in ordinary way related to the pore aligned and pore density.

Synthesis and oxidation of silver nanoparticles

H. Qi, D. Alexson, O. J. Glembocki, S. M. Prokes, U.S. Naval Research Lab. (United States)

Nano-particles (NPs) have attracted much attention due to their potential applications in catalysis, biology, computing, solar cells and optoelectronic devices. For example, silver (Ag) NPs have been widely used to enhance the surface sensitivity of some spectroscopic measurements, such as fluorescence, Raman scattering, and second harmonic generation. However, the oxidation process is seldom studied in detail on the nanoscale. Here, we demonstrated a fast and easy way to synthesize Ag NPs on NWs and silicon substrates by an electroless (EL) plating approach. The stability property of these EL-produced homogeneous Ag NPs was investigated by surface enhanced Raman spectroscopy (SERS) techniques, showing that the attachment of thiol to the Ag surface can slow down the oxidation process, and the SERS signal remains strong for more than ten days. Furthermore, we examined the surface oxidation kinetics of the Ag NPs depending as a function of NPs size and size distribution by monitoring the oxygen amount in the composites using energy dispersive x-ray (EDX). Results indicate that the EL plated Ag NPs shows faster oxidation rates than those produced by e-beam (EB) evaporation. We attribute this to the fact that the EL produced silver particles are very small, in the 20nm range, and thus have high surface energy, thus enhancing the oxidation. These studies provide extensive information related to the Ag NP oxidation which should be helpful in extending the Ag lifetime for various applications.

Formation of organic nanodots with a minimum diameter of 40 nm using conventional vacuum vapor deposition

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In recent years, organic electronics with unique morphological and optoelectronic characteristics have been developed extensively. To further enhance the characteristics of devices, great attention has been devoted to controlling the nanostructures in the devices. However, these are a few reports on the nano-structures based on small molecular weight materials. In this study, we report the formation of organic nanodots with diameters less than 100 nm using a simple, practical and highly controllable method which involves combing a conventional vacuum deposition process with a self-assembled monolayer (SAM) technique. SiO2/Si wafers with a thickness of 300 nm were treated with hexamethyldisilazane (HMDS) and then used as the substrates for deposition. Two categories of organic semiconducting materials were deposited as materials with low molecular weights. These were TPD and N,N’-di(1-naphthyl)-N,N’-diphenylbenzidine (-NPD) which have a tendency to form an amorphous morphology, and pentacene,-sextiophene (-6T) and fullerene (C60) which have a tendency to form a crystalline texture in their thin films. The nanostructures had a minimum diameter of 40 nm, indicating that cluster formation occurred in the gas phase during vacuum deposition. The size and shape of the nanostructures were controlled by the underlying SAMs, organic semiconducting materials, film thickness and substrate temperature.
Conference 7948: Advances in Photonics of Quantum Computing, Memory, and Communication IV
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7948-01, Session 1

The low temperature: do we need it?
Z. U. Hasan, Temple Univ. (United States)

Cryogenic operating temperatures are necessary for the success of some of the most exciting futuristic technologies such as quantum computing, ultra-dense memories, terabits per square inch, and many more. In all these cases the volume of the cryogenic accessories adds to the volume of the device rendering it wastefully bulky. Progress is being made on both sides. On one hand, some recent hardware schemes developed for quantum computing for example do not need these low temperatures, thus eliminating the need of bulky cryogenics. On the other hand, reducing the size of coolers has taken a leap forward; in future laser cooling of bulk material may provide cooling on a chip. This talk will review the status of the field in this area. It will attempt to assess the future of self-cooled devices and their potential in revolutionizing the quantum and nano-photonic technologies.

7948-02, Session 1

Deep tissue (phantom) imaging with spectral hole burning in Pr:YSO
H. Zhang, Texas A&M Univ. (United States); M. Saboooni, L. Rippe, S. Kröll, Lund Univ. (Sweden); C. Kim, L. V. Wang, Washington Univ. in St. Louis (United States); P. R. Hemmer, Texas A&M Univ. (United States)

To extract small amount of modulated sideband from carrier background is the key task for different techniques utilized in ultrasound-modulated optical tomography (UOT). We have successfully implemented a narrowband spectral filter with persistent spectral hole burning (PSHB) in Pr:YSO crystal to image through thick highly scattering media. Our work shows that, with PSHB technique, UOT modality is potentially able to achieve ~mm resolution beyond optical hard limit (~5cm).

7948-03, Session 1

Improving the imaging ability of ultrasound-modulated optical tomography with spectral-hole burning
X. Xu, H. Liu, Washington Univ. in St. Louis (United States); S. Kothapalli, Stanford Univ. (United States); L. V. Wang, Washington Univ. in St. Louis (United States)

Ultrasound-modulated optical tomography (UOT) is a hybrid imaging technique based on detection of the diffused light that is modulated by a focused ultrasonic wave inside a scattering medium. With the combined advantages of ultrasonic resolution and optical contrast, UOT is ideal for deep tissue optical imaging. Its growth in popularity and application, however, is hindered by the low efficiency in detecting the modulated diffused photons. The difficulty results from the small modulation depth of the modulated light, the spatial incoherence of the speckled light wave front, and the temporal incoherence associated with the speckle decorrelation. Research activities on UOT have therefore been centered on improving its signal detection efficiency by exploring various technical solutions to these problems. A prime example is the use of spectral-hole burning (SHB) in UOT. By applying SHB crystal as a spectral filter, one modulation sideband of the diffused light can be efficiently selected while all the other frequency components are strongly suppressed. Immune to both the spatial and temporal incoherence of the signal with a high enough on/off ratio, SHB can boost the UOT imaging ability dramatically and push it towards practical applications. We compare here, in the context of tissue imaging, SHB with the other technologies that have been applied to UOT, and identify the unique features that make SHB a preferable tool for UOT. Looking into the future research efforts, we also discuss the desired improvements from the SHB side, which will help UOT pave the way from research to everyday life.

7948-04, Session 1

High-resolution large dynamic range spectral filtering at 800 nm using Tm3+:YAG crystals
A. Louchet-Chauvet, R. Lauro, Lab. Aimé Cotton (France); P. Goldner, Ecole Nationale Supérieure de Chimie de Paris (France); F. Ramaz, Ecole Supérieure de Physique et de Chimie Industrielles (France); T. Channé, J. Le Gouët, Lab. Aimé Cotton (France)

The programmable filtering capabilities of trivalent thulium ion-doped YAG crystals have been investigated for two decades in the prospect of high resolution processing of classical and quantum optical signals. Programmable filtering relies on the modification of the absorbing ions’ spectral distribution. Starting with a large optical density sample, one opens a transparency window in its absorption band by optically pumping the active ions into a long-lived shelving state where the ions no longer absorb at the operation wavelength. In Tm3+:YAG the transition at 793nm offers an absorption bandwidth of 20GHz with a programming resolution of a few tens of kHz. The very sharp spectral resolution is associated with the long upper level lifetime T1 ~ 0.5ms. The ions are usually shelved in a metastable state with a Tm = 10ms lifetime, which sets the lower limit of the residual population in the transparency window to T1/Tm = 1/20 of the initial population. This limit represents a serious obstacle for demanding optical filtering applications, such as ultraspectral optical tomography, where a large dynamic range is required.

We recently investigated a different shelving scheme where the Tm3+ ions are optically pumped to a ground state nuclear Zeeman sublevel. An external magnetic field is used to help optical photons to flip the nuclear spins. The shelving time is then increased to several seconds, which reduces the residual population in the transparency window by orders of magnitude.

7948-05, Session 2

Coherence in quantum photo-cell: effect of Fano coupling
K. E. Dorfman, M. O. Scully, A. A. Svidzinsky, Texas A&M Univ. (United States)

In the recent article entitled: “Quantum photocell: Using Quantum Coherence to Reduce Radiative Recombination and Increase Efficiency” we analyzed a toy photocell illuminated by a monochromatic slice of solar spectrum and demonstrated that we can mitigate radiative recombination and enhance efficiency via quantum coherence [M. Scully, PRL 104, 207701 (2010)].

Namely we have shown that when the ground (excited) state is a doublet coherently driven by a microwave field, it is possible to cancel or reduce emission (absorption). Thus, there is a possibility of altering the balance between emission and absorption and reducing radiative recombination while keeping absorption intact. This preceding coherent drive model illustrates the role of quantum
coherence in a simple way. However, we ask: Is it possible to generate coherence without the use of an external field? Here we found that quantum noise induced coherence via Fano coupling yields a result similar to the one achieved earlier, namely, vanishing emission of incident resonant radiation with nonzero absorption. This can substantially enhance power generated by the photovoltaic cell as compared to the “two-level” device based on a single p-n junction.

7948-06, Session 2

Photon echoes in scattering media

P. Goldner, Ecole Nationale Supérieure de Chimie de Paris (France); J. Le Gouët, T. Chaneilère, Lab. Aimé Cotton (France); A. Ferrier, Ecole Nationale Supérieure de Chimie de Paris (France)

Photon echo refers to a time-delayed non-linear coherent optical response to resonant excitation by a specific sequence of light pulses. At first sight, the coherent buildup of such a signal would require high quality optical materials. Indeed, photon echoes are normally recorded in transmission experiments on transparent samples. However, optical waves can propagate coherently in random media, as revealed by the backscattering peak or the random laser in the multiple scattering regime. Coherent propagation in random media can also be combined with non-linear optical processes and coherent anti-Stokes Raman scattering (CARS) can be observed in polycrystalline and opaque media.

In the continuation of CARS investigations, we report on the first observation, to the best of our knowledge, of a photon echo emission from a strongly scattering medium. The latter is a polycrystalline powder of praseodymium doped yttrium silicate (Pr:Y2SiO5) with particle sizes ranging from 130 μm to 300 nm. At liquid helium temperatures, we observed 2 and 3 pulse photon echoes emitted as diffuse light in reflection geometry. Coherence lifetimes of the optical transition have been investigated as well as signal construction, revealing that echoes are generated across different particles.

Measuring photon echoes on powders offers an attractive access to the coherence time T2 in cheap and easily produced new compounds in the prospect of classical and quantum processing. Combination of narrow homogeneous linewidths and scattering medium could also lead to new applications, like spectral filtering for ultrasound optical tomography.

7948-07, Session 2

Different optical centers in Eu-doped MgS and CaS thin films for ultra-high density spectral storage applications

F. J. Bezares, Z. Hasan, J. Park, Temple Univ. (United States)

The doping of Eu into MgS:Eu as well as CaS:Eu thin films, produced by Pulsed Laser Deposition (PLD), offer a lot of potential for the development of ultra-high density (Terabits per sq. in.) spectral storage devices. These storage capacities are made possible by the use of spectral holeburning technique where many spectral holes can be burned into the inhomogeneously broadened Zero Phonon Line (ZPL) of the Eu ion’s 4f-5d electronic transition inside the MgS and CaS lattice. Here it is shown that adding additional trace amounts of impurities such as O2, Cl- and HCl to these thin films creates different optical centers with shifting spectral positions. By changing the growth environment inside a hi-vacuum vapor deposition chamber, the composition of the target material to be ablated during thin film deposition, or both, the crystal field environment around Eu ions is altered thus shifting in energy the characteristic ZPL in the optical spectrum of these materials. Laser-induced fluorescence and absorption spectroscopy results show evidence of the creation of these new optical centers and offer a new approach for the improvement in the storage capacities of spectral storage thin films. Some interesting aspects concerning long-term spectral degradation studies performed on these materials will be presented as well.

7948-08, Session 2

Coherent detection of ultrasound using spectral hole burning media

J. W. Tay, Univ. of Otago (New Zealand)

Optical detection of ultrasound involves the detection of ultrasonically tagged photons which appear as phase modulation on the light. The detection sensitivity is related to the etendue or light collection efficiency. Classical interferometers have their etendue restricted to ~2π due to the antenna theorem. Fabry-Pérot interferometers do better with etendue of ~10^-3 sr mm^2. Using adaptive imaging techniques allow much greater etendue. Recent advances in this area have generated fast, efficient photoelectroactive crystals. However speed is still an issue for in vivo applications and high intensity reference beams are required which generally scatter and contribute significantly to the detected noise.

Here we demonstrate a detection scheme using the dispersive properties of a spectral hole engraved in a rare-earth sample. Rare-earths have been shown to be useful for ultrasound detection, have large etendue and do not require intense beams for high sensitivity. Due to a steep change in absorption, light passing through the hole obtains a phase shift as dictated by the Kramers-Krönig relations. We apply this phase shift on the carrier portion of the light to obtain a beat signal between carrier and sidebands thereby converting phase modulation to amplitude modulation. This allows sensitive detection with moderate optical depths. We have measured a position equivalent noise of 46 pm/√(Hz) which is comparable to the theoretically achievable shot noise detection.

7948-09, Session 2

High Q/V photonic crystal cavities for cavity QED and microwave photonics applications

I. Bulu, Y. Zhang, M. Loncar, Harvard Univ. (United States)

In this work, we propose and demonstrate high Q/V photonic crystal cavities at microwave frequencies for cavity QED applications. The structure that we propose is based on our previous work on photonic crystal nanobeam cavities. The beam has an aspect ratio of 2:1 and it supports a TM polarized guided mode. The cavity is introduced through a set of tapered holes, that is, the periodicity (hole-to-hole distance) and the hole’s size are gradually increased from the cavity ends to center region. The tapered design method allows us to engineer the photonic bands and minimize scattering losses. The structure is designed to support a resonant mode confined in the air region of the cavity at 17.4 GHz. The photonic crystal cavities were fabricated on low loss alumina. The theoretical quality factor of the resonant mode is estimated to be 2.5 million. The quality factors were measured by transmission spectroscopy and we fit a Fano model. We measured quality factors as large as 30000. The quality factor was limited by the material losses of alumina and can be significantly improved by using sapphire. The modal volume of the designed cavity was 0.989 cubic wavelengths. We finally investigate the interaction of a classical radiation source with the photonic crystal cavity. We believe microwave cavities based on our photonic crystal beam design are attractive platforms for cavity QED experiments with the Rydberg states of atoms as a result of high Q-factors, small modal volumes, and an easily accessible air mode.

7948-10, Session 3

Optimal multi-photon phase sensing with a single interference fringe

G. J. Pryde, G. Xiang, B. L. Higgins, H. M. Wiseman, Griffith Univ. (Australia); H. F. Hofmann, Hiroshima Univ. (Japan); D. W. Berry, Univ. of Waterloo (Australia)

Multiparticle entangled states can help to increase the precision of phase measurements. When the N photons are in a maximally entangled state,
the phase uncertainty can be as low as 1/N, which is sqrt(N) times more precise than the standard quantum limit (SQL). To achieve this optimal phase sensitivity, it is necessary to distinguish even and odd photon numbers by performing a parity measurement at the output of the interferometer. However, parity measurements are extremely difficult to realize with current photon detection technologies, since they require high-fidelity resolution of N+1 different photon distributions between the output ports. In recent experiments, researchers have demonstrated precision beyond the SQL, for two and four photons, using only one or two photon-number detection patterns instead of parity measurements. To realize efficient phase sensing at higher photon numbers, it is therefore important to consider the optimal phase sensitivities obtained when only a single interference fringe is detected.

Here we show that for single fringes, the maximally-entangled NOON state does not achieve optimal phase sensitivity when N>4. Instead, the optimal single fringe sensitivity is achieved by the Holland-Burnett (HB) state, which is generated by the interference of two input beams with equal photon numbers. We experimentally demonstrate the enhanced phase sensitivity of a single photon-counted fringe of the six-photon HB state and show that it has a higher phase sensitivity than a single NOON fringe of equivalent visibility. Specifically, our single-fringe six-photon measurement achieves a phase variance three times below the standard quantum limit.

7948-11, Session 3

Bounds on entangled imaging

G. N. Gilbert, S. P. Pappas, Y. S. Weinstein, MITRE Corp. (United States)

We present a detailed theoretical analysis of quantum imaging intended to reveal under what conditions it is superior to imaging with non-entangled photons in order to determine practical bounds on quantum imaging systems. Employing a Fourier optical approach to imaging with non-separable states, our analysis includes a description of the generation, propagation and detection of entangled light signals taking into account diffraction and photon population statistics. Specific attention is directed to nonlinear propagation phenomena which may enable entangled light to propagate without diffraction, and compensate for other deleterious propagation effects.

7948-12, Session 3

Heisenberg-limited quantum sensing and metrology with superpositions of twin-Fock states

C. C. Gerry, Lehman College (United States)

Quantum optical interferometry (quantum metrology) requires super-sensitivity, or Heisenberg-limited, phase shift measurements (the best that can be achieved for linear phase shifts, according to quantum mechanics) and super-resolution. Many of the proposed schemes for quantum optical interferometry can achieve the former but not that latter. My presentation will deal with attempts to achieve both with the proper observable for measurement (photon number parity) and the proper states. I shall first review the NOON state and maximally entangled coherent state approaches and discuss their limitations due to difficulties in state production and problems with losses. On the other hand, it is known that quantum metrology with twin-Fock states with large photon numbers and parity measurements is Heisenberg-limited in the limit that the photon numbers are large. But these twin-Fock states that need to be presented simultaneously on opposite sides of a beam splitter are hard to generate. I discuss the prospect of using continuous variable superpositions of two-Fock states as an alternative. The two-mode squeezed vacuum state is one possible state for this purpose, and though it leads to Heisenberg-limited phase uncertainty it does not lead to super-resolution. However, I show that the pair coherent states are quite suitable for this, leading to Heisenberg-limited sensitivity and to super-resolution.

7948-13, Session 3

Super-resolution at the shot-noise limit with coherent states

J. P. Dowling, P. M. Anisimov, Louisiana State Univ. (United States)

We propose a super-resolving interferometric metrology strategy, which achieves the shot-noise limit. It requires only the production and transmission of ordinary laser beams in the form of coherent states of light. Hence, unlike the issues concerning the propagation of nonclassical states of light, such as squeezed light or entangled Fock states, this scheme suffers no worse degradation in the presence of absorption and loss than a classical coherent LADAR system.

7948-14, Session 3

Multiparticle entanglement and quantum interferometry

A. Smerzi, Univ. degli Studi di Trento (Italy); L. Pezze, Lab. Charles Fabry (France)

The central goal of interferometry is to estimate a phase shift with the highest possible sensitivity given a finite number of particles. On the one hand, irreducible quantum fluctuations limit the accuracy of an interferometer via the Heisenberg uncertainty principle. On the other hand, quantum entanglement has the potential to revolutionize interferometry by allowing a phase estimation with sensitivity overcoming the standard quantum (shot-noise) limit, 1/N^(1/2), and eventually reaching the ultimate bound 1/N, the so-called Heisenberg limit. Here, N is the total number of particles.

In this talk, the interplay between multiparticle entanglement and quantum interferometry [1] is discussed by using the quantum Fisher information, which provides a measure of the statistical distance among quantum states.

Phase sensitivity bounds are retrieved also in the case of fluctuating number of particles [2]. Our analysis thus concerns most of the current experiments on precision measurements where the number of particles is known only in average.

7948-18, Session 4

Experimental implementation of the universal transpose operation

H. Lim, Y. Ra, Y. Kim, 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 universal transpose of quantum states is an anti-unitary transformation that is not allowed in quantum theory. In this work, we investigate approximating the universal transpose of quantum states of two-level systems (qubits) using the method known as the structural physical approximation to positive maps. We also report its experimental implementation in linear optics. The scheme is optimal in that the maximal fidelity is attained and also practical as measurement and preparation of quantum states that are experimentally feasible within current technologies are solely applied.

7948-19, Session 4

Imaging trapped ions with a microfabricated lens for quantum information processing

E. W. Streed, B. G. Norton, A. Jechow, Griffith Univ. (Australia); T. J. Weinhold, The Univ. of Queensland (Australia) and Griffith Univ. (Australia); D. Kielpinski, Griffith Univ. (Australia)

Trapped ions are a leading system for realizing quantum information processing (QIP), with all basic operations demonstrating excellent performance and a clear roadmap to large-scale implementations. Integrated technologies for the large-scale roadmap have largely been demonstrated with one key exception: a highly parallel optical interconnect that can efficiently couple the strongly divergent dipole radiation patterns produced by ions to easily manipulated single optical modes. Microfabricated phase Fresnel lens (PFL) arrays can fill this gap with their high numerical aperture, diffraction-limited performance, and large-aperture integrated in-vacuum microfabricated PFL. The observed collection efficiency of 4.2±1.5% is similar to the current state of the art and sufficient for scalable quantum computing. An ion signal to background scatter contrast ratio of 23+/-4 was observed, even though our laser beam’s 1/e2 diameter was only 2.5x smaller than the electrode separation. The imaging system had a minimum spot size of 3.7+/-0.3 microns, limited by residual ion motion. The observed >100 micron field of view and 19.4+/-2.4 micron depth of field indicate alignment tolerances sufficient for integrating PFL arrays with multiple processing zone microfabricated ion traps. Our approach also provides an integrated solution for high-efficiency optical coupling in neutral atom and solid state QIP architectures.
We present a status report on our program aimed at exploiting the transverse degree of freedom of the photon to perform quantum key distribution at a high transmission rate. Specifically, we aim to transmit more than one classical bit of information per photon by making use of the large information capacity of the transverse degree of freedom of the photon. We present experimental results that quantify our progress in this area.

7948-21, Session 5

Efficient photon number detection with silicon avalanche photodiodes

O. Thomas, Z. L. Yuan, J. F. Dynes, A. W. Sharpe, A. J. Shields, Toshiba Research Europe Ltd. (United Kingdom)

Highly efficient and low noise single photon detectors are a prerequisite for quantum information processing based on photonic qubits. For many applications in quantum information processing, these detectors must also be able to resolve the number of photons in an optical pulse. For over a decade, silicon avalanche photodiodes (Si-APD) have been the detector of choice for single photon detection at visible wavelengths due to their practicality, high quantum efficiency and low dark count noise. Their spectral response also makes them compatible with a number of quantum light sources. However, Si-APDs are currently believed to be threshold devices that detect only the presence or absence of photons, but not the photon number.

We demonstrate here an efficient photon number detector for visible wavelengths using a fast-gated Si-APD. Using sub-nanosecond voltage gates and the self-differencing technique, the device is able to resolve up to four photons in an incident optical pulse. The detection efficiency at 600 nm is measured to be 73.8%, corresponding to an avalanche probability of 91.1% of the absorbed photons, with a dark count probability below 1.1 x 10^-6 per gate. We also consider the capability of the device for the Bell-state measurements used in quantum information processing, which require that we distinguish between photon number states with N = 0, 1 and ≥ 2, in terms of the photon number error. This performance and operation close to room temperature makes fast-gated silicon avalanche photodiodes ideal for optical quantum information processing that requires single-shot photon number detection.

7948-22, Session 5

Generation of optical Schrödinger cat states by number-resolved photon subtraction from squeezed vacuum

T. Gerrits, S. Glancy, T. S. Clement, B. Calkins, A. E. Lita, National Institute of Standards and Technology (United States); A. J. Miller, Albion College (United States); A. L. Migdall, National Institute of Standards and Technology (United States) and Joint Quantum Institute, Univ. of Maryland (United States); S. W. Nam, R. P. Mirin, E. Knill, National Institute of Standards and Technology (United States)

We have generated and measured an approximation of an optical Schrödinger cat state by photon subtraction from squeezed vacuum. Photons are probabilistically subtracted from squeezed vacuum and detected with a photon-number-resolving transition edge sensor (TES). The detection at least one photon indicates the presence of the cat state which is measured by homodyne detection. Using the TES, we were able to subtract up to three photons from a squeezed light pulse and generate an optical Schrödinger cat state with fidelity of 0.59 and a size of 2.75 photons. The highest negativity of the Wigner distribution at the origin was -0.115, a clear indication for the quantum character of the generated cat state. As predicted by theory, we see an increase in the cat state size and fidelity while subtracting more photons. By improving the squeezing purity and the heralding efficiency we will be able to generate high fidelity cat states at high rates in the near future. These promising results show that high efficiency detectors with photon number resolving capabilities are the route to perform quantum information experiments with high generation rates and cat states with mean photon number greater than 2.

7948-23, Session 5

N-bits all-optical circular shift register based on semiconductor optical amplifier buffer

E. Lazzeri, G. Berrettoni, G. Meloni, Scuola Superiore Sant’Anna (Italy); A. Bogoni, L. Poti, Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy)

In the perspective of a future all-optical communication network optical shift register will play an important role especially for what concerns several binary functions, such as serial to parallel conversion and cyclic operations, that are involved in techniques allowing error detection and correction as parity check, or cyclic redundancy check.

During the last decades, several attempts of realizing circulating memories or shift register in the optical domain were made, with some limits in terms of functionality, number of bit to be stored (under three), scalability or photonic integrability.

In this paper, we present a new approach to realize a circulating optical shift register consisting in an SOA-based optical buffer (OB) and a bit selecting circuit (BSC). The OB is integrable and is able to store a finite number of bit N at high bit rate. The BSC returns consecutive bits at a lower clock rate, achieving proper shift register function. In particular, the bit selection function is realized by means of four wave mixing (FWM) in a Kerr medium, and cancellation of one sequence is allowed to enable new sequence storing. The proposed scheme presents good scalability because the number of bits to be stored and shifted only depends on the cavity length and on the sequence bit rate fB. No further elements are needed to be added to the design if the number of bits increases. Experimental validation of the scheme for fB=50MHz and fB=236MHz shows optical signal to noise ratio per bit penalty of 5.6dB at BER=10^-9.

7948-24, Session 6

Photonic interference between different sources

S. V. Polyakov, A. Muller, A. Ling, N. Borjomscaia, E. B. Flagg, National Institute of Standards and Technology (United States); E. Van Keuren, Georgetown Univ. (United States); A. L. Migdall, G. S. Solomon, National Institute of Standards and Technology (United States)

We demonstrate interference between photons emitted by two single-photon sources of different physical natures. This is a key indicator of the indistinguishability of single-photon states emitted by different sources and is necessary for quantum information applications requiring high fidelity interchange between different physical qbit systems. In our experiment, one photon is produced by a semiconductor quantum dot (QD) and the other is produced via parametric downconversion (PDC).

We are particularly interested in the interconnection between PDC-based sources and QD-based sources because PDC is currently the workhorse system for many quantum information applications including both processing and communication, while QDs relying on the well developed field of semiconductor engineering offer great scalability potential.

We measure indistinguishability of the two photons by sending the two photons into the two input ports of a beamsplitter and looking for the two photons exiting in the same spatial mode. This “Hong-Ou-Mandel” interference allows us to quantify that indistinguishability. We make the measurement by comparing the interference seen when the two photons are input with the same polarization versus when they are orthogonally polarized, where no interference occurs. Using the probability of coalescence of the photons (into a single output channel) from the two sources defined as: P_c=(1-A^2)/A, where A, is the number of...
counts in the peak of the second-order crosscorrelation function for each polarization, integrated over the temporal extent of the peak, we get $P_c = (16 \pm 3)\%$, within 50% of the theoretical maximum. We propose a path to achieve the indistinguishability needed for quantum information applications.

7948-26, Session 6

**Informational geometric analysis of superactivation of zero-capacity optical quantum channels**

L. Gyongyosi, S. Imre, Budapest Univ. of Technology and Economics (Hungary)

The superactivation of zero-capacity quantum channels makes it possible to use two zero-capacity quantum channels with a positive joint capacity at the output. Currently, we have no theoretical results for describing all possible superactive zero-capacity channels, hence there should be many possible still undiscovered combinations. Our method gives an algorithmic solution to the superactivation problem of zero-capacity quantum channels, and provides an efficient algorithmic solution for discovering all possible “superactive” channels. To discover these superactive zero-capacity channels, an extremely large set of possible quantum states has to be analyzed, however an efficient algorithmic framework is still missing for this purpose. We show a fundamentally new method of finding the conditions for “superactive” zero-capacity optical quantum channels. The proposed informational geometric method computes the joint capacity of zero-capacity quantum channels, based on the clustering of channel output states and an extremely efficient convex hull calculation algorithm. To study the superactivation of zero-capacity quantum channels, we introduce a new geometrical representation, called the quantum informational “superball”. The output of the constructed method is the radius of the smallest quantum informational superball. The proposed algorithm uses a fast clustering method with Delaunay tessellation to construct the convex hull of quantum states and to compute the radius of the quantum superball.

In our paper, we will show a possible solution to the superactivation of quantum channels. The proposed algorithm can be a very valuable tool for improving the results of fault-tolerant quantum computation and possible communication techniques over noisy optical quantum channels.

7948-28, Session 6

**Nonlinear strong and weak pulse generation for the B92 protocol**

A. Prabhakar, S. T. Thevan, Indian Institute of Technology Madras (India)

The B92 protocol, proposed by Bennet, requires the transmission of a strong and a weak pulse from Alice to Bob. Maintaining synchronization between the two pulses is often difficult. We demonstrate a scheme wherein 100 pico-second pulses, with 6 MHz repetition rate, from an active mode-locked Er-doped fiber ring laser are used as a pump in a four-wave mixing (FWM) experiment. A continuous wave DFB laser acts as the idler. Both pump and idler are amplified through a gain-saturated EDFA before being fed into 6m of highly nonlinear fiber. The pump (strong) and one of the resulting FWM components (weaker) are both tuned to lie on the ITU grid, allowing easy transmission along an optical channel. At the receiver, Bob’s end, the strong and weak pulses are demultiplexed. We have also deployed a self-gated avalanche photodetection (APD) system that allows the strong pulse to trigger the APD. By using the chromatic dispersion in the optical channel, we ensure that the gate signal generated by the strong pulse arrives a few pico-seconds before the weak pulse. This adds an additional layer of security in the transmission. We have observed a QBER of less than 10% when using this scheme and attempts by an eavesdropper to intercept the transmission also degrade the self-gating mechanism, and introduce quantifiable errors.

7948-25, Session 7

**Properties of nitrogen-vacancy centers close to the diamond surface: charge state, spectral linewidth, and preferential orientation**

K. C. Fu, Hewlett-Packard Labs. (United States) and Univ. of Washington (United States); C. M. Santoro, Hewlett-Packard Labs. (United States); P. E. Barclay, Hewlett-Packard Labs. (United States) and Univ. of Calgary (Canada) and National Institute for Nanotechnology (Canada); A. Faroq, Hewlett-Packard Labs. (United States); D. Twitchen, M. Markham, Element Six Ltd. (United Kingdom); R. G. Beausoleill, Hewlett-Packard Labs. (United States)

The combination of the long electron state spin coherence time and the optical coupling of the ground electronic states to an excited state manifold makes the nitrogen-vacancy (NV) center in diamond an attractive candidate for quantum information processing. To date the best spin and optical properties have been found in centers deep within the diamond crystal. For useful devices it will be necessary engineer NVs with similar properties close to the diamond surface. We report on properties including charge state control, low temperature spectral linewidth, and preferential orientation for near surface NVs formed either in CVD growth or through implantation and annealing.

7948-27, Session 7

**Gigahertz quantum control and nanoscale placement of single spins in diamond**

G. D. Fuchs, D. M. Toyli, Univ. of California, Santa Barbara (United States); C. Weis, T. Schenkel, Lawrence Berkeley National Lab. (United States); D. D. Awschalom, Univ. of California, Santa Barbara (United States)

Fast coherent control is critical to quantum information processing due to the practical need for fault tolerance and environmental decoupling. We present experiments with nitrogen vacancy (NV) centers in diamond that probe the room temperature dynamics of a single electronic spin strongly driven by a large amplitude oscillating field where new physics emerges [1]. Using coplanar waveguides patterned on diamond substrates we generate microwave magnetic fields large enough to produce spin rotations on the same timescale as the Larmor precession. Surprisingly, we find that coherent spin flips occur in less than a nanosecond under these conditions - faster than expected in conventional spin resonance. In addition to ground state manipulation, these techniques are used to observe and control spin coherence in the orbital excited-state [2], allowing for differentiation between phonon-induced dephasing, orbital relaxation, and coherent electron-nuclear spin interactions. These studies offer a pathway to rapid storage of quantum information using single nuclear spins. Finally, we present developments in spatially controlling ion implantation that enable the fabrication of NV center arrays in diamond for future spin-based quantum computing architectures [3].


Nuclear feedback in a single charged quantum dot under pulsed optical control

T. D. Ladd, D. L. Press, K. De Greve, P. L. McMahon, Stanford Univ. (United States); B. Friess, C. Schneider, M. Kamp, S. Höfling, A. W. B. Forchel, Julius-Maximilians-Univ. Würzburg (Germany); Y. Yamamoto, Stanford Univ. (United States)

The control of a single electron spin in a self-assembled semiconductor quantum dot using single, ultrafast optical pulses has emerged as a promising route for high-speed, optically driven quantum information processing. One remaining obstacle is the need to compensate for the drift of random nuclear fields. This problem may be aided by one of several recently discovered nuclear feedback phenomena observed in quantum dots under coherent control. In particular, we show how the coherent manipulation of a single electron spin hyperfine-coupled to a nuclear ensemble may stabilize the random drift of that ensemble. This observation may enable complex sequences for dynamical decoupling and assist in scaling to multiple-qubit operations.

Control and coherence of the optical transition of single defect centers in diamond

R. Hanson, Kavli Institute of Nanoscience Delft (Netherlands)

We demonstrate coherent control of the optical transition of single Nitrogen-Vacancy defect centers in diamond. On applying short resonant laser pulses, we observe optical Rabi oscillations with a half-period as short as 1 nanosecond, an order of magnitude shorter than the spontaneous emission time. By studying the decay of Rabi oscillations, we find that the decoherence is not caused by the resonant laser, but is instead dominated by off-resonant laser-induced spectral jumps. By using a low-power probe pulse as a detuning sensor and applying post-selection, we demonstrate that spectral diffusion can be overcome in this system to generate coherent photons.

Picotesla-scale magnetometry with diamond NV centers

V. M. Acosta, M. P. Ledbetter, Univ. of California, Berkeley (United States); A. Jarmola, Univ. of California, Berkeley (United States) and Laser Ctr, Univ. of Latvia (Latvia); L. J. Zipp, Univ. of California, Berkeley (United States); D. Budker, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States)

Recently, a new technique for measuring magnetic fields at the micro-Picotesla-scale has emerged based on optical detection of nitrogen-vacancy (NV) electron spin resonances in diamond [1,2]. This technique offers the possibility of measuring magnetic fields from a single electron spin, or even a single nuclear spin, in a wide temperature range from liquid-helium to well beyond room temperature. Sensors employing ensembles of NV centers promise the highest sensitivity [3], and pilot NV-ensemble magnetometers have very recently been demonstrated by several groups.

We demonstrate detection of the spin state of NV centers in diamond using optical absorption at 1042 nm. With this technique, measurement contrast and collection efficiency can approach unity, leading to an increase in magnetic sensitivity compared to the more common method of collecting red fluorescence. Working at 77 K with a sensor with active area 30 x 30 x 100 microns^3, we project shot-noise limited sensitivity of a few pT/Hz^{1/2}. We use this technique to operate a dual-channel gradiometer prototype that is well-matched for detection of J-coupling spectra in microfluidic NMR chips [4]. We also report measurements of the radiative lifetimes and other properties of the 1042 nm transition, which shed new light on the NV optical pumping mechanism.


Diamond defect center spin clusters

J. Wrachtrup, P. Neumann, F. Jelezko, H. Fedder, F. Reinhard, B. Naydenov, Univ. Stuttgart (Germany)

Diamond defect centers are a leading contender in solid state quantum information physics. A wealth of information is known meanwhile on the properties of individual impurities which has paved the ground for controlled defect center engineering. Defects are now being implanted into e.g. photonic structures to enhance their interaction cross section with photons. The talk will describe how to engineer interacting spin clusters in diamond. We will show how to specifically engineer certain spin states had how e.g. entanglement can be improved in these clusters.

Probing hole spin coherence in a quantum dot

B. D. Gerardot, Heriot-Watt Univ. (United Kingdom)

A grand challenge in quantum information science is finding a coherent quantum state in a semiconductor. One promising candidate is a hole spin in a self-assembled quantum dot. Previously, we discovered the hole spin relaxation and dephasing times to be ~1 ms and >1 μs, respectively. However, the role of the dipole-dipole part of the hyperfine interaction remains unexplored, as does the effect of heavy-hole / light-
between the TE and TM modes. The phase values are grouped into two basis sets \( B_1 = \{0, \pi\} \) and \( B_2 = \{\pi/2, -\pi/2\} \) which form two non-orthogonal bases. The key bit 0 is encoded as either phase 0 or \( \pi/2 \) and bit 1 as \( \pi \) or \( -\pi/2 \). The advantages of the proposed scheme over schemes that use electro-optic modulator are 1) true single-sideband modulation, 2) modulation frequency greater than 25GHz which simplifies the requirements on the optical filter at the receiver, and 3) increased security due to a quantum bit error rate (QBER) of 37.5% for simple intercept/resend attack. We describe the details of transmitter and receiver for the proposed scheme and derive the QBER for a simple intercept/resend attack.

7948-36, Session 9

Photonic circuits for coherent feedback quantum control

H. Mabuchi, Stanford Univ. (United States)

While many groups are working to understand the quantum optical input-output properties of individual nanophotonic devices, relatively little effort has yet been devoted to developing a corresponding circuit theory. Motivated by applications in both quantum computing and in classical ultra-low-power optical logic, our group has been working to apply the aforementioned new tools from coherent feedback quantum control theory to this problem. Rather than working in a single-photon limit we work with coherent electromagnetic fields (which can be arbitrarily weak if desired), which is more natural for robust classical information processing and surprisingly sufficient for quantum computational tasks such as quantum error correction. In this invited talk I plan to sketch the details of a photonic circuit that autonomously implements continuous quantum error correction using coherent feedback, and to discuss the broader impact of the modeling and analysis tools that we have used to design the circuit and to study its expected performance.

7948-37, Session 9

Quantum optics with microwave photons and cavity-based hybrid quantum systems

D. I. Schuster, The Univ. of Chicago (United States)

When a superconducting is qubit coupled to one (or more) cavities, the coherent interaction between a single photon in the cavity can dominate over decoherence of the cavity and qubit, realizing the strong coupling limit of cavity QED. By applying resonant microwave pulses and rapidly changing the cavity-qubit detuning using on-chip flux biasing of the qubit full control over both the qubit state and the quantum state of light in the cavity can be achieved. Adding an additional “measurement” cavity to monitor the qubit independently allows the qubit to be used as a non-destructive probe of a “storage” cavity in a single shot manner. Such quantum non-demolition measurements could be used for several quantum information processing tasks such as error correction, preparation by measurement, and one-way quantum computing. While superconducting circuits show great promise as an element of a quantum information processor, it is likely that similar to their classical analogs, a quantum computer will rely on many physical systems to perform different tasks. Microwave cavities can serve as a universal quantum bus for connecting between superconducting circuits and other natural quantum systems such as electron and nuclear spins, atoms, molecules, or crystal impurities. These systems could enhance the storage time, or enable long distance quantum communication via optical upconversion among other things. A general approach to coupling will be described and preliminary experiments on coupling super conducting cavities to electron spin ensembles will be discussed.
7948-38, Session 9

Cavity quantum electrodynamics based quantum low-density parity-check encoders and decoders
I. B. Djordjevic, The Univ. of Arizona (United States)

Quantum information processing (QIP) is an exciting research area with numerous applications. In order to perform an arbitrary quantum computation, a minimum number of gates, known as universal quantum gates, is needed. The QIP, unfortunately, relies on delicate superposition states, which are sensitive to interactions with environment, resulting in decoherence. Moreover, the quantum gates are imperfect and the use of quantum error correction coding (QECC) is essential to enable the fault-tolerant computing and to deal with quantum errors. The QECC based on structured quantum LDPC codes offers a number of advantages thanks to the sparness of corresponding quantum check-matrix. It has been recently demonstrated by author that universal quantum gates can be implemented in integrated optics and all-fiber technologies. The most critical gate, the CNOT-gate has been implemented as a probabilistic device. The CNOT gates from linear optics provide only probabilistic outcomes and as such are not suitable for large-scale computation (in the order of thousand and above). On the other hand, the nonlinear Kerr phase shift up to π/4 at the single-photon has been demonstrated by Fushman et al. by using the cavity quantum electrodynamics (CQED)-based devices, which can be used as a starting point towards the deterministic CNOT-gate implementation. In this paper, we show that arbitrary set of universal quantum gates can be implemented based on COED. We then show that the quantum gates from Clifford group needed in QECC can also be implemented using the same technology. We further show that encoders and decoders for quantum LDPC codes can be implemented based on Hadamard and CNOT gates using COED. Finally, we perform the Monte Carlo simulations and evaluate performance of several classes of quantum LDPC codes suitable for implementation in CQED technology.

7948-39, Session 9

Modification of the spontaneous emission rate of nitrogen-vacancy centers in diamond by coupling to plasmons
A. Faraon, Hewlett-Packard Labs. (United States); Y. C. Jun, Stanford Univ. (United States); P. E. Barclay, K. C. Fu, C. M. Santori, Hewlett-Packard Labs. (United States); M. L. Brongersma, Stanford Univ. (United States); R. G. Beausoleil, Hewlett-Packard Labs. (United States)

Nitrogen-vacancy centers in diamond are widely studied both as a testbed for solid state quantum optics, and for their applications in quantum information processing and magnetometry. Here we demonstrate coupling of nitrogen-vacancy centers charged with a single electron to gap plasmons in metal nano-slits. We use diamond samples where nitrogen-vacancy centers are implanted at an accelerating voltage of 50keV. The nitrogen-vacancy centers can reach implantation depths as deep as 100nm, with the maximum concentration at a depth of 60nm. Diamond ridges, whose width can be as small as few tens of nanometers, are first fabricated using electron beam lithography and dry plasma etching. Then, a 120nm thick silver layer is deposited thus creating silver slits where the diamond ridge filled the gap. Theoretically, for a slit width of 50nm, enhancements of spontaneous emission rate up to 15 are achievable. For maximum enhancement, the dipole should be located in the middle of the slit and oriented along the electric field direction in the metal-insulator-metal waveguide. We measure enhancements of the spontaneous emission rate of the zero photon line by a factor of 3 at a temperature of 8K. The enhancement is lower than the theoretical prediction because of several factors including: the spatial distribution of nitrogen-vacancy centers inside the slit, dipole orientation not aligned with the electric field direction in the optical mode of the slit, and the roughness of the metal.

7948-40, Session 9

Towards efficient nanophotonic coupling to NV centers
P. E. Barclay, Univ. of Calgary (Canada); K. C. Fu, C. M. Santori, A. Faraon, R. G. Beausoleil, Hewlett-Packard Labs. (United States)

The diamond nitrogen-vacancy (NV) center is an impurity which possesses well defined optical transitions and optically addressable electronic spins with long coherence times. These properties make the NV center a promising system for quantum information processing and magnetometry. Integrating NV centers with nanophotonic devices would improve the efficiency of NV optical readout and control, and enable scalable optical coupling between multiple NVs. In this presentation we review our recent progress in diamond-based nanophotonics, and present recent experiments using hybrid GaP-diamond microcavities at liquid He temperature, in combination with fiber tapers, to improve collection efficiency of NV photoluminescence. Hybrid GaP-diamond microdisk devices with mode volumes < 8 cubic wavelength in GaP, and supporting modes with Q above 10000 are optically coupled to NV centers near the diamond surface. Using a nanopositioning system installed inside a liquid He cryostat, a sub-micron diameter fiber taper is positioned in the near field of the microdisks, and shown to provide improved collection efficiency of microcavity coupled photoluminescence. We also discuss progress in studying photonic crystal nanocavities realized from this hybrid material system.

7948-41, Session 10

Quantum optics with single molecules
S. J. Goetzinger, Y. Rezus, R. Lettow, M. Pototschnig, J. Hwang, A. Renn, G. H. Zumofen, V. Sandoghdar, ETH Zurich (Switzerland)

In this talk we shall review our quantum optical experiments with single molecules at cryogenic temperatures. In the first experiment, we show that photons can be efficiently coupled to a single emitter without the need for a microresonator [1], resulting in a strong extinction of a weak laser beam. The situation changes when a second, pulsed laser inverts the population of the molecule. Depending on the power of this laser, we can switch from an attenuation of the weak probe beam to amplification. The latter is achieved via stimulated emission and demonstrates that a single molecule can act as an optical transistor [2]. In another experiment we exploit the fact that single molecules serve as independent frequency-tunable single photon sources with a flux of more than one million photons per second [3]. By tuning the frequencies and spectral widths of two individual remote molecules, we can explore various aspects of two-photon interference [4]. Finally we discuss the potential of our experimental approach for exciting a single molecule with the photons emitted by another molecule.


7948-42, Session 10

A solid-state atomic ensemble as a light-matter quantum interface
C. Clausen, I. Usmani, F. Bussieres, N. Sanguoard, H. de Riedmatten, M. Afzelius, N. Gisin, Univ. of Geneva (Switzerland)

The efficient transfer of quantum information between single photons and quantum memories is an important requirement for Quantum Information Science. In particular, it is necessary for scalable implementations of quantum information networks and repeaters. In recent years, atomic
ensembles have emerged as one of the most advanced systems to harness the quantum connection between matter and light. Here, we will describe our efforts to build a light-matter quantum interface for single photons using atomic ensembles in a solid-state environment. The interface is implemented with rare-earth ions doped into crystals, providing a large number of stationary atoms with good coherence properties. We are using the atomic frequency comb storage protocol, which has the advantage of allowing time multiplexing to store multiple qubits. After an introduction, our recent results will be reviewed, starting with the mapping of tens of photons qubits onto a neodymium-doped crystal having a transition wavelength at 883 nm. We then show how this ensemble is used to map and retrieve heralded single photons generated through spontaneous parametric down conversion. Finally, we will demonstrate that storage of a 883 nm signal photon preserves the energy-time entanglement it shares with its corresponding 1339 nm idler photon. This type of interface is an excellent candidate to realise memories for quantum repeaters.

7948-43, Session 10

Interference of single photons from two separate semiconductor quantum dots

E. B. Flagg, A. Muller, S. V. Polyakov, A. Ling, A. L. Migdall, G. S. Solomon, Joint Quantum Institute (United States)

We demonstrate interference between photons emitted by two independent quantum dots in separate samples excited by a pulsed laser. Their emission energies are tuned into resonance using strain. Comparison of interference with parallel and orthogonal polarizations indicates that the photons have a coalescence probability of 18.1% and the coincidence rate is below the classical limit. Post-selection of coincidences within a narrow time window increases the coalescence probability to 47%. The probabilities are below unity due to dephasing of the excitonic states before emission, and the post-selected probability is additionally reduced by the detector time response.

7948-44, Session 11

Quantum interface between photons and electron spins in a semiconductor

H. Kosaka, Tohoku Univ. (Japan)

Spin is a quantum property of photons and electrons. For spin-based quantum information technology, preparation and readout of the electron spin state should be spin coherent. We demonstrate that the polarization coherence of light can be transferred to the spin coherence of electrons in a semiconductor quantum nanostructure [1], and the prepared coherence of the electron spin can also be read out with light by the developed tomographic Kerr rotation method [2]. We also demonstrate that a single photon is efficiently converted into a single electron trapped in a gate-defined quantum dot, and the charge state is detected with an adjacent quantum point contact [3]. We further demonstrate that the spin coherence of a single electron trapped in one of double quantum dots is manipulated all-electricaly and read out via the Pauli spin blockade [4]. These demonstrations were carried out in a condition where the up/down spin basis states of electrons remained degenerated under an in-plane magnetic field, in which condition the entire Poincare sphere representing polarization states of photons can be mapped onto the Bloch sphere representing spin polarization states of electrons. All of these functions are needed to build all semiconductor quantum repeaters and distributed quantum computers.


7948-45, Session 11

Novel single photon sources in diamond

I. Aharonovich, S. Castelletto, Univ. of Melbourne (Australia); D. Simpson, B. Gibson, A. Stacey, J. Orwa, B. Johnson, The Univ. of Melbourne (Australia); S. Tomijenovic-Hanic, The Univ. of Sydney (Australia); J. McCallum, A. Greentree, L. Hollenberg, S. Prawer, The Univ. of Melbourne (Australia)

Diamond is one of the most important hosts of room-temperature single photon sources. Diamond hosts bright single photon sources that can be imaged and used for applications such as quantum key distribution. Initial work focused on the negatively-charged nitrogen-vacancy (NV) color centre due to its brightness, ease of fabrication, and relatively well-understood level structure. However NV has many problems, including small Huang-Rhys factor and photochrome. Early searches for alternative single photon sources identified the nickel-related NE8 centre [1], and the silicon-vacancy centre [2]. NE8 is difficult to fabricate on demand, and silicon-vacancy has significant non-radiative transitions, so neither centre is ready to displace NV.

Recently, we have discovered centres with improved single photon properties over NV [3-6]. In particular we have identified a family of chromium-related centres [4]. They are relatively easy to manufacture, have short lifetimes (a few nanoseconds), no photo-blinking, and some show ideal two-state emission. With high Huang-Rhys factors and emission around 750nm, prospects for fiber integration are good. Here we describe these centers’ properties, growth conditions, and prospects for applications such as quantum key distribution.


7948-46, Session 11

Two-photon interference using electrically tunable remote quantum dots

R. B. Patel, Toshiba Research Europe Ltd. (United Kingdom) and Univ. of Cambridge (United Kingdom); A. J. Bennett, Toshiba Research Europe Ltd. (United Kingdom); I. Farrer, C. A. Nicoll, D. A. Ritchie, Univ. of Cambridge (United Kingdom); A. J. Shields, Toshiba Research Europe Ltd. (United Kingdom)

One of the criteria for the physical implementation of quantum computing is that it must be possible to manipulate individual qubits to prepare them in same well-defined state. In schemes involving linear optics and single photons from self-assembled quantum dots, this requirement can be intractable as quantum dots form with a distribution of emission energies. We have designed a structure based on InAs quantum dots embedded in an adjacent quantum point contact [1], and the prepared coherence of the electron spin can also be read out with light by the developed tomographic Kerr rotation method [2]. We also demonstrate that a single photon is efficiently converted into a single electron trapped in a gate-defined quantum dot, and the charge state is detected with an adjacent quantum point contact [3]. We further demonstrate that the spin coherence of a single electron trapped in one of double quantum dots is manipulated all-electrically and read out via the Pauli spin blockade [4]. These demonstrations were carried out in a condition where the up/down spin basis states of electrons remained degenerated under an in-plane magnetic field, in which condition the entire Poincare sphere representing polarization states of photons can be mapped onto the Bloch sphere representing spin polarization states of electrons. All of these functions are needed to build all semiconductor quantum repeaters and distributed quantum computers.


7948-46, Session 11

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energy. This opens up the possibility of transferring quantum information between remote solid-state systems.

9748-47, Session 11

Single-qubit quantum gates using magnon-photon interactions

P. Kumar, Indian Institute of Technology Madras (India)

We propose the use of spin wave (SW)-optical interactions to realize single-qubit quantum gates. The fundamental TE and TM modes, represented by the kets, |₀;TE> and |₀;TM> form a two-level quantum system. These kets are coupled by SWs of angular frequency Ω rad/s due to Faraday effect. By adjusting the phase of the SWs, single-qubit gates-CNOT, CZ, CPHASE-can be realized. Quantum mechanically, this is the result of magnons scattering off the optical photons. The advantages of the proposed scheme are 1) high speed gating due to SW frequency > 25GHz; 2) ease of integration as the gates can be realized in thin film magnetic heterostructures, and 3) efficient operation in the C-band (1550nm) making it suitable for photonic communications. We show that SW-optical interactions can be used to realize efficient semi-classical quantum Fourier transform, an important step in many quantum algorithms.

9748-64, Session 12

A light emitting diode for entangled photons

M. R. Stevenson, Toshiba Research Europe Ltd. (United Kingdom); C. L. Salter, Toshiba Research Europe Ltd. (United Kingdom) and Univ. of Cambridge (United Kingdom); I. Farrer, C. A. Nicoll, D. A. Ritchie, Univ. of Cambridge (United Kingdom); A. J. Shields, Toshiba Research Europe Ltd. (United Kingdom)

Existing sources of entangled photons require a laser excitation, imposing a practical limit on their potential for large-scale quantum information applications [1]. For the widely used parametric down-conversion sources, zero or multiple photon-pairs are usually emitted due to the probabilistic nature of the non-linear process. This presents an additional fundamental limitation in the form of efficiency and errors. Here we demonstrate the first electrically driven entangled light source, based on a layer of InAs quantum dots embedded in a p-i-n light emitting diode structure, with potential to operate 'on-demand' [2].

A quantum dot can emit a pair of photons by the radiative decay of the biexciton state to the ground state to produce the entangled Bell state |ψ+> [3,4]. The biexciton state is formed by carrier capture from current passing through the diode. Polarization dependent cross-correlation measurements between biexciton and exciton photons were performed at ~5K with a dc injection current of 31nAμm-2. The fidelity of the measured photon pairs to the expected Bell state |ψ+> reaches a maximum of 0.71±0.02 for photon pairs emitted simultaneously, which is comparable to similar optically driven sources. Furthermore the device can be operated in ac mode with measured fidelity up to 0.83±0.03.

The detected photon pairs are shown to violate Bell’s inequality, indicating the quality of entangled light is sufficient for applications such as quantum key distribution [5]. The fidelity may be increased further by increasing the speed of the device to minimize re-excitation during pulsing, and by reduction of background light.

Electrically-pumped photonic nanowire single-photon source with an efficiency of 89%

N. Gregersen, Technical Univ. of Denmark (Denmark); J. Claudon, Commissariat à l’Énergie Atomique (France); T. R. Nielsen, J. Mørk, Technical Univ. of Denmark (Denmark); J. Gérard, Commissariat à l’Énergie Atomique (France)

The single-photon source (SPS) is a central device in quantum cryptography and in linear optics quantum information processing. A key figure of merit is the efficiency, defined as the number of photons per trigger detected by the collection optics. Achieving a high efficiency requires careful tailoring of the photonic environment, traditionally performed by placing a quantum dot (QD) inside a high-quality micro-cavity. However, strong sensitivity to surface roughness has limited the efficiency of this approach to 44%.

Recently, a new SPS design based on a QD embedded in a photonic nanowire was proposed. Here, a geometrical effect ensures good coupling between the QD and the optical mode, and a regular tapering section is employed to control the far field emission profile. Unlike cavity-based approaches, the photonic nanowire SPS features broadband spontaneous emission control and high tolerance towards surface roughness. This has lead to a record-high measured efficiency of 72% for an optically pumped device. However, for practical applications electrical pumping is desired. Since metal contacts strongly absorb and scatter light, the implementation of electrical contacts without compromising the efficiency poses a challenge.

In this work we propose a new electrically-pumped photonic nanowire SPS design. For realistic parameters, the design features an efficiency of 89% predicted by numerical simulations. The new design includes an inverted tapering section, in which the optical mode is adiabatically expanded inside the nanowire to ensure a low-divergence output beam while minimizing the relative modal overlap with the metal contacts.
Nonlinear enhancement in photonic crystal waveguide with spot-size converter
M. Shinkawa, Yokohama National Univ. (Japan); T. Baba, Yokohama National Univ. (United States)

We have proposed and demonstrated SOI lattice-shifted photonic crystal waveguides as a low-dispersion on-chip slow light device and evaluated their nonlinear enhancement. In this study, we integrated the device with spot-size converters (SSC) using CMOS process. The SSC consists of inverse-tapered Si wire, and allows high-power input and clearer nonlinearities. The coupling loss between lensed fiber and Si wire is suppressed to 3 dB per facet. Therefore the power in the fiber preceding the device is reduced and self-phase modulation (SPM) in the fiber suppressed, but sufficient to observe clear nonlinear effects in the LSPCW. In the measurement, 1.5-ps wide pulses at ~1.55 m from mode-locked laser was amplified and coupled to four samples: (A) Si wire only; (B) Si wire with 300- m long LSPCW (group index ng = 65); (C) ibid (ng = 34); (D) ibid (ng = 28). We measured input-output characteristics up to a pulse peak power of 10 W, at which negligible SPM occurs outside the SOI device. For sample A, the output power began saturating at 0.54 W from two-photon absorption (TPA). For B-D, the threshold power decreased to 0.009, 0.105 and 0.18 W, respectively. SPM was observed simultaneously: at 10 W, the pulse spectrum did not change distinctly in A, while exhibited 70% broadening in C. Four-wave mixing was also observed for two synchronized pulses. These results indicate that low-dispersion slow light can be exploited for low-power compact functional devices such as optical limiters and wavelength converters.

Slow and fast light in photonic crystals with gain and loss
A. Sukhorukov, The Australian National Univ. (Australia)

No abstract available

Optofluidic dispersion engineering of photonic crystal waveguides
A. Casas Bedoya, P. Domachuk, C. Grillet, C. Monat, S. Tomljenovic-Hanic, E. Magi, B. J. Eggleton, The Univ. of Sydney (Australia)

Optofluidics, the marriage of photonics and microfluidics, uses the inherent flexibility of confined fluids to reversibly tune photonic structures beyond traditional fabrication methods. Photonic crystals (PhCs) are well suited to optofluidic tuning; their periodic air-hole microstructure is a natural candidate for housing liquids. This microstructure enables PhCs to strongly control light on the wavelength scale. Defects purposefully introduced during PhC fabrication can support guided optical modes, forming waveguides or cavities; their dispersion can be engineered by fine alteration of individual PhC holes in or around the structure. This engineering requires very high fabrication tolerances and is irreversible once performed. Optofluidic tuning of PhC waveguides, however, is completely reversible and only limited by the properties of available fluids. Infiltration of the PhC microstructure surrounding a waveguide modifies the local refractive index profile through the liquid used and the amount of microstructure filled. In this paper we demonstrate experimentally for the first time, optofluidics slow light dispersion engineer of photonic crystals waveguides. We have modified the group velocity dispersion using a technique based on selective liquid infiltrations to precisely and reversibly change our structures, leading us to obtain slow light regions over different bandwidths. We also present how the amount of fluid infiltrated into the photonic crystal microstructure strongly influences the waveguide dispersion.

Large-core photonic microcells for coherent optics and laser metrology
F. A. Benabid, Univ. of Bath (United Kingdom)

No abstract available

A novel grating based temporal buffering approach
N. J. Copner, Univ. of Glamorgan (United Kingdom)

The creation of adaptive temporal buffering in telecommunications is becoming increasingly important as the technology migrates to an All Optical Network (AON). Here we describe a simple but effective way of manipulating the data's spectral components phase so as to effect not only dispersion but induce temporal delays. Using a diffraction grating the author illustrates a way of creating both a nonlinear (dispersion) and linear (group delay) phase change as a function of wavelength. The author will describe some of the basic physics behind this approach and some of the practical limitations. In particular, the loss roll off and the effective coherence reduction as we extend to large wavelength ranges or large dispersions are discussed. Novel optical approaches are presented which will help to eliminate these degrading effects. Initial experimental results are presented to illustrate some of the effects presented.

Recent advances in tunable optical delays and their applications
A. E. Willner, The Univ. of Southern California (United States)

No abstract available

Broadband slow light with a swept-frequency source
R. Zhang, Y. Zhu, D. J. Gauthier, Duke Univ. (United States)

We introduce a new concept for stimulated Brillouin scattering (SBS) slow light that is applicable for broadly-tunable frequency-swept sources such
as that used in optical coherence tomography. It allows slow light to be
achieved, in principle, over the entire transparency window of the optical
fiber. The key idea is to pump the SBS process with a beam that is
derived from the swept source, but shifted to a higher frequency equal to
the Brillouin frequency shift of the fiber using a Mach-Zehnder modulator.
In this way, the pump beam frequency automatically tracks the swept-
source signal frequency as they enter the fiber and hence are always
near the SBS resonance frequency, where SBS amplification and the
associated slow light delay are largest. The fact that the pump and signal
beams counterpropagate through the fiber causes a small detuning
between the beams, which decreases the slow light effect. This detuning
increases with increasing fiber length L and with the source sweep rate
R. We demonstrate a SBS slow light delay of more than 1 ns over a wide
bandwidth at 1550 nm using a 2-km-long highly nonlinear fiber with a
source sweep rate of 20000 MHz/ms. To understand the swept-source
SBS slow light, we developed a mathematical model that characterizes
the gain profile and delay as a function of sweep rate and frequency
detuning. The theoretical simulation shows great agreement with the
experiments. This research provides a path toward practical applications
of the SBS slow light technique that use swept sources.

7949-09, Session 2

Polarization attributes of stimulated Brillouin scattering slow light in fiber
A. Zadok, M. Tur, A. Eyal, Tel Aviv Univ. (Israel); L. Thevenaz,
Ecole Polytechnique Fédérale de Lausanne (Switzerland)
No abstract available

7949-10, Session 2

Slow light fibre systems in microwave photonics
L. Thevenaz, S. Chin, Ecole Polytechnique Fédérale de Lausanne
(Switzerland); P. Berger, J. Bourderionnet, Thales Research &
Technology (France); S. Sales, J. Sancho-Dura, Univ. Politècnica
de Valencia (Spain)
No abstract available

7949-11, Session 3

Manipulating slow light propagation using optical nanofibers with low finesse cavity
K. Hakuta, K. P. Nayak, F. L. Kien, The Univ. of Electro-
Communications (Japan)
No abstract available

7949-12, Session 3

A chirped grating based white light cavity for high-speed data buffering and gravitational wave detection
Y. Jang, H. Yum, Northwestern Univ. (United States); P. R.
Hemmer, Texas A&M Univ. (United States); S. M. Shahriar,
Northwestern Univ. (United States)
No abstract available
In the past few years, slow light has received much attention not only for scientific interests but also for the potential applications, such as enhancing the light-material interaction, optical switching, and optical storage. Recently, intensive research has started to be directed to slow light propagation in plasmonic structures because of the significant advantage that light could be trapped in artificially designed plasmonic structures within nanoscale dimensions. Here, we experimentally demonstrate that plasmonic metamaterials, three-dimensional supercrystals composed of colloidal Ag nanoparticles (AgNPs), can generate broad-band surface plasmon modes at visible frequencies and the group refractive index of these surface modes can reach to around 30 with a general Kretschmann light coupling configuration. The three-dimensional plasmonic metamaterials are fabricated by layer-by-layer assembly with colloidal AgNPs. In particular, their plasmonic properties are tunable by the number of stacked layers, lattices spacing of supercrystal, size of nanoparticles, and dielectric constant of the surrounding media. Moreover, the plasmonic waves are perpendicularly confined in the stacking direction due to the finite thickness, resulting in prominent Fabry-Perot resonances. These resonances play an important role in the cutoff frequencies for the slow wave surfaces that propagate in the interface of surrounding air and plasmonic metamaterials. In our experiment, the dispersion relations of these surface plasmonic polaritons were measured with a Kretschmann-Raether configuration to directly couple the free-space light in and out of these surface modes. Furthermore, according to our analysis, one of the slow propagating surface modes show a high group refractive index of about 30 and a high figure-of-merit of about 15 with the free-space wavelength at 577 nm.
Ultrasound-modulated optical tomography is a hybrid imaging modality which combines the advantages of ultrasound resolution and optical contrast. In this way small buried tumors can be detected inside health tissue without surgery. To be useful for real clinical applications, ultrasound 'tagged' photons (signal) must be separated from 'untagged' photons (background noise) to very high degree. So far spectral hole burning (SHB) in rare earth crystals has demonstrated the most encouraging preliminary results, but residual leakage of untagged photons is still a problem. Here we show that slow light can provide an additional temporal degree of freedom that enhances the SHB filtering enough to permit few-cycle ultrasound pulse detection in deep tissue phantoms and real chicken breast tissue.

On chip silicon platform for slow and fast light

Tunable optical delay hole burning and ground state depletion effects in cesium vapor
M. D. Anderson, G. Perram, Air Force Institute of Technology (United States)

Optically tunable pulse delays in cesium vapor were demonstrated by pumping several D2 transitions (F'=4, F''=3,4,5) burning holes in the D1 absorption spectrum (F'=4, F''=3,4). A modified sub-Doppler absorption spectroscopy setup was used with counter propagating beams intersecting in the cesium vapor cell held at a constant temperature between 40°C and 120°C. The continuous wave D2 pump is set at a fixed power and frequency detuned from an absorption peak at 852.357 nm. A Gaussian 7-ns full-width at half-maximum probe laser pulse is scanned across part of the D1 absorption spectrum from 894.600 nm to 894.610 nm. Zero-delay time is determined when the probe is detuned far off resonant frequency and the value is subtracted from the arrival time for each pulse to calculate the pulse delay. Probe laser optical delays followed Kramers-Kronig model prediction for Cs D1 at 109.5°C without D2 pump laser. Delays up to 24 ns were achieved by detuning from resonance +/-10 GHz. Next optical control of D1 probe pulse delay was demonstrated by varying D2 pump intensity. At various D2 pump powers tunable delays were observed and the predicted delay from measured absorption spectra matched model predictions. Additionally absorption changes rapidly across a narrow frequency range in the neighborhood of a burnt hole. Delay effects in agreement with model predictions were observed along with rapidly varying frequency-dependent absorption in the vicinity of spectral holes. Tuning of the optical pulse delay is obtained closely matched Kramers-Kronig model predictions using Voigt lineshapes and full hyperfine structure.

Optical Ramsey interference and its performance in D1 line excitation in rubidium vapor for implementation of a vapor cell clock
G. S. Pati, Delaware State Univ. (United States); F. K. Fatemi, M. Bashkansky, U.S. Naval Research Lab. (United States); S. M. Shahriari, Northwestern Univ. (United States)

Spread spectrum technology with single photons and slow light
C. Chuu, C. Belthangady, Stanford Univ. (United States); I. A. Yu, National Tsing Hua Univ. (Taiwan); G. Yin, J. M. Kahn, S. E. Harris, Stanford Univ. (United States)

A quantum memory with telecom photon conversion
A. M. Kuzmich, Georgia Institute of Technology (United States)

No abstract available
Localized structures in bidirectional ring lasers

J. R. Tredicce, L. Colombo, L. Gil, Institut Non Linéaire de Nice Sophia Antipolis (France)

No abstract available

Practical considerations for a fast-light enhanced helium-neon ring laser gyroscope

J. Schaar, Los Gatos Research, Inc. (United States); S. M. Shahriar, Northwestern Univ. (United States)

No abstract available

Slow-light interactions in liquid crystal light-valves and applications for adaptive interferometric detection

S. Residori, U. Bortolozzo, J. Huignard, Institut Non Linéaire de Nice Sophia Antipolis (France)

No abstract available

Enhancing the sensitivity of interometer using fiber resonators

Y. Zhang, J. Wang, X. Zhang, H. Wu, J. Zhang, Y. Cai, P. Yuan, Harbin Institute of Technology (China)

No abstract available

A zero-area Sagnac superluminal ring laser for high-sensitivity accelerometry

J. Yablon, H. Yum, Y. Tu, S. M. Shahriar, Northwestern Univ. (United States)

No abstract available

SBS based radar true time delay

M. J. Steiner, D. R. Walker, M. Bashkansky, U.S. Naval Research Lab. (United States)

No abstract available

Nonlinear light matter interactions in slow light photonic structures: performance metrics

J. B. Khurgin, The Johns Hopkins Univ. (United States)

Strong confinement of the electromagnetic field and reduction of the group velocity can be achieved in various Slow Light Structures can greatly enhance the strength of light matter interactions. These interactions include various nonlinear effects as well as spontaneous emission. Based on these well understood observations a number of devices based on slow light had been proposed, including all-optical and electro-optical modulators and switches, various sensors, and the device sfor quantum communication and information processing.

All these slow light devices inevitably rely upon existence of strong optical resonances, and the resonances are always accompanied by strong dispersion and significant loss. As a result, the bandwidth of SL devices becomes limited.

In this presentation I will address the issue of trade off between the bandwidth and other important characteristics of SL devices - switching power, size, average power dissipation, noise floor, and others. I will show that different photonic schemes (for example single rather than coupled resonators) may be more applicable for different nonlinear effects. I will identify the most promising application niches for the nonlinear devices based on slow light. I will also compare performance of the all-dielectric and plasmonic slow wave devices.

Energy considerations in slow and fast propagation of light

R. W. Boyd, Univ. of Rochester (United States); P. Narum, Norwegian Defence Research Establishment (Norway); D. J. Gauthier, Duke Univ. (United States)

No abstract available

Pulse distortion in linear slow light systems: theoretical limits and compensation strategies

M. González-Herráez, Univ. de Alcalá de Henares (Spain); L. Thevenaz, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No abstract available

Resonance photonic structures: from light basics towards quantum-matter quill and hardware design

I. V. Melnikov, E.L.S. Co. (Russian Federation)

No abstract available
Influence of non-linear interactions on electromagnetic-field propagation in quantized many-electron systems

V. L. Jacobs, U.S. Naval Research Lab. (United States)

No abstract available
7950-01, Session 1

Orbital angular momentum of light as a tool for nanophotonics

G. Molina-Terriza, MacQuarie Univ. (Australia)

The possibility to control separately the Orbital Angular Momentum (OAM) and the Spin Angular Momentum (SAM) of light in paraxial beams, has opened the path to an immense amount of applications. At the same time, there has been an intense effort to study and to understand theoretically and experimentally the phenomena related with the OAM of light. In particular, there has been an ongoing interest in understanding the relation between the OAM, the SAM and the total Angular Momentum of electromagnetic fields beyond the paraxial approximation. This is of special relevance to situations where radiation interacts with material particles of a size of the order or smaller than the wavelength, a situation typically encountered in atomic physics and more recently in the field of nanophotonics.

In this article I will present some examples where studying the exchange of OAM between light and macroscopic objects can give us a better insight of the object structure. I will also review two experimental methods to retrieve that spiral information, which will help us to understand in which situations the spiral information can be useful. Then, I will show how to control the multipolar content of an electromagnetic field, i.e. the total AM content of a general field, with OAM modes. This result will allow us to smoothly travel from the macroscopic world to the subwavelength level, i.e. the nanoworld. I will then show you a recent experiment where the use of OAM modes and their superpositions allow us to control the inner modes of metallic nanorods [7].

7950-02, Session 1

Angular momenta and spin-orbit interaction of nonparaxial light in free space

K. Y. Bliokh, National Univ. of Ireland, Galway (Ireland); M. A. Alonso, Univ. of Rochester (United States); E. A. Ostrovskaya, The Australian National Univ. (Australia)

We re-examine the problem of the identification of the spin and orbital parts of the angular momentum (AM) of an electromagnetic wave, which has a long history and has posed fundamental difficulties both in quantum electrodynamics and classical optics.

We give an exact self-consistent solution in terms of the fundamental photon operators and unify previously disjointed results:

(i) non-canonical orbital AM and spin AM operators obtained for the second-quantized fields;

(ii) non-commutative photon position operator and Berry monopole field in momentum space;

(iii) separation of the spin and orbital parts of Poynting energy flows.

We show that the polarization-dependent non-paraxial part of the orbital AM arises from Berry-phase terms describing the spin-orbit interaction (SOI) of light. A similar effect occurs dynamically upon spin-to-orbital AM conversion in focusing and scattering of polarized light. Other manifestations of the SOI are the spin and orbital Hall effects of light (i.e., transverse shifts of the field centre of gravity) which are described by our position operator and take place even in free space. We apply the general theory to Bessel-beam solutions where the fundamental operators manifest themselves in immediately observable orbital- and spin-dependent intensity distributions.

7950-03, Session 1

Evolution of orbital angular momentum entangled bi-photon propagating through a turbulent atmosphere

F. S. Roux, National Laser Ctr. Trust (South Africa)

Orbital angular momentum (OAM) entangled bi-photons are a resource for the higher dimensional implementation of quantum cryptography, which allows secure communication over various channels. In the case where free-space is used as communication channel the initial OAM entangled bi-photon loses some or even all of its entanglement because of the scintillation that it experiences while propagating through the turbulence in the atmosphere. This decoherence of OAM entanglement has so far only been studied for the case of weak turbulence. Unfortunately, it is the more challenging strong turbulence scenario that is relevant for the practical implementation of free-space quantum communication through the atmosphere. Using an approach that differs from previous approaches, we derive a 'Master-equation' for the evolution of an OAM entangled bi-photon during propagation through turbulence. However, in our approach the equation contains a derivative with respect to the propagation distance instead of time. The principle is to consider the propagation over an infinitesimal distance of OAM basis states through a random medium. This approach allows one to include, not only the effect of turbulence of arbitrary strength, but also the effect of the inner and outer scale of the turbulence, as represented by the Tartarskii and von Karman spectra. The resulting expression gives the rates of decoherence for arbitrary initial OAM entangled states and can be use to calculate the concurrence, which measures the amount of entanglement, as a function of propagation distance for different initial entangled OAM states.

7950-04, Session 2

The macro-tweezer: a long-range optical mirror trap to catch large and highly motile micro-organisms

G. Thalhammer, R. Steiger, S. Bernet, M. A. Ritsch-Marte, Innsbruck Medical Univ. (Austria)

Here we report for the first time the optical trapping of large actively swimming organisms, as for instance Euglena protists and dinoflagellates of 30-70µm length. The 3D all-optical trapping and guiding within a volume of 2mm x 1mm x 2 mm of these highly motile organisms, swimming with a typical speed of 200 µm/s, was made possible utilizing a mirror trap with a side-view prism and a spatial light modulator.

Adverse bio-effects are kept low as trapping occurs outside focal spots. We expect our approach to open possibilities in the optical handling of individual 50-100µm size motile micro-organisms that could hitherto not be envisaged, such as e.g. contact-free holding for taxonomy and photography, selective collecting or tagging, or contamination-free collection for PCR. Straightforward implementation in microfluidic devices, or applications in tissue engineering, such as live cell lithography, also seem promising.

7950-05, Session 2

Development of a two-photon polymerization and optical tweezers microscope for fabrication and manipulation of microstructures

N. D. Ingle, S. K. Mohanty, The Univ. of Texas at Arlington (United States)
We report the development of a two-photon polymerization (TPP) and optical tweezers microscope, for fabrication of microstructures and optical manipulation of the micro-fabricated structures. The system is based on an inverted Nikon microscope with a tunable Ti: Sapphire femto-second laser coupled to the laser port above the epifluorescence port. Scanning of the sample was performed using a Nanonics AFM Multiview piezo stage and the exposure time was controlled by a Uniblitz shutter. In the mode-locked condition we fabricated both nano particles and wire-structures using the two-photon process. The size of the TPP nanoparticle and wire-structure was found to depend on the fs laser intensity, wavelength and exposure time. Changing the axial positioning of the focused TPP laser beam caused the structures to be fabricated a few microns above the surface of the glass substrate. The same laser was then employed in the mode lock-OFF condition to trap the nanoparticles/wire-structures and manipulate them even in a highly viscous medium. This allowed in-situ corrective positioning of the polymerized structures. Further tracking of the TPP nanoparticle in the medium and in the tweezers beam allowed estimation of its size. These results will be presented along with use of the TPP structures in biological applications.

Optical vortex singularities and atomic circulation in evanescent waves
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The total internal reflection of an optical beam with a phase singularity can generate evanescent light that displays a rotational character. At a metalized surface, in particular, field components extending into the vacuum region possess vortex properties in addition to surface plasmon features. These surface plasmonic vortices retain the phase singularity of the input light, also mapping its associated orbital angular momentum. In addition to a two-dimensional patterning on the surface, the strongly localized intensity distribution decays with distance perpendicular to the film surface. The detailed characteristics of these surface optical vortex structures depend on the incident beam parameters and the dielectric mismatch of the media. The static interference of the resulting surface vortices, achieved by using beams suitably configured to restrict lateral in-plane motion, can be shown to give rise to optical forces that produce interesting dynamical effects on atoms or small molecules trapped in the vicinity of the surface. As well as trapping within the surface plasmonic fields, model calculations reveal that the corresponding atomic trajectories will typically exhibit a variety of rotational and vibrational effects, significantly depending on the extent and sign of detuning from resonance.

Hybrid optical transport trap: loading and unloading of microscale objects using a microfabricated optical fiber into optical tweezers
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Optical tweezers are being routinely used to hold and immobilize a microscopic object which has enabled spectroscopic analysis of the trapped samples. We demonstrate development of a hybrid optical transport trap (HOTT) which combines a tapered fiber-optic trap for transport of microscopic objects into and out of the optical tweezers trap in an orthogonal geometry. The tapered fiber tip was fabricated by chemical etching method. The other end of the tapered fiber was coupled to a near-infrared fiber Laser delivering power up to 100 mW in both loading and unloading conditions. For small cone angle of the tip, the microscopic objects (polystyrene and red blood cells) were found to be trapped in two-dimensions and pushed along the axial direction by domination of scattering force. This was found to be in consistency with the estimated axial forces caused by the beam profiles emerging from the small cone angle tapered fiber tip. While for loading of the microscopic objects into the optical tweezers trap, the fiber tip was placed ~ 30 microns away from the tweezers trap, unloading was carried out in presence of the tip close(<15 microns) to the tweezers trap. Since the tapered tip can be easily integrated onto a microfluidic channel, the proposed configuration can find potential applications in lab-on-a-chip devices. Currently, we are pursuing high-throughput analysis of the red blood cells using the HOTT.

Adaptive shaping of complex pulsed nondiffracting light fields
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Emerging applications like smart wavefront sensing, multichannel processing or superresolving microscopy with ultrashort pulses require advanced techniques for flexible shaping. A promising approach is to generate non-Gaussian beams with programmable phase maps of phase-only displays. Recently we reported on the generation of pulsed fringe-free Bessel beams (“needle beams”) wth optimized angular profiles. Such beams behave propagation invariant over extended regions (pseudo-nondiffracting) not only with respect to their spatial profile but also in temporal domain. Here, the concept of needle pulses is further extended. It will be shown that stacked light slices, tubular beams or pixelated images can be composed from nondiffracting constituents. Arrangements of small local phase axicons were programmed in a liquid-crystal-on-silicon spatial light modulator (LCOS-SLM). By adaptive shaping strategies, target distributions at certain planes are approximated. In particular, solitary and arrayed needle beams deviating from rotational symmetry were studied in theory and experiment (stability of propagation, cross-talk). The generation of curved (non-Airy) beams with asymmetric Fresnel axicons is discussed. Tubular beams with and without orbital angular momentum are introduced. A modified Shack-Hartmann wavefront sensor based on distinguishable needle beams with higher deflection sensitivity is presented. The improvement of the spot tracking quality is evaluated. It is concluded that strongly curved wavefronts can easily be detected by analyzing statistical moments of the intensity distribution with a fast algorithm. At slight changes, the concept could also work for information encoding/decoding in free-space communication systems. The studied approaches suggest to generalize the term “nondiffracting” to more complex light fields.

Complex light with optical singularities induced by nanocomposites
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Actual freshly prepared nanocomposites from nematic 5CB doped with multi-walled carbon nanotubes (MWCNTs) were tested first by assemblage of main informative techniques: (a) high-resolution singular and polarization optics, (b) differential scanning microcalorimetry of phase transition picks, (c) temperature and concentration dependences of electrical conductivity and conductivity vs. transverse applied voltage, (d) effects of thermal incubation on the aggregates microstructure and electrical conductivity. The “long” and “short” MWCNTs with aspect ratio
-500 and -50 were prepared. Van-der-Waals attraction of MWCNTs and 5CB molecules anchoring on their side surfaces lead to spontaneous formation of microsize aggregates with MWCNTs skeleton and ramified fractal borders surrounded by the strained birefringent 5CB interfacial layers at 0.0025±0.01 wt. % for “long” and at 0.005±0.5 wt. % for “short” MWCNTs. According measurements and built theory, volume of captured 5CB molecules is 2-2.5 order greater than the total volume of MWCNTs involved. Propagating laser beams scatter on aggregates, ramified borders and induce appearance of speckled complex light with optical singularities and inhomogeneous elliptical polarization. Electrical conductivity of nanocomposites grows strongly when aggregates touch and form irregular grating (percussion effect). Applied transverse field increases few times the volume of interfacial 5CB layer and light scattering. Thermal incubation governs aggregates microstructure and conductivity. The interfacial layer disappears during 5CB transition to isotropic liquid what diminishes strongly light scattering. Combinations of MWCNTs with other nanoparticles were investigated also. Totality of obtained results shows new family of managed nanoelements can be created on the base of nematics doped by MWCNTs.

7950-10, Session 3

Measuring extremely complex ultrashort pulses with time-bandwidth products exceeding 65,000 using multiple-delay crossed-beam spectral interferometry

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Every aspect of optics depends upon the ability to measure light. And with recent progress in the fields of high-intensity lasers, continuum generation, and arbitrary-waveform generation, the need for techniques to accurately measure pulses with very large time-bandwidth products (TBPs) is increasing. High-intensity lasers, for example, use chirped-pulse amplification, which involves chirped pulses with ns pulse lengths and TBPs approaching 10^6.

Although the applications for such complex pulses are numerous, the current state-of-the-art is limited by experimental constraints such as sensitivity, spectral range/temporal resolution, or spectral resolution/temporal range. As a result of such experimental limitations, it has been asserted that “time interleaving” could be the solution to the problem of measuring complex pulses. And we have recently reported the first device that temporally interleaves both the intensity and phase of a complex pulse resulting in fs temporal resolution and many-ps temporal range. As a result, it overcomes the spectral and temporal limitations associated with other techniques.

In this paper, we measure the complete electric field of extremely complex ultrafast waveforms using the simple linear-optical, interferometric pulse-measurement technique, MUD TADPOLE. The waveforms were measured with 40 fs temporal resolution over a temporal range of ~3.5ns and had time-bandwidth products exceeding 65,000. The approach is general and could allow the measurement of arbitrary optical waveforms.

7950-11, Session 3

Helical ionizing channels generated with ultrafast interfering Bessel laser pulses

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Nondiffracting beams, such as Bessel and Airy beams, have been an area of enormous interest for the optical community. Understanding and controlling the linear diffraction that gives rise to these beams and superimposing multiple beams allows a wide variety of beam structures to be obtained in the laboratory. This paper reports a novel double helix beam in which two irradiance peaks rotate about the optical axis as the beam propagates. Ionized plasma channels can be created using an ultrashort laser pulse and linear diffraction to shape and control the beam during propagation. By generating a helical beam geometry with a 12 mJ femtosecond laser, ionized helical channels have been obtained in the laboratory. This is one of many engineered ion channel geometries that can be obtained from pulsed nondiffracting beams, and should provide avenues to new applications for ultrafast lasers.

Fermionic transformation rules for spatially filtered light beams in conical refraction

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In conical refraction, when a collimated light beam passes along the optical axis of a biaxial crystal it refracts conically giving rise to a characteristic ring intensity pattern in the transverse plane. At each position of the ring the light electric field is linearly polarized with the polarization plane rotating along the ring such that every two opposite points of the ring present orthogonal linear polarizations. With a pinhole located at the ring plane, we have spatially filtered a small part of the ring and experimentally reported that this filtered light does not yield a uniform ring pattern when it refracts along the optical axis in a second biaxial crystal, called the analyzer in what follows. Instead, after crossing the analyzer the filtered beam splits into two light beams with orthogonal linear polarizations that correspond to two opposite points of the otherwise expected second ring of conical refraction.

We have experimentally derived the transformation rules for the intensity of the filtered beam for an analyzer rotated an angle w around the optical axis. Unexpectedly, the intensity of the filtered light beams follows the transformation rule \[|\cos(w/2)|^2\] of spin 1/2 particles, in contrast to the well known Malus law of \[|\cos(w)|^2\] followed by double refraction.

Measuring the orbital angular momentum of light

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At both classical and quantum levels, information can be encoded in light. This encoding utilizes various properties of the light, including its intensity, frequency and polarization. For example, the sense of circular polarization sets the spin angular momentum of the photon in one of two states and therefore naturally carries binary data. By contrast, light’s orbital angular momentum (OAM) can take any discrete value, giving increased information capacity. However, although it is possible to encode a photon with any OAM, measurement is not straightforward. For example, holograms can test for a single OAM state, but the outcome is binary. Interferometers can test for multiple states, but testing a large number of states is technically prohibitive. These difficulties limit the application of OAM in classical and quantum regimes. Here we present a method to efficiently sort OAM states using two optical elements by performing a coordinate transformation, such that each OAM input state
is mapped to a different lateral position at the output aperture. This optical system potentially makes available the high information capacity of OAM in both classical and quantum applications.

7950-14, Session 4

Orbital angular momentum induced beam shifts

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It is well established that a bounded Gaussian (TEM00) beam that is reflected or transmitted differs in propagation with plane waves due to diffraction corrections. The most famous of these shifts are the Goos-Hänchen (GH) shift in which the beam is displaced parallel to the plane of incidence, and the Imbert-Fedorov shift in which the shift is perpendicular. Moreover, these two beam shifts can be separated into a spatial and an angular shift.

Here we present experiments on the spatial GH shift and angular IF shift when a beam has an orbital angular momentum (OAM). LGn0 beams are made to reflect from a BK7 prism and the longitudinal and transverse polarization differential shifts of the reflected beam are measured. We observe that the magnitudes of the induced GH and IF shifts increase with OAM. The OAM induced GH and IF shifts are related since the spatial GH shift comes from the same phenomenon responsible for the angular IF shift. The OAM couples these two shifts. Our experimental results agree well with our theoretical predictions.

Our results are significant for optical metrology since optical beams with OAM have been extensively used in both fundamental and applied research.

7950-15, Session 4

Generation of an optical vortex with a topological charge of l=4 by use of double-pass configuration with an axially-symmetric polarization element

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A double-pass optical vortex generator using an axially-symmetric polarization element is presented.

White-light vortex, namely the optical vortex with a broadband spectrum, has attracted attentions because of potential applications such as the ultrafast spectroscopy and the astronomical coronagraph. We previously developed an achromatic method to generate a white-light vortex with a topological charge of l=2, using an axially-symmetric polarization element. The method has a distinct feature that it is free from the spatial- and topological-charge-dispersions, which have often been with the standard techniques using a spatial-light modulator and a spiral phase-plate, and thereby the method is suited for use with the broadband light. With this method, we have demonstrated the generation of an almost octave spanning ultra-wideband optical vortex pulse.

In this presentation, we describe a modified method for the generation of the white-light vortex with a topological charge of l=4. While the previous system has a limitation that the vortex only with l=2 can be generated with the radially symmetric polarization element, a larger topological charge can be realized in principle with other polarization elements. However, it is not easy to fabricate them with sufficient spatial-uniformity and achromaticity. In order to overcome this technical restriction and improve the method with versatility, we introduced a double-pass configuration into the optical vortex generator so that the topological charge is doubled. With this configuration, we can generate an optical vortex with the topological charge of l=4 even using with an axially-symmetric half wave plate, which is relatively easy to fabricate.

The operation of this method was demonstrated with a preliminary experiment with a monochromatic laser light.

7950-16, Session 4

Raman optical activity by light with spin and orbital angular momentum

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Optical activity in quartz, due to enantiomerically specific interactions between the chiral quartz molecules and the chirality of circular polarization, is well known. It has also been shown that the chirality of helically phased Laguerre-Gaussian modes, optical vortices, have no enantiomerically specific interaction with chiral molecules in the dipole interaction as exhibited through circular dichroism. In this work, we experimentally investigate Raman optical activity in the scattering of light with spin and orbital angular momentum. The spin and orbital angular momentum of light are associated with circular polarization and the helical phase structure of Laguerre-Gaussian modes, respectively. Cylindrical vector beams, beams of light with cylindrically symmetric transverse polarization and amplitude, can be expressed as the linear superposition of orthogonal circular polarized first order Laguerre- Gaussian modes of opposite topological charge. In this work, we generate light with varying combinations of spin and orbital angular momentum by transforming a cylindrical vector beam into a circular polarized Laguerre-Gaussian mode using a combination of quarter wave plates and linear polarizer. Raman back scattered light of a circular polarized Laguerre-Gaussian beam propagating along the optic axis of a c-cut uniaxial birefringent quartz sample is collected with a spectrometer. The resulting Stokes shifted spectra is analyzed with respect to the effect of varying combinations of spin and orbital angular momentum of the incident light on the relative intensities of the Stokes shifted Raman peaks. A reformulation of the traditional quartz polarizability tensor and the circular polarization electric field from Cartesian to cylindrical coordinates is discussed.
We experimentally demonstrate the generation of a class of spatially variant polarization beams called hybrid vector beams. Hybrid vector beams have cylindrically symmetric amplitude and a spatially varying degree of polarization ellipticity in their transverse profile about the beam axes, varying from linear to elliptical to circular every 45 degrees. These beams are unique from other spatially varying polarization beams, such as the cylindrical vector beams that are linearly polarized everywhere, in that they possess every state of polarization. The hybrid vector beams are expressed as the superposition of orthogonal linear polarized Laguerre-Gaussian modes of opposite topological and their generation has been demonstrated interferometrically and at the output of optical fibers where the local angular momentum has been shown to be non-zero. In this work, we describe a method for the generation of various hybrid vector beam polarizations based on the transformation of various cylindrical vector beams using conventional wave plates. In this way, we can tailor the hybrid vector beam’s polarization profile by changing the gradient of polarization ellipticity and ellipse orientation. The Stokes parameters for the overall polarization of each hybrid vector beam generated are experimentally measured and mapped numerically. The ability to control the spatially varying polarization ellipticity and therefore the non-zero local angular momentum may have potential applications in optical trapping applications such as optical tweezers and optical molasses.

7950-17, Session 5

Waves near varying boundaries: spatial shifts, localization, and Dirichlet points
M. R. Dennis, Univ. of Bristol (United Kingdom)

We are used to complex light fields in the vicinity of edges due to complicated geometries such as apertures or structured surfaces. However, strong reflective effects can occur if the boundary conditions (Fresnel coefficients) vary continuously with position along even a straight boundary. A simpler picture of scalar reflection will be discussed, initially motivated by the similarity in the spatial Goos–Hänchen shift of a polarized electromagnetic beam incident on a dielectric and a scalar beam incident on a boundary with mixed Robin boundary conditions [1]. Working in the scalar picture, the effect on bound states of spatially-varying Robin boundaries will be described [2], including the Anderson localization-like effect on angular momentum of sinusoidally varying the Robin boundary in a circular enclosure [3]. When, at a point on the boundary, the Robin parameter is infinite (corresponding to Dirichlet conditions), the problem may require further regularization (self-adjoint extension), which will be described in terms of separable geometries involving polar and parabolic coordinates.

Finally, some indications about possible realizations of varying boundary conditions for waves will be discussed, including surface acoustic and electromagnetic metamaterials.


7950-18, Session 5

Cylindrical vector beam generation from a multicore optical fiber
G. Milione, H. I. Sztul, R. R. Alfano, The City College of New York (United States); D. A. Nolan, M. Etienne, J. McCarthy, J. Wang, Corning Inc. (United States)

A method for the generation of cylindrical vector beams based on the design of a multicore optical fiber is presented. The principle of operation is based on the property of birefringence in polarization maintaining elliptical cores. This design consists of N elliptical cores symmetrically arranged in a circular array about the fiber axis, where the orientation of each core’s major axes has an azimuthally varying distribution. The guided mode of each core rotates an incident polarization according to the core’s orientation in the array, and the array’s overall birefringence can be described using a Jones matrix analysis. Coherent superposition of the azimuthally distributed polarization outputs from each individual core in the far field produces a cylindrically symmetric amplitude and polarization state. In this way, a Gaussian beam coupled at the fiber input can be transformed into a cylindrical vector beam. This method differs from conventional methods of cylindrical vector beam generation by optical fibers, as it does not rely on the direct excitation of the higher order TM, TE, and HE fiber modes. We experimentally investigate the fabrication of this multicore fiber design with N=6 cores of varying core size and spacing using Stokes polarimetry measurements of the fiber output in the near and far field. The efficiency of the design and numerical simulations of the far field output for scaling to more then N=6 cores and varying core spacing is discussed.

7950-19, Session 5

Structured light and multipoles
D. L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

The representation of three-dimensional fields by multipolar decomposition is a well understood and widely employed methodology. Whilst its most familiar application is to the scalar fields associated with charge distribution, it is a technique that is also valuable for understanding the physical attributes of vector and tensor fields, especially in connection with the electromagnetic fields of structured light. Although the transition multipoles that determine the strength of optical transitions may have a mathematical representation that is congruent to that of the beam, they have a different physical provenance. It can be shown unreasonable to assume that a beam component of a given order signifies a detection process necessarily involving a transition of the same multipolar character. To resolve the issue requires analysis of the electromagnetic near-fields associated with the transition multipoles. Near-field and paraxial attributes of the beam have significantly different characteristics, indicating a propagation-dependent temporal evolution of quantum electrodynamical origins. Results of the analysis also exhibit novel connections with optical angular momentum.

7950-20, Session 5

Engineering the spin-orbit coupling of the Rashba-Dresselhaus type for cold atoms
G. Juzeliunas, Vilnius Univ. (Lithuania)

We present a novel scheme simulating the spin-orbit coupling of the Rashba-Dresselhaus (RD) type for cold atoms. The RD coupling is described by a vector potential proportional to the spin-1/2 operator. It applies both to electrons in semiconductors and also to cold atoms with two relevant internal states corresponding to the spin up and spin down states. For cold atoms, the RD coupling can be generated by means of the tripod scheme in which the laser beams couple three atomic ground states with an extra state [1-4]. The corresponding RD coupling is formed for atoms populating two internal dark states. However, the dark states are not the ground states of the tripod atom. This is a drawback in studying effects due to the RD coupling for the Bose-Einstein condensation [5]. Here we propose and analyze an alternative setup involving a double tripod scheme of the atom-light coupling. By properly setting the atom-light interaction, one can arrive at a twice degenerate atomic ground state subject to the RD coupling. We consider an implementation of this scheme using the Raman transitions between the hyperfine levels of the ground state manifold.

Generalized spherical vector wave functions expansion of arbitrary electromagnetic fields: basic formalism

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We present an analytical solution to a 100-year old problem in scattering theory: How to expand an arbitrary incident field in terms of Vector Spherical Wave Functions (VSWF). This problem arises in calculations of the scattered and internal fields created by a spherical micro-particle placed at an arbitrary position relative to an incident electromagnetic beam, when it is necessary to perform a VSWF expansion with respect to the center of the particle. Such calculations are essential for working out the optical forces acting on the particle. The VSWF base functions are given by terms such as \( j_{n}(kr)X_{nm}(\theta \phi) \), where \( j_{n} \) are spherical Bessel functions and \( X_{nm} \) are vector spherical harmonics. The knowledge of the expansion coefficients is essential for a precise calculation of forces, torques, scattering and internal fields of particles, independent of the particle’s size. Mie found almost the only example of an analytical expression for the BSCs for an incident plane wave in 1908. One century after Mie’s work, much effort is therefore devoted to evaluating these coefficients in different cases, usually by time-consuming numerical computation. After the laser, however, a great number of different optical beams, such as Gaussian, Laguerre-Gaussian, Hermite-Gaussian, Bessel, very high numerical aperture beams, are being used for several purposes, from super resolution microscopy to optical trapping and spinning of particles. Therefore, there is an urgent need to describe all these electromagnetic beams in terms of SVWFs. Moreover, the basis for the numerical calculations performed today is still incomplete in the sense that any expansion is complete only if one finds numerical values for its coefficients. But this task was actually never accomplished, except for plane waves, because the integrals used to extract the coefficients are evaluated only over the solid angle, an important non-cancelling radial dependence in the equations being ignored. Even worse, the non-cancelled Bessel function has plenty of roots that can generate zeros at one side and non zero numbers at the other side of an equality. In what we believe is a breakthrough in scattering theory, we show how to extract a numerical value for the BSC for any arbitrary incident beam, without neglecting this radial dependence. The generalized formalism reduces exactly to Mie’s results for the special case of an incident plane wave.

Optical waveguide trapping forces on hollow glass spheres

P. Lovhaugen, B. S. Ahluwalia, O. G. Hellesø, Univ. of Tromsø (Norway)

Three dimensional finite element method is employed to determine optical trapping forces on hollow glass spheres on an optical waveguide. The evanescent field from the waveguide only stretch out a few hundred nanometers above the waveguide surface. This means that even low-index hollow spheres experience a trapping force, as the primary interaction between the field and the glass sphere happens in the outer shell. We describe how the optical forces vary with shell thickness and particle size. For a given diameter there exists a transient (minimum) shell thickness, above which hollow glass spheres can be trapped on the waveguides. Hollow glass spheres with shell thickness less than the transient shell thickness become low index particles in the region seen by the evanescent field, and are thus repelled away from the optical waveguide. We also discuss how buoyant forces relate to the transient condition. The simulation results are compared with experimental data of trapped hollow spheres.

Manipulating functionalized 2PP structures on the BioPhotonics Workstation

T. Matsuoka, M. Nishi, M. Sakakura, K. Hirao, Kyoto Univ. (Japan); D. Palima, S. Tauro, A. R. Banas, J. Glückstad, Technical Univ. of Denmark (Denmark)

In its standard version, the BioPhotonics Workstation (BWS) can generate multiple controllable counter-propagating beams to create real-time user-programmable optical traps for stable three-dimensional control and manipulation of a plurality of particles. We have traditionally used the counter-propagating geometry to achieve stable three-dimensional trapping while maintaining a large working distance by using microscope objectives with relatively lower numerical apertures. The BWS affords independent control of the counterpropagating beam patterns and we have earlier exploited this to correctly match the corresponding pairs of counterpropagating beam traps. More generally, however, the counterpropagating geometry opens a new degree of design freedom for lightshaping that grants access to independently patterning the counterpropagating beams to realize novel lightscapes. We show results of optical micromanipulation experiments that illustrate new modes of three-dimensional optical control that would otherwise be difficult if not impossible to achieve when using single-sided illumination.
from the counter-propagating trapping geometry. We suggest that this combination can lead to completely new methods to communicate with micro- and nano-sized objects in 3D and potentially open for enormous possibilities in nano-biophotonics applications.

7950-25, Session 7

Optical sculpting

K. Dholakia, Univ. of St. Andrews (United Kingdom)

Optical micromanipulation is a powerful non-contact technique where micrometre sized particles can be grabbed, moved and generally manipulated solely with light. This is their fortieth anniversary and their impact and usage are stronger and wider than ever. In recent years there has been a proliferation of activity in this area, fuelled, in part, by the recognition that we need to advance the "optical toolkit". This essentially means creating more elaborate 2D and 3D light patterns (beam shaping or sculpting) that can create an optical landscape. The ability to alter both the phase and amplitude of light at will with both static and dynamic diffractive optics opens up a wealth of new applications that even go beyond manipulation into biophotonics.

I shall describe recent work at St Andrews looking at new methods of wavefront correction to allow particle trapping in turbid media. Furthermore, I will describe how we can shape light to create ‘non-diffracting’ light fields moving on linear and parabolic trajectories that has an impact in cell transfection and path clearing.

7950-26, Session 7

Geometric phase associated with transformations of cylindrical vector beams

G. Milione, H. I. Szul, R. R. Alfano, The City College of New York (United States)

We present a geometric phase arising from transformations along the surface of a Poincaré sphere representation for cylindrical vector beams. Poincaré sphere representations for the spin and orbital angular momentum states of light associated with circular polarization and Laguerre-Gaussian modes, respectively, are now well known. Cylindrical vector beams, light modes with cylindrically symmetric amplitude and polarization, such as radial and azimuthally polarized beams, are expressed as a superposition of orthogonal circular polarized Laguerre-Gaussian modes of opposite topological charge. In this work, two spheres are described where the poles of each sphere are circular polarized Laguerre-Gaussian modes, with spin and orbital angular momentum of equal or opposite values, and points along the equator are cylindrical vector beams. It has been experimentally demonstrated that a transformation along a closed path on the surface of the spin and orbital spheres acquires a geometric phase proportional to half the area of the enclosed path. This geometric phase manifests itself through a phase shift of the state undergoing transformations and is measured interferometrically. In this work, we experimentally measure an equivalent geometric phase associated with transformations of the surface of the cylindrical vector beams. Transformations are carried out using combinations of wave plates and cylindrical lens mode converters, and the geometric phase is measured through the resulting interference of the beam undergoing transformations and a Gaussian reference beam.

7950-27, Session 7

Evolution of optical vortex distributions in stochastic vortex fields

F. S. Roux, National Laser Ctr. Trust (South Africa)

Stochastic vortex fields are, for example, found in laser speckle, stochastic vortex fields. Evolution of optical vortex distributions in free-space propagation that are obtained from numerical simulations, will be presented. A variety of different stochastic vortex fields are used as input to these simulations, including vortex fields that are homogeneous in their vortex distributions, as well asinhomogeneous vortex fields where the topological charge densities vary sinusoidally along one or two dimensions. Some aspects of the dynamics of stochastic vortex fields have been uncovered with the aid of these numerical simulations. For example, the numerical results demonstrate that stochastic vortex fields contain both diffusion and drift motions that are driven by local and global variations in amplitude and phase. The mechanisms for these will be explained. The results also provide evidence that global variations in amplitude and phase are caused by variations in the vortex distributions, giving rise to feedback mechanisms and nonlinear behavior.

7950-28, Session 7

Probing quantum cores of optical vortices with atoms

J. B. Götte, M. R. Dennis, Univ. of Bristol (United Kingdom)

At the centre of an optical vortex the phase of a classical light field is singular and the intensity has a perfect zero [1]. In quantum optics, however, this singularity does no longer exist and is superseded by a core of finite radius, in which quantum effects dominate. This was first pointed out by Berry and Dennis who showed that, for an atom inside such a core, the rate of spontaneous emission may exceed stimulated emission [2]. More recently, Barnett found that in quantum optics interactions with the electromagnetic field near the node drive quantum transitions in the atom [3], [4].

More specifically, the absorption of light inside the vortex core leads predominantly to a state excited in both the electronic and motional degrees of freedom of the atom. We examine Barnett’s scenario in more detail recasting the formulation in terms of abstract atomic states to a more concrete realisation involving excited angular momentum modes of the atom inside a harmonic trap. We consider the effects of the degeneracy in the excited state, and present and interpretation of this phenomenon in the language of superoscillatory spatial frequencies close to the optical singularity [4].


7950-29, Session 8

Optical lift

G. A. Swartzlander, Jr., Rochester Institute of Technology (United States)

An optical analog of hydrodynamic lift is discussed, whereby a cambered “lightfoil” in a stream of photos experiences motion in the transverse direction. The lightfoil is found to reach a stable orientation, whereupon it undergoes uniform motion. Numerical investigations of shaped particles in a uniform, non-focused, light stream suggest a mechanism for steering particles without controlling the driving light field, but rather, by controlling the shape, orientation, or refractive index distribution of the particle.
One may imagine constructing "a light engine" from an array of such particles. Experimental observations of this "optical lift" effect also be presented.

7950-30, Session 8

**Microparticle sorting using a slot waveguide splitter**

S. Lin, K. B. Crozier, Harvard Univ. (United States)

Integrated optical trapping using the evanescent fields of photonic devices such waveguides and microcavities opens up new opportunities for the micromanipulation of small objects. The efficient sorting of micro-particles based on properties such as size and refractive index in a passive manner could be very useful for applications in the biological and environmental sciences. Here, we demonstrate a novel sorting mechanism using a 3-dB optical splitter whose outputs comprise a channel waveguide and a slot waveguide. Optical force calculations using the Maxwell Stress Tensor method based on 3D-FDTD show that, on small particles (d < 1 µm), the slot waveguide exerts a larger optical force than the channel waveguide. By contrast, the channel waveguide traps larger particles (d > 1 µm) more stably. Here we experimentally demonstrate that this size selectivity can be employed to sort particles with different sizes. In the fabricated coupler device, 3-dB optical splitting of TM mode incident light is achieved via careful selection of the coupling length. We demonstrate the sorting mechanism by mixing particles with diameters of 2 µm and 320 nm. The 2 µm particles continue to be pushed along the channel waveguide after leaving the coupling region, while the 320 nm particles are transferred to the slot waveguide. The sorting rate is determined by the speed of particles moving along the waveguide, and can be dramatically enhanced by parallel integration of multiple channels. This passive, label-free, all optical sorting mechanism could be used to sort live cells, aerosols, or other microparticles.

7950-31, Session 8

**Optical trapping efficiencies from n-phase cylindrical vector beams**

B. J. Roxworthy, K. C. Toussaint, Jr., Univ. of Illinois at Urbana-Champaign (United States)

Since the advent of optical tweezers in the 1980's, there has been continual interest in the optical forces involved in trapping. In particular, the effect of the input beam intensity distribution and polarization structure has been studied thoroughly. In this work, we present the use of n - phase cylindrical vector beams in optical trapping. The vector beams are created via a Mach-Zehnder interferometer equipped with tunable phase plates, and the “n” prefix indicates the relative phase between the Hermite-Gaussian modes comprising the output beam. The optical trapping efficiency is measured via the Stokes' drag force method for radial and azimuthal vector beams with n = 0 and π, giving a total of 4 unique input beams. Additionally, their trapping efficiencies are compared with that of a standard input Gaussian beam of equal input power. We find that the axial trapping efficiency can be optimized by increasing the amount of longitudinal (z) polarization at the focal plane of the trapping objective. Further, the lateral trapping efficiency is determined by the focal spot diameter, as expected, and can be similarly tuned by varying the relative phase between the vector beam eigenmodes. The results suggest that cylindrical vector beams may be tuned such that both axial and lateral trapping efficiencies can be maximized.

7950-32, Session 8

**Characterization of optical trap for metallic particles using external magnetic field**

V. S. Jadhav, W. A. Sayyad, Univ. of Pune (India) and Anna Univ. (India); G. R. Kulkarni, Univ. of Pune (India); B. M. Jaffar Ali, Anna Univ. Chennai (India)

We report a method to optically trap and micromanipulate metallic particles using IR laser. The experiment demonstrates the trapping of metallic particle using low numerical aperture objective lens (0.6 N.A). Unlike single beam gradient trapping of dielectric objects, the optical trapping of metallic particles occurs due to diffraction effect. We thus provide evidence for non-gradient forces playing a dominant role in the trapping of metallic particles, in here for the case of 3µm Fe particles, efficient trapping occurs at off-axis position (in the side lobes) of a focused laser beam. The optical trap is characterized by measuring the external magnetic field required to dislodge the Fe particle, and was found to be 0.03T to 0.1T for laser power 13 to 88mW in the sample. We further show that the characterized optical trap can be used to study non-ferrous metallic particles.
Interferometry is a noncontact and nondestructive technique. It is used as a diagnostic tool for in-situ measurements. The sensitivity of the technique is unsurpassed. Detectors operating at higher temperatures. 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. We are also undertaking shape engineering of the dots to produce infrared detectors operating at higher temperatures.

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Experimental evidence for laser cooling of Yb:YLF to 120 Kelvin
S. D. Melgaard, D. Seletskiy, The Univ. of New Mexico (United States); A. Di Lieto, M. Tonelli, Univ. di Pisa (Italy); M. Sheik-Bahae, The Univ. of New Mexico (United States)
We utilize highly sensitive spectroscopic local temperature probe to ascertain cooling performance of Yb:YLF crystal as a function of wavelength and temperature. A minimum achievable temperature of 120 K is measured at pump wavelength corresponding to E4-E5 Stark manifold transition. Results verify current model for laser cooling cycle as well as demonstrate the lowest temperature achievable by means of optical refrigeration to date.

Optical cooling in Nd-doped crystals and nanocrystalline powders revisited
A. J. Garcia-Adeva, R. Balda, M. Al Saleh, S. Garcia-Revilla, J. Fernandez, Univ. del Pais Vasco (Spain)
The present authors recently demonstrated that the efficient infrared-to-visible upconversion process in Nd-doped KPb2Cl5 crystal and powder can lead to local internal and bulk optical cooling. These results showed that new cooling channels based on upconversion processes can be of paramount importance in the search of new rare-earth-doped materials for optical cooling.

In the present work, we report on infrared thermography measurements in Nd-doped KPb2Cl5 crystal and powder above and below the barycentre of the 4F3/2 level that were performed in order to assess the relative weights of both the direct anti-Stokes absorption processes and those assisted by either excited state absorption or energy transfer upconversion processes in the cooling of the material. As the laser induced temperature changes are usually small, we used a special configuration of the samples that allowed us to obtain differential measurements where an undoped sample acted as a temperature baseline. This method allows us to ascertain whether the recorded temperature changes are optically induced or they are due to some other effect.

7951-06, Session 2

Raman cooling of semiconductor devices: feasibility study

J. B. Khurgin, The Johns Hopkins Univ. (United States)

Laser refrigeration of solids is a promising technology capable of remotely removing heat from a small active device with minimum expended energy. Currently efficient laser cooling has been achieved in rare earth doped insulator, but cooling of semiconductor device has not been attained due to large background absorption and nonradiative recombination. One way to avoid these two deleterious effects is to consider cooling by Anti-Stokes Raman scattering. In this talk feasibility of Raman cooling will be addressed and the requirements for all the components will be established.

7951-07, Session 2

Radiation balanced holmium fiber lasers

S. R. Bowman, N. J. Condon, S. O’Connor, U.S. Naval Research Lab. (United States); T. Ehrenreich, S. Christensen, Nufern (United States)

Fiber lasers provide useful high brightness sources for many applications. Holmium doped fibers lase in an eyesafe spectral region. In order to increase the average power of fiber lasers, we are exploring the possibility of operating holmium fibers lasers near the radiation balance condition. At the radiation balance condition, the absorbed optical power is equal to the total radiated optical power; with negligible waste heat. Specifically, we are considering a single-mode 2.1µm Ho:Silica fiber lasers that is resonant pumped using several multi-mode thulium fiber lasers. Thulium fibers lasers pumped in the near-IR have proven to be an efficient way to generate high powers; at 2.0µm. Material characteristics such as background absorption and non-radiative quenching are being measured. Laser performance issues such as pump coupling efficiency, fluorescence guiding, and thermal loading are being modeled. The analysis of performance and projected power flow in this novel type of fiber laser will be presented.

7951-08, Session 2

A conceptual study of a fiber-optical approach to solid-state laser cooling

D. T. Nguyen, College of Optical Sciences, The Univ. of Arizona (United States); J. Wu, Z. Yao, J. Zong, A. Chavez-Pirson, NP Photonics, Inc. (United States); J. Weiss, C. Shanor, R. Binder, College of Optical Sciences, The Univ. of Arizona (United States)

Recently, laser cooling of solids has seen tremendous progress. The optical cooling process is based on optical pumping of a solid state system and subsequent escape of up-converted photo-luminescence light (also known as anti-Stokes fluorescence). It works particularly well in high-quality rare-earth doped glasses. A possible new application has been envisioned by the Office of Naval Research, namely the optical cooling of high-power rare-earth doped glasses. A key potential benefit is the possibility to transfer heat in the form of anti-Stokes fluorescence through the fiber away from the cooling device. This allows the heat to be dumped at almost arbitrarily chosen locations. Also, the optical cooling system combines the proven benefits of rare-earth doped glasses with the mature fiber and fiber laser technology. We have designed a first-generation all-fiber cooling system that includes a fiber laser, an optical resonator built with fiber Bragg gratings, a cooling segment, and a remote-heat dump fiber. We will discuss key performance parameters of our design, such as the dependence of the cooling efficiency on the doping concentration, the dependence of temperature gradients on the design parameters, and light propagation characteristics including luminescence extraction and re-absorption by the rare-earth dopants. Our study is based on theoretical simulations and experimental data, and includes a critical discussion of both advantages and future challenges of the all-fiber cooling systems.

7951-09, Session 3

Cooling a mechanical resonator near the ground state of motion using a side-band resolved microwave resonator

K. C. Schwab, California Institute of Technology (United States)

We have developed the techniques to cool the motion of a radio-frequency nanomechanical to a state near the quantum ground state of motion, with occupation factor \( \langle n \rangle \approx 4 \). The technique relies on the parametric coupling to a distributed microwave resonator. I will discuss this technique, its history, the limitations we encountered, and the prospect for further improvements. We require the development of an ultra-low phase noise microwave source with phase noise < -195 dBc/Hz. Cooling was limited by three separate effects: heating of both the mechanical and microwave resonator due to high microwave powers, and a weak \( (10^{\wedge} -18 \text{ N/Hz}) \) non-thermal force noise which blocked thermalization below 100mK.

7951-10, Session 3

Efficient optomechanical cooling in one-dimensional interferometers

P. Domokos, Research Institute for Solid-State Physics and Optics (Hungary); A. Xureb, T. G. M. Freegarde, P. Horak, Univ. of Southampton (United Kingdom)

We present a one-dimensional scattering theory [1] which enables us to describe a wealth of effects arising from the coupling of the motional degree of freedom of scatterers to the electromagnetic field. Multiple scattering to all orders is taken into account. The theory is applied to describe the scheme of a Fabry-Perot resonator with one of its mirrors moving. The friction force, as well as the diffusion, acting on the moving mirror is described. In the limit of a small reflection coefficient, the same model provides for the description of the mechanical effect of light on an atom moving in front of a mirror.

Then, we consider the general case of an interferometer comprising an arbitrary configuration of generic `beam splitters’ and calculate the velocity-dependent radiation field and the light force exerted on a moving scatterer [2]. We show that the fields in multiple-pass interferometers, such as the Fabry-Perot cavity, exhibit great sensitivity not only to the presence but also to the motion of any scattering object within the optical path. We find that a simple configuration, in which the scatterer interacts with an optical resonator from which it is spatially separated, can enhance the optomechanical friction by several orders of magnitude.
The cooling has been achieved by pumping the near IR transition at 870 nm concentration of erbium as high as 80% by formula, in the crystals used. The efficiency and low temperatures of cooling have been attributed to a high concentration of erbium. We have seen bulk crystal cooling by as low as 6 degrees below room temperature in elpasolite crystals. The high concentration of erbium. We have seen bulk crystal cooling by as low as 6 degrees below room temperature in elpasolite crystals.

Laser cooling in materials with high concentration of erbium

Z. U. Hasan, Z. Qiu, J. Lynch, Temple Univ. (United States)

Laser cooling of erbium based solids is of great importance. It has many potential applications in communications, surveillance and medical science, to name a few. This talk will review our recent work on laser refrigeration of solids in stoichiometric hexachloroepasolite crystals with high concentration of erbium. We have seen bulk crystal cooling by as low as 6 degrees below room temperature in elpasolite crystals. The high efficiency and low temperatures of cooling have been attributed to a high concentration of erbium as high as 80% by formula, in the crystals used. The cooling has been achieved by pumping the near IR transition at 870 nm which is the weakest transition of erbium.

Growth and optical characterization of holmium-doped potassium lead chloride


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. Oriented absorption and fluorescence spectra of this material (nominal concentration ~1%) were acquired. With UV pumping, strong emission was observed at multiple wavelengths in the visible and near-infrared; this is to be expected from a low phonon energy host material like KPB2Cl5, where many excited states that would be quenched in an oxide are metastable. The 5I7 → 5I8 transition in the vicinity of 2 µm exhibited a long fluorescence lifetime of 10.4 ms, comparable to the lifetimes observed in fluoride hosts and longer than the 8 ms reported for (Yb,Ho):YAG. 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. This has potential implications for the development of fluorescence-cooled high-power lasers operating in the “eye safe” spectral region.
7951-16, Session 4

**Effects of photon transport, emission saturation, and reflection losses on thermophotonic cooling**

J. Oksanen, J. Tulkki, Aalto Univ. School of Science and Technology (Finland)

In thermophotonic cooling (TPC) the requirement of efficient photon extraction out of the semiconductor material is removed by the absorption of the light within the semiconductor structure. TPC cooling currently offers one of the most viable approaches to observing electroluminescent cooling of semiconductors in practise. We discuss the preliminary measurement data on an experimental realization of a thermophotonic cooler. We also present a detailed numerical model which realistically accounts for the current and photon transport as well as various loss mechanisms like the mirror losses and the nonradiative losses in the structure. The model essentially consists of the semiconductor equations for current transport and the radiative transfer equation for the photon transport. Based on the developed model and the experimental measurements we will also discuss the predicted performance figures for TPC.
Light peak

H. Cheng, J. Ko, C. Krause, M. Gao, Intel Corp. (United States)

Optical-interconnect technology has long been used for router systems in both the Telecom & the Datacom applications. Even though there are some adoptions of optical technology in the server space such as the high performance computing (HPC), there is little to no penetration of optical technologies in the PC space. The barriers are the usage models, cost, power, & form factor. Since optical links is just a big data pipe, new applications & usage models are required to make the optical interconnect an interesting technology in compared with the copper link particularly in the PC space. In this presentation, various usage models of the optical-interconnect on the PC/Server applications will be discussed. Clearly, optical interconnect is good at high data-rate & long-reach. However, there are significant disadvantages on the cost associated with the cable termination & the transceiver modules. To understand what the true limitations are, “cost”, “power”, & “form factor” will be scrutinized in details. Methods to drive down the cost, to lower the power, & to make the form factor smaller/thinner are all critical to the optical technology adoptions.

The Intel “Light Peak” technology is a new optical interconnect technology that address the above issues. This 10Gb/s optical link breaks the barrier on the cost, power, & form factor previously set by the optical link used in the datacom space. The goal is to utilize the large bandwidth provided by the optical link to create the new usage models that copper solution can’t excel. The optical solution also provides a path for the future technology scalability.

1060nm VCSEL for intra-chip optical interconnection


As the importance of the Green-IT and spreading photonic interconnection has increased, the demand for low cost and energy effective solutions with high reliability is strongly desired.

We have reported our systematic reliability and low jitter study for InGaAs-strained QW “green” 1060nm VCSEL developed in Furukawa Electric. In this report, our continuous study result expanding to intra-chip application in terms with power consumption connected to commercial drive IC and long term reliability test is shown.

As for the low power consumption study, we evaluated the discrete device and observed clear eye opening at 10Gbps with power dissipation level of 140UJ/bit with I.4 mA bias current and 75mVpp voltage swing level. In addition, good matching performance with commercial VCSEL driver IC of IPvD12x12 developed by IPtronic with the same bias current level was obtained.

In the reliability test, our intensive long term aging tests of over 300pcs devices per test have been reached up to 14,000hours at 70degC and 90degC and no applicable change was observed in threshold current and output power. In the conference, we would like to update the long term reliability test result with additional test condition for FIT number study in wear-out will be presented.

Based on the above experimental results, our 1060nm VCSEL with low power consumption level of sub-pJ/bit and high reliability would be projected to a light source for intra-chip application.

850nm oxide high-speed VCSEL development at Avago

J. Wang, C. Ji, D. Soderstrom, J. Tong, L. Giovane, S. Ray, Avago Technologies Ltd. (United States); Z. Feng, F. Hopfer, J. Hwang, Avago Technologies Singapore (Singapore); T. Sale, S. J. Taslim, C. Chu, Avago Technologies Singapore (United States)

The design of 850 nm oxide VCSEL has been engineered to meet the emerging 16 G Fibre Channel application over the extended temperature range to support transceiver module operation from 0C to 85C. The design includes the optimization of the Al-composition, the grading layer and the doping profile of both the n-type and p-type DBRs for low electrical series resistance and low thermal impedance while minimizing optical losses from free carrier absorption. The VCSEL is fabricated leveraging Avago’s volume 10G VCSEL manufacturing process. The p-metal contact pad is placed on top of a thick benzocyclobutene (BCB) layer to reduce the capacitance associated with the bond pad. The VCSEL’s small-signal modulation response has been characterized over the extended temperature range and will be presented with VCSEL simulation results. The large-signal eye diagrams of the VCSEL show superior high-speed performance over the entire extended temperature range. We will also present the results of accelerated life testing.

New high speed VCSEL product development at Emcore

C. Xie, N. Li, W. Luo, C. Lei, X. Sun, L. Zhao, D. Jensen, EMCORE Corp. (United States)

In this paper, we summarize the recent VCSEL development effort at Emcore. The focus of this effort is on performance, reliability and manufacturability. We will report the performance of Emcore’s 140bps VCSEL for the new fibre channel application. We will also present the work on manufacturing both singlet and various VCSEL arrays, with performance up to 10Gbps, using a universal mask set to deliver both high performance and high manufacturability. The reliability data and the work on wafer level burn-in will be updated as well.

High power VCSEL systems for tailored intensity distributions

H. Moench, Philips Research (Germany); M. Miller, Philips Technologie GmbH U-L-M Photonics (Germany); S. Gronenborn, P. Loosen, Fraunhofer-Institut für Lasertechnik (Germany)

New laser applications with moderate requirements on brightness but demanding intensity distributions show an interesting market potential. Arrays of high power VCSELs offer a unique opportunity to create a target intensity distribution which is tailored to the needs of a specific application. The concept presented here images the near field of the VCSEL onto the target. This is achieved by a combination of micro-lenses and field lenses in order to superimpose many VCSELs in an array. This optical system can be simple and the freedom to realize a wide variety of different intensity distributions with one and the same optics is large. The only variation is in the shape of the VCSEL aperture, which is well defined by lithography and does not affect subsequent process steps. Furthermore the optical superposition of many individual
VCSEL apertures on the target allows uniform distributions unaffected by single device failures. Also electrical control of the intensity profile can be achieved in a simple laser module without the need of changing the optics or moving parts in the setup. The laser modules can be scaled easily in power and size and allow a straightforward realization of top-hat beams with round or rectangular shape, ring-shaped beams or a long line focus. In all these aspects a VCSEL solution can be superior to equivalent concepts based on edge emitting laser diodes.

7952-07, Session 2

Record high temperature high-output power red VCSELs

K. Johnson, M. Hibbs-Brenner, W. Hogan, M. Dummer, K. Dogubo, G. Berg, Vixar (United States)

Red VCSELs (650-690nm) are of interest for a number of applications such as industrial sensors, medical sensors, printing, scanning, and consumer electronics. However, challenges remain in achieving the required output power, temperature range, modal structure and reliability for some applications. Record high temperature operation and output power has been achieved in red VCSELs and will be reported in this paper. The study has examined the effect of emission wavelength, cavity resonance-gain peak offset, aperture size, metal-aperture overlay, mirror composition and grading, and current and optical confinement means on the temperature performance and output power. There is no silver bullet: attention to every detail of the design is required to achieve optimal results. At a wavelength of approximately 680nm, CW lasing up to 105°C has been achieved for a small diameter, single-mode device. Single-mode output power >2mW is achievable at room temperature, while >1mW single-mode output power is maintained at 60°C. Larger aperture (>8µm), multi-mode devices lase CW at temperatures up to 80°C, with more than 1mW of output power achieved at 70°C. The highest CW output power observed from a single aperture device at room temperature is 14mW. A tightly packed multiple aperture array on a single chip emits more than 40mW. Pulsed operation, with pulse widths less than 1µsec and duty cycle less than 10%, have been shown to increase the peak output power by approximately 4X.

7952-08, Session 3

Phenomenological study of VCSEL wearout reliability

J. K. Guenter, B. Hawkins, R. A. Hawthorne III, Finisar Corp. (United States)

It has been traditional in discussions of VCSEL reliability to consider it as having a single major wearout component, with known temperature and current acceleration. Beyond this major component all other causes of failure are lumped into a small random failure component with an assumed but not characterized-lower activation energy. Because reliability testing to assess the wearout acceleration requires very long test times to generate failures in the lowest-stress conditions, it is often assumed that the model that has been successful describing reliability in 850-nm data communications VCSELs can be extended to VCSELs of other wavelengths without significant modifications. This paper examines that assumption with regard to several VCSELs of different designs, and with emission wavelengths from below 800 nm to above 900 nm. A careful analysis reveals that even well-behaved wearout degradation might have several components whose relative contributions differ somewhat for different designs, with different resulting performance effects.

7952-09, Session 3

Reliability study of encapsulated VCSELs

K. D. Choquette, D. M. Grasso, M. Kasten, Univ. of Illinois at Urbana-Champaign (United States); D. McElfresh, D. Vacar, L. D. Lopez, Oracle (United States)

Studies of the reliability of vertical cavity surface emitting lasers (VCSELs) have focused on device structures utilized for commercial applications, such as data communication sources. We have fabricated different VCSEL device structures, including etched mesas and dielectric encapsulation, and have subjected them to lifetime testing at elevated temperature and humidity to determine fabrication parameters that impact the reliability of VCSELs. We will describe the matrix of device structure parameters considered, the testing and analysis procedure, and finally the reliability results.

7952-10, Session 3

Spin induced gigahertz polarization oscillations in vertical-cavity surface-emitting laser devices

M. Li, J. Hendrik, H. Soldat, N. C. Gerhardt, M. R. Hofmann, Ruhr-Univ. Bochum (Germany); T. Ackemann, Univ. of Strathclyde (United Kingdom)

The capabilities of spin controlled vertical-cavity surface-emitting lasers (VCSELs) such as high-speed modulation and amplification of spin information due to the nonlinearity above threshold offer a promising method of communication with enhanced bandwidth. Here we investigate the circular polarization dynamics of VCSELs on a picosecond time scale after pulsed spin injection at room temperature. A hybrid excitation technique combining continuous-wave unpolarized electrical excitation in the vicinity of a polarization switching point and pulsed polarized optical excitation is applied. The experimental results demonstrate ultrafast circular polarization oscillations with a frequency of 11.6 GHz, only very weakly dependent on cw bias and temperature. This feature distinguishes them from intensity relaxation oscillations, whose frequency strongly depends on the excitation strength. The oscillations are long-lived, longer than 5 ns, which is much longer than the spin relaxation time in this device. Via theoretical calculations based on a rate equation model we analyze these oscillations as well as the underlying physical mechanism. The oscillations are due to a beating of two phase coupled linear polarized modes, which coexist only in the vicinity of the polarization switching point with roughly equal decay rates. The frequency of the oscillations is given by the frequency difference of two linear modes which is known as the effective birefringence in VCSELs. That opens a possibility to control the frequency of the oscillations by tuning the birefringence. We investigate theoretically how the oscillations can be initiated by a suitably shaped current pulse in future electrically pumped spin-VCSELs.

7952-11, Session 3

Electrical characterization of tunnel junction based long wavelength VCSELs

A. Consoli, Univ. Politécnica de Madrid (Spain); J. Arias, Univ. Miguel Hernández de Elche (Spain); J. M. Tijero, F. J. López Hernández, I. Esquivias, Univ. Politécnica de Madrid (Spain)

1550 nm VCSELs are becoming a real alternative to standard edge emitting lasers in high speed communication applications. A complete characterization and modeling of the electrical properties of low cost commercial VCSELs is necessary to design the driving electronics, as well to determine the main parameters needed to simulate the device performance in optical links. The use of tunnel junction (TJ) in monolithic designs increases the complexity of the electrical properties in
comparison with edge emitting lasers.

In this work we present results on the electrical characterization of commercially available fiber pigtailed 2.5 Gb/s VCSEL, based on InAlGaAs active region, TJ, air-gap aperture and InAlGaAs/InAlAs mirrors. The subthreshold Current-Voltage (I-V) characteristics were measured and the results were fitted to the analytical expressions of an equivalent circuit considering the TJ in series with the active junction and series resistance. The electrical parameters of both junctions were determined, showing that the TJ was responsible for most of the voltage drop at threshold. The frequency electrical impedance of the devices was measured with a vector network analyzer up to 10 GHz. The results were analyzed using different small signal equivalent circuits, which included the TJ, the cavity parasitics, and the electrical access. A good agreement between the experimental and the equivalent circuit impedances at different bias was obtained by considering the dynamic resistances of the active and tunnel junctions extracted from the I-V characteristics, yielding reasonable values of the recombination A, B and C coefficients.

7952-12, Session 4
Single-mode and tunable GaSb-based VCSELs for wavelengths above 2 um
M. Amann, S. Arafin, K. Vizbaras, Walter Schottky Institute (Germany)

No abstract available

7952-13, Session 4
Modeling of compact Pd coated VCSELs for hydrogen sensing
C. A. Edwards, G. Shine, L. Goddard, Univ. of Illinois at Urbana-Champaign (United States)

We have designed compact VCSEL sensor arrays for use in hydrogen gas detection. We are using 980nm VCSELs coated with Pd which has been proven to react with hydrogen. During this reaction the device undergoes hydrogen induced lattice expansion (HILE) which causes two distinct effects that can be detected at the output. These two effects are a red-shift in the emission spectrum and an increase in output power. Palladium has a face centered cubic lattice structure and is said to be in the \(-\)phase when no hydrogen is present. Once the hydrogen concentration reaches the level denoted by \(-\)max, the \(-\)phase begins to appear and the lattice starts to expand. When the hydrogen concentration reaches the critical value \(-\)max, the \(-\)phase becomes dominant and the \(-\)phase fades away. At this point, the lattice has been shown to expand up to 3.5% of its original value. This expansion leads to a red-shift in the emission spectrum and the increase in output power. The VCSELs we have designed are optically pumped at 915nm and top emitting at 980nm. The top DBR is anti-reflective at 915nm and highly reflective at 980nm. The bottom DBR is highly reflective at both 915nm and 980nm. This will allow the pump beam to enter in through the top of the VCSEL, make two passes through the active region, and exit back out through the top. The top and bottom DBRs have 20 and 30 pairs respectively. The bottom of the VCSEL is 20µm in diameter and the aperture is 1.5µm in diameter and is etched down to just above the active region. An oxide aperture has been placed 10nm below the bottom of the active region and will consist of AlAs with a 1µm diameter aperture. The active region contains two cladding layers comprised of Al0.4Ga0.6As as well as two strain-compensating layers made up of GaAst0.6P0.4S. The MQW region contains three 8nm In0.20Ga0.80As quantum wells separated by 10nm of GaAs. The Pd coating is 10nm in thickness. Our calculations for the initial electrically pumped model show an output power of about 3mW at a bias 8mA and about 2.8V from Pd. The threshold current is about 200µA giving us a current density of about 10kA/cm². The addition of the Pd coating creates a slight increase in the threshold current density and drops the output power by about 50%. At the critical concentration of 4% hydrogen, the output power increases about 10%. The loss, calculated as L=1-(R+T), is 0.441 without hydrogen and 0.398 at 4%.

We plan to create compact VCSEL arrays that can be used to detect various trace gases simultaneously. Each column of VCSELs in the array will be coated with a different material that will react with a specific trace gas. The different materials and their effects in the presence of trace gases are currently being explored by other members within our group. Each row of VCSELs has a different diameter in order to vary the sensitivity. By using an achromatic array to focus the pump light and to collect the emitted light, we can image the entire array simultaneously on a CCD for fast gas quantification. We are also working on the design and implementation of the testing station that will be used to collect and analyze the data which will help verify our design.

7952-14, Session 4
A VCSEL based system for on site monitoring of low level methane emission
A. Kannath, Geotechnical Instruments (UK) Ltd. (United Kingdom) and Geotechnical Instruments Ltd, Leamington Spa (United Kingdom); J. Hodgkinson, Cranfield Univ. (United Kingdom); R. Gillard, R. Riley, Geotechnical Instruments (UK) Ltd. (United Kingdom); R. P. Tatam, Cranfield Univ. (United Kingdom)

Continuous monitoring of methane emissions has assumed greater significance in the recent past due to increasing focus on global warming issues, as methane is a potent greenhouse gas. Many industries have also identified the need for ppm level methane measurement systems as a means of gaining carbon credits. Conventional instruments based on NDIR spectroscopy are unable to satisfactorily meet customer demands of high selectivity and sensitivity coupled with fast response times. Here we discuss the development and performance characteristics of a robust tunable diode laser spectroscopy (TDL-S) based system for accurate ppm level measurements of methane. We demonstrate the feasibility of such a system for applications in an industrial scenario such as residual methane measurement whilst monitoring the output of flare stacks and exhaust gases from methane combustion engines.

The VCSEL based system employs a Wavelength Modulation Spectroscopy (WMS) scheme with second harmonic detection at 1651 nm. Optimum modulation frequency and ramp rates were chosen to maintain high resolution and fast response times which are vital for the intended applications. Advanced data processing techniques and optimised curve fitting procedures were used to achieve long term sensitivity of the order of 10-5 in absorbance. Cross interference from other gases was studied to ensure the system is immune to such effects and its inherent design features make it ideal for large scale commercial production. The instrument maintains its calibration and when coupled with the associated gas sampling and conditioning systems, offers a completely automated continuous monitoring solution for remote on site deployment.

7952-15, Session 4
Efficient vertical-cavity surface-emitting lasers for infrared illumination applications

Infrared illumination is used in the commercial and defense markets, for surveillance and security, for high-speed imagery (such as explosive events), and for military covert operations. Preferred emission wavelengths are in the 8x and 9x nm regions. The light engine is generally comprised of light bulbs, light-emitting diodes, diode-pumped solid-state lasers, or edge-emitting lasers. However, these approaches have several short-comings such as poor life-time (light bulbs), high-
Vertical-cavity surface emitting lasers (VCSELs) are the digital photonic sources used in short distance optical interconnects that are used by the thousands within data centers. One advantage of the VCSEL is its relatively low operating power; nevertheless, all semiconductor lasers fundamentally require increased photon cavity density (increased relaxation oscillation frequency), and thus increased electronic injection above threshold, in order to operate at higher modulation speeds. Hence we are exploring new digital modulation approaches for VCSELs that can operate at low power, ideally near the laser threshold. Several approaches for mode modulation under development in my laboratory will be reviewed. Rather than modulate the amplitude of a laser mode, we seek to change the mode (i.e. change the boundary conditions of the cavity and thus its optical modes) in a manner that effectively changes the output. An example is longitudinal mode modulation within a composite resonator vertical cavity laser. By varying the electronic induced refractive index within the two coupled optical cavities, the longitudinal mode can be "pulled" out of the wafer surface or "pushed" into the substrate, thus modulating the top laser emission. Another example is VCSEL polarization modulation, in which the laser injection remains constant, but the mode polarization changes. The objective of all of these mode modulation techniques is the effective digital variation of the laser output using a very low power input signal where the laser can be operated near threshold, independent of the modulation frequency.

High-speed highly temperature stable 980 nm VCSELs operating at 25 Gb/s at up to 85 °C for short reach optical interconnects

A. Mutig, Technische Univ. Berlin (Germany); J. A. Lott, VI Systems GmbH (Germany); S. S. Blokhin, P. Moser, P. Wolf, W. Hofmann, A. M. Nadtochiy, A. Payusov, D. Bimberg, Technische Univ. Berlin (Germany)

The progressive penetration of optical communication links into traditional copper interconnect market greatly expands the applications of vertical cavity surface emitting lasers (VCSELs) for the next-generation of board-to-board, module-to-module, chip-to-chip and on-chip optical interconnects. High temperature stability of the VCSELs is indispensable since these laser devices typically reside directly on or near integrated circuit chips. While 850 nm is the current standard wavelength for local and storage area networks, potential competitive standards at 980 nm have many critical advantages for short reach systems including: smaller operational voltages, deeper potential wells that suppress the escape of injected non-equilibrium carriers, and transparency of the GaAs substrate. Here we present 980 nm oxide-confined VCSELs operating error-free at data bit rates of up to 25 Gbit/s at temperatures as high as 85 °C without adjustment of the drive current and peak-to-peak modulation voltage, thus simplifying the design and lowering the power consumption of the driver circuit electronics, and reducing the production and operational costs of the transmitter or transceiver modules. To facilitate our analysis of the limiting physical processes inside the VCSELs we perform small and large signal modulation experiments at various temperatures from 20 to 85 °C. We demonstrate maximum bandwidths around 13-15 GHz that are very temperature insensitive. The maximum parasitic cut-off frequencies extracted from the measured small signal modulation data are at all temperatures larger than 22 GHz. Our results demonstrate the suitability of our VCSELs for practical high speed and high temperature stable short-reach optical link applications.

Energy efficient VCSEL digital modulation sources

K. D. Choquette, Univ. of Illinois (United States)

Internet usage continues to increase in virtually every county on our planet, which will require the construction of new and/or expanded data centers, accompanied by an increased demand for energy. In order to sustain the increased demands of the internet infrastructure, there is a need for photonic digital systems that require less energy for generation or switching per bit of information. Vertical cavity surface emitting lasers (VCSELs) are the digital photonic sources used in short distance optical interconnects that are used by the thousands within data centers. One advantage of the VCSEL is its relatively low operating power; nevertheless, all semiconductor lasers fundamentally require increased photon cavity density (increased relaxation oscillation frequency), and thus increased electronic injection above threshold, in order to operate at higher modulation speeds. Hence we are exploring new digital modulation approaches for VCSELs that can operate at low power, ideally near the laser threshold. Several approaches for mode modulation under development in my laboratory will be reviewed. Rather than modulate the amplitude of a laser mode, we seek to change the mode (i.e. change the boundary conditions of the cavity and thus its optical modes) in a manner that effectively changes the output. An example is longitudinal mode modulation within a composite resonator vertical cavity laser. By varying the electronic induced refractive index within the two coupled optical cavities, the longitudinal mode can be "pulled" out of the wafer surface or "pushed" into the substrate, thus modulating the top laser emission. Another example is VCSEL polarization modulation, in which the laser injection remains constant, but the mode polarization changes. The objective of all of these mode modulation techniques is the effective digital variation of the laser output using a very low power input signal where the laser can be operated near threshold, independent of the modulation frequency.

High-speed single-mode quantum dot and quantum well VCSELs

N. N. Ledentsov, VI Systems GmbH (Germany); A. M. Nadtochiy, Technische Univ. Berlin (Germany); S. S. Blokhin, Connector Optics LLC (Russian Federation); P. Wolf, P. Moser, Technische Univ. Berlin (Germany); J. A. Lott, V. A. Shchukin, VI Systems GmbH (Germany); W. Hofmann, D. Bimberg, Technische Univ. Berlin (Germany)

We show that single mode quantum dot and quantum well vertical cavity surface emitting lasers (VCSELs) can reach resonance frequencies as high as 18 GHz and are capable of operating error free at data bit transfer rates of 25 Gb/s and faster. These single mode and high power VCSELs are of great interest for spectroscopy and for extending the reach of optical fiber link systems.

Higher speed VCSELs by photon lifetime reduction

P. Westbergh, J. Gustavsson, B. Kögel, Å. Haglund, A. Larsson, Chalmers Univ. of Technology (Sweden); A. Joel, IQE Europe Ltd. (United Kingdom)

We have investigated the effects of photon lifetime reduction on the performance of high speed 850 nm vertical cavity surface emitting lasers (VCSELs). By shallow etching (25 - 55 nm) of the upper layer of the top distributed Bragg reflector (DBR) we effectively control the photon lifetime by changing the degree of out-of-phase reflection from the semiconductor-air interface. With this technique, the photon lifetime is reduced by up to 80% and both static and dynamic properties of the VCSEL are improved. By determining the bias current dependencies of resonance frequency, damping rate, and parasitic cut-off frequency as a function of etch depth, we find that the modulation bandwidth of the VCSEL is initially limited by damping, but as the photon lifetime is reduced the damping limit is extended and the bandwidth increases until thermal and parasitic limitations set in. By optimizing the photon lifetime we are able to enhance the 3dB modulation bandwidth of 7 µm oxide aperture VCSELs from 15 GHz to a record value of 23 GHz; a bandwidth improvement of more than 50%. Data transmission experiments show that this high bandwidth allows for error-free transmission (BER < 10-12).
We show that both phenomena occur simultaneously at the same level of injection locking for low (high) enough levels of bias current applied to the device.


We report the relation between the transverse modal processing functions can be performed by using transverse mode regeneration, inversion and optical memory [1]. These all-optical signal processing functions are performed by using transverse mode selection in multimode VCSELs under appropriate optical injection [1].

In this work we perform an experimental study of the transverse mode selection in a 1550-nm multi-mode VCSEL subject to external optical injection. Our VCSEL emits in two linearly polarized transverse modes with parallel polarizations. We consider a “parallel polarized optical injection” configuration in which linearly polarized light from a tunable external laser source is injected parallel to the linear polarization of the free-running VCSEL. We report the relation between the transverse modal selection and the injection locking properties of multi-mode VCSELs. We show that both phenomena occur simultaneously at the same level of injected optical power if large enough values of wavelength detuning between the injected light and the fundamental transverse mode of the VCSEL are considered. For small enough wavelengths of wavelength detuning the injected power required to select the fundamental transverse mode of the VCSEL is smaller (higher) than that needed for the occurrence of injection locking for low (high) enough levels of bias current applied to the device.

Vertical-cavity surface-emitting lasers (VCSELs) are very promising devices for all-optical signal processing functions such as signal regeneration, inversion and optical memory [1]. These all-optical signal processing functions can be performed by using transverse mode selection in multimode VCSELs under appropriate optical injection [1].

We report the demonstration of a fully micro-fabricated vertical-external-cavity surface-emitting laser (VECSEL) operating at wavelengths near 850nm. The external-cavity length is on the order of 25 microns, and the external mirror is a dielectric DBR with a radius of curvature of 130 microns that is micro-fabricated on top of the active semiconductor portion of the device. The longer cavity enables narrower laser linewidths and micro-fabrication of the external mirror preserves the manufacturing cost advantages of parallel lithographic alignment.

Vertical-cavity surface-emitting lasers (VCSELs) and their scaling properties. Lithographic VCSELs have simultaneous mode- and current-confinement defined only by lithography and epitaxial crystal growth. The lithographic process of these devices allows getting uniform device size throughout a wafer and easy scaling to manufacture very small lasers. The semiconductor’s high thermal conductivity enables the small lithographic VCSEL to have lower thermal resistance than an oxide-aperture VCSEL, while the lithographic fabrication produces high VCSEL uniformity even at small size.

Data are presented demonstrating lithographic vertical-cavity surface-emitting lasers (VCSELs) and their scaling properties. Lithographic VCSELs produce output power of 4.7 mW, with threshold current of 320 µA and slope efficiency of 0.7 W/A at emission wavelength of 980 nm. These VCSELs also have single-mode single-polarization lasing without the use of a surface grating, and have >25 dB side-mode-suppression-ratio up to 1 mW of output power. Lifetime tests demonstrate that 3 µm VCSEL operates for hundreds of hours at high injection current level of 85 kA/cm² with 3.7 mW output power without degradation. Scaling properties and low thermal resistance of the lithographic VCSELs can extend the VCSEL technology to manufacturable and reliable small size lasers and densely packed arrays with long device lifetime.

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Dual-wavelength vertical-cavity surface-emitting lasers based on asymmetric photonic crystal structures

B. Guan, X. Guo, Beijing Univ. of Technology (China)

Intense interests in wavelength engineering of vertical-cavity surface-emitting lasers (VCSELS) sources with photonic crystal (PC) structure are stimulated by continuing quest for smaller, faster, and more function optoelectronic devices in recent years. In this paper, a dual-wavelength VCSEL with asymmetric 1D PC structure is designed, where the light modes can be localized by the defect layer. The wavelength of the VCSEL can be separated in the real space with the aid of a single Al0.8Ga0.2As defect layer. The wavelengths of the VCSEL can be located at 979.7 nm and 943 nm with the aid of the Al0.8Ga0.2As defect layer in 1D photonic crystal structure. Specifically, the dual-wavelength lasing of the VCSEL with high quality factor is realized with the same light propagation direction for both wavelengths. Moreover, the relative spacing and position of the two wavelengths could be tuned by just changing the thickness of defect layer and the refractive index contrast of the asymmetric PC structure, which will promote the formation of the multi-defect mode states. The relative peak position of these two wavelengths could be tuned from ~33nm to ~50nm by changing the refractive index contrast of the asymmetric PC structure, which will promote the formation of multi-defect mode states. The results indicate that the above VCSEL structure, of which the wavelengths can be finely engineered, does not lose the device integrity and affect quantum wells material properties. Such VCSEL structure can be applied in various optoelectronic devices such as amplifiers, modulators, low threshold optical bistable switches, photo-detectors, etc.
Quantum dot composite light sources

D. W. Grund, Jr., D. W. Prather, Univ. of Delaware (United States)

In this effort, we present the most recent progress towards fabrication, testing, and system integration of Quantum Dot (QD) composite materials. These materials are important steps towards easy integration of a light source on silicon. QD composites are formed by incorporating QDs in a host material which acts to protect and maintain the characteristics of the QDs, as well as to act as a patterning matrix for lithography and etching. In this effort, commercially available IR emitting PbS QDs (Evident Technologies) were incorporated with several host materials such as PMMA and Titania Sol-Gel and were optically tested for photoluminescence, amplified spontaneous emission, and gain. We will present recent testing results as well as comment on the system integration aspects of this effort.

Gain and absorption characteristics of bilayer quantum dot lasers beyond 1.3 μm

A. M. Mohammed, H. Shahid, S. C. Chen, D. T. Childs, R. J. Airey, K. Kennedy, R. A. Hogg, The Univ. of Sheffield (United Kingdom); E. M. Clarke, P. Spencer, R. Murray, Imperial College London (United Kingdom)

Quantum dot (QD) materials are commercialized in the 1.0 μm to 1.3 μm region. However, many of the properties of QD lasers (zero chirp, temperature insensitive operation, single photon emission) are particularly attractive at 1.55 μm. In this paper, we report on the analysis of molecular beam epitaxy (MBE) grown GaAs and InGaAs capped bilayer QD laser material via a number of characterization techniques. The InGaAs capped bilayer QD lasers extends the room temperature lasing wavelength to 1450nm. The further analysis of the materials using the multi-section technique [5] allows the gain and absorption spectrum to be obtained under various CW and pulsed bias conditions, and at a range of temperatures. The spectral measurement of gain demonstrates that net modal gain is achieved beyond 1300nm at room temperature for an InGaAs capped QD active layer. The concept is that the lower lying QD layer controls the QD density of the upper layer, and the growth conditions of the upper QD layer can determine the emission wavelength.

Temperature dependence and physical properties of GaAsSb/GaAs QW lasers

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We investigate the temperature dependence and performance limiting non-radiative processes in MBE grown 1.3μm GaAsSb/GaAs QW lasers with different structures (grown under same growth conditions) to aid in the design and optimization of low cost GaAsSb/GaAs-based edge-emitting lasers and VCSELs. The threshold current density (Jth) of a 1xQW (L0611) and 2xQW (L0612) devices are measured to be 327 Acm-2 and 207 Acm-2, respectively, at room temperature (RT), both emitting at ~1291nm. The lower Jth in device L0612 compare to device L0611 is consistent with the MQW devices (L0612) providing a lower threshold carrier density. From the temperature dependent facet and spontaneous emission measurements for device L0612 we estimate that the relative ratio of the radiative (Jrad) and non-radiative currents at Jth are ~33% and ~67%, respectively, at RT, compared with ~28% and ~72% for devices L0611. This is consistent with the reduced influence of the non-radiative recombination in device L0612. The characteristic temperature (T0) value is higher in device L0612 (73K) than device L0611 (69K) near RT. The application of hydrostatic pressure shows that the Jth increases with pressure much faster than Jrad for both devices, suggesting the presence of carrier leakage in these devices. The threshold current for device L0611 and device L0612 increased by ~63% and ~52% respectively up to 7 kbar at RT also consistent with reduced non-radiative recombination in the MQW devices.
eliminating the Si-InP substrate, where the optical confinement factor of membrane DFB lasers with a thinner core layer (less than 200 nm) by From these lasing properties, potential operation characteristics of real signal modulation bandwidth of 4.8 GHz was obtained at the bias current (SMSR) of 41 dB at a bias current of 2 times the threshold and the small length of 300 µm, the stripe width of 2.0 µm, and the index-coupling-processes and obtained a threshold current of 7.0 mA and the external differential resistance at the threshold current was around 20 Ω which is a factor of 2.8 as compared to 20µm wide ridges whereas in quantum well ridge lasers threshold current density increases by a factor of 9 for the same pair of ridge widths. We show that this different dependence on ridge width corresponds to the different lateral diffusion characteristics of the quantum well and self assembled quantum dot material.

7953-05, Session 1
The lateral ambipolar diffusion length in quantum dot lasers
D. Naidu, A. Sobiesierski, P. M. Smowton, Cardiff Univ. (United Kingdom)
Using the segmented contact technique we separate out the lateral out-diffusion current in shallow etched quantum dot ridges of different width and by fitting this out-diffusion data we obtain the ambipolar diffusion length as a function of the intrinsic carrier injection level. The measured data reveals two regimes of reduced diffusion that can be explained by a mechanism involving the thermal redistribution of carriers via the wetting layer. In a high performance 5 layer quantum dot structure operated at 350K the diffusion length varies between 0.75 and 1.5 µm as the peak modal gain increases from 5 to 11cm-1.
In dot-in-well quantum dot samples fabricated into deep etched ridge lasers we demonstrate the reduced width dependence of threshold current density as compared to quantum well material, which is identical except for the presence of the dots and wetting layer. For example in 3µm wide quantum dot ridges operated at 300K threshold current density increases by a factor of 2.8 as compared to 20µm wide ridges whereas in quantum well ridge lasers threshold current density increases by a factor of 9 for the same pair of ridge widths. We show that this different dependence on ridge width corresponds to the different lateral diffusion characteristics of the quantum well and self assembled quantum dot material.

7953-06, Session 2
Lateral current injection GaInAsP/InP laser for membrane based photonic circuits
S. Arai, N. Nishiyama, T. Okumura, T. Shindo, Tokyo Institute of Technology (Japan)
Toward realization of ultra-low power consumption lasers for on-chip optical interconnection in next generation LSI, we proposed membrane BH-DFB lasers, consisting of a thin semiconductor core layer sandwiched by low refractive-index claddings with high index-coupling grating structure, and demonstrated CW operation up to 85°C under an optical pump. As a step toward ultra-low power operation under a current injection, we realized lateral current injection type 5-QW GaInAsP/InP lasers with a thin core layer (only 400 nm) grown on a semi-insulating (SI) InP substrate by 2-step regrowths of n-InP and p-InP cladding layers. A room-temperature CW operation of Fabry-Perot cavity laser was obtained with a threshold current of 11 mA and an external differential quantum efficiency of 33% for the cavity length of 720 µm and the stripe width of 1.7 µm. The rise-up voltage was observed to be 0.8 V and the differential resistance at the threshold current was around 20 Q which is 2-3 times higher than that of our conventional DH lasers due to relatively thin current injection layer (400 nm) and wide distance between n- and p-electrode pads of around 15 µm.
Then we realized DFB lasers with 30 nm thick surface grating of amorphous silicon (a-Si) by the similar structure and fabrication processes and obtained a threshold current of 7.0 mA and the external differential quantum efficiency from the front facet of 43% for the cavity length of 300 µm, the stripe width of 2.0 µm, and the index-coupling-coefficient of the grating of 100 cm-1. A side-mode suppression-ratio (SMSR) of 41 dB at a bias current of 2 times the threshold and the small signal modulation bandwidth of 4.8 GHz was obtained at the bias current of 30 mA.
From these lasing properties, potential operation characteristics of real membrane DFB lasers with a thinner core layer (less than 200 nm) by eliminating the SI-InP substrate, where the optical confinement factor of the active layer as well as the index-coupling-coefficient the grating can be enhanced by a factor of around 3, will be discussed.

7953-07, Session 2
700-730nm emitting deep etched DBR InP/AlGaInP quantum dot lasers
S. Shutts, G. T. Edwards, P. M. Smowton, Cardiff Univ. (United Kingdom)
Self assembled InP quantum dots offer a range of emission wavelengths from 645 - 750 nm making them useful for laser applications in Photodynamic therapies and Bio-photonic sensing. To date InP/AlGaInP QD laser structures grown by MOVPE have been demonstrated with threshold current densities as low as 150 Acm-2 for 2mm long lasers with as cleaved facets and emitting between 700-750 nm. By optimising the quantum dot size distribution it is possible to achieve broad and relatively flat topped gain spectra that are ideally suited to devices incorporating deep etched Distributed Bragg Reflectors (DBRs), with relatively narrow stopbands. Here we describe the optimisation of a single stage etch process suitable for producing anisotropic microstructures and the resulting deep-etched DFB lasers.
We use the broad gain spectrum, measured using the segmented contact method, to explain the wide range of lasing wavelengths that can be obtained by varying the grating structure and the relative insensitivity of threshold current. For example, measurements of emission wavelength on a 4 µm wide DBR ridge laser show they can be tuned up to 16 nm from the peak emission of a ridge laser with cleaved facets. Gain spectra taken over a temperature range between 220 and 320 K show a temperature sensitivity in peak gain wavelength of 0.13nm/K and lasers fabricated with cleaved facets have a similar dependence. DBR structures improve this behaviour, with a temperature dependence in peak wavelength of 0.07nm/K, for a 1500µm long DBR laser operated over the same temperature range.

7953-08, Session 2
Index-coupled holographically patterned 1.3um quantum dot distributed feedback lasers fabricated with a combined MBE/ MOCVD process
J. Hu, D. J. Klotzkin, Binghamton Univ. (United States); J. Huang, X. Sun, N. Li, EMCORE Corp. (United States)
Quantum dot (QD) lasers have been widely studied due to their attractive features of low-threshold current density, high gain, low chirp and superior temperature stability. Previously 1.3 µm QD distributed feedback (DFB) lasers have been fabricated with the metal surface gratings, which are lossy and (being typically written by e-beam lithography) are difficult to fabricate in a manufacturable way. Here, index-coupled 1.3 µm DFB lasers using wafer-level interference lithography for grating patterning were fabricated using molecular beam epitaxy for QD growth and molecular oxide chemical vapor deposition for grating overgrowth. Analysis of broad area devices gives a material transparency current density of ~300A/cm2. Single mode, ridge waveguide devices with various cavity lengths of were AR/HR coated and tested. Typical DC characteristics of 1000 m devices were threshold currents of ~40mA, slope efficiency of ~0.22W/A, and SMSRs >40dB. Demonstration of a feasible process for wafer level fabrication along with elimination of the deleterious effects of the metal surface grating, may allow these devices to make commercial inroads. Further characterization of the QD DFB laser bars is ongoing.
High power distributed feedback and Fabry-Perot Al-free laser diodes at 780 nm for rubidium pumping


Development of techniques such as atom optical pumping, for atomic clocks and matter-wave interferometers (gyrometer, accelerometer, gravimeter and gradiometer), requires laser diodes with high power and excellent spectral (narrow linewidth) and spatial qualities together with high reliability.

We have developed high power Fabry-Perot and distributed Feedback lasers diodes emitting at 780nm corresponding to the D2 line of Rubidium.

We have realized a Fabry-Perot laser diode, without aluminium in the active region, with a cavity length and a waveguide width of respectively 1mm and 4µm and an AR/HR coating on the facets. We obtain a low threshold current around 40mA and a high slope efficiency of 1W/A at 20°C. We obtain a good beam quality M² of 2 at 200mW. These lasers diodes are very interesting to be inserted in extended cavity.

For DFB lasers, we used a second order grating in GaInP/GaAsP/GaInP. We calculated the coupling coefficient KL of 1.5 for a length of 2mm, for a width of 4µm. These lasers show a low threshold current (around 65mA) with a slope efficiency around 0.37W/A. We have obtained at 25°C, 145mA an optical power of 25mW at the D2 line of Rubidium with a side mode suppression ratio around 44dB. By the self-heterodyne method, we measured a low linewidth of our DFB laser at 780nm around 1.25MHz (lorentzian fit).

Narrow-linewidth distributed feedback lasers with laterally-coupled ridge-waveguide surface gratings fabricated using nanoimprint lithography

M. M. Dumitrescu, J. Telkkala, A. I. Laakso, J. Viheriala, J. Karinen, T. Leinonen, M. Pessa, Tampere Univ. of Technology (Finland)

The distributed feedback (DFB) edge-emitting lasers with buried gratings require two or more epitaxial growth steps, bringing in the difficulties associated with the overgrowth, complicating the device fabrication and increasing the device cost. To avoid the problematic overgrowth we have used laterally-coupled surface gratings, which enable easy integration of the DFB laser with other devices and are applicable to different materials, including Al-containing ones, like GaAs/AlGaAs, InP/InAlGaAs.

894nm laterally-coupled DFB (LC-DFB) lasers have been fabricated for pumping Cesium-beam atomic clocks, which require narrow-linewidth emission. The lasers have been fabricated using a highly productive and cost-effective UV nanoimprint lithography technique, which can pattern a full wafer in a few minutes at an extremely high resolution.

Cross saturation characteristics of inhomogeneously broadened InP quantum dash optical amplifiers: fundamental properties and applications

G. Eisenstein, Technion-Israel Institute of Technology (Israel)

The inhomogeneously broadened gain of nano structure based optical gain media exhibits complex cross saturation properties which can be harnessed for several multi wavelength applications and have also a fundamental aspect which may lead to new important applications. This paper will survey telecom type applications in the Gbit/s range and introduce a newly discovered phenomenon occurring in quantum dash gain media where a combination of nonlinear two photon absorption, high excitation levels, the special gain function and the gain inhomogeneity enable an instantaneous gain response all across the gain spectrum resulting from a short pulse excitation near the gain peak.

Development of 1.3µm high-speed directly-modulated DFB and DBR lasers with surface gratings

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The paper presents the progress achieved in developing 1.3um high-speed distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers within the EU-FP7 STREP project “Development of low-cost technologies for the fabrication of high-performance telecommunication lasers (DeLight)”.

The lasers developed in the DeLight project are based on laterally-coupled ridge-waveguide (LC-RWG) surface gratings and are fabricated in a single growth and processing sweep, which avoids overgrowth, simplifies the device fabrication and reduces the device cost. The device fabrication cost is further reduced by using a highly productive and cost-effective UV nanoimprint lithography technique, which can pattern a full wafer in a few minutes at an extremely high resolution.

The particularities of the LC-RWG gratings (including the effects of the grating geometry, of the fabrication imperfections and of the facet reflectivities) are presented and designs of high-speed DFB and DBR lasers with LC-RWG gratings are discussed. 1.3um DFB and DBR lasers with LC-RWG gratings have been fabricated, both from InP-based and GaAs-based epitaxial wafers (including legacy epitaxial wafers with epilayer structures not designed for LC-RWG gratings) and small-signal modulation bandwidths up to 18GHz have been obtained. Since the electron-photon resonance limits the direct modulation bandwidth, laser structures with photon-photon resonances (PPRs) extending the direct optical amplifiers: fundamental properties and applications
1.55um directly modulated CCIG lasers fabricated by surface-defined lateral feedback gratings

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For next generation of fibre-to-the-home or high speed datacom systems high performance low-cost directly modulated lasers are of large interest. In this paper we are reporting the fabrication and characterization of Coupled Cavity Injection Grating (CCIG) lasers, which are multi-section devices with separate gain, grating and phase sections. By choosing the right operation conditions, CCIG lasers have the potential to overcome the bandwidth limitation of the laser material for direct modulation by a factor of 3-5. For the first time such complex devices were realized with a low-cost, nanoimprint compatible fabrication process based on surface defined gratings. The process is based on a single lithography and etching step on a fully grown laser structure. No overgrowth is necessary. An ICP-RIE dry etching process was developed, which allow in InP compounds high aspect ratios > 1:20.

Typical device geometries of the investigated devices are 400 µm of gain section length, 400 µm grating and 100-400 µm phase section, respectively. We successfully fabricated devices with SMSRs of > 50 dB. SMSRs contour plots as function of phase and grating currents show already in the static properties different instability islands where in the neighborhood a bandwidth enhancement by exciting the photon-photon resonance (PPR) is expected. First initial dynamic measurements without PPR enhancement exhibited a -3dB bandwidth of more than 15 GHz. Operation in the bandwidth enhancement mode should allow direct modulation speeds of > 40 GHz. Dynamic properties in different operation conditions is under investigation and will be presented at the conference.

40 Gbit/s directly modulated lasers: physics and application

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Low cost and compact transmitters are key components for short reach and datacom applications in fibre communication systems. Bit rates of 40 Gbit/s are beyond the speed limitation of conventional directly modulated lasers. Lasers with an integrated electro-absorption modulator (EML) represent one possible solution. An attractive alternative are Passive Feedback Lasers (PFL). Here, the modulation bandwidth is significantly increased by an integrated feedback section. Underlying physics and functionality of the PFL are presented as well as the successful realization at wavelengths in the 1300 nm and 1550 nm regions. The performance of these PFLs is demonstrated in system experiments.

Recent results of blue and green InGaN laser diodes for laser projection

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Blue and green InGaN based laser diodes are of great commercial interest for mobile laser projection. The next generation of laser based projection devices scale up in lumem and resolution. The race is now on to improve output power, performance and reliability of the laser light sources. The GaN based laser field has recently benefited from next generation blue single mode lasers with output power up to 200mW and from exciting epitaxial growth related innovations for direct green laser diodes.

Today, a key parameter for blue laser in embedded mobile applications is the wall plug efficiency. We report improvements of the performance of blue InGaN laser in view of efficiency and life time. Furthermore for direct green laser emission, we present pioneering work on long wavelength InGaN laser diodes. Based on the growth improvements of In-rich InGaN-quantum wells with higher material quality we demonstrate direct green laser emission up to 529nm with 50mW output power in cw operation.

Gain characteristics of deep UV AlGaN quantum wells lasers

J. Zhang, H. Zhao, N. Tansu, Lehigh Univ. (United States)

Significant advances of high-performance III-Nitride diode lasers emitting in the visible spectral regime have been achieved for III-Nitride light-emitting diodes (LEDs) for solid state lighting and display applications. In contrast, the advances in the laser diodes in the deep UV wavelength regimes remain challenging because: 1) the challenges in growing high-quality high Al-content AlGaN materials; 2) the lack of understanding in the optical gain characteristics of the active region employed in this spectral regime (220-300 nm). The improved understanding in the physics of optical gain of high Al-content AlGaN quantum wells (QWs) will enable the identification of the limitations and potential solutions for achieving low-threshold and high-efficiency lasers in the deep UV spectral regime.

Here, the gain characteristics of high Al-content AlGaN QW active region are analyzed. The calculation is carried out by employing a self-consistent 6-band k · p formalism for wurtzite semiconductors. The characteristics of the gain and spontaneous emission rate of high Al-content AlGaN QWs are compared with those of low Al-content AlGaN QWs. The crossover of crystal-field split-hole (CH) and heavy hole (HH) bands for high Al-content AlGaN QWs is found to have significant impact on the gain properties for active region emitting in the deep UV spectral regime. The TM-polarized spontaneous emission and material gain are dominant for AlGaN QW with Al-contents above 70%. The optical gain analysis shows that large TM-polarized material gain as achievable for high Al-content AxInGa1-xGa quantum wells, which indicates the feasibility of TM lasing for deep UV lasers emitting at ~220-230 nm.

Plasmonic cladding InGaN MQW laser diodes


The formation of the transversal waveguide in GaN based laser diodes is considered as one of the crucial problems of nitride optoelectronics. The difficulty is related to the existing lattice mismatch between GaN waveguide and AlGaN cladding layers. This mismatch makes the AlGaN layers to be under tensile strain which leads to layer cracking and defect generation. Thus only cladding layer characterized by a low value of thickness/composition product have an acceptable quality. This limitation leads to poor mode confinement, a pronounced leakage of light to the substrate and increased mode losses. Moreover AlGaN cladding suffers
from the refractive index reduction at longer emission wavelength. In the present work we propose the solutions based on the use of the highly doped GaN material in which the refractive index is reduced via the plasmaonic type effect. As shown in our experiments the electron concentration of 5x10^19cm^-3 causes the reduction of the refractive index of GaN by about 2% which is fully comparable with 10% AlGaN. Additionally such a cladding layers are under very small strain of the compressive character and shows the reverse trend in the wavelength dependence of the refractive index contrast (the contrast increases with the wavelength). Thus this type of cladding is ideal for blue and green nitride devices. In this work we present the examples of violet and blue devices having very good near field patterns and good threshold parameters which employ this concept.

7953-18, Session 4

High peak power picosecond optical pulse generation from GaInN semiconductor diode lasers

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All-semiconductor, compact and reliable high peak power optical pulse source emitting in the blue-violet wavelength is highly desired for realization of the next generation three dimensional (3D) optical storage system based on two-photon absorption. For this purpose, we have been studying various pulse generating schemes such as gain-switching, self-pulsating, mode-locking operation using GaN-based laser diodes (LD). Gain-switching and self-pulsating LD has great advantage for practical application since optical pulses are generated by a single LD. However, to achieve a very high peak power, a combination of a mode-locked laser diode (MLLD) and semiconductor optical amplifier (SOA), generally known as a master oscillator power amplifier (MOPA), is the most promising scheme.

We have developed the bisectional laser diode (BS-LD) consisting of the gain and saturable absorption (SA) section, which enables the independent control of SA by applying reverse bias voltage to the SA section. Our external cavity MLLD consists of 600 µm BS-LD, a wavelength selecting bandpass filter, and an external mirror. Passively mode-locked oscillator produced 3 ps duration clean optical pulses without noticeable subpulse components with 1 GHz repetition at the wavelength of 404 nm. We have also developed GaN-based SOA for the first time. The SOA with linearly flared waveguide structure was optimized to achieve effective amplification. Optical pulses from the MLLD were amplified to the peak power of over 100 W. This is, to our knowledge, the highest peak power single-transverse-mode optical pulses ever demonstrated for GaN-based devices.

7953-19, Session 4

Dynamics of GaN-based laser diodes from ultraviolet to green

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A knowledge of the dynamic properties of blue and green laser diodes (LD) is essential for applications like flying spot projection, where a high modulation rate is necessary, as well as for the realization of advanced devices such as ultra short-pulse laser diodes in the (Al,Ga)N material system.

We present a systematic study of the dynamics of nitride laser diodes with different emission wavelengths ranging from ultraviolet (400 nm) to green (520 nm). The current-dependent relaxation behaviour of the laser diodes above threshold is analyzed with high temporal and spectral resolution, where a clear tendency towards slower dynamics is observed for increasing emission wavelength. This tendency also applies for the charge carrier lifetimes below threshold, which are deduced from electroluminescence decay measurements. The measurement of the charge carrier lifetimes provides a link between the pump currents and the charge carrier density in the quantum wells.

We compare the experimental results to rate equation simulations to investigate on the origin of the differences in the dynamical behaviour as function of the laser wavelength. Parameters required for these simulations are the optical gain and the anti-guiding factor of the laser diodes, which are both determined from electroluminescence spectroscopy using the Haki-Paoli method.

We use the parameters derived from these different measurements in a consistent and quantitative model to gain information on the laser dynamics at different emission wavelengths.

7953-20, Session 5

Quantum cascade lasers: genetic algorithm design and broadband operation

J. Faist, R. Terazzi, A. Bismuto, A. Hugi, M. Beck, ETH Zurich (Switzerland)

We demonstrate that the combination of a density-matrix based simulation software with good control of the epitaxy enables a true “quantum engineering” of structures based on ab-initio modeling. Using a genetic algorithm approach, active region designs were automatically generated, trying to optimize their wallplug efficiency. The resulting devices, operating at 4.3 µm were then grown and processed; their efficiency was larger than the reference devices.

In another experiment, tuning of broadband devices over more than 300 cm-1 was achieved in continuous wave. The same devices were also operated in continuous wave without frequency selective element as broadband sources for a Fourier transform infrared spectrometer. Spectroscopy of gases was demonstrated with better signal over noise than in reference measurements with a globar.

7953-21, Session 5

The relevance of positive differential conductivity for quantum cascade lasers

A. Wacker, Lund Univ. (Sweden)

A central feature of Quantum Cascade Lasers (QCLs) is the periodic repetition of identical active structures forming the cascade for the electron flow through the device. For operation, the bias must drop homogeneously over the entire structure which requires the presence of negative differential conductivity in each period as otherwise domains with different electric field will form. As the gain transition itself is associated with a source of negative differential conductivity, this has to be balanced by other processes. This feature is discussed in detail and various strategies are discussed, which help in the classification of existing device concepts. Example simulation results are shown including a new THz design which should operate well above 200 K.

7953-22, Session 5

Temperature dependence of the key electro-optical characteristics for mid-infrared emitting quantum cascade lasers

D. Botez, Univ. of Wisconsin-Madison (United States); S. Kumar, Massachusetts Institute of Technology (United States); J. Shin,
High-power, broadband emission in the THz range is desirable for a number of applications including imaging and spectroscopy. In this work we demonstrate broadband laser emission at THz frequencies from quantum cascade laser structures based on heterogenous cascades. The active material is composed by five stacks of three different active regions. The design of each active region relies on a diagonal transition between a bound state and doublet of states tunnel coupled to the upper state of a phonon extraction stage. This kind of design features an high efficiency combined with a low threshold current density. We designed the three active regions in order to cover the spectral region between 2 THz and 3 THz. From bandstructure calculation the three gain curves should peak at 8.8 meV (2.1 THz), 9.8 meV (2.4 THz) and 12 meV (2.9 THz). A gain bandwidth of 600 GHz, including Stark shift, was already observed on a homogeneous cascade structure lasing from 2.6 to 3.2 THz Laser emission from standard double metal laser ridges realised with the heterogeneous gain material is indeed observed over a bandwidth of nearly one THz, spanning from 2.24 THz to 3.2 THz. Peak powers of more than 2 mW from a double metal waveguide and maximum operating temperatures of 100 K are reported. Threshold current density as low as 230 A/cm² are observed. Electrical transport characteristics of the devices show features possibly related to electric field inhomogeneity.

7953-25, Session 6

Terahertz quantum cascade lasers with designer plasmonic collimators

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Surface plasmons have found a broad range of applications in photonic devices at visible and near-infrared wavelengths. In contrast, longer-wavelength surface electromagnetic waves, known as Sommerfeld or Zenneck waves, are characterized by poor confinement to surfaces and are difficult to control using conventional metallo-dielectric plasmonic structures. However, patterning the surface with properly designed plasmonic structures can effectively tailor the dispersion properties of surface plasmons, leading to markedly improved field confinement at infrared wavelengths and beyond. I will discuss the physical principles of three designer plasmonic structures; these are plasmonic Bragg gratings, spoof surface plasmon structures, and channel polariton structures. We demonstrate that by directly sculpting designer plasmonic structures on the highly doped semiconductor facets of terahertz quantum cascade lasers, the performance of the lasers can be markedly enhanced. The beam divergence of the lasers was reduced from ~180 degrees to ~10 degrees, the directivity was improved by over 10 decibels, and the power collection efficiency was increased by a factor of about 5 to 6 compared with the original unpatterned devices. We achieve these improvements without compromising high temperature performance of the lasers. Plasmonics offers a monolithic, compact, and low-loss solution to the problem of poor beam quality of quantum cascade lasers and may have a large impact on applications such as sensing, light detection and ranging (LiDAR), and heterodyne detection of chemicals.
By combining the two stabilization techniques we show that all the longitudinal modes of a multimode QCL emitting at ~2.4THz can be phase-locked, paving the way to the use of these sources for high power, direct THz frequency synthesis.

7953-27, Session 7
Monolithically integrated THz transceivers

M. C. Wanke, M. Lee, C. D. Nordquist, M. J. Cich, Sandia National Labs. (United States); A. D. Grine, LMATA Government Services (United States); C. T. Fuller, J. L. Reno, Sandia National Labs. (United States)
Invited Talk - see short abstract

7953-28, Session 7
Stimulated Smith-Purcell semiconductor THz sources

D. D. Smith, Texas A&M Univ. (United States)

We show that the simple three-layer planar semiconductor device consisting of a Gunn drift region, a dielectric layer and a metallic grating generates stimulated Smith-Purcell radiation whose frequency is determined solely by the ratio of domain velocity to grating period. The radiation is monochromatic, coherent, and strongly polarized along the axis of the device.

The Smith-Purcell effect is observed by focusing a DC vacuum electron beam near a metallic grating. Image-charge transients on the grating spontaneously generate low-power incoherent radiation. Bunching the beam stimulates coherent radiation whose power varies as the square of the charge of the bunch. This approach is used in high-power free-electron lasers and masers.

The spontaneous Smith-Purcell effect in semiconductors is very weak and only observable at low temperatures. However, the Gunn effect provides the semiconductor analog to a bunched electron beam. Drift velocity of order 10^5 m/s and submicron grating period give fundamental oscillation frequency in the low THz range. We estimate the Gunn domains by applying the Butcher-Fawcett method to published materials characteristics.

Exploration of several materials is promising, and simulations of the device agree well with analytic calculation of the radiated power. The radiative area of the device is small, thus an integrated dipole antenna significantly increases the output power. InP yields radiated power density of 30nW per micron of device width at 0.27 THz. The new III-N materials look exciting: A hypothetical InN device yields 3.5uW/um at 0.25THz and 21nW/um at 1THz. The device is simple to fabricate, operates at room temperature, and warrants experimental investigation.

7953-29, Session 7
Upper limits on terahertz difference frequency generation power in quantum well heterostructures

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There is currently considerable interest in terahertz (THz) difference frequency generation (DFG) utilizing near-resonant intersubband nonlinearity in quantum cascade lasers and other quantum well heterostructures [1-3]. Such devices were shown to operate at room temperature, but their power demonstrated so far has been rather low. In all previous works the intracavity configuration was studied, in which the nonlinear mixing region was placed inside a pump laser cavity. Here we obtain the upper limits on the THz DFG power that can be achieved in intersubband quantum well systems under external optical pumping. We consider arbitrarily strong optical fields and include all resonant absorption, pump depletion, and nonlinear saturation effects by self-consistently solving three coupled wave equations, the Poisson equation, and density matrix equations. Although we use a GainAs/AlInAs double quantum well heterostructure as an example, our analysis is applicable to any material system possessing resonant second-order optical nonlinearity. The maximal THz DFG power is reached for intermediate pump intensities of the order of the saturation intensity. Further increase of the pump intensity results in the decrease of the maximum THz DFG power and in the shift of this maximum towards larger frequency detunings from resonance with intersubband transitions. We analyze the dependence of THz power from the length and doping of the nonlinear mixing region, and present the design of the optimal structures.


7953-30, Session 8
A monolithic Ge-on-Si laser

L. C. Kimerling, Massachusetts Institute of Technology (United States)

A Germanium laser is a significant building block for a ubiquitous, monolithically integrated optical power supply. We have observed net gain and lasing in Ge-on-Si waveguide structures with polished end facets. Direct gap optical transitions can be engineered in Germanium with a combination of tensile strain and n-type doping. The tensile strain, a fortuitous consequence of Ge-on-Si epitaxy, raises the light-hole band and reduces the energy separation between the direct and indirect minima of the conduction band. The n-type doping occupies states in the direct conduction band valleys to a position of energy degeneracy with the direct gap minimum. In the resulting structure, light confinement is achieved by the high refractive index of the Ge, and injected carriers recombine radiatively across the direct gap. Remarkably, the radiative quantum efficiency for this unique band structure increases with both doping and temperature. The first optically pumped devices show lasing oscillations for wavelengths from 1580 to 1620nm with a threshold of ~30kW/cm2.

7953-31, Session 8
Carrier recombination mechanisms in monolithically integrated Ga(NAsP)/(BGa)P QW lasers on Si

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An efficient light source monolithically integrated on a silicon substrate is one of the key components to combine the advantages of optical data processing with the mature silicon microelectronics technology. In this work we present a comprehensive study of the threshold current and its temperature dependence in monolithically integrated Ga(NAsP)/(BGa)P QW lasers on (001) silicon substrates grown by MOVPE. Electrically injected lasing operation is observed in these silicon-based broad-area lasers up to 120K. The important recombination mechanisms of the lasers are investigated by measuring both facet and spontaneous emission spectra in the temperature range of 40-120K. The characteristic temperature is measured on these devices to be 135K at 80K, which
drops to 52K at 120K. The temperature dependence of the radiative current density is much weaker than threshold current density (Jth), which indicates that the non-radiative process increases superlinearly with increasing temperature. From the measured Jth and its radiative component we found that non-radiative processes are becoming more dominant at higher temperature in these lasers and contribute to ~45% of the Jth at 120K. The application of hydrostatic pressure shows that the Jth increases with pressure much faster than radiative current, suggesting the presence of a carrier leakage path in these devices. The pressure co-efficient for the band gap of the device is measured to be ~6.1 meV/kbar and Jth for the devices increased by ~30% up to 7 kbar at 120K. Further prognosis for room temperature lasing on silicon with this approach will be discussed in more depth at the conference.

7953-32, Session 8

Electrically pumped diode lasers on silicon substrates based on Ga(NAsP)/GaP multi-quantum well heterostructures

S. Rogowski, R. Ostendorf, G. Kaufel, W. Pietschen, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); S. Liebich, K. Volz, W. Stolz, M. Zimprich, Philips-Universität Marburg (Germany); B. Kunert, NAsP III/V GmbH (Germany)

The monolithic integration of optoelectronic devices, including efficient light emitters such as laser diodes, into conventional Si-based devices and circuits is a challenging task. This is mainly due to the indirect electronic bandgap of silicon which makes it a poor light-emitter. One promising approach to overcome this drawback is the growth of direct bandgap III/V compound semiconductor material, like the dilute nitride Ga(NAsP)-material system, on silicon substrate. This material system can be grown lattice matched on silicon, which allows to avoid misfit dislocations detrimental to the performance of laser diodes.

In this work we report on electrically pumped diode lasers based on a Ga(NAsP) multi-quantum well (MQW) active region. The lasers have been grown by metal organic vapour phase epitaxy (MOVPE) pseudomorphically on Si and, for reference purposes, GaP. The lateral structure of the devices was fabricated using a multiple mask layer processing sequence.

By inductively coupled plasma (ICP) etching, ridge-waveguides with different lengths and widths were fabricated. On Si-substrate an additional ICP etching step was developed in order to produce etched facets. Electrically pumping of the quantum wells was achieved by applying top p- and lateral n-contacts.

Electro-optical characterization of the ridge-waveguide lasers was performed at room temperature in pulsed and for the low current regime also in cw-operation. Additional optical waveguide analysis was performed. The results show distinct light emission at 975 nm being consistent with photo-luminescence measurements.

7953-46, Session 8

Hybrid silicon ring laser

D. Liang, M. Fiorentino, Hewlett-Packard Labs. (United States); J. E. Bowers, Univ. of California, Santa Barbara (United States); R. G. Beausoleil, Hewlett-Packard Labs. (United States)

Hybrid silicon platform provides a solution to integrate active components (lasers, amplifiers, photodetectors, etc.) with passive ones on the same silicon substrate, which can be used for building an optical interconnect system. Owing to the advantages in footprint, power consumption, and high-speed modulation, hybrid silicon microring lasers have been demonstrated as a potential candidate for on-chip silicon light source. In this talk we review the progress to improve the performance of recently demonstrated compact microring lasers with ring diameters of 25 and 50 microns. Approaches to enhance optical mode and electron-hole recombination, which result in threshold reduction and efficiency improvement, and reduce device thermal impedance, which improves device thermal performance are discussed. Design tradeoff and concerns are included. Up to 5 GHz 3 dB bandwidth is shown in direct modulation experiment, while 10 GHz is projected theoretically if device heating is negligible. Power consumption from the perspective of pJ/bit is analyzed. A picture of future microring-based optical transceiver is unfolded at the end.

7953-47, Session 8

Self-organized InAs quantum dot tube lasers and integrated optoelectronics on Si

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High performance 1.3 - 1.55 µm micro- and nanoscale lasers, that can be monolithically integrated with Si waveguides and modulators are in demand for the emerging chip-level optical communications. Such high performance devices can be potentially realized using rolled-up quantum dot tube cavities, which are formed when a coherently strained quantum dot heterostructure is selectively released from the host substrate. Compared to conventional optical microcavities, they can be fabricated using standard photolithography process and can exhibit epitaxially smooth surface, directional emission and controlled polarization. In this context, we have investigated the molecular beam epitaxial growth, fabrication and characterization of both 1.3 µm InAs/GaAs and 1.55 µm InAs/InP quantum dot tube devices. We have demonstrated 1.2-1.3 µm InAs/GaAs quantum dot tube lasers, with an ultralow threshold of 4 µW at room temperature. In addition, we have achieved strong 1.55 µm coherent emission from InAs/InP quantum dot tubes. We have further demonstrated that the 3-dimensionally confined optical modes can be precisely tailored by using either a bottle-like surface geometry or by embedding a microbend at the tube inner surface. With the use of substrate-on-substrate and fiber taper assisted transfer processes, such novel nanophotonic devices can be achieved on Si or any other platform. Work is currently in progress to demonstrate electrically injected 1.3 and 1.55 µm self-organized quantum dot tube lasers by employing a novel lateral p-i-n junction design. The achievement of such nanoscale lasers on Si, as well as their monolithic integration with Si-based waveguides and modulators will be presented.

7953-33, Session 9

Wavelength-stabilized pump diodes for wide operating temperature range frequency-doubled green lasers

M. Kanskar, D. Barton, J. Cai, T. Garrod, Y. He, M. Klaus, T. Klos, R. Lu, M. G. Martin, R. S. Williamson III, D. Olson, AlfaLight, Inc. (United States)

Green lasers for consumer, industrial and military applications require a wide operating temperature range. Monolithically wavelength-stabilized diodes near 808 nm provide an efficient, cost-effective solution for pumping Nd-doped host materials that can be frequency doubled over a large temperature range. We report on the integration of Bragg grating inside a broad-area semiconductor laser cavity forming a low-loss DFB laser. Single emitters with less than 0.3 nm emission bandwidth and wavelength tuning coefficient of 0.062 nm/K has been achieved. Two broad-area, high-power DFB lasers near 808 nm have been used to pump Nd:YVO4 to generate 1064 nm which was frequency doubled using KTP to produce 532 nm green laser. Center wavelength of one of the DFB pumps was chosen to overlap with Nd-gain profile from -20°C to 10°C and the other one was tuned to overlap from 10°C to 55°C. Only one pump operated at a time in the cold or hot, keeping temperature range in a constant power mode. The electrical-to-optical power conversion efficiency of the pumps was nominally 50%. Optical-to-optical power conversion efficiency from 1064 nm to 532 nm was at least
24% in the entire operating temperature range and produced a constant 450 mW of green power. These wavelength-stabilized pumps offer an efficient and cost-effective solution for other frequency-doubled green laser architectures as well.

7953-34, Session 9

670nm nearly diffraction limited tapered lasers with more than 30% conversion efficiency and 1 W cw and 3 W pulsed output power

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CW high brightness red emitting laser diodes are necessary for the pumping of fs-solid state lasers, spectroscopy, photodynamic therapy, and flying spot display technology. Beside this, pulsed pump-sources for the non-linear frequency conversion towards the UV are requested. Data for 670 nm-tapered lasers with a vertical divergence of 31° (FWHM) will be presented. The devices are based on a GaNP single quantum well embedded in AlGaNnP waveguide layers. Compared to previously reported material, the structure has an improved material quality with a transparency current density of 165 A/cm², an internal efficiency of 0.86, small internal losses of 1.5 cm⁻¹, and a good temperature stability with T₀ = 105 K.

2 mm long tapered lasers were fabricated in a standard process, using reactive ion etching for the index-guided structures and ion implantation for the definition of the contact window in the tapered section. The properties of devices with 500 µm or 750 µm long ridge waveguide (RW) section and a flared section with 3° or 4° taper angle will be compared.

In CW-operation an output power up to P = 1 W with a conversion efficiency of 30% were obtained. In pulsed mode (pulse length 300 ns, repetition rate 1 kHz) up to 3.3 W output power was measured. The beam propagation ratio M² is nearly diffraction limited and smaller than 2.5 up to 1 W (CW) and up to 3 W (pulsed).

CW reliable operation at 500 mW over 1,000 h will be shown without a deterioration of the beam quality.

7953-35, Session 9

Versatile 1 W narrow band 976 nm light source

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We report on development of novel curved waveguide (CW) laser devices, where the emission wavelength centered at ~976 nm is stabilized to a 20 dB bandwidth of less than 100 picometer by using fiber Bragg gratings (FBG). Radiation from the curved waveguide laser is coupled using an anamorphic fiber lens into a single mode polarization maintained fiber containing the FBG, the latter acting as a front reflector. The high power gain chip is based on Oclaro's InGaAs/AlGaAs quantum well laser. Use of the curved waveguide geometry allows to eliminate residual reflections in the optical path of the cavity, which is formed by the rear chip facet and the FBG. It is well known that additional reflections lead to significant deterioration of the spectral and power stability. The devices, assembled in telecom type housings, provide up to 1 W of low-noise and kink-free CW power.

In addition pulse operation in nanosecond range is also investigated. The spectral stabilization time to the wavelength of the FBG is limited by the external cavity roundtrip of ~2 ns. The achieved side mode suppression ratio is well below -50 dB.

Numerous applications can be envisioned for these devices. For instance devices with high power and ultra-narrow spectral bandwidth allow greater flexibility in the choice of parameters for frequency doubling applications. In pulsed mode the device can be used in the special sensing applications where spectral stability is crucial.

7953-36, Session 9

1 W semiconductor based laser module with a narrow linewidth emitting near 1064 nm

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Narrow linewidth high-power lasers find application in fields like coherent optical communication, spectroscopy, or laser cooling. Semiconductor lasers combine high efficiency, robustness, small size and the feasibility of narrow linewidth operation. However, monolithic semiconductor lasers with an output power of 1 Watt or more usually do not feature stable single-mode, narrow linewidth emission. The application of a monolithic master oscillator power amplifier (MOPA) concept can provide single-mode operation at high output power, however, the spectral emission properties (frequency, linewidth) of such a system are typically not stable due to optical feedback and coupling of amplified spontaneous emission from the amplifier to the oscillator. An optical isolator between the amplifier and the oscillator can suppress feedback effects, however, this typically increases the size and weight and decreases the mechanical stability.

We present a micro-integrated MOPA concept (footprint: 10x50 mm²) which uses a micro-isolator. The oscillator, a distributed Bragg reflector laser, is optimized for narrow linewidth operation. The amplifier consists of a ridge waveguide entry and a tapered section. The module features stable single-mode emission and a linewidth of only 100 kHz (FWHM) and 10 kHz (Lorentzian contribution) on a time scale of 100 µs at an output power of 1 W. It can be tuned mode-hop free by 450 GHz. The spectral characteristics of the MOPA equal the characteristics of the MO except for a higher ASE background.

To our knowledge this is the first time that a micro-integrated MOPA system with narrow linewidth, stable single-mode and high-power operation is demonstrated.

7953-37, Session 10

Advances in the development of type-I quantum well GaSb-based diode lasers

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Diode lasers grown on GaSb substrates operate at room temperature in wide spectral region from below 2 µm to 3.5 µm. These devices employ InGaAsSb quantum wells (QW) with bandgap adjustable from 0.35 to 0.65 eV by varying Indium and Arsenic composition as well as QW thickness. Diode lasers having active regions with bandgaps from 0.5 to 0.65 eV, i.e. with 20 - 40 % of Indium and emitting at 1.9 - 2.5 µm, generate above 1 W of continuous wave (CW) output power from 100 µm wide apertures. Corresponding linear laser arrays produce more than 10 W of CW or 25 W of quasi-CW optical power. These laser diodes demonstrate threshold current densities below 100 A/cm² - same if not better than that of state-of-the-art GaAs-based diode lasers operating below 1 µm, i.e. with active region bandgap above 1.24 eV. The reason is fundamental - low electron density of states, hence reduced transparency and threshold carrier concentrations. This advantage remains in effect for active regions operating at 3 µm, i.e. having increased Indium and Arsenic contents of about 50 % and 20 %, respectively. High power diode lasers operating at 3 µm generate above 300 mW of output power and demonstrate thresholds near 200 A/cm² at room temperatures.
The breakthrough in mid-infrared GaSb-based type-I QW diode laser performance was achieved after the quaternary AlGaInAsSb alloy was introduced to replace quaternary AlGaAsSb as a barrier material. The advantage offered by use of quaternary barrier is substantially improved carrier confinement in active QWs. This improves device temperature stability and made CW room temperature operation of the 3.4 μm emitting diode lasers with output power above 40 mW a reality. The challenge to increase the wavelength and output power level of GaSb-based type-I QW diode lasers operating above 3 μm is associated with limitations in material quality of quaternary alloys with high Indium and Aluminum contents as well as with an extent to which the carrier confinement can be secured.

We will report on the recent development of the high power 2 μm diode lasers with improved beam properties and power conversion efficiencies. The results of characterization of the 3 - 3.5 μm emitting lasers operating in CW regime up to 50 OC and generating hundreds of mW of output power will be presented. We will discuss the development of the single spatial and spectral mode 2 - 3.4 μm mid-infrared diode lasers with output power in excess of 50 mW.

The roadmap to improve the performance parameters of GaSb-based 2.5 - 3.5 μm emitting diode lasers by using growth on virtual GaInSb substrates will be presented. The experimental results for high power CW room temperature operated diode lasers grown on virtual substrates with lattice constant larger than that of GaSb will be discussed.

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7953-38, Session 10

High-power continuous-wave interband cascade lasers


Interband cascade lasers have made rapid progress recently owing to the lower-than-expected and nearly-wavelength-independent Auger coefficients in the mid-10-19-28 cm3/s range and a careful optimization of the waveguide structure to achieve internal loss as low as 0.6 cm-1. Narrow ridges with widths ranging from 3.2 to 15.1 μm were fabricated from 6-inch wafers using a combination of dry etching by Cl-based inductively coupled plasma and a phosphoric-acid-based clean-up etch and were covered with 5-μm-thick electroplated gold. Subsequent characterization demonstrated that the degradations of threshold current density and differential slope efficiency were modest for widths larger than 3.5 μm. The 11.1 and 13.0-μm-wide uncoated ridges produced up to 45 mW per facet of cw power at 20°C, and displayed maximum wall-plug efficiencies of 3.5% per facet. The 5.1 μm x 3 mm ridge without any facet coatings operated cw to a new record of 345 K. We also fabricated distributed-feedback lasers by etching 4th-order gratings, with 2000 nm period and 1000 nm amplitude, into both sidewalls of the ridges. For operation at T = -20°C, >45 mW of cw output was generated in a single spectral mode at ≈3.6 μm. The tuning range is ≈11 mm for any temperature between 0 and 25°C, and tuning by up to 25 nm is possible if both current and temperature are varied. At T = 23 °C, a shorter-wavelength device generates up to 30 mW of single-mode cw power near the strong methane absorption line at ≈3.315 μm.

7953-39, Session 10

Room-temperature 4.0-μm broadened optical pumping injection cavity lasers

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The optical pumping injection cavity (OPIC) laser concept was developed to enhance the efficiency of optical pump beam absorption, and this work focuses on epitaxial configurations designed for broadband absorption around 1850 nm, an optimal pump wavelength for transmission through GaSb substrates that allows for epi-down mounting for improved heat management, while minimizing the photon decrement. The OPIC devices presented in this work have InAs/GaSb/InAs/AlSb type-II W active regions with a thicker GaSb/AlAsSb distributed Bragg reflector on top in order to enhance reflectance back into the active region for epi-down mounting. Results are presented for optical pumping at 1850 nm as well as for resonant optical pumping, as the cavity resonance varies with temperature due to shifts in lattice constant, refractive index, and gain. Pumping at 1850 nm resulted in lasing from 78 K up through 310 K. At 78 K, the actual pump cavity resonance is ~1840 nm, and with increasing temperature the resonance shifts to longer wavelengths beyond 1850 nm. Emission wavelengths range from 3.59 μm at 78 K to 4.01 μm at 310 K for 1850 nm optical pumping. The broadened OPIC configuration presents a distinct advantage over earlier reported OPIC devices as the broader resonance allows for efficient emission across a wide temperature range for a single pump wavelength (e.g., 1850 nm), providing over 400 nm of wavelength tuning. Results will be compared with a second broadened OPIC with emission wavelengths beyond 4 μm that temperature tunes across the carbon dioxide spectral line at 4.2 μm.

7953-40, Session 10

InGaAs/AlInAs quantum cascade laser sources based on intracavity second harmonic generation emitting in 2.6 - 3.6 micron range

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We discuss design and performance of short-wavelength InGaAs/AlInAs/InP quantum cascade laser sources based on intra-cavity second harmonic generation. A passive heterostructure tailored for giant optical nonlinearity is integrated on top of an active region and patterned for quasi-phase-matching. We demonstrate room-temperature operation of different devices with second harmonic output at 3.6, 3.0, and 2.6 microns and second-harmonic conversion efficiencies above 1mW/W2.

7953-41, Session 11

High average power short wavelength InGaAs/AlAs(Sb)/InP quantum cascade lasers

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We review the development of short wavelength (3 µm < < 3.8 µm) quantum cascade lasers (QCLs) based on the deep quantum well, strain compensated InGaAs/AlAs(Sb)/InP materials system towards continuous wave operation. Recently, we have demonstrated significant improvements of laser performance in pulsed regime up to 400 K. We review the development of short wavelength lasers operating at high duty cycle (up to 50%) and emitting high average output power (several hundreds of milliwatts).
High performance quantum cascade lasers with broadband gain spectra

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We present novel QC laser designs with multiple transitions from strongly coupled upper states to lower states to achieve a broad gain spectrum as well as high performance.

We first demonstrated two QC laser designs with gain bandwidths of more than 250 cm⁻¹ in the 7-9µm wavelength region. At the operational electrical field, the lowest injector states are strongly coupled with the upper state in the active region, generating multiple (three or more) transitions to the lower laser state to contribute to a broadband elelctromission (EL) over a large electric field range. The first embodiment of a design at ~8µm enables external cavity tuning over 190 cm⁻¹ in pulsed mode operation at 0°C.

We also demonstrated a QC laser structure based on a "continuum-to-continuum" active region in the 4-5µm wavelength region with a gain spectrum of ~430 cm⁻¹ in pulsed mode - 160 K, high peak power (up to 5 W) and high wall plug efficiency (WPE, up to 20%) were achieved for ridge lasers with as cleaved facets, in pulsed mode operation at 295 K. The WPE of a ~5.5µm wide, 4 mm long buried-heterostructure laser is up to 23% at 295 K and 44% at 80 K in pulsed mode, demonstrating that it is possible to make a wide gain spectrum compatible with high power and efficiency performance.

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Transport and gain in quantum cascade laser: model and equivalent circuit

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A simple rate-equation based model for transport and gain in quantum cascade laser is developed. According to the model IV characteristics of quantum cascade laser can be well described by equivalent circuit containing serial connection of a Schottky diode, tunnel diode and a field effect transistor. As a consequence, quantum cascade laser can be described in terms accessible to circuit designers.

Mode synchronization and multistability in quantum cascade lasers

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We study the multimode operation regimes of broad active region mid-infrared Quantum Cascade Lasers (QCLs). Starting from Maxwell-Bloch equations we arrive at a system of nonlinear differential equations, which takes into account phase-sensitive interactions between transverse modes. Our study includes full modal dynamics and as a limiting case, the dynamics of transverse modes with a large number of interacting longitudinal modes, which allows us to average over the longitudinal dependence. We present an analytical model for the modal dynamics and its numerical analysis. We show the possibility of the coherent coupling of several transverse modes which results in a number of nonlinear effects including frequency and phase locking between transverse modes, bistability, and beam steering of the near and far fields. The range of modal frequency shift and the effects of amplitude and phase fluctuations on the modal stability are explored. The theoretical results are in agreement with our experimental measurements of far field and spectra of buried heterostructure QCLs.

3.5-um strain balanced GaInAs/AlInAs quantum cascade lasers operating at room temperature

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We demonstrated room temperature lasing at 3.44 and 3.55 µm under pulsed and continuous wave (CW) operations, respectively. Both are the shortest wavelengths ever achieved from quantum cascade lasers with a strain balanced GaInAs/AlInAs material on InP substrate at room temperature, to the best of our knowledge. With the back facet high reflection coated, a maximum output power of 14 mW was obtained at 10°C under CW operation. Laser structure, temperature performance and thermal management will be presented in detail at the conference.

Molecular beam epitaxy for high spectral bandwidth quantum dot sources for optical coherence tomography applications

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High power and high bandwidth GaAs based quantum dot (QD) superluminescent diodes (SLDs) and optical amplifiers are of interest for application in biomedical imaging of skin tissue such as optical coherence tomography (OCT). In this paper we describe a systematic study of the key MBE parameters affecting 1200-1300nm quantum dot-in-well structures with a view to optimization for broadband applications. The key parameters we have addressed for realizing broadband QDs are the deposition temperature (including InGaAs and GaAs capping), QD InAs deposition thickness and deposition rate. The effect of reducing temperature is to increase the QD areal density and size inhomogeneity. However, as the QD density increases, coalescence of the QDs results in additional non-radiative defects, evidenced by a strong reduction in photoluminescence (PL) efficiency. In order to benefit from the broad size distribution and high density of low temperature growth the amount of InAs deposited to form the QDs may be reduced. In this study we have varied deposition temperature, rate and amount of InAs deposited to form QDs. A systematic PL studies is carried on these samples which allowed the maximization of the efficiency of the spontaneous emission (SE). The PL intensity of test structures is shown to correlate to SE efficiency in electroluminescence tests of fabricated devices. Further AFM allowed the maximization of dot density and size non-uniformity which in turn lead us to broadband gain in the system. A maximum 3dB bandwidth of 160nm is obtained for SLDs fabricated from a sample grown with optimized conditions. This corresponds to a coherence length and theoretical axial resolution in OCT system of 4µm.
Comparison of gain measurement techniques for 1.3μm quantum dot lasers

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A wide range of techniques are available for gain measurements, but are rarely compared as they often require different fabricated device structures to allow the measurements. Quantum dots devices are an area of ever increasing interest with their current commercial application in biomedical imaging, displays and optical communications. The spectral measurement of gain is vital for device engineering of these structures. In this paper we report on the direct comparison of Hakki-Paoli and multi segmented contact techniques utilizing a single-mode multi-segmented device structure. We describe the relative advantages and disadvantages of these two complementary techniques over a range of current densities. The Hakki-Paoli technique requires high spectral resolution bringing disadvantages in requiring highly stable experimental conditions and high resolution spectroscopy. However the monitoring of a single Fabry-Perot mode allows temperature effects to be entirely eliminated. This allows gain spectra at high current density with constant cavity temperature to be obtained allowing the unambiguous study of free carrier effects. The multi segmented contact method enjoys higher coupling efficiencies compared to Hakki-Paoli allowing the measurements to be performed with less stringent sensitivity, integration periods and lower instrument resolution requirements. However under continuous wave operation the multi segmented contact method cannot reliably access high current densities due to self-heating. In addition to our comparison of the relative merits of these two techniques, their combination allows a thorough analysis of QD laser material over a wide range of current densities, allowing details of the carrier distribution and effects of free carriers to be deduced.

Optical gain in erbium lithium niobate titanium diffused waveguides

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In this effort, we describe our recent progress towards demonstrating optical gain in Erbium doped Lithium Niobate and its potential for use in Erbium Doped Waveguide Amplifiers (EDWAs) and lasers. By introducing Erbium into Lithium Niobate we were able to achieve both gain at telecom wavelengths and Electro-Optic (EO) modulation in a single material. We focus on Lithium Niobate grown in the presence of Erbium available from Roditi. In this work we discuss photoluminescence, amplified spontaneous emission, gain, and lasing of various configurations of EDWAs and amplifiers. We present experimental as well as simulation results.

Controlled intermixing of multiple quantum wells for broadly tunable integrated lasers

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A broadly tunable MOW laser utilizing a combined impurity-free vacancy disordering and beam steering techniques is proposed and investigated experimentally. The device consists of a beam-steering section and an optical amplifier section fabricated on a GaAs/AlGaAs MQW p-i-n heterostructure substrate. The beam steering section forms a reconfigurable single mode waveguide that can be positioned laterally by applying electrical currents to two parallel contact stripes. The active core of the gain section contains a GaAs/AlGaAs MQW that is progressively disordered such that an optical beam steered through the selected region experience a peak in the gain spectrum that is determined by the degree of disordering of the MQWs. Furthermore the MQW in the beam-steering section is disordered to the largest extent to minimize optical beam attenuation. The MQW structure was intermixed using an impurity-free vacancy induced disordering technique. The MQW sample is encapaculated with a SiO2 film grown by plasma enhanced chemical vapor deposition (PECVD). The beam steering region is coated with a 400nm thick SiO2 film whereas in the gain section, the SiO2 film is selectively etched such that the thickness grades linearly ranging from 0 to 325nm. The disordering of the entire slab region is then induced by a single rapid thermal annealing step at 975°C for a 20s. Experimental results showed a controllable 10 to 60nm wavelength blue shift of the peak of the photoluminescence spectrum corresponding to the change in SiO2 caps thickness and a lateral beam steering range up to 20 µm over the slab region.

Low threshold short cavity quantum cascade lasers

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We report the study of achieving low-threshold quantum cascade lasers (QCLs) for low-power chemical sensing applications. By cleaving a laser with very short cavity and applying a high-reflection (HR) coating on both facets of a laser cavity, a QCL threshold of  30mA at 20K,  50 mA at 80K, and  120mA near room temperature were achieved. The QCL structure used in the experiment is a strain balanced InGaAs/InAlAs superlattice with an emission wavelength at 4.8µm. The laser is fabricated into buried heterostructure waveguide and cleaved as a short cavity device with lengths of 0.5mm and 1mm. A metal-on-insulator HR coating is then applied to one side or both sides of the laser cavity. Experiment results of QCLs with 28 periods and 60 periods of active stages are presented. Some typical measured results are described in the following: for the 28-period 1mm long QCL device, a current threshold of 70mA is observed at 80K when both facets are HR coated, whereas for the same device without HR coating, the threshold is around 210mA. For the 28-period 0.5mm-long QCL, a current threshold as low as 65mA and injecting electrical power of less than 700mW is observed at cryogenic temperature. As the number of QCL active stages increases, the QCL current threshold is further reduced. A 60-period 0.5mm long QCL device with both facets HR coated expresses a current threshold of 30mA at 20K and ~50mA at liquid-nitrogen temperature. Further and significant improvement can be achieved and will be reported in the meeting.

Thermal investigation of mid-infrared quantum cascade lasers under quasi-continuous-wave operations

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We report the study of temperature effect on the output characteristics of quantum cascade lasers (QCLs). There is a great demand for high average power QCL applications. However, room temperature continuous wave (CW) operation is challenging due to the high bias voltage and high bias current QCL nature. Furthermore, the low wall-plug efficiency reality creates severe problems. Most input power becomes heat. By operating QCL at quasi-CW mode, on the other hand, it is possible to minimize the thermal effect and produce higher average power than that of CW operation. We developed a compact model to calculate the temperature dependence of modal gain, current threshold density and combined them with thermal simulation results from the COMSOL package. Optical output of a QCL under pulsed, CW, and quasi-CW operation conditions can be calculated. Simulated results yield good agreement with the experiments. From the simulation we observe that shutting off...
the QCL before the core temperature reach a very high temperature can speed up the cooling off time and eventually reach a lower average core temperature. This helps to operate the laser at higher average gain with higher efficiency. Simulation shows that under quasi-CW operation mode using a duty cycle of ~50%–60%, QCLs can generate maximum average power, which is much higher than that of CW mode operations. Simulation also shows that under quasi-CW operation, with a fixed duty cycle, the shorter the pulse, the lower that laser core temperature and the better the QCL performance. Detailed study results will be reported.

7953-45, Session 12
Performance and reliability of high power 7xx nm laser diodes

High power diode lasers, in 7xx-nm wavelength range are used for various applications. For example 79x-nm devices are used for solid state pumping for crystals such as Ho:Cr:Tm:YAG and Nd:YLF, 760nm devices are used for Rb alkali laser pumping and 792-nm devices are used for Tm-doped fiber laser pumping. Compared to 808-nm diode lasers that have been developed extensively in the last 20 years, high power lasers in the 7xx-nm wavelength range present greater challenges for achieving operation power, efficiency, temperature performance and reliability.

This paper will present recent progresses on 7xx-nm laser diodes for the above attributes. Material systems and quantum well designs will be reviewed for devices at various wavelengths. Important aspects of device fabrication and heat-sink/bonding processes will be addressed. Both single emitter and bar performance data will be included. Single emitter devices, with 200nm wide emitting widths, show up to 10W reliable operating power with peak efficiencies of more than 65%. Accelerated life testing at 12A, 50°C heat-sink temperature has been running for thousands of hours. High temperature performance and high COMD threshold (> 20W) will also be shown. Life-test failure modes will also be discussed. In summary, with advanced epitaxial structure design and MOCVD process, critical facet passivation and advanced heat-sink and bonding technology, 7xx nm devices have been demonstrated with high performance and reliability similar to those of 808nm devices.

7953-46, Session 12
Very high modulation efficiency two-sections tapered laser diode at 1060nm for free space optical communications
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We present high-brightness tapered laser diodes at 1060nm with record modulation efficiency for free-space optical communications. We have developed Al-free active region tapered lasers at 1060 nm, which contain a straight ridge waveguide section of 1 mm length, three possible lengths of tapered section (2, 3 and 5 mm) with two possible taper angles (4° and 6°). Those devices can be modulated in amplitude with a suitable modulating current on the ridge section and a fixed CW current on the taper section. The 6mm total length, 4° device can deliver a high power of 5W CW at 8.5°C when the ridge current Ir is 323mA and the taper current It is 9.16A, together with a very good beam propagation factor (M²<2). In static regime, when the taper current It = 6.9A, the output power moves from 99 mW (Ir = 0 mA) to 2.49 W (Ir = 40 mA), which corresponds to a very high modulation efficiency (ME) of 59.8 W/A under static operation and an optical modulation amplitude (OMA) of 2.48W.

In the dynamic regime, the 3mm total length, 4° device can be operated at 1 Gbps, showing high ME of 16 W/A and an OMA of 580mW when It is 1.5A an Ir oscillate from 10 to 45mA. The 4mm total length, 6° device can be operated at 700 Mbps, showing high ME of 19 W/A and OMA of 1.66W when the Ir is 2.5A an oscillate from 22 to 106mA.

7953-47, Session 12
Compact ps-pulse laser source with free adjustable repetition rate and nj pulse energy on microbench
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We present a new picoseconds light source with an integrated pulse picker on a 5 x 4 cm microbench arrangement consisting of a master oscillator, an ultra fast pulse picker element and integrated high-frequency electronics. The master oscillator with a total length of 10 mm consists of 5 sections (1500 µm gain section, 8000 µm cavity section, 200 µm DBR section, 100 µm monitor section, 200 µm saturable absorber section). Pulses with a width of 10 ps and a peak power of 1 W are generated by hybriode mode locking. Despite the long cavity, the repetition rate is 4.3 GHz, which is too high for many applications. In order to reduce the repetition rate to values between 1 kHz and 100 MHz, one has to pick single pulses out of the continuous pulse sequence generated by the mode-locked laser. For this purpose a semiconductor pulse picking element based on a multi-section ridge waveguide, which acts as an optical gate, and a tapered section for pulse amplification is developed. Selective pulse picking with a free choice of the repetition rate is achieved by driving a part of the RW section by a high frequency GaIn-high-electron mobility transistor with low capacitances and high current density. If a current pulse with a width of about 200 ps (smaller than the spacing of the pulses) is injected, the RW section becomes transparent and an injected optical pulse can pass the RW section. This pulse is subsequently amplified by injecting short current pulses with a width of 2 ns and a peak current of 20 A into the tapered section. Pulse energies in the nJ range at a frequency of 16 MHz are obtained. To maximize the pulse energy the delay between the injected pulse and the amplifier current pulse plays an important role. Detailed investigations of the pulse generation using this new picoseconds light source, the high current switch driver and the influence of the delay between light and current pulses will be presented.

7953-48, Session 12
Low-cost high-reliability 830nm single mode lasers for consumer electronics and CTP applications
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For consumer electronics and computer-to-plate (CTP) applications, the requirements are very stringent to develop low-cost 830nm lasers manufactured using high-volume compatible processes while exhibiting excellent reliability.

830nm narrow stripes (NS) achieve more than 200mW of single mode (SM) power. Owing to Oclaro facet passivation, the lasers, with a 1.2mm cavity length, can be driven up to 800mW (roll over limited) without running into COD. At 400mA, 380mW is reached at 15°C, while at 75°C, 280mW is obtained. Across the whole temperature range the devices remain single lateral mode. Reliability tests on about 200 devices at 200mW, 60°C for 2200h revealed neither failures nor wear out. For applications where the cost of external wavelength stabilization is
Mitigation of thermal lensing effect as a brightness limitation of fiber coupled laser diodes

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Recent efforts to improve the reliability of high-power broad area lasers operating in the 9xx nm wavelength band have yielded single emitter diodes with excellent reliability to >15 W. In applications requiring fiber coupling, brightness requirements limit the typical power rating to 10 W, due to a rapid increase in the slow-axis divergence, and hence reduction in beam quality, with drive current. In this work, we show that thermal lensing (rather than carrier- or gain-induced guiding) in the slow axis is the predominant cause of beam quality degradation. We also report on recent efforts to mitigate thermal lensing by directly engineering the thermal path of the emitter. Some of the techniques which are presented include the use of cavity length scaling and high thermal conductivity heatsinks. For example, a design which utilizes an improved metallization recipe leads to a demonstrated 10% improvement in thermal resistance and associated improvement in overall beam quality. It is expected that approaches such as these are critical to enabling continued scaling of high-brightness fiber coupled laser diodes.

A novel approach to finite-aperture tapered unstable resonator lasers

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Tapered unstable resonator lasers (TURL) with the optical resonator formed by the cleaved facets, a single mode ridge waveguide (RW) section for mode filtering and a large mode volume tapered section provide nearly diffraction limited light up to 10 W. However, the RW downsizes the usable mode volume and therefore lowers the output power for technologically limited device dimensions. We present a novel approach of a Finite Aperture Tapered Unstable Resonator Laser (FATURL) without RW but with the resonator formed by two distributed Bragg reflectors (DBRs) with different lateral widths. The wider DBR (>60μm) is located at the rear-facet and the narrow one (≤25μm), embedded in the tapered gain region, at the front-facet. This provides a much larger mode volume for a given device length compared to TURL and brings the benefit of a lower thermal and electrical series resistance resulting in higher possible output powers. However, higher order lateral modes must still be suppressed for a good beam quality. We show by an analysis of the passive resonator using a Fox-Li approach that an increased discrimination of the lateral resonator mode losses is obtained for certain ratios of DBR widths. Additional spatial-temporal simulations of the active resonator using a travelling wave equation based model support these findings. The principle of operation is proved by fabrication and experimental characterization of a first generation of devices.
Control of slow axis mode behavior with waveguide phase structures in semiconductor broad-area lasers

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An increase in the output power of semiconductor waveguide lasers is commonly achieved through broadening the stripe width of the active waveguide region. However, the resulting amplification of high order modes may degrade the beam quality of the laser diode. Further, filamentation and high peak power densities will limit the lifetime of the device by optical facet damage. We report an approach to control the slow axis mode behaviour by embedding diffractive phase structures directly into the waveguide layers of the active laser region. Using this technique it is possible to enhance the amplification by increasing the overlap with the gain region, whilst additional diffraction losses for higher order modes are generated. By shaping the zero order mode the output beam quality can be increased and a high efficiency of the device maintained. Finally, we discuss manufacturing techniques of these monolithic waveguide lasers and show how to integrate phase structures through an additional lithographic step. In our experimental realization we will demonstrate that microstructured broad area lasers show a smooth transversal mode shape with significantly reduced current dependency.

Recent results on widely tunable quantum cascade lasers

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Mid-IR (3 - 20 µm) quantum cascade (QC) devices are being designed that exhibit increasingly large gain bandwidth for use in a laser cavity. As opposed to semiconductor diode gain media, this broad gain bandwidth can be created by design; cascade gain sections with different energy spacings can be incorporated into the same device, or novel designs involving electron transitions from bound to continuum energy levels can result in a gain bandwidth that is greater than 30% of center wavelength. Tuning these new QC devices into widely tunable lasers presents many challenges. Frequency selective elements, coatings, and optics have to be designed that can operate over a much broader wavelength range than their counterparts in the near-IR or visible. This challenge has many benefits for commercial lasers, however. Fixed wavelength or narrowly tunable mid-IR lasers can be created over a broad spectral range from a single type of gain chip. Widely tunable lasers suitable for survey spectroscopy or spectroscopic chemical identification can be built. An external cavity QC laser (EC-QCL) design with tunable frequency selective feedback elements has realized the broadest tuning ranges to date for QC lasers. In the present study, EC-QCL results are presented for a broad range of QC gain devices. Tuning ranges and performance are considered for CW and pulsed operation. Fixed wavelength and broad tuning EC-QCL designs are discussed, along with applications that are enabled by widely tunable lasers in the mid-IR.

High performance continuous-wave room temperature 4.0 µm quantum cascade lasers with single-facet optical emission exceeding 2 watts

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A strain-balanced, AlInAs/InGaAs/InP quantum cascade laser structure, designed for light emission at 4.0 µm using non-resonant extraction design approach, was grown by molecular beam epitaxy. Laser devices were processed in buried heterostructure geometry. An air-cooled laser system incorporating a 10 mm by 11.5 µm laser with antireflection coated front facet and high reflection coated back facet delivered over 2 W of single-ended optical power in a collimated beam. No signs of laser performance degradation were observed after over 150 hours of preliminary reliability testing of the laser system with periodic hourly laser turn on/off to subject the laser to a large thermal stress. The 4.0 µm laser system, owing to their compact size, high WPE and excellent reliability should be ideal sources in commercial and defense applications requiring ~4.0 µm laser sources. Maximum continuous wave room temperature wallplug efficiency of 5.0% was demonstrated for a high reflection coated 3.65 mm by 8.7 µm laser mounted epi-side down on an aluminum nitride submount.

Highly power efficient distributed feedback quantum cascade lasers at 4.55µm

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Current challenges in small IR optical sensors and sensor networks for portable, lightweight system design are mostly related to the input power and heat dissipation required for laser operation. Battery life and operation in remote areas are greatly enhanced by devices with long lifetime, low power consumption, and requiring minimal system calibration and maintenance. For these reasons the prospect of highly efficient, low-power consuming distributed feedback (DFB) quantum cascade (QC) lasers, is very appealing for field applications both in environmental research and in industrial process control.

In this paper we present our most recent results on DFB QC lasers operation. The devices were grown by metalorganic vapor phase epitaxy and fabricated into buried heterostructure lasers. The devices have shown single mode emission at wavelengths around 4.55µm. Due to their low threshold current (I=170mA, J=1.4kA/cm²), the lasers have been mounted epi-side up on C-mount heat sinks delivering both pulsed and continuous single-mode output with CW powers close to P=100mW. CW emission was measured at room temperature on a single mode with a side mode suppression ratio (SMSR) of 30dB. The wavelength sensitivity to temperature changes has shown a CW tuning coefficient of 0.3nm/K, lower than the typical values (~0.5nm/K) in devices with higher power consumption and worse thermal resistance. The measured thermal resistance of the epi-up devices, estimated by the wavelength shift of the emission spectrum, is about 10K/W and can be greatly improved with epi-down mounting and sealed packaging.

Broadband quantum cascade laser arrays for mid-infrared spectroscopy

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Quantum cascade lasers are semiconductor lasers that emit in the mid-infrared from 3 to 24 µm, including the “fingerprint” region of molecular absorption. Arrays of distributed-feedback quantum cascade lasers can be made as single-mode tunable high brightness sources covering a wide range of mid-infrared frequencies with potential applications in spectroscopy. We present recent developments in device and
distributed feedback grating design leading to increased output power and improved single-mode selection of such arrays. We also significantly advanced the beam quality of arrays, using spectral beam combining concepts, which is crucial for long range sensing applications.

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7953-58, Session 14

**Spectral beam combining of infrared quantum cascade laser arrays**

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Spectral beam combining provides a very simple way of coupling the output of a linear array of laser emitters into one coaxial beam while maintaining the diffraction limited beam quality of a single emitter. We combined the output of electrically driven InP-based quantum cascade (QC) laser arrays by applying the concept of spectral beam combining in an external cavity (EC) setup. The EC setup, consisting of collimating optics, a diffraction grating, and a partially transmitting outcoupling mirror, provides wavelength selective feedback and forces each single emitter on the QC mini-bar to operate at a well defined wavelength, being different for each emitter. Furthermore, the EC setup allows a certain degree of tunability of the central wavelength during operation by rotating the grating.

We demonstrate that spectral beam combining can be applied as a useful approach towards power-upscaling at different wavelengths in the mid- and far infrared region. Up to 8 individual QC lasers are combined with an optical coupling efficiency of 60% for an array of 6 emitters. The averaged power of the coupled QC laser array surpasses the output of single emitter by a factor of 4 when coupling 8 emitters.

Beyond that, we show that the wavelength spread enforced by the beam combining setup can be utilized to realize a rapidly tunable laser source when firing each individual emitter of the QC laser array separately.

7953-59, Session 15

**Design and operation of mid-IR integrated DBR tunable lasers**

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Integrated distributed Bragg reflector (DBR) tunable quantum-cascade-lasers (QCLs) with separated thermal controls on gain and grating sections were fabricated and characterized. With a thermoelectric (TE) cooler dedicated for the grating section, a tuning range of 65 nm, centered at designed wavelength, 4.7 µm, was achieved under pulse mode operation. To better understand the heat flows within two sections and the temperature profiles across the entire laser assembly, we established a 2D thermal model that simulates the actual device configuration. The device was a 2.5-mm-long DBR QCL epi-side down mounted on a copper heatsink with a 1.0-mm-long grating section separated from the heatsink and thermally controlled by a TE cooler. A 10W of heat constantly generated in the gain section was modeled while external boundaries were assumed thermally insulated except for bottom gain and grating sections which were in direct contact with the heatsink and the TE cooler. Varying the heatsink temperature, as expected, had little effect to the grating section temperature. By varying the TE cooler temperatures, between -50°C to 50°C, it is possible to tune the wavelength over 100 nm. We also investigated the thermal response time, which is determined by the combined TE cooler thermal response time, less than 2 ms according to the manufacturer specification, and the material heat transfer time. In the simulation, a material heat transfer time of 25.5 ms at 80% of rising/falling temperature was preliminarily obtained. The result is critical for agile wavelength tuning applications such as multiple gases detection.

7953-60, Session 15

**Type-I GaSb based diode single lateral mode lasers operating at room temperature in 3.1 - 3.2 µm spectral region**

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Broad area type-I GaSb based diode lasers have recently achieved 100 mW continuous wave room temperature powers in 3.1-3.2 µm spectral region. Some applications such as single frequency sources for spectroscopy require single lateral mode operation. We characterize and compare two types of lasers with similar structures and various ridge widths emitting at 3.1 and 3.2 µm. We obtain 35 and 25 mW of continuous wave single lateral mode power from 8 and 13 µm wide ridge lasers emitting at 3.1 and 3.2 µm respectively. This constitutes three fold improvement compared to the previous result. Both devices had ridges etched to the depth leaving approximately 350 nm of the top p-cladding in the areas outside the ridges. For 3.2 µm emitting lasers the dielectric thickness was 260 nm while it was nearly doubled (530 nm) for 3.1 µm emitting lasers. Gain spectra were measured by Haki-Paoli technique for various ridge widths. From gain spectra we extract differential gain and internal loss from low energy tail. We find that internal loss in thin dielectric, 3.2 µm emitting laser is about 14 1/cm while it is 7 1/cm in thick dielectric, 3.1 µm emitting laser for the ridge widths of 13 and 8 µm exhibiting single lateral mode operation respectively. Internal losses measured on broad area, 100 µm wide lasers processed from the same materials are similar and around 6-7 1/cm. We discuss reasons for the internal loss increase with the aid of simulation of optical mode field and loss in our waveguide structures.

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infrared around 2 \mu m. Different laser samples without any filter elements and with filters for the selection of the fundamental transverse mode (#0; TMS0) are prepared and characterized. Just for a proof of principle also samples for the selection of higher order modes, here exemplarily mode #6 (TMS6) and #8 (TMS8), have been processed and investigated. The free spectral range between the longitudinal modes is found to be around 0.33 nm corresponding to the BAL’s total-resonator length 2d = 1.65 mm (with an effective refractive index \( n_{eff} = 3.8 \)). This result strongly emphasizes that both resonator branches act together as one entity.

7953-62, Session 15

Near-IR induced negative photoconduction and its relationship with optical quenching of mid-IR quantum cascade lasers (QCLs)

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We report in this work the Near-IR induced negative photoconduction (NPC) on Mid-Infrared Quantum Cascade Lasers (QCLs). The NPC depends on the coupled Near-IR intensity and wavelength, the QCL bias voltage, and the bias pulse width when the QCL is operated under pulse mode. A group of strain-compensated InGaAs/InAlAs, 4.8\,\mu\,m room temperature mid-IR QCLs, were used in the experiment. The pump lasers are near-IR lasers with wavelengths at 1.2\,\mu\,m and 1.55\,\mu\,m. When the device is biased, the generated electron-hole pair by the Near-IR photons will be swept off the active region like a photoconductor. Some of the holes will be trapped at the valence band hetero-structures and start to create internal field build-up. This will cause the band-bending of the QCL superlattice and reduce the current flow. From the oscilloscope we observed that after ~50\,ns, the QCL responds to the incoming near-IR photons changing from positive photo-conductance (PPC) to NPC. When the QCL is operated above lasing threshold, the Near-IR induced band-bending will cause misalignment of QCL energy levels, which will not only reduce the electron flow but also reduce the mid-IR optical output as we call it “optical quenching”. We have previous observed that a near-IR laser with good quenching ability can modulate the mid-IR laser with speeds way above 100 MHz, which excludes the possibility of a thermal origin of these results. This Near-IR induced optical quenching effect has the potential to provide all optical modulation of Mid-IR Quantum Cascade Lasers.

7953-63, Session 15

Novel mid-IR coupling technique

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Signal modulations and coherent signal detections are important for both communications and remote sensing... etc. applications. Photonic integrations have been helpful to the implementation of these systems with benefits of reducing size, weight, cost, and with the possibility of improving system efficiency and performance. Integrated DFB-laser modulator, integrated coherent receivers and transceivers have demonstrated at near-IR wavelength regions. However, due to the difficulties of monitoring waveguide coupling in the mid-IR wavelength range, photonic integrations in the mid-IR wavelength range are nearly totally under-developed. We report in this work a novel mid-IR laser waveguide coupling technique that can simplify and optimize laser waveguide coupling in the mid-IR wavelength range. It can also greatly help the development of mid-IR integrated optics. The coupling method we developed relies on the negative photo-conductivity (NPC) of quantum cascades lasers (QCLs) at low bias voltages. When the incoming mid-IR photon has a photon energy near the optical transition and majority of the carriers are at the lower state, the NPC happens as a result of upward transitions, which creates a current flow against the existing current. Up to 10 times resistance changes (~1Mohms to ~10Mohms at low temperature) have been observed when the waveguide couplings are optimized. The measured device resistance is also linearly increasing with the input power within a few mW mid-IR power coupled into the waveguide. As an experimentally result, the NPC changed to positive photo-conductance (PPC) when the QCL bias current is increased to over the transparency current and reaches population inversion.

7953-72, Session 15

Two-dimensional surface emitting single mode quantum cascade laser arrays

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Quantum cascade lasers (QCLs) are well established as reliable laser sources in the mid-infrared (MIR) spectral region. Since the MIR region is rich in molecular absorption features these coherent sources of light are attractive compact emitters for a broad range of applications, such as medical diagnostics, pollution monitoring, environmental sensing of the greenhouse gases responsible for global warming, and remote detection of toxic chemicals and explosives. For most applications, broadly tuneable QCL devices operating at a single desired frequency are of special importance. Broadband single-mode operation can be achieved by fabricating linear arrays of distributed-feedback (DFB) QCLs [1], or by incorporating QCLs within an external cavity configuration [2]. While the former allows only one-dimensional arrangement and shows significant grating period induced variations in threshold currents and optical power, the external cavity versions are complex to build, require careful alignment and high-quality antireflection coatings. A two-dimensional integration of such coherent emitters is appealing since it allows for on-wafer testing and scalability at the wafer level, which consequently reduces the fabrication costs and effort.

We describe compact two-dimensional broadband single mode QCL arrays based on ring cavity surface emitting lasers, as a basic building block [3]. A 16-element array exhibits a mode-hop free linear tuning range of ~180 cm\(^{-1}\) (7.5 - 8.7 \mu m) at 293 K. Given by the facetless nature of the single emitters the threshold current densities and the optical power simply reflect the gain profile and do not significantly depend on the individual grating design. Such widely tuneable laser arrays allow the realization of miniaturized mid-infrared spectrometers.

REFERENCES


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Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XV

7954-01, Session 1

Energy efficient lighting for the human biological clock
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During the past century the development of light sources has been driven by the intention to increase energy efficiency and lighting quality for good vision. The development of Solid State Lighting is representing the summit of this process. Progress was mainly based on improvements of light sources, while the basic design principles for lighting were thought to be fundamentally well understood.

But by beginning of the new millennium the existence of a formerly unknown type of photoreceptor in the human eye has been proven. This photoreceptor is primarily sensitive in the blue spectral range and is responsible for transducing light signals directly into the brain where they significantly contribute to the control of essential biological functions like setting of the circadian clock, the sleep-wake-cycle, daytime activation and similar important processes. This unexpected finding has been followed by intensive scientific research as well as by efforts of the lighting industry to develop suitable lighting solutions to improve human health and well being by taking into account the biological effects of light into the design of light sources and applications.

The paradigms for good lighting design are shifting. Biological effects of light on humans have grown to an important factor to be respected in lighting design. The assessment of light with respect to its biological effects is essential. Standardization activities have been started on national levels (e.g. DIN in Germany) as well as globally (CIE) to build up a sound base for description of lighting with respect to its biological effects.

Beneficial effects of light on human health and well being have been proven in many different applications, e.g. in nursing homes for elderly residents but also in schools, offices or on workplaces with insufficient daylight.

While the first steps have been made with conventional lighting technology using especially blue enhanced fluorescent lamps, latest improvements of LED technology are now allowing to realize more and more advanced solutions with LED.

As it is mainly the blue content of a spectral light distribution which counts for biological effects, the unique advantage of LED is the wide range of spectral tunability which allows to design lighting scenarios with enhanced as well as with reduced biological effectiveness. The design of artificial “daylight” or “nighttime” scenarios is possible while demands on lighting quality for vision is maintained.

Besides rating the visual efficiency of a lighting solution it is important to assess also its biologically rated efficiency. As biologically effective lighting is addressing a second system in the human body a measure for energy efficiency beyond lumen per watt is required for a proper description.

The presentation will introduce to the basic mechanisms of biological effects of light and show how different light spectra can be assessed with respect to their biological effectiveness. Other lighting parameters affecting the biological rating of light in praxis will be shown and explained by examples of realized applications. Finally ideas for the assessment of a biologically rated energy efficiency will be presented.

7954-03, Session 1

Human health and well-being: promises for a bright future from solid state lighting
M. S. Rea, Rensselaer Polytechnic Institute (United States)

Electric lighting technologies can disrupt the 24-hour daylight/dark-night exposure pattern. These “unnatural” patterns of light and dark, like those that can be experienced by shift workers and airline personnel, have a wide variety of consequences for our health, from insomnia to breast cancer. Unlike the conscious appreciation of visual information obtained through the eyes, enabling us to take voluntary action to approach opportunities or avoid threats, we have no direct conscious awareness of the state of our circadian clock so we are, in effect, unable to take appropriate action to improve our well-being in response to an “unnatural” pattern of light and dark incident on our retinas.

Technologies are needed to provide us with information about the state of our circadian system such that we can take appropriate action to avoid and to correct light-induced circadian disruption. In addition to the implicit promises of solid state lighting to improve energy efficiency and the quality of the visual environment, solid state lighting sources and controls also offer a hope for maintain our health and well-being by precisely tailoring light and dark throughout the 24-hour day. By controlling the timing, duration, intensity and spectrum of retinal light exposure throughout the 24-hour day, many of the maladies associated with modern society such as obesity and cancer may be corrected.

7954-04, Session 1

Daytime light, performance, and sleep
D. Kunz, Charité Universitätsmedizin Berlin (Germany)

No abstract available

7954-05, Session 2

The efficiency droop in GaInN light-emitting diodes
E. F. Schubert, J. Cho, Rensselaer Polytechnic Institute (United States)
The efficiency droop is one of the major challenges in GaN-based light-emitting diode (LED) technology. There are two fundamentally different locations for non-radiative carrier recombination that can lead to droop. The first location for droop-causing recombination is outside the quantum wells (QWs) forming the active region of the LED. The second location for droop-causing recombination is inside the QWs.

Droop-causing recombination outside the quantum wells has been proposed to be caused by lack of carrier capture into the QWs, escape from the QWs, the electron-attracting properties of the spacer-EBL (electron-blocking layer) interface, the p-type doping properties of the EBL, and the asymmetry in transport properties between electrons and holes in GaN [1-6].

Droop-causing recombination inside the quantum wells has been proposed to be caused by carrier delocalization occurring at high carrier densities so that the delocalized carriers can diffuse to dislocations where they recombine non-radiatively. Droop has also been proposed to be caused by Auger recombination [7, 8].

In this presentation we will discuss the potential mechanisms causing the efficiency droop including polarization effects in the III-V nitrides, doping, asymmetry of carrier transport, carrier delocalization, and Auger recombination. We will also establish the functional dependence of the efficiency droop on the carrier concentration. The experimentally determined functional dependence is compared to theoretical physical models. The comparison allows one to attribute the experimentally observed droop to a suitable theoretical model.

References:


emission peak from the following narrower wells within QWVs. These results are in good agreement with the result obtained from APSYS simulation.

Based on the results mentioned above, a high-efficiency InGaN-based LED with LT-GaN pre-strained layer and QWVs has been fabricated, which demonstrated an improvement in output power of 36% at current density of 22 A/cm² and 71% at current density of 244 A/cm². Besides, the efficiency droop was alleviated to be about 17% from maximum at current density of 22 A/cm² to 244 A/cm², which is much smaller than 54% of conventional LED.

7954-08, Session 2

Microscopic model for internal efficiency of InGaN light-emitting diodes

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Attempts to understand InGaN LED internal efficiency are based mostly on a total carrier density (N) picture, with carrier losses modeled by dN/dt = -αN, where A, B and C are empirical fitting parameters. In spite of its wide usage, the total carrier description has important inadequacies. First, with this many free parameters, predictions or fits of experimental data can be ambiguous. Secondly, A, B and C are often associated with Shockley-Read-Hall (SRH), radiative recombination and Auger carrier losses, respectively. Such associations are not strictly accurate and evidence for error appears as discrepancies between the results from rate equation modeling and those from microscopic calculations.

In this paper, we describe an improved LED radiative efficiency model. While the approach remains based on rate equations, these equations describe electron and hole occupations in each momentum (k) state. The difference allows bandstructure properties to enter directly into the rate equations, allowing the comparison of intrinsic performance between different quantum-well (QW) structures, e.g., between those emitting at different wavelengths. The model treats carrier scattering physics more precisely, thus allowing us to take better advantage of results from microscopic calculations. Lastly, the spontaneous emission contribution is determined based on the bandstructure and carrier distributions, rather than assuming a BN2 term, where B is a static fitting parameter. These factors lead to a more stringent evaluation of physical mechanisms proposed for efficiency degradation and provide a more comprehensive picture of the interplay of different contributions to LED performance, especially under high excitation or high temperature conditions.

7954-09, Session 3

Randomized micro lens arrays for color mixing

J. A. Muschaweck, OSRAM Opto Semiconductors GmbH (Germany)

Color homogeneity is a key issue for LED lighting. To achieve sufficient flux, efficiency and color rendering, LED luminaires have to use multiple LEDs, whose brightness and color properties differ. To mix greenish white LEDs using phosphor with red monochromatic LEDs is an especially promising approach to achieve both high efficacy and good color rendering at warm white colors. However, even for luminaires using only white LEDs, color and brightness of the LEDs varies due to random selection within LED bins, or by using LEDs from different bins. For diffuse illumination, color mixing is not too difficult, but for collimated light, good color mixing is a key challenge to the optical system. Micro lens arrays are known to provide extremely good color mixing while increasing beam divergence only slightly. However, in their standard forms with (i) hexagonal lenslets or (ii) circular lenslets with blackened triangles, they create beam patterns with (i) sharp edged hexagon or (ii) less efficient sharp edged circular distributions, instead of the round, soft edged beam shapes needed for general lighting. This is due to the fact that the lenslet shapes are imaged to the far field. It is not possible to choose the lenslet shapes freely: the lenslet edges depend on the lenslet positions, forming a Voronoi diagram. We present various approaches to perturb the regular lenslet positions, forming a smooth round beam, while keeping the superior properties of standard micro lens arrays.

7954-10, Session 3

Intelligent sensor for color and proximity control in solid state lighting applications

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LED wavelength and luminosity shifts due to temperature, dimming, aging, and binning uncertainty can cause large color errors in solid-state light-mixing applications. Color light sensors combined with feedback circuits can compensate for these LED shifts. Design requirements include high dynamic range (~100dB) with excellent linearity and flexibility for tailoring sensor response. Cypress Semiconductor has prototyped several color sensor architectures for this color-feedback application, including a single chip integrated solution consisting of configurable photo-diode arrays connected to read-out and programmable systems-on-chip (SoC) circuits. The PSoC is a standard Cypress product and is a true programmable system-on-chip which integrates analog and digital peripheral functions, memory, and a micro-controller. The PSoC integration with color and proximity sensors adds on-chip intelligence functions for color detection, color control, and proximity sensing. Light-based proximity sensors use the near-infrared spectrum to detect the presence and/or motion of nearby objects. Proximity sensors require filters which pass near-infrared and block visible light. A novel near-infrared filter was integrated with the visible light sensor. This new proximity sensor detects light in the spectral range of 700 - 1100nm with peak responsivity at 850nm, with a ~30dB suppression of visible light signal.

7954-11, Session 3

Effect of C-plane coverages of patterned sapphire substrate on the lighting efficiency of GaN-based LED

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Patterned-sapphire substrate technique has been widely used to improve the external quantum efficiency of GaN-based LED. The pattern morphology and the c-plane coverage are the two key factors affecting the ultimate external quantum efficiency. Numerous patterning features on the patterned-sapphire substrate, such as, circle cavity, square cavity, hemisphere bumps, and trenched stripes, have been reported and demonstrated to greatly enhance the external quantum efficiency. However, how does the pattern coverage influence the external quantum efficiency is yet to be understood.

In this study, we used a mask-free wet-etching process to produce a so-called nature patterned-sapphire substrate (n-pss). With varying the etching temperature, different pattern coverages of the unique pyramidal pattern can be created on the c-plane sapphire surface. Then, MOVCD GaN-based LED epitaxial layers were grown on the n-pss with different pyramidal pattern coverage. After that, MOVCD GaN-based LED epitaxial layers on the n-pss with different pyramidal pattern coverages were processed into horizontal LED chips. In this talk, we will report the effect of the c-plane coverage of the patterned sapphire substrate on the ultimate improvement of the external quantum efficiency of GaN-based LED.
7954-12, Session 3

Glare effect of LED indoor illumination

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In previous literature, glare can be divided into direct glare, indirect glare, and background glare, whereas direct glare is the mainstream to the various glare assessment methods such as BGI, VCP, LC, CGI, and UGR. The reason why these studies do not focus on indirect glare and background glare is that the intensity of traditional light sources is not enough to produce numerous reflections on object surfaces. But it will be a significant problem if we use LED as indoor illumination. In this study, we investigate the relationship between light scattering and glare of LED indoor lighting devices. We also analyze the direct and indirect glare from light source to the eye, and the background glare from light source through the environment to the eye. After making simulation by Monte Carlo Ray Tracing method, an optimal LED lighting model for indoor illumination can be obtained. Finally, we will simulate visual images from different glare indices.

7954-13, Session 4

Improvement of efficiency droop by employing InAlN electron blocking layers in III-N visible LEDs grown by metalorganic chemical vapor deposition

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We have compared device performance of blue and green LEDs having InAlN EBLs with LEDs with conventional AlGaN EBLs. The lower growth temperature, larger conduction-band offset, and lattice-matching capability of InAlN EBLs are expected to enhance the internal quantum efficiency of blue or green LEDs, compared to conventional AlGaN EBLs, by reducing the strain and the thermal damage of the InGaN quantum-well active layer during EBL growth, providing a larger electron confinement effect, and reducing the strain-induced defect generation. The LED structures were grown on c-plane sapphire substrates and consist of a 3- m-thick Si-doped GaN layer with an electron concentration of n~5×10^{18} cm^{-3}; a five-period InGaN/ GaN multiple-quantum-well active region; a 20-nm-thick Mg-doped InGaN electron blocking layer with an electron concentration of n~5×10^{18} cm^{-3}; a 5-nm-thick Mg-doped InGaN/GaN multiple-quantum-well cladding region; and a 20-nm-thick Mg-doped InGaN/GaN multiple-quantum-well contact layer with a hole concentration of p~2×10^{18} cm^{-3}. LEDs with an InAlN EBL show higher EL intensities than LEDs grown without an InAlN EBL or with an AlGaN EBL. This result indicates that the InAlN EBL is effective in confining electrons in areas with either high defect density or that contain strong recombination areas. These areas are energetically separated from areas with either high defect density or that contain strong recombination centers. At elevated densities carriers occupy energetically higher states and spill over into regions with high defect recombination. At the onset of this spill-over the losses should scale about like (N-N_0)^2, with one factor (N-N_0) coming from the linear density dependence that is usually assumed for defect recombination and the other factor arising from the efficiency droop. This can be accomplished by advanced designs of the active region of GaInN LEDs.

7954-14, Session 4

Polarization-mismatch-reduced AlGaN/GaN multiple quantum well light-emitting diodes with reduced efficiency droop

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A fundamental problem facing GaInN light-emitting diodes (LEDs) is the occurrence of the efficiency droop, that is, the gradual decrease of the efficiency at high injection currents. Since the efficiency droop has been demonstrated to be the single largest loss mechanism of LEDs at high current levels, it is mandatory that this deleterious effect be mitigated. This can be accomplished by advanced designs of the active region of GaInN LEDs.

The droop of the internal quantum efficiency requires a non-radiative carrier loss mechanism that increases stronger with carrier density (N) than the radiative loss. Assuming a regular power law for the losses, this means that the non-radiative loss has to increase with a density dependence stronger than the N^2. This is why Auger losses, which scale about like N^3, have been assumed a viable candidate for the cause of the droop despite the fact that calculations have found the Auger losses in these materials generally too small to explain the droop.

Here we show that a density-activated.bounds process that is zero below a threshold density N_0 and then scales proportional to (N-N_0)^2 can also reproduce the experimentally measured droop results [1]. We propose density-activated defect recombination as a possible explanation for the efficiency droop in GaN-based diodes.

7954-15, Session 4

Density-activated defect recombination as a possible explanation for the efficiency droop in GaN-based diodes

J. Hader, J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States); S. W. Koch, Philipps-Univ. Marburg (Germany)

The droop of the internal quantum efficiency requires a non-radiative carrier loss mechanism that increases stronger with carrier density (N) than the radiative loss. Assuming a regular power law for the losses, this means that the non-radiative loss has to increase with a density dependence stronger than the N^2. This is why Auger losses, which scale about like N^3, have been assumed a viable candidate for the cause of the droop despite the fact that calculations have found the Auger losses in these materials generally too small to explain the droop.

Here we show that a density-activated loss process that is zero below a threshold density N_0 and then scales proportional to (N-N_0)^2 can also reproduce the experimentally measured droop results [1]. We propose density-activated defect recombination as a possible explanation for this process.

The model assumes that at low densities most carriers occupy areas that are mostly defect free. These areas are energetically separated from areas with either high defect density or that contain strong recombination centers. At elevated densities carriers occupy energetically higher states and spill over into regions with high defect recombination. At the onset of this spill-over the losses should scale about like (N-N_0)^2, with one factor (N-N_0) coming from the linear density dependence that is usually assumed for defect recombination and the other factor arising from the fact that with increasing density more recombination centers can be reached by the spill-over carriers.


7954-16, Session 4

Carrier recombination mechanisms and efficiency droop in GaInN/GaN light-emitting diodes

The "efficiency droop" in GaInN/GaN multi-quantum well (MQW) light-emitting diodes (LEDs) is the gradual decrease of efficiency as the injection current density surpasses a relatively low value that typically ranges between 0.1 and 10 A/cm² [1, 2]. In order to comprehensively investigate the efficiency droop, we analyze the carrier recombination inside quantum wells (QWs) by means of $An + Bn^2 + Cn^3$, and carrier recombination outside of QWs by means of a carrier-leakage term $fn$ [1, 3, 4], where $n$ is carrier concentration. $A$, $B$, and $C$ represent Shockley-Read-Hall (SRH), radiative, and Auger coefficient, respectively. The leakage term $fn$ is expanded into a power series. We show that the ABC + fn model gives excellent fits to the experimental efficiency-versus-current curves of GaInN/GaN LEDs. The fn term can have 2nd, 3rd, and higher-order contributions to the recombination rate. The total 3rd-order non-radiative coefficient (which includes a leakage and an Auger contribution) is found to be $8 \times 10^{-29}$ cm⁶s⁻¹ [A = 6 $\times 10^{-6}$ s⁻¹, B = $10^{-10}$ cm⁻³s⁻¹ $\times 3^3$, C = 5, 6)]. The extracted third-order non-radiative coefficient is much larger than the reported theoretical Auger coefficient ($10^{-34} \sim 10^{-31}$ cm⁶s⁻¹-1) [7, 8]. A peak internal quantum efficiency of 70% is obtained from fitting blue LED efficiency data using the ABC + fn model.

Reference:
Technological advancements in solar lighting systems based on optical fiber bundles is a cost-effective way of countering the rising global energy needs during the day. A key challenge in such lighting systems is the development of a passive optical system that can provide reasonably uniform illumination all through the day without using any moving parts.

The focus of our research is the development of the above passive solar collector system. However, a major drawback is the availability of solar radiation only for a limited time. In this paper, we report the demonstration of a LED-array based testbed that simulates the solar radiation at different times of the day. Specifically, the testbed consists of seven different LED assemblies that can be configured to simulate the sun’s position and intensity at any time of the day. The LED assemblies are fixed on a semi-circular metal frame, the focal point of which is a light collector housing located 50 cm away that can accommodate different optical assemblies of interest. The intensity of the LED assemblies are controlled individually using a home-built microcontroller-based circuit and are found to be uniform within 5% and provide collimated radiation over a width of 2 cm.

Preliminary experiments were conducted using a Fresnel lens plate as the stationary optical element and a four-detector panel placed at the focal plane of the lens. The LED assemblies at the different angles were found to focus at different points across the focal plane underlying the need for an aplanar optical element with different sections optimized to collect light from a specific range of angles. Work is underway to design and test such an optical element, the results of which will be presented at the conference.

7954-20, Session 6

Direct microscopic correlation of optical and structural properties of non-polar m-plane GaN on patterned Si substrates using cathodoluminescence spectroscopy

J. Christen, F. Bertram, S. Metzner, Otto-von-Guericke-Univ. Magdeburg (Germany); X. Ni, N. Izumyukaya, H. Mokoç, Virginia Commonwealth Univ. (United States)

One approach for beating the negative impact of internal polarization fields of group-III nitrides (Quantum Confined Stark Effect) is the growth on semi- or nonpolar crystal planes. m-plane GaN is realized on Si substrates by initiating growth on the vertical [111] sidewalls of stripe-patterned SiNx masks in [110] direction 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 spectroscopy. 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. Even the intensity of the InGaN emission is drastically lowered in this region giving local fingerprints of strain splitting of the valence band of QWs grown along the a- and m-axes. This leads to a strong modification of the selection rules for interband emission allowing a high degree of linearly polarized light to be emitted through the top growth surface. Our m-plane GaN/GaN MQWs structures reach a polarization ratio of ~0.7 at 480 nm and this value grows to ~0.9 at 515 nm peak wavelength. For a-plane structures, we always find lower values of ~0.6 at 480 nm - 510 nm. Deploying m-plane LEDs with such a high degree of polarization should result in significant power savings for LCD displays technologies.

7954-22, Session 6

Growth of non-polar GaN crystals on the alternate substrates

M. M. C. Chou, C. Chen, J. Lu, C. Li, National Sun Yat-Sen Univ. (Taiwan)

Non-polar free-standing a-plane GaN [11-20] and m-plane [10-10] single crystal was fabricated on the closely lattice-matched [100] LiAlO2, [010] LiGaO2 substrate by a modified hydride vapor phase epitaxy (HVPE) method. The influence of the growth temperature on the crystal quality was studied. The surface morphologies were characterized by scanning electron microscopy. Structural properties of the GaN epilayers are investigated by X-ray diffraction and transmission electron microscopy. High resolution transmission electron microscopy shows the in-plane structural relationship of [10-10]-GaN \( \parallel [100] \) LiAlO2 and [11-20]-GaN \( \parallel [010] \) LiGaO2. Optical properties examined by photoluminescence spectroscopy exhibited a strong emission peak at 3.348 eV. Our results suggest that LiAlO2 and LiGaO2 are the promising substrates in the development of nonpolar GaN homoepitaxy.

7954-23, Session 7

High-power AlInGaN deep UV LED lamps and their system applications

A. M. Khan, Univ. of South Carolina (United States)

Since their first demonstration in early 1990’s, AlInGaN based blue-white large area LED lamps with powers in the 1 Watt range are now available for solid state lighting applications. Since 2001, our group has developed sub-300 nm emission Deep-ultraviolet LEDs (DUV LEDs) with AlGaN multiple quantum well active regions over sapphire substrates. These LEDs are an ideal replacement for mercury lamps for air-water purification, polymer curing and bio-medical instrumentation applications. However to date the AlGaN MQW based DUV LEDs have suffered from
low quantum efficiencies, premature power saturation and difficulty in light extraction. The primary reasons for these issues are: 1) Availability of low-defect substrate templates 2) Active layers’ polarization management and 3) Availability of processing and Packaging schemes similar to those adopted for visible LEDs. Thus the emission powers and the efficiencies of 250-280 nm DUV LEDs to date are limited to 1-2 mW (20 mA pump current) and 1-2%. Recently several research groups including ours have experimented with new approaches to address these issues. We now report 280 nm Lamps with cw-powers as high as 100 mW and pulsed powers well over 300 mW. These high powers required the use of laterally overgrown AlGaN layers with thicknesses well over 10 µm and new Micro-LEDs and Vertical conduction device geometries. In this paper we will review the progress to date, the remaining issues and some new approaches that are being implemented to address them. We will also discuss the application of DUV LEDs in water purification systems.

7954-24, Session 7

Efficient 350 nm LEDs on low edge threading dislocation density AlGaN buffer layers

R. Gutt, T. Passow, W. Pletschen, M. Kunzer, 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)

Improving the crystal quality of AlGaN epilayers is essential for efficient III-nitride-based LEDs with emission wavelengths below 365 nm. Here, we report on two approaches to overcome this difficulty related to the growth of AlGaN-based structures, which are known to be effective for MOVPE of GaN layers. Firstly, we grew AlGaN on thin GaN nucleation islands which exhibit a three-dimensional faceted structure. Lateral overgrowth of such islands can lead to lateral bending of dislocation lines at the growing facets. Secondly, ultra-thin SiNx interlayers were in-situ deposited. They can act as nano-masks reducing the dislocation density above the SiNx layers. Both approaches result in reduced asymmetric HRXRD –scan peak widths, indicating a reduced edge-type dislocation density. They are suitable for Al concentrations of at least 20%, i.e. for LEDs emitting around 350 nm. Full LED structures were grown on these buffer layers and are compared to structures grown on a purely 2D grown low Al-content AlGaN nucleation layer. Electroluminescence measurements were taken on-wafer without any measures to improve light extraction and heat dissipation. The light output power at 20 mA for the 3D nucleated LED structure is 0.14 mW which corresponds to an increase by a factor of 6 compared to similar LED structures grown in 2D mode. The same LED structure grown on a buffer containing SiNx nano-masking layers provided a further enhancement with an output power of 0.51 mW at 20 mA. The output power rising to 1.05 mW at a current of 40 mA.

7954-25, Session 7

ITO/Al based reflector for high-power UV LEDs via thermal and plasma treatments

D. J. Chae, D. Y. Kim, D. H. Kim, S. J. Kim, Korea Univ. (Korea, Republic of); S. Jeon, Korea Photonics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

AlGaN based ultraviolet (UV) light-emitting diodes (LEDs) have been exploited due to their potential applications in the sterilization market. In this work, we report the electrical and optical properties of indium-doped tin oxide (ITO)/Al based p-type reflector with thermal and fluorne-based plasma treatments for high-power vertical-type ultra-violet light-emitting diodes (LEDs). First, a 200 nm-thick ITO film was deposited and thermally treated from 300°C to 700°C using rapid thermal annealing. Al was then deposited on it right after SF6 plasma treatments at the surface of the ITO for 10 min. Following SF6 plasma treatments, it is expected that Ohmic behaviors of the ITO film on the p-type AlGaN layer are improved since electric dipoles at the ITO surface may be increased due to the large electronegativity of fluorine species, which can increase the work function of ITO and so, accordingly, decrease the Schottky barrier height (SBH) between the ITO and AlGaN. In addition, the reduction of the interface roughness between the ITO and Al after SF6 plasma treatment, is supposed to increase the reflectance of the proposed ITO/Al reflector. As a result, ITO/Al reflectors after annealing at 650°C and SF6 plasma treatments for 10 min, showed very low specific contact resistance (ρ) of 9.36×10-4 Ω cm2 and a reflectance of 70% at the 365 nm wavelength.

7954-26, Session 8

Nitride nanowire structures for LED applications

H. Riechert, Paul-Drude-Institut für Festkörperelektronik (Germany)

This talk will outline the potential advantages of nanowire structures for the use in LEDs as well as the challenges which need to be overcome towards the realization of real-world devices. Our experimental results pertain to growth by MBE and mostly refer to nitride nanowires, with some insight added from our experiments on arsenide nanowires. In comparative investigations on catalyst-induced and catalyst-free growth of GaN nanowires under otherwise identical conditions we find clear evidence that the latter approach is far superior with respect to both structural and optical properties. An added benefit of this procedure is that it works best on Si, thereby holding the promise of easy upscaling of epitaxial area.

Using in-situ growth studies combined with TEM, we have elucidated the mechanism of nanowire nucleation and the factors determining the initial nanowire diameter in catalyst-free GaN nanowire growth. A major challenge that is presently witnessed by many groups is the controllable inclusion of InGaN into nitride wires of small diameters. This holds in particular for In-contents aiming at emission in the green. We will show by a combination of XRD, TEM, strain simulation and PL that such structures can remain defect-free and show intense luminescence even though regions of very high In-content arising from In-segregation are contained in our structures.

Finally, the talk will attempt to review the performance of nanowire-based group-III nitride LEDs reported so far.

7954-27, Session 8

III-nitride nanowires: novel materials for solid-state lighting

G. T. Wang, Q. Li, J. Huang, A. A. Talin, A. Armstrong, Sandia National Labs. (United States); P. Upadhya, R. Prasankumar, Los Alamos National Lab. (United States)

Although planar heterostructures dominate current solid-state lighting architectures (SSL), 1D nanowires (NWs) have distinct and advantageous properties that may eventually enable higher efficiency, longer wavelength, and cheaper devices. The unique ability of NWs to relieve strain enables dislocation-free material, high In incorporation towards the realisation of real-world devices. Our experimental results allowing green-red wavelengths to be achieved, and growth on arbitrary substrates. However, in order to fully realize the potential of nanowire-based SSL, several challenges exist in the areas of controlled nanowire synthesis, nanowire device integration, and fast-turning and controlling the nanowire electrical, optical, and thermal properties. In this talk I will discuss the aligned growth of GaN and III-nitride core-shell NWs, along with extensive results providing insights into the NW properties obtained using cutting-edge structural, electrical, thermal, and optical nanocharacterization techniques. The topics I will cover include: wafer-
scale aligned NW growth; ultrafast carrier dynamics via pump-probe spectroscopy; in-situ TEM studies of NW breakdown and deformation; deep-level optical spectroscopy of NW defects; spatially-resolved cathodoluminescence studies of band-edge and defect luminescence in NWs; strain-related spatial variation of In incorporation in InGaN shells; NW lasing; NW device fabrication and characterization; and work towards flexible NW platforms. I will also discuss a novel application of vertically-aligned GaN NW arrays as strain-compliant templates for the lateral growth and coalescence of high quality nonpolar a plane GaN films on lattice-mismatched sapphire. Sandia National Laboratories is a multi-program laboratory 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.

7954-28, Session 8
Enhancement of light extraction efficiency of InGaN quantum wells light-emitting diodes using TiO2 microsphere arrays
X. Li, Y. Ee, R. Song, N. Tansu, Lehigh Univ. (United States)

High-efficiency and low-cost light-emitting diodes are of great importance for solid state lighting. Due to large refractive index discrepancy between GaN (n=2.5) and air (n=1), significant light generated from the active region is trapped inside the semiconductor layer. Low-cost and practical approach in enhancing the light extraction efficiency in nitride LEDs provides significant reduction in cost in solid state lighting technologies. Recently, the use of SiO2 microsphere arrays and SiO2 / polystyrene (PS) microspheres arrays deposited on nitride LEDs have led to increase in light extraction efficiency by 1.6 times and 2.5 times, respectively.

In this work, we present the use of TiO2 microsphere arrays deposited on nitride LEDs, with the goal of increasing the escape cone from the nitride LEDs attributed to the larger refractive index of the TiO2 microspheres in comparison to that of SiO2 microspheres. The deposition of TiO2 microsphere arrays were performed by Langmuir-Blodgett method and rapid convective deposition. In our experiment, 520nm diameter TiO2 microsphere arrays were deposited on nitride LEDs consisting of 4 periods of 2.5nm thick InGaN-GaN QWs emitting at 450 nm. The scanning electron microscopy measurements indicate that the use of Langmuir-Blodgett technique led to sub-monolayer deposition, while the use of rapid convective deposition resulted in close-packed monolayer microsphere arrays. The electroluminescence measurements from the nitride LEDs with microsphere arrays exhibited 1.85 times improvement in output power in comparison to that of devices without microspheres monolayers, and further comparison of devices with different microsphere diameters will be performed.

7954-29, Session 8
White light emitting devices based on ZnO-Si nanoparticle multilayers
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Nanoparticle based light emitters can combine benefits of both organic light emitting diodes like large area emission and cost-effective fabrication, and crystalline solid state devices like high robustness against humidity or UV radiation. We combine n-doped ZnO nanoparticles and p-doped Silicon nanoparticles from the gas phase to fabricate light emitting devices that consequently avoid the usage of organic support layers. The fabrication process allows for low-cost production and principally compatible with printing techniques. The devices consist of a multilayer structure, where each layer is fabricated by spin-coating of nanoparticle dispersions, resulting in thin homogeneous layers with controlled thicknesses down to 100 nm. Transparent-conductive-oxide (TCO) coated glass is used as a substrate and Al was deposited by thermal evaporation as top contact. Naturally n-doped ZnO nanoparticles prepared under Zn-rich conditions in order to foster pronounced emission across the whole visible range, build the active light emitting layer. Even without any further support layers, these devices show electroluminescence for low DC biases. By introducing boron-doped Si nanoparticles as an inorganic support layer between the TCO and the optically active ZnO nanoparticles, a substantial enhancement of the quantum efficiency is observed and the device lifetime is increased to more than 300 h under continuous operation. As both defect-related emission in the visible spectral range and near-band gap emission in the near UV-range contribute the emission, surprisingly high colour rendering indices between 92 and 95 and color temperatures between 3200K and 4500K are achieved, although the quantum efficiency still has to be improved.

7954-30, Poster Session
Hybrid nanocrystal enhanced white light emitting diode
R. Shirazi, O. Koplyov, B. Kardyln, Technical Univ. of Denmark (Denmark)

A hybrid light emitting diode (LED), which uses non-radiative energy transfer for down-conversion of light from primary LEDs is shown to effectively produce white light. Colloidal InP/ZnS nanocrystals emitting at 615nm are used as the energy acceptors in these hybrid-LEDs. Two geometries of the device are compared: standard quantum well GaN/InGaN LED (emitting at 440nm) as well as nanostuctured LED as well as, both of which facilitate small separation between the nanocrystals and the emissive layers of the LED. The standard diode is easy to fabricate and the processing related efficiency losses are minimal. However electrical contacting of the LED remains a challenge. The nanostructured LED provides larger contact area between nanoparticles promoting non-radiative energy transfer however their processing is more challenging.
We characterised both components of the LEDs separately and the final device in order to study the effect of the non-radiative energy transfer on the total radiative efficiency of the quantum well. Only weak effects were observed. Both devices are shown to the more efficient when generating white light of high correlated colour temperature (CCT). The colour rendering index is low, but it can be improved by using nanocrystals of different dimensions. An important feature of the hybrid LEDs is different temperature dependence of emission from both components of the hybrid, which leads to strong dependence of CCT with brightness. This feature of the hybrid LEDs may define their potential applications.

7954-45, Poster Session

Enhanced optical emission from organic light-emitting diode mediated with gold nanoparticles

S. Fukui, G. Obara, A. Zenidaka, Y. Tanaka, S. Takahashi, M. Obara, Keio Univ. (Japan)

We present an increase in the light extraction efficiency of organic light-emitting diodes (OLEDs) with Au nanoparticles. The analysis of the output optical performance by use of 3D FDTD simulation method and the experimental results are reported. Light extraction efficiency of conventional OLEDs has remained 20%, approximately, because most of the light emission is trapped in the waveguide. This makes the overall efficiency of OLEDs low for displays and solid-state lighting applications. In previous studies on inorganic LEDs, metal nanoparticles were placed on the device by an annealing method to induce localized surface plasmons. The plasmons can improve the light extraction efficiency from LEDs. Light extraction efficiency mediated with surface plasmons is determined by the size and density of metal nanoparticles. In this paper, we calculated the optimal diameter and the density of Au nanoparticles for luminescent wavelength by FDTD method. We fabricated OLEDs by optimal diameter and density gold particles by spin-coating method to avoid a thermal damage in the organic layer. A significant increase in the light extraction efficiency was achieved. The obtained results indicate that this method will be able to solve the current technical issues of low overall efficiency of OLEDs.

7954-46, Poster Session

Electroluminescence kinetics of variable-gap HgCdTe structures with Ohmic contacts

B. S. Sokolovsky, R. M. Kovtun, Ivan Franko National Univ. of L'viv (Ukraine); A. V. Shevchenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

The paper investigates by means of numerical modeling the electroluminescence kinetics of the structures based on variable-gap semiconductors with linear coordinate dependence of bandgap. It has been studied in detail the case of homogeneously doped n-type variable-gap structures with Ohmic contacts which are characterized by large magnitude of the light absorption coefficient. By taking into account quasielectric field occurring in these structure the spatial charge carrier redistribution caused by electric current has been found what allowed to calculate the spec-tral and integral intensities of radiative carrier recombination and their time evolution. When electric current flows in the direction of bandgap increase positive electroluminescence arises in the spectral range corresponding to the interval of band-gap change in the structure. The time of relaxation of this electroluminescence monotonously decreases with increasing the applied voltage. For opposite direction of electric current broadband negative electroluminescence generates with its relaxation time being characterized by non-monotonous dependence with maximum reaching at applied field strength approximately equal to the value of built-in quasielectric field strength. Results of numerical modeling are presented for the case of HgCdTe variable-gap solution which is a promising material for creation of IR sources.

7954-47, Poster Session

Improved electrical properties of Ni/Al Ohmic contacts to nonpolar a-plane n-type GaN

D. H. Kim, S. J. Kim, D. J. Chae, D. Y. Kim, Korea Univ. (Korea, Republic of); S. M. Hwang, Korea Electronics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

Recently, nonpolar a-plane GaN light-emitting diodes (LEDs) have received an attention due to its potential advantages in terms of device applications, as compared to polar GaN LEDs. These potentials would arise from the absence of built-in polarization fields and thereby higher radiative recombination rates in such material systems. However, these nonpolar LEDs still suffer from serious problems related to either growth or device fabrication, such as high density of threading dislocations, basal stacking faults, high forward voltage drop, and low output power. In addition, due to the opposite direction of spontaneous polarization originating from different Ga- and N-face surface in nonpolar GaN films, the Ohmic behavior of nonpolar LEDs with typical Ti/Al contacts become gradually worse as increasing the annealing temperature.

In this work, we report on the Ohmic behaviors of Ti/Al and Ni/Al contacts to nonpolar n-type GaNs by using the transfer line method and Schottky diode measurement. In particular, specific contact resistance (\(\rho\)) and Schottky barrier formations as a function of annealing temperature are investigated in detail. Currently, we observed the \(\rho\) of 5.8×10^{-5} from Ni/Al contact while typical \(\rho\) of the Ti/Al contact is as low as 1.6×10^{-3} \(\Omega\)-cm2 after thermal annealing at 700°C. The reduction of the \(\rho\) (or improved electrical properties) observed from the Ni/Al contact can be attributed to the defect-assisted tunneling, which may occur due to the barrier thinning at the Ni/nonpolar n-type GaN interface, via NiAl-alloying. More details on the experimental results will be presented at the conference.

7954-48, Poster Session

Enhancement of the light extraction efficiency of GaN-based vertical light-emitting diodes with nanosphere lithography technique

J. W. Yang, J. I. Sim, H. M. An, D. H. Kim, S. J. Kim, K. Ho, T. G. Kim, Korea Univ. (Korea, Republic of)

High-power and high-efficient GaN-based vertical light-emitting diodes (LEDs) have been used in various fields, including backlight units (BLUs) for liquid crystal display (LCD), traffic signals, and indoor illuminators. However, the external quantum efficiency of GaN LEDs is fundamentally limited (4%) by total internal reflection (TIR) due to Fresnel reflection between GaN medium (n=2.46) and air (n=1). In order to avoid TIR, several researchers have investigated various methods, including nanosphere lithography (NSL), to enhance the light extraction in the vertical direction of LEDs. However, the effect of the NSL with or without wet etching (i.e. KOH) on the efficiency of GaN-based vertical LEDs have not been reported yet.

In this work, we investigate the enhancement of light extraction in GaN-based vertical LEDs using NSL, in which n-GaN layers have been patterned on a nano-size scale using reactive ion etching (RIE) and wet etching. The polystyrene nanosphere of 500 nm diameter were used as mask to make patterns in the etching process with BCl3 and C2H2 as the gas source. As a result, vertical LEDs with both the NSL and wet etching processes on the n-GaN layer showed 180 mCd, which is 12.5 % higher brightness than 160 mCd obtained from wet etching only. More details on the performance of vertical LEDs proposed in this work will be presented at the conference.
Efficiency enhancement of blue InGaN LEDs with indium composition graded InGaN barriers

T. Wang, J. Chang, M. Tsai, Y. K. Kuo, National Chianghua Univ. of Education (Taiwan)

In recent literatures, the quantum efficiency of blue InGaN light-emitting diodes (LEDs) is quite limited under relatively high driving current with conventional GaN barriers due to poor injection efficiency of hole. In this study, the efficiency enhancement of blue InGaN LEDs with indium composition graded InGaN barriers is proposed. The energy band diagram, carrier concentration in the quantum wells, diagram of hole current, radiative recombination rate, L-I curve, and internal quantum efficiency are investigated numerically. The simulation results show that the InGaN LED with graded InGaN barriers has better performance over its conventional GaN barriers due to enhanced efficiency of hole injection. The simulation results also suggest that under relatively high current the internal quantum efficiency and output light power are markedly improved when the traditional GaN barriers are replaced by graded InGaN barriers. According to the phenomena, the new-designed LED has promising potential in solid state lighting.

Light-emitting electrochemical cells (LECs): next-generation lighting devices based on liquid processes and ionic organometallic complexes

W. Sarfert, D. Hartmann, G. Schmid, S. Meier, Siemens AG (Germany); H. Bolink, Univ. de València (Spain)

LECs are flat, thin lighting tiles that are prepared from solution and operate at low voltages with electrodes that are stable in air. Their simple device architecture and solution-processability enables cost-efficient production. Therefore, LECs promise to open up new markets and device architecture and solution-processability enables cost-efficient production. Therefore, LECs promise to open up new markets and applications. Within the European funded project CELLO efficient emitter materials and device concepts to be manufactured by high through-put printing and coating techniques are currently being developed. We will present an overview about our recent advances in material and device development with regard to stability, turn-on time and efficiency.

Layer cross-fading in OVPD-based OLED for optimized carrier distribution and exciton recombination

H. Kalisch, F. Lindla, M. Bösing, RWTH Aachen (Germany); D. Bertram, Philips Technologie GmbH (Germany); A. Vescan, RWTH Aachen (Germany); M. Heukens, AIXTRON AG (Germany) and RWTH Aachen (Germany); R. H. Jansen, RWTH Aachen (Germany)

Organic light emitting diodes (OLED) have the potential to leverage the transition to Solid State Lighting. In the course of their development, OLED have evolved from single-heterostructure devices towards more elaborate stacks consisting of various functional layers such as carrier injection, carrier transport, carrier and exciton blocking and emissive layers (EML). In order to control the distribution of electrons, holes and excitons in biased OLED, advanced concepts based on multi-component mixed layers and compositional gradients will be introduced. In this context, organic vapor phase deposition will be described as suitable coating technique with maximum deposition parameter control. This means that parameters (e.g. temperatures and carrier gas fluxes) can be individually set for all source materials with high precision. Virtual host materials formed by mixing primarily electron-conducting and primarily hole-conducting matrix materials with locally varied compositions are the basis for layer cross-fading (LCF). This method allows to control the location and size of the recombination zone in EML by individually accessing the effective electron and hole carrier mobility via the composition of an (additionally emitter-doped) virtual host material. Monochrome, yellow and white OLED with different concepts in the emission region will be compared with respect to processing stability, luminous efficacy as well as stability of color coordinates with rising luminance. Hybrid (i.e. based on red and green phosphorescent and blue fluorescent emitter materials) white OLED with 23.1 lm/W and 27.9 cd/A (@1000 cd/m², without improved outcoupling) at color coordinates (0.44, 0.41) based on the LCF method will be presented.

New concept for In-Line OLED manufacturing

U. Hoffmann, H. Landgraf, M. Campo, S. Keller, M. Koening, Applied Materials GmbH (Germany)

A new concept of a vertical In-Line deposition machine for large area white OLED production has been developed. The concept targets manufacturing on large substrates (≥ 4 in. 750 x 920 mm²) using linear deposition source achieving a total material utilization of ≥ 50 % and tact time down to 80 seconds.

The new developed linear evaporation sources for the organic material achieve thickness uniformity on Gen 4 substrate of better than ± 3 % and stable deposition rates down to less than 0.1 nm/min and up to more than 100 nm/min. In our system a deposition rate of 100 nm/min roughly corresponds to material flow from the source of about 0.1 g/min.

For Lithium-Fluoride but also for other high temperature materials like Magnesium or Silver a high temperature linear source has been developed. Again, the thickness uniformity on Gen 4 substrate is better than ± 3 %.

For Aluminum we integrated a vertical oriented point source using wire feed to achieve high (> 150 nm/min) and stable deposition rates.

The machine concept includes a new vertical vacuum handling and alignment system for Gen 4 shadow masks. A complete alignment cycle for the mask can be done in less than one minute. The alignment accuracy using an active CCD camera alignment is in the range of several 10 µm.

Adapted OLED stacks enabling accurate emitter characterization

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The optical features of the internal dipole emission have major impact on the radiation pattern and overall device efficiency of organic light-emitting diodes (OLEDs). In recent years, the characterization of OLED emitter properties by optical analysis of far-field radiation patterns of OLEDs in electrical operation was established as an in situ investigation method. However, in order to observe the internal features of the dipole emission in the OLEDs far-field accurately, well adapted devices should be utilized to optically enhance the feature of interest. Although this is a crucial point, the potential of adapted devices to OLED characterization has not been investigated universally yet.

In our contribution we provide general directives how the OLEDs layered stack is to be designed in order to enable for precise measurements of the active optical properties of the emissive material (internal electroluminescence spectrum, profile of the emission zone and dipole moment orientation) by radiation pattern analyses. Basically, we utilize the fact that the emitter-cathode distance is most crucial to enhance or suppress certain dipole contributions to the far-field. A model layered
system is discussed and universal emitter positions suitable to determine the internal feature of particular interest at most accuracy are deduced. Furthermore, we evaluate the real benefit of conducting radiation pattern analyses utilizing a glass-hemisphere for such investigations.

7954-35, Session 10

Photometric design for color-conversion LEDs using narrow-emitter nanophosphors

H. V. Demir, Nanyang Technological Univ. (Singapore)

To combat energy problem of the limited sources and address environmental concerns escalating with increasing carbon footprint, it is critical to exploit possible ways of improving energy efficiency. Today efficiency in artificial lighting is particularly important because lighting consumes a substantial level of total electricity generation around the globe and there is room for improving lighting efficacy via solid-state-lighting. Among various forms of artificial lighting, both outdoor and indoor lighting deserves special attention. For outdoors, major safety problems can be caused due to poor street lighting for nighttime vision, and a large portion of the energy expenses of a local community may come from outdoor lighting. To address these problems in outdoor lighting we investigate color-conversion white light-emitting diodes (LEDs) and demonstrate LED designs that enable excellent nighttime vision with high color-rendering-index (CRI) using combinations of spectrally narrow-band luminophors (e.g., nanophosphors of quantum dots). To achieve high-efficiency street lighting, our LED designs exhibit a high ratio of efficacy in the scotopic (<0.0005cd/m2) vision range to that in the photopic (>3cd/m2) vision regime, also known as scotopic-to-photopic ratio (S/P). In our designs, this exceeds the typical S/P=2.5 barrier of conventional sources. Similarly, indoor lighting is also important for potential energy saving and warm-white color-conversion LEDs are good candidates. In this study we demonstrate our results related to the performance limits and photometric tradeoffs of using narrow-emitter nanophosphors, studying ~200M designs. We show that it is possible to achieve CRI>90 with a luminous efficacy of optical radiation >380lm/Wpt in the warm-white region.

7954-36, Session 10

Luminescent features of novel sol-gel derived lanthanide doped oxyfluoride nano-structured phosphors for white LED

A. S. Gouveia-Neto, A. da Silva, L. Bueno, E. Costa, Univ. Federal Rural de Pernambuco (Brazil)

Solid-state light sources for lighting purposes, are of great scientific and technological interest owing to their wide variety of benefits over daily used incandescent and fluorescent illuminant systems, with advantages ranging from energy consumption to environmental issues. Amongst various approaches, LED-based white light sources are regarded as the next generation solid-state lighting technology due to the fact that they possess valuable properties including low power consumption, high electrical energy to light conversion efficiency, long life, and low-cost and easy maintenance. Moreover, they have environmental advantages because their production do not require emission of green house gases(CO2), and provokes no mercury pollution. Essentially, there exist two approaches to produce white light employing LEDs: color addition using LEDs producing the three primary, or a combination of complementary colors light, and by the combination of emission from a blue or ultraviolet LED excited downconverted light from a phosphor. Thus, one demands for novel phosphors that may produce high downconversion efficiencies and allow suitable combinations of rare-earth activators which can diversify the emission wavelengths.

Rare-earth doped oxyfluoride 75SiO2:25PbF2 nano-structured phosphors for white-light-emitting diodes were synthesized by thermal treatment of sol-gel derived glasses. Luminance features of Eu3+, Sm3+, Tb3+, Eu3+/Tb3+ and Sm3+/Tb3+ ions incorporated into PbF2 nanocrystals dispersed in the aluminosilicate glass matrix and excited with UV(395 nm) and blue(405 nm) LEDs was evaluated. The luminescence exhibited strong emissions in the red(600, 610, 650 nm), green(540, and 560 nm) and blue(485 nm) wavelength regions. White-light emission was observed in samarium and terbium activated phosphors employing UV-LED excitation. The results indicated that there exist optimum annealing temperature and activator ion concentration in order to obtain intense emission light with higher color rendering index. Results suggest that the nanocomposite phosphor herein reported is a promising novel contender for white-light LED applications.

7954-37, Session 10

Electrical properties of O2 plasma-treated Ti/Al ohmic contacts to N-face n-type GaN

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GaN based vertical light-emitting diodes (VLEDs) have been considered typical device structures for high-power applications due to such advantages as an efficient heat sink and uniform current spreading. To fabricate high performance VLEDs, low-resistance and high quality ohmic contacts are required. For Ga-face n-GaN of lateral-type LEDs, the contact resistivity of 10-5 ~10-6 Ω·cm2 were easily achieved. For N-face n-GaN of VLEDs, however, it is still challenging to achieve effective ohmic contacts since the [000-1] N-face is grown with an opposite polarity to [0001] Ga-face. This difference in the surface structure makes it difficult to use Ti-based electrodes for low-resistance ohmic contacts to the N-face n-GaN.

In this work, we investigated the effect of O2 plasma treatments on N-face n-GaN for the electrical properties of nonalloyed Ti (50 nm)/Al (35 nm) contacts. The N-face n-GaN samples prepared by using metal organic chemical vapor deposition (MOCVD), a laser-lift off (LLO) and dry etching processes to expose the N-face n-GaN layer. As a result, the electrical behavior was improved by increasing the time of the O2 plasma treatment (0 s, 120 s and 180 s). After the 180 s O2 plasma treatment, the specific contact resistance of the Ti/Al on N-face n-GaN was dramatically reduced to 2.53 × 10-5 Ω·cm² from the 4.3 × 10-1 Ω·cm² seen in the as-deposited case. This improvement can be attributed to a reduction in the Schottky barrier height (SBH) due to the formation of donor-like surface defects such as VN or ON done by the O2 plasma treatment. More details on the experimental result will be presented at the conference.

7954-38, Session 10

Process to measure particulate down-converting phosphors and create well-correlated software models of LED performance

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White light-emitting diodes that use down-converting phosphors have been utilized in the illumination industry for several years. In many cases, little information needs to be known about the physics and performance of the phosphor itself to design, optimize, and simulate the light emission of the LED for the purpose of creating secondary optics. However, the importance of accurately accounting for the effect of the phosphor cannot be overstated when designing the LED package or when performing a tolerance analysis, for instance. The difficulties in gathering or measuring the relevant performance metrics of the phosphors are significant barriers to achieving accurate predictions in illumination software packages.

This paper describes a simple, repeatable process to measure several phosphor performance metrics that are used, in turn, to create a model of the same phosphor in a commercially-available illumination software...
GaN was approximately 2x10^8 cm^-2. These non-polar and semi-polar materials include the {11-22} GaN were 722 and 319 arcsec along the azimuth parallel and perpendicular to the r-plane PSS results. {11-22} plane GaN growth on the r-plane PSS. r-plane sapphire substrate. The c-GaN growth from c-plane like side wall on a-plane sapphire substrate and {11-22} plane GaN can be grown on w-plane GaN. The PSS reduces the dislocation density in GaN and enhances the light emitting diodes (LEDs) with high quality and larger diameter by metal-organic vapor phase epitaxy (MOVPE). For example, m-plane GaN can be grown on the PSS with high quality and larger diameter by metal-organic vapor phase epitaxy (MOVPE) (2). The light emitting diodes (LEDs) with high external quantum efficiency and performance in various applications. We will report on the mechanisms involved in the conversion, package requirements, and advantages of the use of luminescent ceramics.

Development of patterned sapphire substrate and the application to grow nonpolar and semipolar GaN for light-emitting diodes

The light emitting diodes (LEDs) with high external quantum efficiency are usually fabricated on the patterned sapphire substrates (PSSs) (1). The PSS reduces the dislocation density in GaN and enhances the light extraction efficiency (LEE) from the LED chip by scattering the light confined in GaN layer by critical angle between GaN (n=2.4) and sapphire substrate (n=1.7) or air (n=1.0). Among many types of PSSs proposed by many researchers, we have developed an advanced PSS fabricated by no sapphire etching. On the other hand, nonpolar plane GaN and semipolar plane GaN are attracting much attention to eliminate the quantum confined Stark effect (QCSE). Recently, we have developed novel technology to grow nonpolar or semipolar plane GaN on the PSS with high quality and large diameter by metal-organic vapor phase epitaxy (MOVPE) (2). For example, m-plane GaN can be grown on a-plane sapphire substrate and (11-22) plane GaN can be grown on r-plane sapphire substrate. The c-GaN growth from c-plane like side wall of the r-plane PSS results (11-22) plane GaN growth on the r-plane PSS. The full widths at half maximum of X-ray rocking curves (FWHM-XRC) of the (11-22) GaN were 722 and 319 arcsec along the azimuth parallel and perpendicular to the c-direction, respectively. Dislocation density of the GaN was approximately 2x10^8 cm^-2. These non-polar and semi-polar GaN are expected to be novel templates for LEDs.


Novel approaches to realizing chemical lift-off of GaN epilayer from sapphire substrate

R. Horng, National Cheng Kung Univ. (Taiwan) and National Chung Hsing Univ. (Taiwan); T. Tsai, C. Yen, M. Hung, C. Pan, D. Wuu, National Chung Hsing Univ. (Taiwan)

In this paper, the SiO2 pattern was directly fabricated on the sapphire substrate. By controlling the growth parameters, a high quality GaN LED structure can be easily grown on the sapphire with SiO2 pattern. We call this process like-ELOG technology. This study reports a GaN LED structure grown on sapphire with SiO2 strips and thin film GaN LEDs, which can be separated from the sapphire substrate using CLO. The SiO2 can be etched by HF and provides a region, which allows the interface between the GaN buffer and sapphire contact with HF. The selective lateral etching of the interface between the sapphire substrate and the GaN epilayers occurs when the SiO2 is being removed. It has been reported that the oxygen can move into the GaN layer through thermal diffusion near the sapphire interface. The oxygen concentration can be larger than 10E20 cm^-3 at the interface of the low-temperature GaN layer and the sapphire substrate, which could result in Ga-O existing at the interface. Given that Ga-O can be etched by HF as the HF comes in contact with the interface, it provides an opportunity for HF etching the Ga-O at the interface, resulting in the GaN epilayers being separated from the sapphire.

Novel approaches for high-efficiency InGaN quantum wells light-emitting diodes: device physics and epitaxy engineering

N. Tansu, H. Zhao, J. Zhang, G. Liu, Y. Ee, H. Tong, T. Toma, X. Li, G. Huang, Lehigh Univ. (United States)

Energy efficiency and renewable energy technologies have significant importance for achieving sustainable energy systems in modern society. Lighting accounts for more than 22% of the total electrical energy usage in US, and technologies based on solid state lighting (SSL) utilizing semiconductor-based material has tremendous promise to replace the existing lighting devices. As compared to traditional incandescent and fluorescent lamps, SSL is more energy-efficient, reliable, and environmentally-friendly. Once widely used, SSL could lead to the decrease of worldwide electricity consumption for lighting by >50% and reduces total electricity consumption by >10%. Rapid progress in SSL research and development has resulted in the advent of light emitting diodes (LEDs) for general lighting applications. Two major challenges for current state-of-art III-nitride based LEDs are 1) ‘green gap’ issue in InGaN quantum well light-emitting diodes, and 2) ‘efficiency droop’ issue in III-Nitride LEDs resulting in output power quenching at high current injection.

In this work, novel approaches to address the major issues related to nitride LEDs will be presented. The studies will include designs, growths, and device characteristics of 1) novel InGaN-based quantum well structures LEDs with enhanced matrix element for realizing green-emitting LEDs devices with high internal quantum efficiency, and 2) novel InGaN QW LEDs device structure with lattice-mismatch AlInN-barrier structure to suppress efficiency-droop in nitride LEDs. The use of polarization engineering leads to a significant improvement in the radiative efficiency of the InGaN QW LEDs, in particular for addressing the charge separation effects in green-emitting nitride devices. The use of graded-growth-temperature profiling to realize 3-layer staggered InGaN QW LEDs has led to 2-3 times improvement in radiative efficiency, in
comparison to that of the conventional InGaN QW LEDs. In addition to the QW engineering approaches, other approaches to improve the efficiency of the nitride LEDs will be discussed as follow: 1) the use of surface plasmon LEDs, 2) new growth approach for dislocation density reduction in GaN semiconductor, and 3) novel approaches for light extraction efficiency improvement of III-Nitride LEDs.

7954-43, Session 11

Optimisation of pattern geometry and investigation of physical mechanisms contributing to improved light extraction from patterned substrate LEDs

M. D. B. Charlton, Univ. of Southampton (United Kingdom); S. Linn, D. Yu, Unilite Corp. (Taiwan)

In this paper we apply non-coherent finite difference time domain modelling methods to the optimisation of geometry for patterned substrate LED devices. We investigate the effect of side wall angle and side wall curvature on far field beam profile and total extraction efficiency for an otherwise conventional P-side up (lateral current spreading) LED with a photonic crystal lattice etched into the underlying Sapphire substrate. We investigate extraction efficiency and far field beam directionality as a function of design parameters including etch depth and lattice pitch. We investigate the effect of lattice pitch ranging from sub diffractive photonic crystal length scales to more conventional multiple order diffractive length scales. Our analytical technique allows examination of the physical mechanisms contributing to performance improvement in each case. We investigate relative contributions made by simple refractive / diffractive effects and more complex photonic crystal scattering mechanisms which give rise to radically modified directionality and improvement in extraction efficiency. Comparisons are made to recent studies of buried photonic crystal LEDs where the patterned layer is positioned much closer to the MQW layer. Benefits in terms of ease of fabrication are also discussed.
Fabricated by spin-coating at their crystalline temperatures are quite non-liquid crystalline low molecular weight compounds, it is not easy to fabricate a uniform thin film due to recrystallization during solvent evaporation. So that we have to find an optimum condition after time-consuming try-and-error varying solvents and concentrations. On the other hand, the polycrystalline films of liquid crystalline materials are witness an explosive development in the fields of nanoparticles and nanostructured materials, such as gold nanoparticles (GNPs), quantum dots (QDs), carbon nanotubes (CNTs), graphene and buckyballs, because of their great technological and fundamental interest. In the next few decades, the creation of wealth of new materials and devices using nanotechnology will be witnessed and the impact of this on the quality of life of people around the world will be immense. Functionalization of such nanomaterials with mesogens and their incorporation in the supramolecular order of liquid crystals is likely to lead to novel materials for many device applications. With this view, we have initiated a research program to functionalize these nanomaterials with discotic and other molecules and disperse them in discotic liquid crystalline matrix. We have observed that discotic-functionalized CNTs can be dispersed in the columnar phases in high amount (up to 10%). Doping of about 1% of discotic-functionalized GNPs in the columnar phase increases the conductivity of the system by more than a million times.

In this talk, the design, synthesis and characterization of some electron-rich and electron-deficient discotic liquid crystals; syntheses, characterization and mesomorphic properties of discotic-functionalized nanoparticles and their insertion in the supramolecular order of DLCs will be presented.

Liquid crystallinity in organic field effect transistor materials
J. Hanna, H. Iino, Tokyo Institute of Technology (Japan)
In recent years, the material research for organic field effect transistors (OFETs) has been focused on organic materials that allow us to prepare polycrystalline thin films by solution processes instead of vacuum evaporation. Because of poor solubility of extended π-conjugated systems, organic solvents, various approaches have been studied. The most popular strategy is chemical modification of an extended π-conjugated system with long alky chains. The resulting alkylated FET materials often show liquid crystal phases at a certain temperature range because it is the same strategy of molecular design for liquid crystalline materials. However, full attention is not paid to the liquid crystallinity in such the materials. In this study, we have demonstrated how the liquid crystallinity is beneficial for fabrication of polycrystalline thin films by using two liquid crystalline model compounds, i.e., a liquid crystalline terthiophene (TTP) and a benzothienobenzothiophene (BTBT) derivative. In spin-coating of any non-liquid crystalline low molecular weight compounds, it is not easy to fabricate a uniform thin film because of recrystallization during solvent evaporation, so that we have to find an optimum condition after time-consuming try-and-error varying solvents and concentrations. On the other hand, the polycrystalline films of liquid crystalline materials fabricated by spin-coating at their crystalline temperatures are quite uniform in millimeter scale thanks to viscous and soft nature of the liquid crystalline phase. The bottom-gate FETs fabricated on SiO2/Si substrates with the films exhibit very high mobility of 0.1 cm2/Vs and 3 cm2/Vs for liquid crystalline TTP and BTBT, respectively, which is comparable to those of the films fabricated by vacuum evaporation. We discuss how the liquid crystallinity, contributes to fabrication of less defective and uniform films and conclude that it is of essential importance in fabricating quality polycrystalline thin films for organic FETs.

Liquid crystalline phthalocyaninines as a self-assembling organic semiconductor for solution-processing thin film devices
Y. Miyake, National Institute of Advanced Industrial Science and Technology (Japan) and Osaka Univ. (Japan); T. Hori, H. Yoshida, Osaka Univ. (Japan); H. Monobe, National Institute of Advanced Industrial Science and Technology (Japan); A. Fujii, M. Ozaki, Osaka Univ. (Japan); Y. Shimizu, National Institute of Advanced Industrial Science and Technology (Japan) and Osaka Univ. (Japan).
Homologues of a phthalocyanine mesogen were studied on carrier mobility behavior by a Time-Of-Flight (TOF) technique to reveal that all mesogenic ones exhibit fast mobility in the order of 10-1 cm2 V-1 s-1 with an amorphous nature. In addition, the transient photocurrent decay curves could be easily obtained even for the crystal phase to give a mobility of > 1 cm2 V-1 s-1. A bulk hetero-junction solar cells with these and PCBM which were fabricated by a solution processing was found to exhibit the high external quantum efficiency (> 70 % at 650-750 nm) and the conversion efficiency reaches over 3 %.

Photonic bandgaps controllable blue phase liquid crystal
T. Lin, C. Wang, H. Liu, National Sun Yat-Sen Univ. (Taiwan).
This study investigates an optically switchable band gap of photonic crystal that is based on an azobenzene-doped liquid crystal blue phase. The trans-cis photoisomerization of azobenzene deforms the cubic unit cell of the blue phase and shifts the photonic band gap. The fast back-isomerization of azobenzene was induced by irradiation with different wavelengths light. The crystal structure is verified using Kossel diffraction diagram. An optically addressable blue phase display, based on Bragg reflection from the photonic band gap, is also demonstrated. The tunable ranges are around red, green and blue wavelengths and exhibit a bright saturated color.

Optically-tunable beam steering grating based on azobenzene doped cholesteric liquid crystal
A. Y. Fuh, H. Jau, National Cheng Kung Univ. (Taiwan); T. Lin, National Sun Yat-Sen Univ. (Taiwan); S. Huang, J. Liu, National Cheng Kung Univ. (Taiwan).
A non-mechanical beam steering diffraction device is an important component in many optical systems, such as optical interconnects,
optical communications, projection displays, and optical data storage. Liquid crystal (LC) devices which provide efficient electro-optical modulation are excellent candidate beam-steering devices because of their low driving voltage and ease of fabrication. Several LC-based beam-steering devices have been developed. The most common configuration is based on a prism-type phase profile. The required blazed-grating phase profile in the LC layer can be achieved using a structure of multiple electrodes onto which a periodically varying potential is applied. The beam steering angle can be varied by changing the periodic voltage profile. The main shortcomings of such devices are the complexity of their fabrication and operation.

Cholesteric liquid crystal (CLC) films with a fingerprint structure are highly promising for use in beam-steering devices. They are easily fabricated because of the self-assembly characteristic of CLC. The special feature of a CLC fingerprint grating is its tunable pitch. Subacius et al. demonstrated a cholesteric grating with a field-controlled period. The diffraction angle can be shifted 15 degrees by varying the applied voltage. Fuh et al. produced an optically controlled cholesteric grating by laser heating and doing with a dichotic guest-host dye.

This study demonstrates an optically switchable beam steering device that is based on an azobenzene-doped CLC fingerprint texture. The photoisomerization of azobenzene varies the pitch of CLC and shifts the diffraction angle of the fingerprint texture. Its tuning is fast and reversible under illumination by light of different wavelengths. The electrical tuning effect is also demonstrated and compared with the optical effect. Combining optical and electrical effects, the present CLC beam-steering device provides a steering range of ~19 degrees.

7955-06, Session 3

Pancharatnam-Berry phase in the optical near field

H. Yokoyama, Liquid Crystal Institute, Kent State Univ. (United States)

The Pancharatnam-Berry (PB) phase, or the geometric optical phase, is the phase difference in the electromagnetic wave generated by the particular “geometry” of polarization transformation, completely independent from the optical path length. The final PB phase shows up immediately upon incidence even before the optical wave starts its travel through the medium. Although it may sound illogical, it is in principle possible to construct an interferometer even inside a sub-wavelength dimension by using the PB phase. I shall explore the nature and the consequences of the PB phase in the optical near field regime, drawing on the Ewald-Oseen extinction theorem.

7955-07, Session 3

Tunable liquid crystal optical microcavities

I. Mu?evic, Univ. of Ljubljana (Slovenia); M. Humar, Jo?ef Stefan Institute (Slovenia)

A small droplet of a nematic liquid crystal, embedded in a polymer or liquid matrix, is an optical microresonator, if the index of refraction of a liquid crystal is higher than that of the surrounding. We have shown in a recent publication [1], that the spectrum of light in the nematic liquid crystal microresonator shows characteristic whispering gallery mode structure. In a ray picture, light is circulating inside the microcavity by subsequent total internal reflections at the liquid crystal-surrounding interface. If the light comes back to the point of origin with the same phase, we have the resonance condition for a particular wavelength. We have shown, that the Q-factors of liquid crystal microresonators are of the order of 10,000, whereas the eigenfrequencies of WGMs in a 10-20 micrometer diameter nematic droplet could be tuned by an external electric field, temperature and strain. The electric tuning is due to the field-induced elastic deformation of the nematic and is nearly hundred times larger compared to tuning in solid materials. This is interesting for application in integrated photonics, where the microresonators are the basic element for many devices. We discuss possibility of tunable lasing in liquid crystal microdroplets.


7955-08, Session 4

Non-linear optical response of native and oxidized lyotropic-like low and high-density lipoproteins studied by using the Z-scan technique

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The non-linear optical response of human native and oxidized low and high-density lipoproteins (HDL and LDL) were investigated by using the Z-scan (ZS) technique. These oxidized particles are highly atherogenic. The oxidation process was mediated by copper and iron in vitro. The ZS signals increase linearly with concentration of native LDL particles in a broad range of concentrations. The copper-oxidized LDL particles do not show non-linear optical response. These behaviors can be attributed to modifications of the particle composition and shape induced by the oxidative process. The main contribution to the non-linear optical response of native LDL and HDL particles comes from the phospholipids’ fraction of the particles. Our results show that copper-mediated oxidation alters the geometry (sphere to discoid), and the particles exhibit a sharp distribution of sizes and homogeneity of shapes. In the case of Fe-mediated oxidation we observed an aggregation of particles and a wide range of sizes (from 10 to 25 nm). The ZS experiments indicate that copper-mediated oxidation drastically modifies the non-linear optical properties of the LDL, flattening completely the typical peak-to-valley response curve. This leads to a thermo-optical coefficient of this sample approximately zero. On the other hand, iron-mediated oxidation still keeps some of the optical properties of the native LDL. The peak-to-valley typical response curve remains but the thermo-optical coefficient of the sample is reduced when compared to the native LDL sample.

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7955-09, Session 4

Three-dimensional finite element modeling of liquid crystal devices

P. J. M. Vanbrabant, J. Beeckman, K. Neyts, Univ. Gent (Belgium); R. W. James, E. Willman, F. A. Fernandez, Univ. College London (United Kingdom)

The excellent electro-optic properties of liquid crystals have been widely applied in today’s omnipresent liquid crystal displays (LCDs) and tunable photonic devices such as waveguides, couplers, filters and photonic crystal fibers. A good understanding of the light propagation in these devices has become essential to continue their further improvement. A finite element framework to combine advanced director calculations with a full-vector optical analysis for three-dimensional device modeling is presented and illustrated with a varied overview of possible applications. The liquid crystal dynamics are first calculated with a time stepping approach allowing modeling of complex phenomena such as reverse nematic flow, defects and disclinations. Next, the obtained director profiles are considered for a beam propagation (BPM) [2] or modelsolver analysis [3] in which a full dielectric tensor is considered in solving Maxwell’s equations to model the inhomogeneity of the anisotropic liquid crystal accurately. Evaluation versions of both solvers are available for download at www.elis.ugent.be/ELISgroups/lcd/research/research.php.
holographic projection displays. Finally, we will describe new paintable lasers that have been used for electric field is used to switch the photonic band gap from red to green. Blue Phase lasers, stable over a 100°C temperature range, in which an generated holograms and medical applications. We will consider new continuously tunable from the ultraviolet to near infrared, with an 8-inch cavity lasers may be continuously wavelength tuned through the parameters that influenced markedly the performance of such LC lasers. Further, through cavity design/construction and using 2-D lenslet arrays of up to 100 by 100 spots we can optimize the gain to give a quasi-
continuous working RGB laser output with powers of Watts in the far field. We will present data on the colour gamut and properties of these lasers. We will show how the narrow band output from these microscopic parameters of the liquid crystals and the dye (as well as the spectral absorption coefficient and peak absorption wavelength), were the key parameters that influenced markedly the performance of such LC lasers. Further, through cavity design/construction and using 2-D lenslet arrays of up to 100 by 100 spots we can optimize the gain to give a quasi-
continuous working RGB laser output with powers of Watts in the far field. We will present data on the colour gamut and properties of these lasers. We will show how the narrow band output from these microscopic cavity lasers may be continuously wavelength tuned through the Flexoelectro-optic effect. Electrostriction or as a function of temperature and we will describe a working prototype multi-wavelength prototype, continuously tunable from the ultraviolet to near infrared, with an 8inch by 5inch footprint and 2inches high used for projection through computer generated holograms and medical applications. We will consider new Blue Phase lasers, stable over a 100°C temperature range, in which an electric field is used to switch the photonic band gap from red to green. Finally we will describe new paintable lasers that have been used for holographic projection displays.

7955-10, Session 4
Multimodal nonlinear optical polarizing microscopy of long-range orientational order in liquid crystals
I. I. Smalyukh, R. P. Trivedi, T. Lee, Univ. of Colorado at Boulder (United States)

We demonstrate orientation-sensitive multimodal nonlinear optical polarizing microscopy capable of probing orientational, polar, and biaxial features of mesomorphic ordering in soft matter systems such as liquid crystals. This technique achieves simultaneous imaging in broadband coherent anti-Stokes Raman scattering, multi-photon excitation fluorescence, and multi-harmonic generation polarizing microscopy modes and is based on the use of a single femtosecond laser and a photonic crystal fiber as sources of the probing light. We demonstrate the viability of this technique for mapping of 3D patterns of molecular orientations and show that images obtained in different microscopy modes are consistent with each other.

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7955-11, Session 4
High efficiency “white light” liquid crystal lasers for use on flexible substrates
H. J. Coles, D. J. Gardiner, S. M. Morris, P. J. W. Hands, T. D. Wilkinson, Univ of Cambridge (United Kingdom)

We briefly describe the background to Liquid Crystal lasers and then consider the key properties of the liquid crystal host & cavity design that lead to high slope efficiency (~70%), low laser thresholds (~nJ/ pulse), narrow line widths (<0.01nm) and quasi-continuous working (3kHz pulse rate) giving average powers of 5mW per pixel or laser spot. The birefringence, the elastic constants and the orientational order parameters of the liquid crystals and the dye (as well as the spectral absorption coefficient and peak absorption wavelength), were the key parameters that influenced markedly the performance of such LC lasers. Further, through cavity design/construction and using 2-D lenslet arrays of up to 100 by 100 spots we can optimize the gain to give a quasi-
continuous working RGB laser output with powers of Watts in the far field. We will present data on the colour gamut and properties of these lasers. We will show how the narrow band output from these microscopic cavity lasers may be continuously wavelength tuned through the Flexoelectro-optic effect. Electrostriction or as a function of temperature and we will describe a working prototype multi-wavelength prototype, continuously tunable from the ultraviolet to near infrared, with an 8inch by 5inch footprint and 2inches high used for projection through computer generated holograms and medical applications. We will consider new Blue Phase lasers, stable over a 100°C temperature range, in which an electric field is used to switch the photonic band gap from red to green. Finally we will describe new paintable lasers that have been used for holographic projection displays.
system has not, as far as we know, been put into practical use due to the blurring of images and the whitening of the scattering film that causes the degradation of contrast.

In this study, we designed a scattering film that causes little blurring of images and whitening by optimizing conditions of light-scattering particles added to a polymer film and addition of the dye. The blurring of images was inhibited by doping polymer film with particles of high relative refractive index. This film diffused the incident light at a small number of scattering times and maintained the sharpness of images. The whitening of the scattering film was inhibited by the addition of the dye, maintaining the viewing angle. Moreover, particle distribution along the thickness direction was controlled. The film in which particles were dispersed and accumulated showed different luminance properties and blurring of images at the same particle concentration. Finally, a directional backlight covered with the optimized scattering film showed equivalent luminance properties to those of a commercial backlight and demonstrated the feasibility of this system.

7955-15, Session 5

Wide temperature range blue phase liquid crystals for Kerr effect devices
J. Xiang, S. Lu, J. Hwang, L. Chien, Kent State Univ. (United States)

We report wide temperature range blue phase liquid crystals for display applications. Systematical analysis of the relationship of dielectric anisotropy value ($\Delta \varepsilon$) and the blue phase liquid crystal (BPLC) temperature range shows that the BP temperature range increases as the $\Delta \varepsilon$ decrease. Additionally, we also find that as the chiral concentration of the blue phase increases, the BP temperature range decreases. The studied BPLCs also exhibit fast response time of 400 ns using IPS cells with a fixed cell gap and electrode line and space of 10 um. These results can be explained based on the defect theory and would give effective guidance during the application of BPLC. Detailed physical, optical, dielectric and electro-optical study will be presented.

7955-16, Session 5

Tuning liquid crystal properties at hybrid glasses interfaces with polarized self-inscribing guided waves
M. P. Andrews, T. Gonzalez, McGill Univ. (Canada); T. Galstian, Univ. Laval (Canada)

Liquid crystal alignment is a crucial step in display manufacture. Alignment is typically achieved with mechanically oriented polymides, though there has been interest in the use of photo-oriented polymer films, and angle deposited SiOx vapor to impose order. Polymers have long been attractive because they are simple to coat and offer tunable interfacial properties through chemistry. Silica is attractive for its optical transparency and hardness. We have adopted an approach that combines the advantages of both polymers and silica. Accordingly, methacrylate monomer substituted silicon alkoxides are hydrolysed to give spin-on glasses whose chemical and physical properties can be systematically varied for use in liquid crystal alignment. Phenyl-substituted alkoxysilanes were incorporated to create systematic variations in the surface energy of the films. Surface energies were evaluated by measuring contact angles. We discovered a form of nonresonant photo-induced anisotropy (PIA) in these glasses. Optical self-writing with polarized guided waves in the spin-on glasses produces birefringence that can be “read out” by waveguide Raman scattering. Application of 4-pentyl-4’-cyanobiphenyl (5CB) liquid crystal results in spontaneous ordering of the 5CB and indicates that PIA in the glasses propagates to the surface of the film. Linearly circularly polarized laser light was used to create PIA in indium tin oxide electrode LC glass cells coated with photo-oriented hybrid organically modified silica glasses. Electro-optic measurements yield liquid crystal tilt angles and anchoring energies (polar anchoring coefficient). These are found to depend on the composition of the glass and the processing conditions of the films. The results suggest a new way of creating alignment layers for liquid crystal displays. The implications of these findings for liquid crystal display technologies will be discussed.

7955-17, Session 6

Bent-core alignment layers
E. K. Mann, W. G. Iglesias, Kent State Univ. (United States); T. J. Smith, Case Western Reserve Univ. (United States); P. Basnet, S. Stefanovic, Kent State Univ. (United States); C. Tschierske, Martin-Luther-Univ. Halle-Wittenberg (Germany); A. I. Jakli, Kent State Univ. (United States); D. J. Lacks, Case Western Reserve Univ. (United States)

Currently, bent-core molecules are widely studied because of their fascinating electromechanical properties and the promising thermotropic biaxial phase. A good alignment layer for these kinds of molecules is crucial both for many applications and the control and understanding of experiments. Because of the shape of the molecule, good alignment is hard to achieve with the common methods used to align regular calamitic molecules.

One potential technique to address this alignment problem uses a monolayer of bent-core molecules as the alignment layer for the bulk. The monolayer is first formed as a Langmuir film at the air/water interface. Langmuir films provide the opportunity to study possible conformations and packing of these complex molecules at a featureless surface. Suitable films can then be transferred onto a solid surface, through Langmuir-Blodgett and Langmuir-Schaefer techniques. We use these transference techniques to deposit a monolayer of two related bent-core liquid crystal molecules, with one hydrophilic end to promote layer stability onto different substrates. We then use these substrates as alignment layer in a liquid crystal cell. The direction and degree of the alignment of the calamitic 5CB, used in preliminary tests, was found to depend on the average packing and surface pressure in the Langmuir film from which the transferred film was made. Molecular simulations of individual and small groups of molecules support this interpretation.

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7955-18, Session 6

A new liquid crystal application: lithography and optoelectronics
H. Jung, Y. Kim, D. Yoon, H. Jeong, KAIST (Korea, Republic of)

Achieving perfect long-range order with soft building blocks at high speed and high resolution is one of the most exciting interdisciplinary research areas in current materials science and nano-biotechnology. Directed self-assembly of soft condensed matter such as block copolymers, supramolecules, surfactants, colloids, and liquid crystals (LCs) have been massively studied to get very periodic and defect free structures for the potential application of micro-fabrication. In this presentation, the new types of lithography by smectic defect and cholesteric mesophase are introduced for the first time. The ordered LC defects array can be obtained using several methods such as surface treatment, micro-size confined system, external field and thermal annealing. The origin and the behavior of LC defect structures are described based on LC physics and brand new defect structures of smectic LC are introduced for the first time in LC research field and are described by theoretical approach.

The present findings at here pose new theoretical challenges and potentially open the way for lithographic applications based on smectic liquid crystalline materials. As a potential application, the highly ordered LC defect arrays and periodic cholesteric array can be used for various lithographic templates such as photolithographic mask, microlens array and superhydrophobic surfaces.
Nematic liquid crystal interfaces for biological and chemical detection

B. R. Acharya, Platypus Technologies (United States)

Nematic liquid crystals (NLCs), have traditionally been used in displays and other electro-optical applications where the orientation of NLC is manipulated using an external electric field to display the information. In recent years, there have been significant advances in unconventional applications of NLCs in photonics, sensors, and diagnostics. In this talk, the application of NLCs for detection of biological entities and vapor phase chemicals will be presented. When NLCs are in contact with another medium (solid, liquid or air) the delicate interplay between the properties of medium and NLCs determines the nature of the alignment assumed by NLCs at the interface. Interfaces functionalized with select biological or chemical entities promote alignment of NLCs in predetermined orientations (perpendicular or parallel to the interface) that are primarily dictated by the interactions at the interface. When these interfaces are exposed to target analytes, the interactions at the interfaces are perturbed and the NLC films undergo orientational transitions from perpendicular to parallel alignment, or vice versa. The orientational transition can be detected, by viewing the film of NLCs between crossed polarizers (optical signal) or by measuring the differential capacitance associated with the change in alignment of NLCs (electrical signal). By engineering surfaces with different interfacial properties, the sensors based on this principle have been demonstrated to selectively detect a wide variety of biological and chemical analytes that have relevance in industrial hygiene, environmental monitoring, homeland security, diagnostics, and biomedical applications. This work was partially supported by the contracts from Department of Defense and Grants from NIH, and NIEHS.

Polar and biaxial properties of mesophases derived from bent-core mesogens with an acute-subtended angle

E. Choi, Kumoh National Institute of Technology (Korea, Republic of); J. Lee, Korea Univ. (Korea, Republic of); W. Zin, Pohang Univ. of Science and Technology (Korea, Republic of)

In this work, we focused on polarity and biaxiality of mesophases formed by V-shaped bent-core mesogens which have an acute-subtended angle (60°) instead of an obtuse-subtended angle (120°). Their mesomorphic properties were investigated by differential scanning calorimetry, polarizing optical microscopy, and synchrotron radiation X-ray diffractometry. In addition, electro-optical investigation was carried out including birefringence, switching current response, IR dichroism, and second-harmonic generation (SHG) measurements. On the basis of the experimental data a plausible model for the mesophase alignments has been proposed.

LC/polymer composite and its applications in photonics devices

X. W. Sun, H. Dai, Nanyang Technological Univ. (Singapore) and Tianjin Univ. (China); D. Luo, Y. Liu, Nanyang Technological Univ. (Singapore)

In this review paper, we will introduce our recent results for applying LC/polymer composite in tunable photonic devices. Our works are mainly focused on three aspects; the first one is the application of LC/polymer composite on the 1D/2D or random tunable lasing source. To achieving the lasing output, 1D/2D photonics crystals structures or random nanostructures fabricated by means of photon induced phase separation based on dye-doped LC/polymer syrup are excited with nanosecond pulsed laser. Experimental results showed the low-threshold, electrical and thermal sensitive lasing output in 1D/2D photonics crystals structures or random nanostructures. The second aspect is to employ the LC/polymer materials as phase-modulated diffraction optical elements. We demonstrated the tunable fly’s eyes lens, switchable fractal Fresnel zone plate and fractal photon sieves, dynamic optical vortex and switchable binary Airy beam, which are all worked as electric-tunable phase optical elements. The last aspect is focused on the fabrication of LC/polymer photonic devices by using of programmable exposure system based on amplitude/phase spatial light modulator (SLM). For projection lithography, the designed pattern coded on the amplitude spatial light modulator is imaged by optical projection system onto LC/polymer composite, after exposure, formed PDL pattern can realize desired phase pattern and shape the incident light into expected intensity profile. For interference lithography, we generate multi-beamlets using the a/p SLM with various polar and azimuth angle, the interfered patterns of these beamlets are exposed on our LC/polymer materials to form different photonics crystals or quasi-PC structures.
properties of LC fibers may, in turn, be utilized to fabricate a variety of electro-optical textiles, and ultimately may introduce an entirely new manufacturing process where weaving will reach well beyond the roll-to-roll manufacturing envisioned for the currently emerging flexible displays printed on flexible plastic substrates.

7955-23, Session 7

Coupled surface plasmon resonance sensor with sensitive liquid crystal layer

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Detecting and identifying toxic chemicals and biological agents at very low levels in gases, in liquids, and on surfaces in real time are of critical national importance. Recently, many sensors technologies have been investigated to develop low cost, portable, and highly selective chemical and biological sensors. Several of the more promising techniques involve liquid crystal (LC) based sensors. In these sensors, the presence of a chemical or biological agent causes a change in the alignment of the liquid crystal material. The collective behavior and high anisotropy of the LC molecules allow for the detection of extremely low levels of targeted agents.

This work presents an optical sensor based on the surface plasmon resonance (SPR) phenomenon involved with liquid crystal (LC) sensitive layer. In this effort, the authors have developed an alternative method to track the state of alignment and degree of ordering of the LC film via the SPR with gold nanoparticles array fabricated on optical fibers tip to enhance the SPR-LC sensitivity. This innovation will transduce the presence of the targeted agents, which deforms the LC profile, into a measurable quantity (the spectral position of the maximum loss in the transmission spectra) via tracking the LC deformation.

The proposed mechanism replaces the present optical transduction in LC-based detectors, 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 presence of the biological and chemical agents, 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.

7955-34, Session 7

Liquid crystalline block copolymers for macroscopic nanodomain orientation and photoinduced microphase separation

D. Han, Y. Zhao, X. Tong, Y. Zhao, Univ. de Sherbrooke (Canada)

We report the design and study of new liquid crystalline block copolymers (LC-BCPs) with which unusual properties and functions can be obtained. On the one hand, we prepared the first LC-BCP comprising regioregular poly(3-hexylthiophene) (P3HT) and a side-chain liquid crystalline polymer (SCLCP) bearing azobenzene mesogens (PAzoMA). With the SCLCP block having a clearing temperature above the high crystal melting temperature of P3HT, surface- and photoinduced orientation of mesogens in PAzoMA can be used to align stripe nanodomains of P3HT on a macroscopic scale. This study demonstrates a promising pathway to achieving and manipulating macroscopically ordered nanodomains of -conjugated polymers. On the other hand, by using arationally designed diblock copolymer composed of two SCLCPs, photoinduced microphase separation in BCPs was achieved for the first time. In this case, the miscibility of the two LC blocks is promoted by the miscibility between the two types of mesogenic side groups, while upon UV light irradiation inducing the trans-cis isomerization of azobenzene mesogens on one block, the shape incompatibility of bent cis isomers with an ordered LC phase drives the two blocks to be microphase separated. This study shows the perspective of using light to process and organize BCP morphology and related nanostructures in a lithography-free manner.

7955-24, Session 8

Liquid crystal Bragg filters

R. L. Sutherland, Mount Vernon Nazarene Univ. (United States); L. V. Natarajan, V. P. Tondiglia, SAIC (United States); C. A. Bailey, M. Duning, A. Voevodin, T. J. White, T. J. Bunning, Air Force Research Lab. (United States)

Bragg filters or gratings have the advantages of spectrally selective reflection and high diffraction efficiency, which make them useful for a variety of applications. Liquid crystal Bragg gratings possess an additional interesting and useful feature in that they are switchable or tunable. In switchable filters the reflection notch can be switched on and off, while in a tunable filter it can be scanned through a broad spectral range. We have explored these types of filters for several years and present a review of some of their more intriguing aspects. Two types of filter have been studied: holographic polymer-dispersed liquid crystals and cholesteric liquid crystals. We describe the Bragg diffraction of these two types of filter and explore their similarities and differences. Here we will focus on switching and tuning by external stimuli such as electric fields as well as thermal and mechanical mechanisms. We further describe the physics of these devices and point out some new features we have observed as well as open questions concerning their behavior.

7955-25, Session 8

Optical properties and applications of liquid crystals in the THz frequency range

C. Pan, National Tsing Hua Univ. (Taiwan)

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 frequency range. In this paper, we review recent available optical constants of selected liquid crystals in this important frequency range and recent advances in liquid crystal THz optic and photonic devices.

7955-26, Session 8

Light directed effects in cholesteric liquid crystal reflectors

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

The selective reflection of cholesteric liquid crystals (CLCs) have been examined for a variety of dynamic optical and photonic applications. One promising means of inducing optical responses in these materials is by using photosensitive mixtures and subjecting them to light. We have used primarily aza-based materials to generate a number of novel optical responses - including large range tuning of more than 2000 nm, photoswitchable reflectors in both normal and reverse modes, and all-optical broadening of the CLC bandgap to yield a reflection bandwidth upwards of 1700 nm. These results, as well as the realization of photoinduced isotropic to CLC (light induced reflectivity) will be discussed.
Origin of iridescence in chiral nematic phase nanocrystalline cellulose for encryption and enhanced color
M. P. Andrews, Y. Zhang, A. G. Kirk, V. P. Chodavarapu, McGill Univ. (Canada)

Iridescence has been widely studied in order to articulate its physical origins and because of its ongoing uses in luster pigments and liquid crystal displays. Iridescence is also shown by solutions of biological nanorods materials like nanocrystalline cellulose (NCC) which can exhibit liquid crystalline behavior under well defined conditions. “Green chemistry” routes to liquid crystal materials and their optical properties are described in this presentation. We show how nanorod suspensions exhibit a concentration dependent isotropic-nematic transition, and how this transition reflects the conditions of NCC suspension. Suspensions of NCC nanorods exhibit orientational helical order in which the director twists to yield a chiral nematic (cholesteric) structure. We observe iridescence from NCC materials. NCC particle size and morphology as functions of acid hydrolysis conditions and cellulose source were examined by TEM. Hydrolysis generally proceeds by degrading the amorphous regions of the cellulose, liberating needles of NCC material that are 5-10 nm wide by 100-200 nm long. Optical, electro-optical and morphological properties of colloidal suspensions were examined and found to depend strongly on synthesis conditions. We show that long range order can be formed as long as colloidal solution flow is controlled within the lamellar regime in vertically oriented flat cells. Long range order is associated with self assembly of the NCC suspensions, allowing us to observe layer structures which are associated with the iridescence of the NCC suspension. Possible applications of NCC materials in encryption technologies and color enhancement of environmentally friendly inks are described.

Holographic polymer dispersed liquid crystal system utilizing the co-polymerizations with siloxane compounds and polypropylene glycol derivatives
T. Takenokura, M. Kurashige, K. Ishida, Y. Ohyagi, M. Watanabe, Dai Nippon Printing Co., Ltd. (Japan); Y. Cho, Pusan National Univ. (Korea, Republic of)

Holographic polymer dispersed liquid crystal (HPDLC) has a feature that can control the diffraction light by electric field. It can be applied to an optical switch or a polarized beam splitter etc. One of the most useful processes for making HPDLC is the well known photopolymerization-induced phase separation (PPS). The performance of HPDLC by PPS is dependent on the distribution of oriented liquid crystal (LC) molecules or size and shape of LC droplets. These are controlled by chemical structure or functional group of polymer matrix.

In this report, the organic-inorganic hybrid materials having sensitivity to laser of 532nm wavelength were synthesized. Polymer matrix was formed with co-polymerization of siloxane-containing materials and poly (propylene glycol) derivatives functionalized with methacrylate groups. Siloxane chain was introduced in polymer matrix to encourage the phase separation of LC and stabilize the grating structure. In addition, poly (propylene glycol) derivatives were designed to control the polymerization rate and extent of phase separation of LC. The characterization of HPDLC samples was evaluated in terms of diffraction efficiency, contrast between diffraction and transparency modes by applying voltage, and switch speed. Also the factors which affect electrical properties of HPDLC will be discussed.

Viewing angle enhancement of inverse twisted nematic liquid crystal displays with four domains by alternating alignment technique
J. Na, J. Hong, S. Lee, Seoul National Univ. (Korea, Republic of)

In these days, liquid crystal displays (LCDs) have been the most important class of flat panel displays used for a wide range of applications from mobile devices of cellular phones and notebook computers to monitors and television sets. Among several LCD modes such as the twisted-nematic (TN) mode, the in-plane switching mode, and the vertically aligned mode, the inverse TN (ITN) mode has been recently paid much attention due to high contrast, fast response, and achromaticity. However, the ITN mode has limited viewing angle properties as the TN mode when no optical compensation is introduced in each pixel, and thus an optical compensation scheme is inevitably required for the enhancement of the viewing characteristics of the LCDs. For example, the patterned VA mode was developed and successfully commercialized but it suffers from the low transmission efficiency and high cost for manufacturing. In this work, we developed an alternating alignment technique based on transfer-printing and bidirectional rubbing processes for producing four domains in each pixel in the ITN configuration. This alternating alignment technique is simple and versatile for developing high-performance LCDs without any photolithographic process for patterned electrodes and protrusion.

Pixelated liquid crystal laser using a sol-gel microcavity
N. Y. Ha, S. H. Lee, Ajou Univ. (Korea, Republic of)

It is well known that the multilayered structure of alternating two materials with different refractive indices and thickness exhibits photonic band gaps (PBGs) at the wavelength satisfying Bragg’s law. Such periodic structure of dielectric functions is a typical example of one-dimensional photonic crystals. Here, the width of the PBG is determined by the contrast of the refractive index, and the spectral position of the PBG depends on the optical path length of each layer. Therefore, multilayered films exhibit characteristic reflection-colors corresponding to the PBGs, but never show multiple colors or PBGs if we use multilayered structures with a single periodicity. In this work, we design a new multiple PBG system including defect structures, and fabricate this system using sol-gel materials of SiO2, TiO2, and mixed SiO2-TiO2.

Next, we consider a dye-doped nematic liquid crystal (LC) layer sandwiched in between two sol-gel films with multiple PBGs, i.e., sol-gel microcavity with multiple PBGs. Here, the dye-doped nematic LC layer is subdivided into three parallel pixels separated by polymer walls to contain the individual Red-Green-Blue fluorescence dyes. Based on novel optical properties of the sol-gel microcavity with multiple PBGs and the accelerated dye-doped LC layer, red-, green-, blue-colored laser emissions are demonstrated by using a single resonator and a single optical pumping. The present system can provide many applications and advances in laser and display technologies.
Fabrication of highly periodic patterning using cholesteric liquid crystal mask

H. Jeong, Y. Kim, J. Lee, J. Kim, H. Jung, KAIST (Korea, Republic of)

The use of tunable and self-assembled structures such as block copolymers and colloids as lithography mask has attracted considerable attention in recent years because the techniques involved are cost-effective and provide versatile route to the fabrication of nano-scaled patterns. Here, we introduce new concept of very simple lithography using periodic cholesteric liquid crystals (CLCs) texture act as a photomask in forming repetitive and uniform patterns in photoresist over large area. Unlike conventional photomask, the technique fabricating CLC mask is very simple, inexpensive and versatile.

We demonstrate that homogeneous arrays of CLCs with its helix in plane (fingerprint texture) under electric field act as a lens to generate periodic light intensity (phase grating) on photoresist. Based on observation by atomic force microscope and optical microscope, we found that the distribution and shape of patterns in photoresist successfully replicates the distribution and shape of the CLCs. We also demonstrate that CLC mask is sensitive to the polarization of the illumination light, indicating the optical selectivity of the CLC mask. Moreover, we show that intrinsic defect of LCs such as disclinations can be transferred onto a corresponding photoresist. We suggest this successful replication of photoresist is attributed to lying helix structure of CLC molecules similar to periodically distorted nematic LC layer generated by electrohydrodynamic instabilities, which manifest itself phase grating for transmitted polarized light.
7956A-01, Session 1

Human factors and optical design considerations for mobile display applications
U. Barnhoefer, Apple Inc. (United States)

A new class of e-reading applications is becoming widespread: newspaper applications with photo and video insets controlled by new dynamic user interfaces; e-magazines that replace their high-quality paper, color-print counterparts; full color interactive children books; picture cookbooks and comic books. What these types of content have in common is that they require fast, full-color gamut, medium to high contrast displays. In this paper, we first review their strong future potential and describe how in the near term a combination of system design methods help to meet the requirements of the new e-reader applications, especially so they perform better in a wide range of ambient light conditions. Some emissive technologies that provide a viewing angle similar to paper, such as IPS or OLED, are not compatible with transflective modes. We present an optical and human factors analysis that shows that surprisingly little extra backlight is needed to compensate for the missing reflective components. We show data on how optimized optical stacks can control unwanted reflections. Furthermore, we quantify how image processing of saturation and gamma can further counteract the effects of unwanted ambient light reflections. By combining several of the described system design methods, it is possible to improve image quality and ambient visibility for both the near term and future technologies for e-reading and mobile display applications.

7956A-02, Session 1

Printing technology for displays and electronic systems
J. Daniel, T. N. Ng, A. C. Arias, L. Lavery, S. M. Garner, B. S. Krusor, B. Russo, Palo Alto Research Center, Inc. (United States)

For the fabrication of electronic devices, printing technology promises reduced cost and can have process advantages such as contact-less materials deposition. However, there are still many challenges with regards to materials or device performance and fabrication processes. Here, we present results on the fabrication of printed display backplanes, printed sensors and sensor electronics as components for printed electronics systems. We have used inkjet printing to fabricate all-additive active-matrix pixel circuits with printed organic transistors. The minimum printed linewidth of ~50 microns is limiting to the pixel fill-factor but with a multi-layer pixel design, a fill factor of ~90% can be achieved for 650 micron pixels. Although the printed pixel size is not suitable for high resolution displays, it is promising for large poster size displays or small-size inexpensive displays in disposable electronic systems. A novel via-contact process is used for the multilayer pixel design and it is also applied to the integration of the pixel circuit with a printed shift register. A 1-gate - 2-data line design is explored to minimize the size of the shift register.

Building on this work, printing methods have been used to fabricate sensors and readout electronics to measure the severity of explosions in the battlefield. Printed inverter circuits, shift registers and memory have been developed for a sensor system in form of an inexpensive disposable tape.

7956A-03, Session 1

Metal oxide transistor technology in rigid and flexible displays
W. B. Jackson, Hewlett-Packard Labs. (United States); R. L. Hoffman, B. Yeh, Hewlett-Packard Co. (United States); O. Kwon, H. Kim, Hewlett-Packard Labs. (United States)

Recently there has been significant progress in incorporating metal oxide transistor (MOT) technology for next generation displays. MOT has been used on display substrates as large as Gen 7 and various portions of the driving electronics have been fabricated using MOT technology. In addition, progress has been made in understanding and controlling metastability in the MOTs. We have investigated the effects of bias stress and illumination on zinc tin oxide (ZTO) and indium gallium zinc oxide devices with various passivation layers, gate dielectrics, and plasma treatments. Unlike amorphous silicon, passivation layers and plasma treatments affect the metastability. Above bandgap light greatly increases the negative bias instability but subband gap light does not accelerate recovery. This observation suggests that charge trapping in the semiconductor is not responsible for the observed metastability. We have measured the threshold shift and hysteresis as a function of bias time, temperature, magnitude, gate dielectric, and surface chemical treatment. In addition we have used self aligned imprint lithography to produce flexible transition metal oxide arrays on 50micron thick polyimide substrates. Full back planes with 2um feature transistors, cross-overs, data and gate lines and hold capacitors have been fabricated using imprint lithography. Fabrication of flexible substrates using transition metal oxides involves fewer layers and processing steps than amorphous silicon so the MOT technology may be less expensive as well as higher performance than amorphous silicon.

7956A-04, Session 1

Single-grain Si TFTs for high-speed flexible electronics
R. Ishihara, Technische Univ. Delft (Netherlands)

Existent e-reader is mechanically stiff because it requires external connection of IC chips of display drivers and controllers. In order to realize a fully mechanically flexible e-reader system, those external circuits must be fabricated on the same flexible substrate. At its present stage, e-readers with a-Si or organic TFTs require, however, still external connection of data driver, because of their low carrier mobilities. We propose a technique that overcomes the problems by forming high speed Si circuits directly on a plastic substrate. We will review our recent progress on the direct formation of high speed Si circuits fabricated with a plastic compatible temperature. Large Si grains with a diameter of 4 microns were formed on predetermined positions on a substrate by a pulsed laser crystallization process. Transistors were fabricated inside a single Si grain with a plastic compatible temperature. Electrical characterization verified that the single-grain Si TFTs are well comparable with TFTs with SOI (silicon-on-insulator) wafers. Various digital and analog circuits, including RF building blocks, have been designed and fabricated based on the single-grain Si TFTs. A cut-off frequency of 5.5 GHz was obtained for the SG-TFTs with a channel length of 1.5 micron.

7956A-05, Session 1

Exploring polymer ferroelectric transistors and diodes for flexible optoelectronics
G. H. Gelinck, Holst Ctr.,TNO Science and Industry (Netherlands)

Ferroelectric polymers can possess spontaneous electric fields that are more than an order of magnitude larger than the breakdown field of SiO2, the most widely used insulating medium for field effect devices. The use of the ferroelectric polarization field thus allows for extremely large modulation of the charge carrier density and electronic properties of semiconducting materials. In this presentation we will discuss the potential of the ferroelectric effect to control and manipulate in a reversible fashion charge transport in diodes and thin-film transistors.
Electrowetting: a flexible e-paper technology

A. J. Steckl, Univ. of Cincinnati (United States)

Electrowetting has proven to be a remarkably versatile technology, with applications in flat panel displays, electronic lenses, microfluidics. We briefly review the operation of EW devices. Then, we discuss EW for e-paper displays, focusing on the flexibility of the EW effect and on EW on flexible substrates.

In the e-paper field, one of the shortcomings of the EW approach is the relatively large power requirement compared to the electrophoretic approach. We report on a method for obtaining complementary operation of EW devices under applied voltage by plasma irradiation of the normally hydrophobic fluoropolymer followed by thermal annealing. In the plasma treated EW device (pEW), the normal two-fluid EW action is reversed after an initial charging step, with the oil layer being displaced at zero voltage and being returned at high voltage. nEW and pEW devices exhibit complementary EW operation. The ability to reverse the polarity of the EW effect by careful processing indicates the flexibility of the technology. Similar to the reduction in power dissipation obtained when nMOS and pMOS transistors are combined in complementary MOS (CMOS), our method can lead to low power operation of two-fluid EW devices. We also report on EW devices on flexible substrates, including natural and synthetic polymers, and metal films.

A new bi-primary color system for print-quality e-paper and electrofluidic displays

J. C. Heikenfeld, Univ. of Cincinnati (United States)

This is an invited talk. Electrofluidic displays were first reported in 2009 by the University of Cincinnati and are now being commercialized by Gamma Dynamics Corp. Recently, bistable and grayscale capable electrofluidic display pixels have been demonstrated with >70% white reflectance and clear potential for video operation. This new pixel structure is fabricated only using simple dry-film photolithography. In addition, a second bistable electrofluidic technology has been developed which requires no pixel borders and no frontal electrode. This new approach should provide even higher reflectance than that of in-plane electrophoretic, electrowetting, or electrochromic displays. These and other recent results in electrofluidic displays will be presented.

Bistable electrowetting displays

K. Blankenbach, Pforzheim Univ. (Germany); J. Rawert, adt Deutschland GmbH (Germany)

ADT’s reflective e-Paper technology, called “No Power” Droplet Driven Display (D³) Technology, is progressing with respect to its features as well as product development. First D³-Display products will be e.g. colored indicators for status information ranging from one to several pixels and 8-Segment displays. These products could replace power consuming LEDs.

Future plans head for larger sized displays and also billboard for out-of-home applications. Its printer-like color rendition, bistability, temperature range and sunlight readability makes ADTs electrowetting approach very suitable even for outdoor electronic billboards. Compared to LED based walls, a billboard equipped with EW pixels stacks will have a significantly lower power consumption which also avoids costly cooling measures.

In summary the current status of droplet-driven display (D³) technology will allow to offer initial low complicity products in 2010. A very promising range of applications is seen for D³- Display products due to their unique product features.

Flexible displays as key for high-value and unique automotive design

R. Isel, BMW Group Research and Technology (Germany)

Actuel Trends
Market overview
Analyse of the upcoming Trends in Car Design
Demands
Design Visions
New Interiors freedom

Improvements in in-plane electrophoretic displays

A. Henzen, IREX Technologies (Netherlands)

Typical motion speed of electrophoretic particles lies around 300 micrometer per second. For switching of a pixel area of 200 x 200 um, this means the best possible switching time with one electrode per pixel would be 300 ms. Using finer, interdigitated electrodes improves the switching time for electrophoretic displays, but reduces aperture significantly.

Secondly, electrophoretic particles in a matrix display will have a tendency to move macroscopically in a certain direction. Over time, this means particles will eventually end up in an area where no or only small lateral fields exist, effectively trapping the particles there. In the end, this will lead to depletion of particles in the active area.

Also, it is possible that previous images show up as a distortion in following images, because of local depletion of particles.

Finally, if particles are switched between two finger-electrodes, all color particles will move into the gap between the electrodes simultaneously. This means the transmission will reduce sharply from the moment of switching, not changing much afterwards. This effect has to be remedied by incorporating particles with varying mobilities and an opaque “storage” electrode, but this puts high demands on the accuracy of the particle size distribution and reduces the available aperture.

The way to solve the obstacles above may well lie in electro-osmosis. Basic difference with electrophoresis is that the liquid inside the electro-osmotic cell moves along with the particles, and does so at much higher speeds than would be obtainable by electrophoresis alone. This can be shown by a full particle and liquid motion model. Typical speeds are around 3 mm / second, allowing a 200 um pixel to switch within 30 ms. Also, the electro-osmotic flow causes vigorous mixing of the particle suspension during switching, recovering particles even from field-free areas.

With carefully selected pixel electrode geometries, particles can be transported over many pixel-pitches before settling on one specific pixel. Using extended pixel-electrodes then takes care of accurate particle distribution inside the pixel area.

Electrophoretic display technologies for e-book readers: system integration aspects

P. Gentric, Texas Instruments France (France)

Emerging screen technologies, such as ElectroPhoretic Displays (EPD) used in E-Book Readers, are changing product requirements and design. We will first show how modern SOC (System On a Chip) capabilities can be leveraged to interface new panel technologies such as EPD in a way that is both flexible and cost effective. Especially we will show how for
EPD driving, the use of SW on generic computing resources (such as embedded DSPs) as well as re-programmable ICs, can significantly lower the system Bill-Of-Material by removing the need for a dedicated driving IC. Considering the development times for these ICs, the gain in flexibility and time to market when using such architectures is also invaluable for panel makers as well as device integrators.

We will secondly review the emerging screen technologies under the angle of system and IC design impact. We will explain power management consequences for IC design, with a focus on Application Engine SOC's for the wireless/portable markets. Indeed, due to their advantageous properties such as bi-stability (effective "zero power" static display) and reflective mode of operation (no backlight) new screen technologies can have a dramatic impact on power consumption for some use cases. We will show for example how for a book reading use case EPD offers a huge (100x) gain in terms of battery life compared to the exact same platform but with a LCD panel.

7956A-12, Session 3

Thin and light weight flexible electronic paper display using QR-LPD technology

R. Sakurai, Bridgestone Corp. (Japan)

We have developed thin and light weight flexible elec-tronic paper display using QR-LPD technology. Novel types of thin and light weight flexible electronic paper display are discussed. This technology can realize the "real paper like" flexible electronic paper in combina-tion with a plastic substrate QR-LPD fabricated by roll-to-roll process.

7956A-13, Session 3

Toner display based on particle control technologies

T. Kitamura, Chiba Univ. (Japan)

In order to read an electronic document, a development of electronic paper that has the convenience of the conventional hardcopy and a capability of access to digital information, is expected. The development a new color display technology has be important. The toner display using tribo-electrically charged black and white particles was reported. We had reported an image contrast of display is improved by using newly designed white particle. In this paper we will discuss the driving voltage and the color image of Color Toner Display using three particles such as white particle, cyan particle and yellow particle.

7956A-14, Session 4

A wide-view transflective display using polymer-stabilized blue-phase liquid crystal

Y. Li, M. Jiao, S. Wu, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Polymer-stabilized blue-phase liquid crystal (BPLC) exhibits several revolutionary features, such as submillisecond gray-to-gray response time, optically isotropic dark state which leads to inherently wide viewing angle, insensitive to cell gap if in-plane switching (IPS) electrodes are used, and no need for alignment layer. Particularly important is that the submillisecond response time enables color sequential display using RGB LED backlight, which triples the optical efficiency and resolution density. Unlike nematic LC devices which are based on the molecular reorientation, the physical mechanism of BPLC is governed by electric-field-induced birefringence, known as Kerr effect.

In this paper, we propose a wide-view and single-cell-gap transflective (TR) LCD using polymer-stabilized BPLC. To reduce operating voltage, we use protrusion electrodes so that the electric fields penetrate deeply into the bulk LC layers. To balance the optical phase retardation and obtain well-matched voltage-dependent transmittance (VT) and reflectance (VR) curves, we design the T and R regions to have different electrode gaps. The wider electrode gap in the R region generates a weaker electric field in order to accommodate the double pass of the ambient light. To obtain wide viewing angle, we employ two broadband wide-view circular polarizers and biaxial films. Simulation results show that both T and R regions of this TR-LCD exhibit a reasonably high optical efficiency, and the operating voltage is below 10V which can be addressed by a-Si TFTs. The viewing angle for T mode is very good, and for R mode is also adequate. Moreover, the VT and VR curves match quite well which enables a single gamma curve driving. As a result, the proposed transflective BP LCD has great potential for mobile display applications.

7956A-15, Session 4

Achromatic reflection by long-pitch chiral-nematic liquid crystal and its application to displays switchable between reflective and transmissive modes

T. Yoon, K. Kim, D. H. Song, J. Kim, Pusan National Univ. (Korea, Republic of)

Chiral-nematic liquid crystals (CLC) have been employed as reflective displays because of the reflective property in the planar state. In order to realize a reflective display, the planar and the focal conic states are used for the bright state and the dark state, respectively. However, the wavelength of the reflected light in the planar state is dependent on the viewing angle. Moreover, only a single color can be displayed with a single CLC layer since the bandwidth of the Bragg reflection does not cover the entire range of visible wavelengths. Stacking of CLC layers is required for achromatic reflection.

We propose a CLC device that reflects infrared light by shifting the bandwidth of reflected wavelengths, by which the planar texture is transparent over the entire visible wavelengths and achromatic reflection through light scattering at the focal conic texture can be achieved without a polarizer. The proposed CLC device has a long pitch, of which the operating voltage for alternation between the two textures is much lower so that achromatic reflective displays with low power can be realized. In addition, the transflective devices switchable between reflective and transmissive modes can be realized by stacking proposed CLC and nematic LC layers. Depending on the location of the CLC layer, two different structures can be realized. When the CLC layer is placed at the top, it can be used as a reflective sub-display, while the CLC device can be an active reflector when it is placed at the bottom. Detailed experimental results and further discussion will be reported in this presentation.

7956A-16, Session 5

(In)Flexible OLEDs: from prototypes to applications

S. Monz, K. Wolf, H. Möbius, Fachhochschule Kaiserslautern (Germany); K. Blankenbach, Pforzheim Univ. (Germany)

Major achievements of this research project on rigid and flexible OLEDs are lifetime enhancement by advanced constant luminance (L) driving, integration into textiles and furthermore the prototype production on flexible PET/ITO substrates of polymer OLEDs. OLEDs were manufactured with spin coating assisted by ink-jet printing. We invented the L=const. driving (instead of usual constant current) which was implemented in order to extend the useful lifetime of OLEDs. We achieved a threefold lifetime improvement by a L=50% drive, using an advanced microcontroller based lifetime model. Various approaches to textile integration incl. evaluation of environmental issues in clothes like moisture were investigated.
Novel solutions for thin film layer deposition of organic materials

J. Kreis, AIXTRON AG (Germany)

Innovative systems for carrier-gas enhanced vapour phase deposition of organic layers offer advanced methods for the precise deposition of complex thin-film layer stacks.

The approach inherently avoids potential short-comings from solvent-based polymer deposition and offers new opportunities.

The process operates at low pressure (thus avoiding complex vacuum setups), and, by employing AIXTRON’s extensive experience in freely scalable solutions can be adapted to virtually any production process and allows for R&D and production systems alike.

Deposition of organic layers and stacks recommends the approach for a wide range of polymer materials (including layers with gradual change of the composition), for conductive layers, for dielectric layers, for barrier systems, for OLED materials, and surface treatments such as oiliophobic / hydrophobic hard coatings.

With the combination of other vapour phase deposition solutions, hybrid systems and other advanced stacks can be realized.

Recent progress of flexible AMOLED displays

H. Pang, K. Rajan, J. A. Silvernail, P. Mandlik, R. Ma, M. G. Hack, J. J. Brown, Universal Display Corp. (United States)

Significant progress has been made in recent years in flexible AMOLED displays and numerous prototypes have been demonstrated. Replacing rigid glass with flexible substrates and thin-film encapsulation makes displays thinner, lighter, and non-breakable - all attractive features for portable applications. Flexible AMOLEDs equipped with phosphorescent OLEDs are considered one of the best candidates for low-power, rugged, full-color video applications. Recently, our team demonstrated a portable communication display device, built upon a full-color 4.3-inch HVGA foil display with a resolution of 134 dpi using a full-color phosphorescent OLED frontplane. The prototype is shaped into a thin and rugged housing that will fit over a soldier's wrist, providing situational awareness and enabling the wearer to see real-time video and graphics information.
Optical isotropic phases towards display application
F. Araoka, H. Takezoe, Tokyo Institute of Technology (Japan)

We demonstrate two optical isotropic states for display application; (1) nano-segregated nematic droplet dispersed in photo-crosslinked polymer and (2) BPIII with very short pitch in UV region using bent-core nematogens with chiral-dopant. In both cases, we can realize complete dark state, which is switchable by applying an electric field. (1) Nematic liquid crystals were mixed with photo-polymerizable monomers, and were illuminated with UV light to form polymer-dispersed liquid crystals. When the nematic droplet size is as small as 150 nm, the film obtained is transparent and gives complete dark under crossed polarizers. There is a clear isotropic-nematic phase transition of the second order. In the nematic phase, electric-field-induced reorientation due to the Kerr effect was observed in a time range of 20 µs. (2) By doping bent-core nematic liquid crystals with chiral dopant, we successfully obtained BPIII over a wide temperature range of ~20 °C. With increasing the dopant ratio, we can easily obtain a very short pitch, which gives a complete dark view under crossed polarizers. Electric-field-induced switching was also confirmed. These optical isotropic states are very useful for display application. There are many advantages over current display modes; (i) no surface treatment, (ii) high contrast ratio, (iii) wide viewing angle, and (iv) fast switching speed.

Advanced surface treatment technology for improving the characteristics of the liquid crystal display
C. Yu, S. I. Jo, Y. Lee, Y. Moon, Hanyang Univ. (Korea, Republic of)

Liquid crystal display (LCD) plays an important role in display devices fields due to their high image quality, stability, and low power consumption. However, LCD intrinsically has some problems such as slow response time and narrow viewing angle. To overcome those problems, many kinds of researches have been reported such as synthesizing new LC materials, designing the electrode structures, complex system with nano-particle and LC molecules, and so on. In this paper, we proposed an advanced surface treatment technology for improving the performance of the LCDs. For modification of alignment surface, we used the UV curable reactive mesogen (RM) which are mixed with alignment layers. The RM monomers within an alignment layer are dissolved in the LCs due to liquid crystalline property of RM and aligned along the LC molecules to reduce the excluded volume. Through UV exposure, the aligned RM monomers are directionally polymerized along the LC alignment and the polymerized RMs can produce and memorize the specific polar and azimuthal angle of LC molecules at specific pattern regions. The degrees of the polar and azimuthal angles are also controlled by UV exposure condition and applied voltage during UV curing process. Our method is very useful to improve the display performance such as response time in whole gray levels and wide viewing characteristics with multi-domains and design the new LC modes.

High-speed displays with low operation voltage using pixel confinement of a deformed helix ferroelectric liquid crystal in the vertically aligned geometry
J. Na, J. Hong, S. Lee, Seoul National Univ. (Korea, Republic of)

Ferroelectric liquid crystal (FLC) displays have attracted much attention for high speed electro-optic (EO) applications since a direct coupling of the spontaneous polarization with an external electric field provides the fast response. Although a deformed helix ferroelectric liquid crystal (DHFLC) in the vertically aligned (VA) configuration allows both the intrinsic gray scales and the extremely uniform alignment, it needs, in general, relatively high voltages for achieving the EO modulation. In this work, we report a high speed displays operated with low voltages on the basis of the pixel-confinement of the DHFLC in the VA geometry. In this pixel-confinement structure, the alignment of the FLC molecules as well as the smectic layers is extremely stable. The operation voltage is decreased by 50% in comparison to a conventional VA-DHFLC configuration and the switching time is a few hundred microseconds. It is found that the pixel-confinement approach to the development of the VA-DHFLC displays provides the low voltage operation, the uniform alignment, the fast response for video-rate images, and the analog gray scale capability with the good linearity.
We introduce new display mode by using a waveguide and a liquid crystal (LC) based light shutter. By using a waveguide, the polarizing films could be eliminated, and a color filter layer also could be eliminated, which is also depends on pixel structures. If this technology is realized for display, higher transmittance could be achieved because the polarizing films and a color filter layer are the main factors to reduce the transmittance in AMLCD. In this paper, the characteristics of waveguide and critical incident angle of light source, and relationship between LC based light shutter and waveguide are investigated. The main mechanism is refractive index variation of the light shutter by the applied electric field, which makes internal total reflection or partial transmission. For example, in our results, the LC based light shutter has the refractive index of ~1.62 and ~1.57 when electric field is applied and not, respectively. As results, the waveguide material should have the refractive index of above 1.63 to make total internal reflection. When the critical incident angle is ~15 degree, we could achieve the good light shutter characteristic. Additionally, the various conditions in waveguide, light shutter, and light source, were investigated, and we optimized the light shutter condition. And the light efficiency could be improved and light polarization is not indispensible, because both of light waves in TM mode and TE mode can be used in our structure. Consequently, we could examine possibility to apply the LC based light shutter for new display mode.

7956B-25, Session 2
Fast response Fresnel liquid crystal lens for 2D/3D autostereoscopic display
Y. Huang, C. Chen, Y. Huang, National Chiao Tung Univ. (Taiwan)

Currently, most display applications major in displaying 2D images. Locating the fixed optical elements such as barrier or lenticular lens on the top of the display, the 3D image is obtained although the 2D image quality is degraded. To overcome above issue, many 2D/3D switchable displays have been proposed. For instance, the 2D and 3D images can be shown by using the switchable the LC lens on and off. Although the conventional LC lens can supply 2D/3D switching property, the slow on/off switching time is still a big issue. Therefore, to reduce the switching time is needed. Because the LC response time can be further improved by reducing cell gap and overdriving method, thus, the fast response Fresnel LC lens with narrow cell gap was proposed. By the multi-electrode controlling method, the liquid crystal was reoriented and had a Fresnel lens-like shape. From the experimental result, the Fresnel LC lens not only performed fast switching rate (~0.8s) without using overdriving method, but also had the benefit of low operating voltage (~3.2volts). Both of them were much better than conventional LC lens. The Fresnel LC lens performed a well focusing ability which was similar to conventional LC lens. Besides, by using overdriving method, the response time of 9s c8 Fresnel LC lens could be further reduced to less than 0.2s. It meant that a fast switching time between 2D and 3D image could be obtained by switching Fresnel LC lens on and off. In the end, the fast switching 2D/3D Autostereoscopic display was also demonstrated.

7956B-26, Session 2
Accommodation response measurement according to angular resolution density in three-dimensional display
Y. Kim, K. Hong, Seoul National Univ. (Korea, Republic of); J. Kim, H. K. Yang, J. Hwang, Seoul National Univ. Bundang Hospital (Korea, Republic of); B. Lee, Seoul National Univ. (Korea, Republic of)

One of the most significant problems in 3D display is that the viewers can suffers from visual fatigue. Researches concentrated on 3D images, especially stereoscopic display, revealed that causes of visual fatigue included anomalies of binocular vision, distortion error of the eyes, conflict between accommodation and convergence of the eye, and excessive binocular parallax. However the causes of visual fatigue are diverse and still highly controversial issues for debate. Among them, conflict between accommodation and convergence of the eye is the most dominant factor with unnatural combination of stimuli in autostereoscopic display based on lenticular lens and lens array method.

Recently highly multi-view display that enables to reproduce natural stereoscopic view was proposed. The angular resolution density is given by the number of perspectives. Therefore it has a possibility to pull out the accommodation of an eye to an object in highly multi-view display. On the other hand, the angular resolution density in autostereoscopic display based on lens method is relatively sparse. It induces conflict between accommodation and convergence of the eye. Therefore angular resolution density is a key to disambiguate one of the reasons to lead visual fatigue in viewing autostereoscopic display.

In this paper, we analyze and measure accommodation response according to angular resolution density when the viewers see autostereoscopic display based on lens method. The simulations are carried out by geometrical analysis and eye modeling. We use different lens arrays for verifying the relationship between angular resolution density and accommodation-convergence conflict.

7956B-27, Session 2
Development of high-frame-rate LED panel and its applications for 3D stereoscopic display
H. Yamamoto, M. Tsutsumi, R. Yamamoto, K. Kajimoto, S. Suyama, Univ. of Tokushima (Japan)

Large LED (light-emitting diode) screen is a prospective media for digital signage for the general public. We have realized several types of stereoscopic large LED displays with polarizing eyewear and without 3D glasses. By using parallax barrier, we can enjoy stereoscopic 3D images without 3D glasses. The horizontal resolution of a viewed image decreases to one-half by the parallax barrier. This degradation is critical for LED because the pitch of LED displays is as large as tens of times of other flat panel displays. One of the solutions for this problem is use of spatio-temporal information. When adjacent pixel information is sequentially shown at each pixel in the LED panel, we will perceive a filled image because our small involuntary eye movements fill the gap between LED lamps with the adjacent pixel information.

In this paper, we report development of a high-frame-rate LED display. Full-color (8-bit for red, green, and blue elemental colors) images are refreshed at 480 fps. In order to transmit such a high frame-rate signal via conventional 120-Hz DVI, we have introduced a spatio-temporal mapping of image signal. A processor of LED image signal and FPGAs at LED modules have been reprogrammed so that four adjacent pixels in the input image are converted into successive four fields. The pitch of LED panel is 20 mm. The developed 480-fps LED display is utilized for 3D stereoscopic display.

7956B-28, Session 2
View image error analysis based on focal mode and virtual mode in three-dimensional display using lenses
Y. Kim, J. Yeom, J. Jung, J. Hong, B. Lee, Seoul National Univ. (Korea, Republic of)

No abstract available
7956B-29, Session 3

High-resolution plasmonic color filters with polarization selectivity and electrical conductivity
L. J. Guo, Univ. of Michigan (United States)

We propose and experimentally demonstrate a type of plasmonic nano-resonator in the form of sub-wavelength grating of metal-dielectric-metal stacks that can filter white light into individual colors with high efficiency (even higher than the traditional colorant based filters used in LCD displays) and with ultra compact dimension. Arbitrary colors can be created by following simple design rules. To prove the principle several devices were fabricated, including rectangular shape color pixels, arbitrary colored patterns and ultrasmall plasmonic spectroscopy, to demonstrate color filtering and spectrum splitting functions in the whole visible band. Besides the filtering effect, the polarization response of the nano-resonators was also investigated. The results show strong polarization dependence and thus the plasmonic color filters integrate the function of polarizer simultaneously, which could greatly benefit the future LCD display by eliminating the need of a separate polarizer sheet. In a related work, we show that sub-wavelength metallic grating structures can function effectively as transparent electrode, and can potentially replace the commonly used ITO electrode, especially in flexible display applications. This is in part due to their superior properties, such as high optical transparency, good electrical conductivity and mechanical flexibility, and the versatility that those properties can be adjusted independently by changing the line width and thickness of the metal grid structure.

7956B-30, Session 3

A new technique for speckle noise reduction of laser projection displays using waveplates
T. Yoshimi, K. Chihaya, W. Sasaki, Doshisha Univ. (Japan); H. Matsubara, A. Hirano, K. Nagashima, Funai Electric Co., Ltd. (Japan)

In laser projection displays, countermeasure technique against glares on the screen called speckle noise is one of the focuses. In particular, it is significant to degrade the coherence of 500nm band LD-pumped solid-state green laser. For example, by shifting and/or tilting the lenses vibrationally against their axes in the optical system of the laser projector, less speckle noises on the screen are typically to be seen because the projected laser beam wavefronts are vibrationally walking about on the screen, resulting in the coherence reduction. In the present work, we have introduced just a waveplate instead of vibrating lenses from viewpoints of compact, inexpensive and weight saving fabrications, and compared with the case of the vibrating plano-convex lenses. In the experiments, a quarter-waveplate with slow axis rotated by 45 degrees against the polarization axis of the incident green laser source was inserted into the optical path of our laser projection display system. Only in such a setup, an enough coherence alleviation may be expected because the polarizations of the beam are to be converted from almost linear to some deformed ellipse through the waveplate, so that the glares on the screen should be relieved when such beams with time-varying polarization patterns are projected and overlaid again and again on the screen by the piezo-electric 2D-MEMS scanner of the projection system. In these experiments, we also measured with the case of half-waveplates. As a result, we have carried out quantitative evaluations of the speckle noise by overlaying the projected images using a CCD camera on the histogram-based estimations of speckle noise intensities. As a consequence, noise reduction of about 20% was attained both for quarter-waveplates and half-waveplates, and about 40% with plano-convex lens. As far as comparisons of the actual visual effects seen on the screen are concerned, the observed degrees of speckle noise made almost no difference with the cases between waveplates and lens.

7956B-31, Session 3

Effect of lamination on the high cyclic bending fatigue of copper thin films on flexible substrate
K. Alzoubi, S. Lu, B. G. Sammakia, M. D. Poliks, Binghamton Univ. (United States)

While today’s display technology is mainly based on rigid-based substrate, flexible display technology has been significantly growing since the last decade. However, Flexible displays are susceptible to many types of stresses during processing and usage. Thin films on flexible substrate are sensitive to ambient conditions. Therefore devices are usually laminated with a protective layer. In this study high cyclic bending fatigue experiments were conducted on 2000 µm thick copper thin films sputter deposited on 5 mil polyethylene terephthalate (PET) substrate laminated with another 5 mil PET layer. High magnification images were used to observe crack initiation and propagating in the thin film laminated devices. The results showed that the presence of laminate layer on stress reduction in the thin film. Furthermore, a lamination layer causes cracks to spread out on a larger area and therefore reduce the chance of the cracks to meet and grow.

7956B-32, Session 3

CMOS dot matrix microdisplay
P. J. Venter, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa); A. W. Bogalecki, INSiAVA (Pty) Ltd. (South Africa); M. du Plessis, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa); M. E. Goosen, INSiAVA (Pty) Ltd. (South Africa); I. J. Neill, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa); P. Rademeyer, INSiAVA (Pty) Ltd. (South Africa)

Display technologies fulfills needs in a wide range of applications. As devices develop towards miniaturization, niche applications for small displays emerge. While OLEDs and LCDs dominate the market for small displays, they have some shortcomings as relatively expensive technologies. This work shows that it is possible to integrate a fully functional display in a completely standard CMOS technology, using light sources based on avalanche electroluminescence. A 512 pixel display is configured in 8 rows and 64 columns providing the capability of rendering alpha numerical characters and any arbitrary graphics of the same format. The pixel itself consists of a number of point sources arranged in a square array. Operation is based on reverse biased pn-junctions in avalanche breakdown. Each point source is optimized for increased current density and light emission is enhanced through light directing structures integrated into the process back end stack, thereby improving both internal and external quantum efficiency respectively. The driving circuitry is integrated on the same die as the active pixels. Columns are swept at a fixed refresh rate, while the rows are energized depending on the required output. The controller can be fully integrated along the display, resulting in a unique capability of CMOS microdisplays, allowing the circuit to be heavily customized. Silicon based active elements also mean operation over an extended temperature range. Given the ease of integration, the reduction in associated cost and the potential benefit of a wider operating temperature range, CMOS may find use in small displays in certain niche applications.

7956B-33, Session 3

Gray scale realization in bistable chiral splay nematic liquid crystal device
C. G. Jhun, Hoseo Univ. (Korea, Republic of); K. Chen, Ningbo Univ. (China); Y. Jin, Z. Hong, S. Han, Y. Zhang, Y. W. Seo, G.
Park, S. Kwon, S. Shin, Hoseo Univ. (Korea, Republic of); J. H. Lee, T. Yoon, J. Kim, Pusan National Univ. (Korea, Republic of); S. M. Chung, ROK Naval Academy (Korea, Republic of)

The common feature of bistable liquid crystal displays (LCDs) is the existence of the two stable states without an external field. The two stable states have the memory effects which can reduce power consumption and make multiplexing capability in the passive matrices unlimited so that there has been increasing interest about bistable LCDs.

A Bistable chiral splay nematic (BCSN) mode was proposed as a recent bistable device. In the bistable chiral splay nematic (BCSN) mode, the splay and π twist states are used for the two stable states. The BCSN mode is a potential candidate of bistable modes, because it can be operated not only as a storage device, but also as a monostable device with a fast response time in the same panel.

The transition between two memory states of a BCSN LCD is strongly coupled with the strength of applied electric fields. In this paper, we investigated the correlation between the horizontal electric fields strength and the bistable property by calculating the bistable. To realize the gray scale of BCSN LCD, we also introduce an inter-digital electrode with varying electrode spacing which causes the varying strength of the horizontal electric fields. The selective transitions by the electrode structure are demonstrated in this paper.

7956B-35, Session 3

Reactive liquid crystal materials for optically anisotropic patterned retarders

O. Parri, G. Smith, R. Harding, K. Skjonnemand, Merck Chemicals Ltd. (United Kingdom); H. Yoon, Merck Advanced Technologies Ltd. (Korea, Republic of); J. Sargent, I. Gardiner, Merck Chemicals Ltd. (United Kingdom)

Merck has developed a range of reactive liquid crystal materials (Reactive Mesogens) that are designed to form thin, birefringent, coatable films for optical applications. Reactive Mesogen (RM) films are typically coated from solution and polymerised in-situ to form thin, optics-grade coatings. Commercial applications for RM films are:
- patterned retarders for transflective LCD's and 3D applications,
- brightness enhancement films for LCD's,
- viewing angle enhancement films for LCD's,
- new viewing modes for LCD's (Blue Phase, PSVA)
- ultra-thin retarder films for consumer electronics (slim DVD, camcorders)

Merck RM materials are customised formulations including reactive liquid crystals, surfactants, photoinitiators and other proprietary additives. We have optimised the materials to achieve the optimum physical performance in each application. In this paper we focus on the optimisation of RM materials to achieve the finest patterning resolution and defined feature shape whilst maintaining good physical properties of the films.

Different methods of patterning RM materials are discussed and the merits of each considered. Two principle patterning methods are discussed, isotropic / anisotropic retarders, and chevron type patterned retardation films.

Polymerisation above the clearing point of a reactive mesogen after a masked UV exposure step can create isotropic regions within the polymerised anisotropic matrix. The patterning definition can be improved by careful formulation of the reactive mesogen mixture, and formulation with novel photoinitiator systems is discussed.
**Conference 7957: Practical Holography XXV: Materials and Applications**

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7957-01, Session 1

**Diffraction specific coherent panoramagrams of real scenes**

J. Barabas, D. E. Smalley, V. M. Bove, Jr., MIT Media Lab. (United States)

We have previously introduced the Diffraction Specific Coherent Panoramagram -- a multi-view holographic stereogram that provides correct visual accommodation as well as smooth motion parallax with far fewer views than a normal stereogram. This method uses scene depth information to generate directionally-varying wavefront curvature, and can be computed at interactive rates using off-the-shelf graphics processors. In earlier work we used z-buffer information associated with polygon views rendered from synthetic graphics models; in this paper we demonstrate the computation of Diffraction Specific Coherent Panoramagrams of real-world scenes captured by cameras. In one example we use specialized cameras that directly produce a depth map for a scene, while in another example we employ machine vision methods to calculate depth maps from images produced by an array of ordinary cameras.

7957-02, Session 1

**Holographic stereogram using 25 cameras in dense arrangement**


In order to display real 3-D objects by electronic holography, we have to capture light information of real 3-D objects at first. Some methods have already been studied for this purpose, such as digital holography, time-of-flight camera, integral photography camera, camera array, and video camera. In order to use for ultra-realistic communications that is our final goal, we should capture real 3-D objects such as human beings under natural light. For this purpose, integral photography camera and camera array would be promising methods. In this paper, we introduce an approach for camera array and show experimental results.

Electronic holography has an ability to reconstruct precise 3-D objects. To do so, high quality and dense 3-D light information is necessary for the input to electronic holography. There are many researches to generate the light information using camera array. For example, loopy belief propagation and graph-cuts are one of the powerful approaches for depth estimation signal processing; however it is even now technically hard to obtain the light information without visible error. Many researches try to develop new good algorithms to obtain the light information. On the other hands, our approach in this paper is to try to reduce the difficulties of the signal processing. Exactly speaking, we developed a camera array in dense arrangement to capture a human face, generate the light information simply, and generate holographic stereogram.

7957-03, Session 1

**Compression of digital hologram for three-dimensional object using wavelet-bandelet transform**

B. T. Le, Q. D. Pham, Z. Ali, N. Kim, J. Park, Chungbuk National Univ. (Korea, Republic of)

Holography is a successful technique for recording and reconstructing three-dimensional (3-D) objects. With the advent of digital holography, and continuing advances in megapixel CCD sensors, we can reconstruct 3-D object from hologram with better quality. However, this method also has a disadvantage of its large data volume. For example, suppose that we have a digital hologram of 1024x1024 pixels with each pixel storing 8 bytes of real information and 8 bytes of imaginary information. Then for a single hologram, we need 16 Mbytes memory in its native format which makes the real-time holography impractical.

In the transformation based compression algorithms of digital 3-D hologram, balance between compression ratio and normalized RMS error is always the core of algorithm development. An approach using Wavelet transform has been reported. The wavelet transform method is convenient to achieve high compression ratio but normalized RMS is also high. In order to solve this issue, in this paper, we propose a hologram compression method using Wavelet-Bandelet transform. The Wavelet-Bandelet transform method is based on combination of the fringe analysis and Wavelet transform. First, we use Wavelet transform to analyze hologram data into low sub-band and high sub-band. Then we use Bandelet transform to analyze fringe on Wavelet coefficients. Bandelet transform is a special method of transformation which decomposes the data along multiscale vectors that are elongated in the direction of a geometric flow. This geometric flow indicates the direction in which the data have regular variations. By considering the geometric flow, the compression can be performed with minimal loss. We can determine approximately the values pixel on each fringe. Therefore, we can increase compression ratio without increasing the normalized RMS error.

7957-04, Session 1

**Accelerating digital holographic deconvolution microscopy using CUDA’s nested concurrency**

Z. Ali, M. Piao, J. Park, N. Kim, Chungbuk National Univ. (Korea, Republic of)

Holography is the ultimate solution to real 3D imaging and visualization. Finally it will replace the existing 3D imaging and visualization technologies. We need to focus on the possible applications and the related needs of each application. Over the years the steady increase in sensor pixel count and resolution leads to the possibilities of larger sample volumes and of higher spatial resolution sampling, enabling the practical use of digital holography. However this increase in pixel count also drives a corresponding expansion of the computational effort needed to numerically reconstruct such holograms.

In this study we have exploited the parallel nature of the computations involved in the process of numerical reconstruction of digitally recorded holograms and utilized CUDA enabled graphics processing unit (GPU) to accelerate the reconstruction process. We have accelerated the deconvolution of the diffraction integral using parallel computing on GPU. As a first step we have recorded hologram of microscopic object with a inline setup using a CCD and a collimated beam from Nd:YAG laser with wavelength 532 nm. The microscopic objective used in the experiment for the microscopic object has focal length 200mm with 10X/0.28, magnification/NA. Then we reconstruct the sample volume by initiating CUDA Kernels for deconvolution of the diffraction integral for multiple depth planes in parallel, so that the images of many depth planes may readily be calculated at the same time, speeding up the reconstruction of the entire volume. We have also reconstructed the entire volume sequentially using CPU. The calculation speed of the GPU was proved to be much faster than that of the CPU. Actually CUDA support bit level concurrency, so the need is to exploit the potential of CUDA’s nested concurrency for such applications. In the future with FERMI architecture and the ability of CUDA for nested concurrency will further accelerate the process of numerical reconstruction which will lead to numerous new possible applications of digital holography.
Calculation method for CGH considering smooth shading with polygon models

K. Yamaguchi, T. Ichikawa, Y. Sakamoto, Hokkaido Univ. (Japan)

Computer-generated hologram (CGH) can reconstruct perfect 3-D objects as well as optical holography, however, reality of the reconstructed objects of CGH is lower than that of optical holography. This problem is caused by the lack of rendering techniques for CGH. To improve the reality of reconstructed objects, we have studied rendering techniques in computer graphics such as reflectance distributions and background images for CGH. Reflectance distributions represent a material of objects surface, and objects with various reflectance distributions are reconstructed by using the previous work.

In this paper, we improve the previous work with shading technique for CGH. The shading technique is also established in computer graphics, and it can render objects with smooth luminance without many polygons. A polygon model which is defined with many polygons is rendered as same as a polygon model which is defined with a few polygons by using the shading technique. However, calculation time of CGH increase according to the number of polygon, so it is necessary for CGH to reconstruct object with high reality from polygon models defined with a few polygon. In order to take into consideration the shading technique, the proposed method interpolates phase differences between a polygon and next polygon. Taking into account the shading technique, polygon models with a few planer patches are reconstructed with smooth luminance and highlight. We carried out the computer simulations and the optical reconstructed experiments. We report the results of these experiments and show the effectivity of our proposed method.

A method of calculating reflectance distributions for CGH with FDTD using the structure of actual surfaces

T. Ichikawa, Y. Sakamoto, A. Subagyo, K. Sueoka, Hokkaido Univ. (Japan)

Computer Generated Hologram (CGH) is made by computer simulation using diffraction theory. However the development of the rendering technology to display images beautifully like the field of Computer Graphics is scarce. The research of reflectance distribution is particularly so few, that texture of each material can not be expressed. We have proposed a calculation method of reflectance distribution for CGH with Finite Difference Time Domain (FDTD) method. FDTD method is one of the electromagnetic field analyses that solve Maxwell’s equations exactly. In this method, reflected light from uneven surface made in the computer is analyzed by FDTD simulation, and reflected light distribution is applied to CGH as object light. This method is possible to express various reflectance distributions from perfectly specular to perfectly diffuse reflections by changing of surface roughness. However, because the structure of made uneven surfaces were not alike to the structure of real surfaces, reflectance distributions similar to the real object ware not necessarily obtained. In this study, to reproduce the outer structure similar to the real objects truly, the outer structure of real objects is measured by atomic force microscope (AFM). Because AFM can measure in nano domain, considerably detailed outer surfaces are obtained. Stricter reflectance distributions are given to CGH by using measurement data. It was confirmed that variation of surface roughness of the measured sample affected three-dimensional images by optical reconstruction. Moreover, we report the relation between the surface roughness of samples and the reflectance distribution.

Instantaneous measurement of surface shape with high accuracy by one-shot digital holography

Y. Iwamaya, 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 such 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 considerably simple setups without imaging lens and their 3-D distributions with no-distortion can be reconstructed numerically. In this work, we propose a new method for non-contacting and instantaneous measurement of 3-D shape of rough surfaces by using one-shot digital holography that improves capability of phase-shifting digital holography. The principle of proposed method consists of grating projection to objects and automatic focusing on an image of objects. One-shot digital holography has been developed for instantaneous recording of the complex-amplitude in-line hologram. The complex-amplitude in-line hologram is extracted from one off-axis hologram by applying spatial heterodyne modulation and spatial frequency filtering. It is possible to measure the complicated shape of moving objects at once by applying the one-shot holography. The acquisition time is less than 1 micro-second needed for recording the complex-amplitude in-line hologram. By comparing the reconstructed images at various reconstructed distances, we can precisely determine 3-D position of each point on the surface. Speckles of reconstructed image are suppressed by applying spatial frequency filtering. Resolution is higher than the conventional digital holography because of low-level speckles. The error ratio smaller than 0.01 is obtained in measurement of 3-D position.

Wide viewing-zone-angle full-color electronic holography system using very high resolution liquid crystal display panels

T. Senoh, K. Yamamoto, T. Mishina, Y. Ichihashi, R. Oi, T. Kurita, National Institute of Information and Communications Technology (Japan)

A wide-viewing-zone-angle full-color electronic holography reconstruction system is developed. Combination of time-division-multiplexing and space-division-multiplexing method are investigated to reduce the number of hologram display panels and the size of optical system, still keeping the reconstruction frame rate high. Viewing-zone-angle is expanded by space-division-multiplexing method with three LCD panels. Full-color holographic image is reconstructed by time-division-multiplexing of RGB color lights. A vertical synchronization signal (V-sync) is extracted from the hologram memory and used to synchronize the RGB color lights with the RGB holograms on the LCD displays. Undesirable lights such as carrier light, phase conjugate light and higher-order diffraction lights are eliminated by half-zone-plate hologram generation method and single sideband beam reconstruction method, adopting 4f(focal length) relay-lens system with a spatial filter. Color aberration and astigmatism caused by the reproduction optical system are analyzed. Color aberration is reduced by generating holograms of R/G/B object with each color aberration compensating distance. Astigmatism caused by the half-mirrors which are multiplexing the reconstructed viewing-zones is reduced by very thin half-mirrors as astigmatism difference is proportional to the thickness of mirrors. Developed system expands the viewing-zone-angle of reconstructed holographic image three times wider than the original system. It enables the binocular observation of reconstructed holographic image in arm-length distance. The system can reconstruct full-color moving image at 3 frames per cycle.
DIY digital holography
S. J. Zacharovas, A. Nikolskij, J. Kuchin, Geola Digital uab (Lithuania)

No abstract available

Color holography for museums: bringing the artifacts back to the people
H. I. Bjelkhagen, A. Osanlou, Glyndwr Univ. (United Kingdom)

Color display holography, which is the most accurate imaging technology known to science, has been used to produce holographic images for display of artifacts in museums. The ‘Bringing the Artifacts back to the people’ project is presented. Holograms of ten different artifacts were recorded using the single-beam Denisyuk color reflection hologram technique.

“White” laser light from the light from three combined cw RGB lasers were used: a red krypton-ion laser, a green frequency-doubled Nd:YAG laser, and an argon-ion laser. Panchromatic ultra-fine-grain silver halide materials were used for the recording of the holograms.

During 2009 the artifacts were brought to St Asaph in Wales to be recorded at the Centre for Modern Optics’ hologram laboratory. One of the artifacts recorded was a 14,000-year-old decorated horse jaw bone from the ice age which is kept at British Museum in London. The recorded color holograms of this and other museum artifacts have been arranged in a touring exhibition. Between 2010 and 2011 the Virtual Artifacts Exhibition will be installed in a number of local museums in North Wales and the borders.

Artistic expression in the development of new technology for three-dimensional imaging
S. Oliveira, M. J. Richardson, M. I. M. Azevedo, De Montfort Univ. (United Kingdom)

Artists such as Tim Macmillan (2010) and Dayton Taylor (1997) use multi-lenses cameras to create the illusion of capturing space and time for different effects, such as frozen moment, live action and slow motion (often seen as a cinemagraphic effect). However, their results are two-dimensional images made with a two-dimensional image capture system. Previous research on the interaction between art and technology has been based on two-dimensional video art; this paper outlines a method of three-dimensional video capture to explore three-dimensional space and the human body. The stereoscopic specialist Ray Zone has written about the evolution of 3-D technology and 3-D film. Zone examines the development of these 3-D techniques and demonstrates the connection between two fields. This research extends our knowledge of Three Dimensional moving image as an art form. In the new art world, Holography has become a method increasingly used to develop kinetic art. In the search of new forms of display and image capture, we examine new techniques such as 3-D, including auto-stereoscopic display, three-dimensional imaging and holography. The aim of this paper is to examine the limitations of these techniques as embodied by the technical restriction of their use.

Changing thoughts: a series of digital art holograms
M. I. Azevedo, Escola Univ. das Artes de Coimbra (Portugal) and De Montfort Univ. (United Kingdom); M. J. Richardson, De Montfort Univ. (United Kingdom)

Light is the one key essential quality of holography and as such holograms are morphologically closer to ‘Optical’, ‘Kinetic’ and ‘Light Art’. In my attempt to explore this ‘Kinetic’ feature I collaborated Martin Richardson in the Modern Holography Program at DeMontfort University, in Leicester between March 2010 and 2011, to produce a series of digital art holograms and lenticulars with an open and experiential reference to light capture as energetic element. These holograms were filmed using a 35mm digital camera on a moving rail system and are as such ‘Stereogram’s’, then printed by GEOLA in Lithuania as reflection holograms measuring 50cm x 60cm.

The title of this series of digital stereographic holograms is ‘Changing Thoughts’. They allude to the interrelationship the observer has in assuming an understanding of what they see, only to suddenly change when they find out that what they are seeing is actually something quite different to what they had understood.

Much critical theorization, in recent times, has focused on the body and related to the work of Merleau-Ponty. And to António Damásio, the word images, means mental patterns with each sensorial way. Not only related at “visual” images nor static objects. But also sonorous images, or body inside images like those described by Einstein when he was trying to solve problems.

3D holographic portraits: presence and absence
R. M. Oliveria, Univ. de Aveiro (Portugal); L. M. Bernardo, Univ. do Porto (Portugal)

Authors writing about the portrait insist on the status of extending the model image portrayed beyond the absence and even death. The portrait also has this ability and suggests immortality. The picture suspends the time, making the absent present.

The portrait has been, over time, one of the themes mostly used in art. No wonder that in holography it is an important subject as well. The face is a body area of privileged communication and expression. It expresses emotions through looks, smiles, movements and expressions. Being Holography, so far, the recording technology that represents the object most similar to the original, with the same parallax, we may fall into a mimetic representation of reality. On Art Holography even by following paths already traversed, the resulting holograms are always different because of the unique concept that each artist-holographer puts into his work. As with any other artistic technology, each artist uses the medium differently and with different results.

Speckle reduction in holography using a time-multiplexing technique
M. Yokouchi, T. Kurihara, Y. Takaki, Tokyo Univ. of Agriculture and Technology (Japan)

Holography is regarded as being an ideal 3D display technique. However, speckle generation is an inherent problem of holography. This study proposes a time-multiplexing technique for reducing speckles. The object points that constitute a reconstructed image are divided into several groups consisting of sparse object points. These object point groups are then sequentially displayed. The sparseness and temporal summation of
the object points suppress speckle generation. The object point group is decomposed into multiple bit-planes to represent the gray scale of the object points and binary holograms are generated from the bit plane patterns using the half zone plate technique. The binary holograms are displayed using a high-speed spatial light modulator (SLM).

A digital micromirror device (DMD) was used as a high-speed SLM. It had a frame rate of 13.333 kHz and a resolution of 1,024×768. Each object point group consisted of 16×24 object points and each object point was generated by a half-zone plate, which was displayed by 64×32 pixels. The object point groups were displayed with eight horizontal shifts and four vertical shifts, so that a total of 32 object point groups were displayed. Each object point group was decomposed into eight-bit-planes; thus, the reconstructed image could be displayed using 256 gray levels. Reconstructed images consisting of 128×96 object points were displayed at a frame rate of 52 Hz. A laser diode was used to illuminate the DMD and its output intensity was modulated. This technique allowed speckle-free images to be generated.

7957-15, Session 3
Quantitative quality measure based on light wave distribution to access 3D display
Y. Sakamoto, Hokkaido Univ. (Japan); F. Okuyama, Suzuka Univ. of Medical Science (Japan)

There are a lot of 3D displaying methods such as stereoscopy, integral photography, holography, etc. Stereoscopy, which is a popular method for 3D movies, has disadvantages of visual fatigue and lack of motion and vertical parallaxes. Meanwhile, it is said that a holography is as ideal 3D displaying technique because it satisfies all of human 3D perception. Conventionally, biological responsiveness is measured by using an actual 3D display in order to evaluate image qualities of 3D displaying method. It has made difficulty to assess image qualities, because it is virtually impossible to prepare various 3D displays that have same parameters of viewing zones, visual fields, etc. Therefore, it is required quality measures for 3D images for quantitative evaluation, which are useful for comparing 3D image quality and a design of a new display system. For example, a signal to noise ratio (SNR) of 3D images is not established, although 2D image SNR is very widely used. Because reconstructed images have blurs in defocused depth, 2D image SNR cannot be applied into 3D images index. This paper proposed some quantitative quality measures to access the 3D display methods. One of them is 3D image SNR that is based on light wave distributions in a space, which are simulated wave propagation from a display to a viewpoint by using a computer. The measures are evaluated by biological responsiveness using stereoscopic display and holographic displays, and the results show that the measures are effective for indicator of 3D display.

7957-16, Session 4
Holographic recording aspects of high resolution Bayfol(R) HX photopolymer
F. K. Bruder, H. Berneth, T. Fäcke, R. Hagen, D. Hönel, Bayer MaterialScience AG (Germany); D. Jurbergs, Bayer MaterialScience LLC (United States); T. Roelle, M. Weiser, Bayer MaterialScience AG (Germany)

We have been developing a new class of recording materials for volume holography, offering the advantages for full color recording and depth tuning without any chemical or thermal processing, combined with low shrinkage and detuning. These photopolymers are based on the two-chemistry concept in which the writing chemistry is dissolved in a preformed polymeric network. This network gives the necessary mechanical stability to the material prior to recording. In this paper we describe several aspects of holographic recording into Bayfol®-HX which are beneficial for its effective use and discuss them within a more elaborate reaction-diffusion model. Inhibition phenomena and the influence of pre-bleach are studied within this model and are investigated experimentally for single hologram recording and angular multiplexed hologram recordings. Also the dark reaction after the exposure period and the minimum allowable waiting time for full hologram formation are addressed. The proper understanding of these phenomena is important for the optimal usage of these new materials in e.g. step-and-repeat mass production of holograms.

7957-17, Session 4
Optimizing diffraction efficiency for reflection holograms with HARMAN holographic emulsions while maintaining narrow band reconstruction
S. L. Smith, De Montfort Univ. (United Kingdom); K. N. Harvey, HARMAN Technology, Ltd. (United Kingdom); M. J. Richardson, De Montfort Univ. (United Kingdom)

De Montfort University Modern Holography research methods have developed narrow band reflection holograms with Harman technologies Holographic emulsions. Results published here show controlled emulsion shrinkage, leading to same wavelength playback with 20 nanometers bandwidth. Conclusions demonstrate narrow band playback capabilities with high diffraction efficiency. Applications include: single and multi-colour Reflection HOE’s, Full Colour holograms and single colour display holograms.

7957-18, Session 4
Optimizing diffraction efficiency for transmission holographic optical elements with Harman holographic materials
S. L. Smith, De Montfort Univ. (United Kingdom); K. N. Harvey, HARMAN Technology, Ltd. (United Kingdom); M. J. Richardson, De Montfort Univ. (United Kingdom)

The focus of this research is to characterise Harman Technologies new holographic emulsions for applications in transmission Holographic Optical Elements (HOE’s). Objectives of the research are to optimise the diffraction efficiency over a number of optical arrangements, primarily those used in Edge-Lit Holographic optical devices. Methods developed across a number of processing regimes exhibit results showing controlled shrinkage, small grain size coupled with optimised processing resulting in very high diffraction efficiencies. Conclusions point to demanding applications that look to HOE’s with various output characteristics, a number of novel approaches to optical design in Edge-Lit optical elements are reviewed.

7957-20, Session 4
Photorefractive amplification at high frequencies
R. M. Kurtz, W. Lu, J. Piranian, RAN Science & Technology, LLC. (United States); A. O. Okorogu, The Aerospace Corp. (United States)

The Fast Photorefractive Effect is a narrowband optical amplification technique that exploits the difference between phase modulation (PM) and frequency modulation (FM) to increase the bandwidth of this amplification. We studied this effect and discovered that it applies only to PM signals, like those from a vibrating surface; FM signals’ amplification bandwidth is similar to that predicted by measurements of the dark decay time. Our experiments in Cu:KNSBN showed a bandwidth of
A nanophotonic hierarchical hologram works in both optical far-fields and near-fields, the former being associated with conventional holographic images, and the latter being associated with the optical intensity distribution based on a nanometric structure that is accessible only via optical near-fields. In principle, a structural change occurring at the subwavelength scale does not affect the optical response functions, which are dominated by propagating light. Therefore, the visual aspect of the hologram is not affected by such a small structural change on the surface, and retrieval in both fields can be processed independently. We propose embedding a nanophotonic code, which is retrievable via optical near-field interactions involving nanometric structures, within an embossed hologram. Due to the one-dimensional grid structure of the hologram, evident polarization dependence appears in retrieving the code. Here we describe the basic concepts, numerical simulations, and experimental demonstrations of a prototype nanophotonic hierarchical hologram with a nanophotonic code and describe its optical characterization.

7957-21, Session 5

Review of selected technological applications of DCG-holograms

C. G. Stojanoff, Holotec GmbH (Germany)

The subject matter of this presentation is to demonstrate the performance characteristics of HOEs fabricated in DCG-material with enhanced properties that are used in the solution of engineering problems. The composition, structure and the physico-chemical and optical properties of the DCG-material are briefly described in the introduction that is followed by detailed discussion of the developing processes used to achieve the essential characteristics required by the various applications. Different procedures are used to achieve specific objectives, such as controlling the spectral characteristics of the HOE by inorganic and/or organic additives and using filler material to enhance the UV or IR performance. Stress induced externally by applied mechanical strain changes the performance of the HOE and is used in engineering applications. The optical characteristics of the HOE are also modified by internally induced stress, such as changing the water content of the polymer or by infusion of filler material and the generation of gradients in the film during the coating process or at some stage of the hologram development. The method of conformal modification is used during the coating and the drying of gelatin films to set the relationship between coiled and helical structures that determine the mechanical properties of the gelatin matrix. Multiple exposures are used to record up to four holograms in single DCG film that are utilized to generate concurrently several monochrome or RGB beams.

The following applications are discussed:

- Photovoltaic
- Shading/glazing of buildings
- Solar photochemistry
- Information display panels
- Metrology
- Interconnects

7957-22, Session 5

Nanophotonic hierarchical hologram: hierarchical information processing and nanometric data retrieval based on nanophotonics

N. Tate, The Univ. of Tokyo (Japan); M. Naruse, National Institute of Information and Communications Technology (Japan); T. Yatsui, T. Kawazoe, The Univ. of Tokyo (Japan); M. Hoga, Y. Ohyagi, T. Fukuyama, Y. Sekine, M. Kitamura, Dai Nippon Printing Co., Ltd. (Japan); M. Ohtsu, The Univ. of Tokyo (Japan)
disposition of distribution of a polarization state on the image of object in this range in real time. Besides compactness, simplicity and relatively cheapness the advantage of such a method is the high accuracy that is more than the accuracy of the similar methods described in the literature as the distortions of a state of polarization of light under investigation are excluded here because of absence of any reflections of light beam during the analysis. Such a method could be applied in polarimetry, astropolarimetry, ellipsometry and in passive systems of remote sensing and target recognition.

In reproduced procedure, after these data were reproduced page by page and stored in the PC, data could be reproduced with no error after de-interleave and error correction. Finally video file could be successfully restructured. These results mean that this system show the feasibility of archive system. Furthermore, as more than 1 TB / CD size of recording capacity is expected, recording capacity could be raised up if blue laser diode and thicker recording medium would be applied.

7957-24, Session 6

Improvement of sensitivity and bandwidth of dynamic holography in photorefractive quantum wells

A. S. Drewery, P. Yu, Univ. of Missouri-Columbia (United States)

Coherence domain dynamic holography based on four-wave mixing in photorefractive multiple quantum wells (PRQW) shows potential as an imaging technique for biological tissues. The dynamic holography is based on the principle of the photorefractive effect using a broadband source in a very thin film (about one micron) in PRQW. Two writing beams, signal and reference beams, form fringes with fringe spacing larger than ten microns. One of the two beams serves as the readout beam, where the diffraction in four-wave mixing is in Raman-Nath regime. One major problem of this technique is relatively low sensitivity. Previous research has shown that the sensitivity is approximately 23dB lower than the optimized sensitivity in a conventional coherence domain imaging technique. This is due to the limited diffraction efficiency in four-wave mixing. In this work, we propose a new method to increase the sensitivity and bandwidth. The method is based on two-wave mixing in PRQW. There are two phase contributions in the two-wave mixing. One is the constant photorefractive phase that is determined by the applied electric field. Another is the excitonic phase that changes from 0 to 6 pi across the light hole and heavy hole excitons and is a linear function of wavelength. We use a complex interferometry to trace the phase in excitons so that the phase can be corrected in the two-wave mixing. This technique is similar to recent developments in spectral domain optical coherence tomography, and provides the advantage of adaptive detection in weak signals through biological tissues.

7957-25, Session 6

Holographic data storage system toward high recording density

N. Ishii, T. Muroi, N. Kinoshita, H. Kikuchi, K. Kamijo, N. Shimizu, NHK Science & Technical Research Labs. (Japan)

We have been studying holographic data storage system as video archive system. This system is expected for large recording capacity and high data-transfer-rate. We have newly developed holographic data storage test equipment where object lens is 0.85 of NA; laser source is 532 nm of wavelength; multiplexing method is angle multiplexing and read out method is using phase-conjugation. Angle multiplexing method, which controls the incident angle of reference beam using galvano scanner mirror and relay lens, was applied and 340 multiplexing were achieved on the same spot using 1 mm photopolymer recording medium. The recorded page data were made using 5:9 modulation code, interleave for error dispersion, and LDPC error correction code. The each reproduced page data showed between 10-4 and 10-3 as raw error rate. To confirm the system feasibility, 1024 x 600 video file compressed with H. 264 was divided to 210 page data and these were recorded.

7957-26, Session 6

Volume polarization holography for optical data storage

D. Barada, Utsunomiya Univ. (Japan) and National Institute of Advanced Industrial Science and Technology (Japan); Y. Kawagoe, H. Sekiguchi, Utsunomiya Univ. (Japan); T. Fukuda, National Institute of Advanced Industrial Science and Technology (Japan); S. Kawata, T. Yatagai, Utsunomiya Univ. (Japan)

Volume holographic memories are anticipated for optical data storage with high density and large capacity. The optical information is recorded as a three-dimensional refractive index pattern on a photo-sensitive medium. General photo-sensitive medium is insensitive for polarization. In this work, the optical information is recorded as a three-dimensional birefringence pattern on a polarization-sensitive medium by polarization holography. The three-dimensional birefringence pattern is generated by multiplex recording. In recording, a laser beam is split into a signal and reference beams using polarization beam splitter. The signal and reference beams are illuminated onto a spatial light modulator (SLM) and a mirror, respectively. The recording information is displayed in the SLM. These two beams are superposed onto a polarization-sensitive medium made of a dye-doped polymer. Then, each polarization state of the two beams is adjusted using wave plates for polarization multiplex recording. Furthermore, it is possible to combine with angular multiplex recording by rotating the medium. In reconstruction, a polarized reference beam is illuminated onto the recorded medium and the incident angle is adjusted. The diffracted beam is observed when the incident angle of the reconstruction reference beam coincides with the incident angle of the recording reference beam. The information is reconstructed by analyzing the diffracted beam pattern. In this experiment, the polarization and angular multiplex recording was demonstrated and confirmed. From the experimental results, polarization holography is expected as a technique for optical data storage.

7957-27, Session 6

Application of synthesized wave fronts for interferometric shape and deformation measurement

J. Kornis, R. Sélèf, Budapest Univ. of Technology and Economics (Hungary)

The analog reconstruction of a wave front and its application in comparative measurement is well known from comparative holography. Due to the recent development of Spatial Light Modulators (SLM) the real-life optical reconstruction of digital holograms became also possible, which means that holographic illumination can be performed using digital holograms. The SLM is also capable to generate manipulated wave fronts by computer (not belonging to an existing object), and multiple such projections can be performed during the measurement time. Using this feature different adaptive measuring systems can be built. The application of such wave front projections is also possible in TV holography. The wave front projection can be virtually too, when the wave front exists only in the computer memory. Methods both for digital holography and TV holography are developed. The essence of the methods both for the deformation and shape measurement is to producing a set of phase...
shifted fringe patterns of the investigated object. Using these fringe systems new contour fringe pattern can be generated.

In our work we present digital holographic and TV holographic methods for shape and displacement measurement using wave front synthesizing methods. Some results of the measurements are also presented.

7957-49, Session 6
**Dynamic energy transfer in a polarization hologram at low intensity of working beams**

G. A. Kakauridze, B. N. Kilosanidze, Institute of Cybernetics (Georgia)

The phenomenon of energy transfer during self-diffraction is considered by means of dynamic polarization holograms. The use of high-effective reversible polarization-sensitive media makes it possible to use beams with low intensities from cw lasers. The transfer is carried out at the expense of phase difference between the interference pattern of working beams and its registration in the medium. The induction of photogyrrotropy together with photoanisotropy by polarized light results in rotation of axis of photoanisotropy at a certain angle which is small enough in real media because of the smallness of photogyrrotropy that causes phase shift less than the optimal value $\pi/2$, when transfer is maximal. To increase phase difference we have used an additional mechanical shift of the medium such that the phase difference reached $\pi/2$. The increase of the intensity of a weak beam up to 300% within the time of tens of milliseconds was obtained for power density of about 50 mW/cm² for a strong beam and 5 mW/cm² for a weak one. We have used a cw DPSS laser with wavelength 473 nm and materials on the basis of azodye containing polymer and side-chain azopolymer. Such a high value of amplification is retained for several tens of seconds, after which amplification decreases. The process is repeated if we return the medium to its original location This effect This effect gives a possibility to amplify coherent light beams by a relatively simple way including the amplification of beams carrying optical information in communication systems.

7957-29, Poster Session
**Light induced anisotropy and gyrotropy in the media on the basis of azo indicators**

V. G. Shaverdova, S. S. Petrova, A. L. Purtseladze, L. Tarasashvili, N. Obolashvili, Institute of Cybernetics (Georgia)

Azo indicators are well known in which when changing acidity they change their properties. It was natural to expect also their appreciable changes of their polarization properties. The results of the carried out experimental research in recording media on the basis of azo indicators - homolog of the Methyl orange introduced into the polymeric matrix are presented in this work. According to the technology developed by us, the samples for the reception of which solvents with various degree of acidity, within values $pH$ 1.68 – 12.48 have been created. Samples were irradiated by the light of argon laser (488 nm) actinic for them. The light induced anisotropy was carried out on a registering recorder and can be described by means of one parameter - the effective anisotropy. As standards the samples of dyes for the reception of which neutral solvent was used have been considered. In a number of dyes the values of effective anisotropy in alkaline and acid media exceed its values concerning corresponding standards. The higher homolog - Heptyl orange and Benzyl orange which are weak or insoluble in water, become water-soluble when using solvents both with alkaline and acid reaction. The interval of appearance of light induced anisotropy has been expanded. We have used the method of the zero-ellipsometry for the research arising in the same samples light induced gyrotropy. Values of circular dichroism and circular birefringence in investigated layers in neutral media have been calculated also at various values $pH$. In the work the received results are discussed and analyzed.

7957-30, Poster Session
**Behavior of MTF parameter from corn honey holographic material at 473nm and 530nm**

R. Velazquez-Xique, A. Olivares-Pérez, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We show a comparative study from the diffraction efficiency parameter of holographic gratings using corn syrup as matrix. As a function from the frequency response of spatial modulation of the material, through photosensitive salts, such as: ammonium dichromate and potassium dichromate. Since both salts have a different molecular weight, it are inferred that with this differences it shows an answer different from the MTF on the gratings. The gratings were constructed with wavelengths at 473 nm and 530 nm respectively.

7957-31, Poster Session
**Albumin holograms**

M. J. Ordóñez-Padilla, A. Olivares-Pérez, R. Vega-Criollo, L. R. Berriel-Valdos, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We presented some emulsion films based in albums gallus gallus and callipepla cali, in order to register holographic gratings. Through the parameter of the diffraction efficiency, like function from the thickness, and concentration of (NH₄)₂Cr₂O₇ salt, it is used like photosensitizer. They registered diffraction holographic gratings with a wavelength of 457 nm, obtaining good results. We make a study of the spatial modulation MTF from the material.

7957-32, Poster Session
**Compact reflection-type holographic recording system with high angle multiplexing**

M. Kanayasu, K. Akieda, T. Ohori, T. Yamada, M. Yamamoto, Tokyo Univ. of Science (Japan)

The study of holographic data storage that uses photopolymer as a recording medium has been done. So far, Off-axis type recording/reconstructing system or Co-axis type recording/reconstructing system has been studied. In Off-axis type system, SNR is expected to be relatively high, but this system has problem of low-speed access due to the set time of galvanometer mirror which is modify element for the reference beam angle. And optical system for shifting of the reference beam angle is complicated, so it is difficult to construct a compact optical disk head. Also what a range of angle is small limits the storage density. While in Co-axis type system, shift multiplexing record is generally performed after speckle pattern is given to reference beam. In such case, the noise result from speckle pattern is generated, and SNR become low value. And a interfere field of reference beam and signal beam is restricted in direction of media film thickness, so it is difficult to make the better storage density by improving media film thickness.

In this paper we propose new system that resolves such problems. We propose the configuration of compact reflection-type holographic memory and the recording/reconstructing method that is expected to increase the multiplicity of angle multiplexing compares with the former system. Also we proposed the patterned media to increase the multiplicity of angle multiplexing compares with the former system. We make the better storage density by improving media film thickness. And this paper shows the simulation and experimental results of recording/reconstructing characteristics with the system that we propose.
Correction method of wavefront aberration on signal quality in holographic memory
E. Kimura, A. Nakajima, K. Akieda, T. Ohori, K. Katakura, M. Yamamoto, Tokyo Univ. of Science (Japan)

One of the problems that affects the practical use of holographic memory is deterioration of the reproduced images due to aberration in the optical system. The medium must be interchangeable, and hence it is necessary to clarify the influence of aberration in the optical system on the signal quality and perform aberration correction for drive compatibility. In this study, aberration is introduced in the reference light beam during image reproduction, and the deterioration of the reproduced image signal is examined. In addition, for a basic study of aberration correction, the correction technique using liquid crystal as a correction device is studied. The image is then displayed as a VGA output by a PC. The VGA output is a two-dimensional pattern with various wave aberration values expressed in terms of Zernike coefficients. When the laser is incident on the liquid crystal, which displays a pattern, a wave aberration pattern specified by the VGA output can be introduced in the reference beam. The difference between the highest and lowest gradation levels, in the pattern in the VGA output. From the result obtained, it is confirmed that aberration is controlled by the shading difference in the image; the image is projected onto the liquid crystal after Zernike polynomial approximation. In this way, we have proved that if an arbitrary Zernike polynomial expression is projected onto a liquid crystal, a corresponding wavefront aberration is obtained. By using this aberration control method, the influence of reference wave aberration on signal quality is cleared.

The electromagnetic wave diffraction from a pyramidal horn antenna in the microwave band
M. Ohki, K. Sato, S. Kozaki, Shonan Institute of Technology (Japan)

In the microwave band, the radiated wave from the pyramidal horn antenna is calculated in the diffraction field by the Fresnel approximation. In addition, the Fresnel approximation has been introduced into the diffraction field with half infinite diffraction plane. This phenomenon is examined compared with the experiment value based on a hologram interpretation.

Optimization of half-tone technology for diffractive microlens fabrication
V. P. Korolkov, Novosibirsk State Univ. (Russian Federation); R. K. Nasyrov, A. R. Sametov, S. Suhih, Institute of Automation and Electrometry (Russian Federation)

Fabrication process is always brings errors in profile formation that decrease diffractive efficiency and wavefront quality. However, the negative effects can be partially compensated by optimization of the fabrication process. General approach for optimization is to simulate fabrication process and iteratively calculate corrections that will increase microlens profile quality. In this paper we have applied optimization for half-tone fabrication method. According to this method exposing of photoresist is produced by forming an image of half-tone mask with variable transmission which is spatially filtered by projection system. Such mask is a grating with the constant step but modulated duty cycle. After exposing of photoresist and its development and etching continuous profile is fabricated. Microlens is simulated as spatial filtering of half-tone mask Fourier spectra with projection objective modulation transfer function. However, due to errors in projection system and non-linear processes in photoresist experimental results are much differ from theoretical ones. We propose to avoid this problem by introducing generalized transfer function of fabrication process. Simulation is made in assumption that all fabrication processed are ideal and there are no non-linear processes. Generalized transfer function in this case is equal to point spread function of projection objective. To define this generalized transfer function we fabricated sample DOEs without optimization. Its profile shape was measured with e-beam microscope. Then inverse problem was solved and transfer function is found. Then corrections are introduced in half-tone mask and diffractive lenses with higher quality were fabricated.

Improvement of camera arrangement in computer-generated holograms synthesized from multi-view images
N. Hayashi, Y. Sakamoto, Y. Honda, Hokkaido Univ. (Japan)

Computer-Generated Hologram (CGH) is a technique that realizes recording optical system of holography by simulation in a computer, and can reconstruct ideal 3D images. Since CGH needs model data of the objects, it is necessary for creating 3D images of real existing objects to model them precisely. However, it is often difficult to obtain model data of them. To solve this problem, many researches about multi-view projection image based methods without using 3D model data have done. CGH using integral photography and CGH using multi-view projection obtained by lens array are examples of them. However, these methods have some problems. First, recording optical systems of them are complex and expensive, and therefore realizing these systems is difficult. Another problem is that camera arrangement is restricted to the plane correspond to the hologram. For 3D display application, such as 3D television system, it is difficult to construct the optical system with such a strict condition. In the past, a method to generate holograms from multi-view images taken with digital cameras has proposed. Additionally, to generate CGHs using multi-view images from randomly arranged cameras, a method using distance transformations, rotations of a light wave, and an algorithm setting up hologram parameter automatically considering information of camera arrangement has proposed. In this paper, the results of numerical reconstructions are compared and both motion parallax and resolution of the reconstructed images are discussed. Proper number of multi-view projections will be derived from this discussion.

Fast calculation method for CGHs by using spherical pre-calculated object light
K. Hosoyachi, Y. Sakamoto, Hokkaido Univ. (Japan)

Holography is one of the three-dimensional technology. Light wave from an object is recorded and reconstructed by using hologram. A computer generated hologram is made by computer simulation. However, an enormous amount of computational time is required for calculating computer generated holograms. In this paper, the purpose is high speed calculation for computer generated holograms. The two main methods to calculate computer generated holograms are the point light method and the methods based on Fourier transforms.
The point light method calculates light wave from complex object, but requires an enormous amount of computation time. The methods based on Fourier transforms calculate CGHs using a fast Fourier transform algorithm, and the calculation speed is faster than one of the point light method. However, the calculation for complex object requires FFTs many times, and the computational time is enormous.

Therefore, we have proposed a fast calculation method of computer generated holograms using cylindrical pre-calculated object light. This method does not require an FFT. Cylindrical pre-calculated object light is made by calculating light wave from a basic object on a semicircle cylinder. This method calculate light of arbitrary object shapes by transforming pre-calculated object light. However, large memory is required. In this paper, we improve this method to reduce memory by using spherical pre-calculated object light. We realized to transfer distance from object to hologram by using spherical pre-calculated object light. Moreover, the computational time of our method is reduced by using graphic processing units.

7957-38, Poster Session

**Consideration of improvement of electro-holographic stereogram**

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)

Electro-holographic stereogram (EHS) is useful for holographic 3D TV because it is constructed from the multi horizontal viewpoint plane images and is compatible to the multi camera stereoscopic image. Each hologram is recorded as a slit hologram (element hologram) but total viewing area and the number of the element holograms have been limited to some extent by the size and the resolution points of LCD. Therefore we used two LCDs for EHS and arranged them horizontally and increased the viewing points to two times and at first we considered how viewing area and reconstructed images of EHS were improved.

Now we are driving for real time system using multi-cameras and multi-processing operation system GPU and we can get real-time moving image using this system.

Also we use LED transmission hologram system and reconstruct the image direct using LED light.

7957-39, Poster Session

**Photoanisotropy in polarization-sensitive media on the basis of polar water-soluble components**

I. Chaganava, G. A. Kakauridze, B. N. Kilosanidze, Institute of Cybernetics (Georgia)

The intensification of interaction of polymer molecules and dyes that are the base of these materials has been carried out by molecular electrostatic forces to obtain polarization sensitive materials with improved characteristics. Different organic dyes capable of photochemical geometric isomerization under the action of actinic polarized light with a wavelength close to the maximum of an absorption spectrum of each dye were used for creating such materials. Various materials have been synthesized on the bases of the polar water-soluble components. The essential improvement of photoanisotropic characteristics of these materials have been revealed due to previously addiction of ionizing functional groups in a chromophoric component. Examples of the materials composed of dyes connected with certain polymers via dipole-ionic bonds are given. The results of investigations of the materials properties are presented. In this way the photoanisotropic materials have been obtained on basis of different polar polymer matrices whose separate macromolecules are capable of interacting with one another by dipole-dipole bonds. A supplementary number of polymer fragments which have no direct connection with dye molecules are also capable of being drawn into the processes of photoanisotropy induction. The influence of such interactions on kinetics and value of attainable photoanisotropy is considered. The possibility of achieving of extremely high values of photoanisotropy have been shown on the samples of materials based on the dyes with expanded number of ionized substituents. The obtained high-effective polarization-sensitive materials can be used for the creation of polarization-holographic elements of a different type and devices on their basis.

7957-40, Poster Session

**Holograms with fluorescent benzyl**

V. Dorantes-Garcia, A. Olivares-Pérez, M. J. Ordóñez-Padilla, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Behavior study of the diffraction efficiency parameter from holographic gratings, with fluorescence inks such as eosin and benzyls. We have been able to make holograms with substances such as fluorescence to blue laser to make transmissions holograms, using ammonium dichromate as photo-sensibilizer and polyvinyl alcohol (PVA) as matrix. Ammonium dichromate inhibit the fluorescence propriety of inks, mixed in a (PVA) matrix, but we show the results of painting hologram method with fluorescence inks and describe how the diffraction efficiency parameter changes as a function of the ink absorbed by the emulsion recorded with the gratings, we got good results, making holographic gratings with a blue laser diode 470 nm. And we later were painting with fluorescent ink, integrating fluorescence characteristics to the hologram.

7957-41, Poster Session

**Three-dimensional optical recording by retardography**

Y. Kawagoe, D. Barada, H. Sekiguchi, Utsunomiya Univ. (Japan); T. Fukuda, National Institute of Advanced Industrial Science and Technology (Japan); T. Yatagai, Utsunomiya Univ. (Japan)

Recently, we proposed retardography as a parallel optical recording technique that works based on polarization of light. This technique records the retardance pattern of an anisotopic object as birefringence on the polarization-sensitive medium using a single beam. Here, the improvement in recording density was achieved only using polarization, but now we propose a method that uses both polarization and volume recording to further improve recording density. The optical information is recorded as a three-dimensional birefringence pattern on a polarization-sensitive medium. In this work, the shift multiplex recording is made, which has Bragg characteristic that appears due to the thickness of the recording medium. The diode laser (405 nm) was used as the source and the spatial light modulator (SLM) was used as an anisotropic object. Recording beam transmitted through the SLM is converged by object lens and irradiated onto the recording medium. The optical setup was made so that the focusing point of the recording beam hits the back surface of the thick recording medium, passing through the front surface. After one recording, the recording medium was shifted perpendicular to the optical axis and another recording was made. During reconstruction, the recorded sample was moved to the two recorded positions and the corresponding recorded patterns were reproduced. When the sample was moved to a position in between the two recorded points, the superposition of both the recorded patterns was reconstructed. From these results, we can confirm that the pattern was successfully recorded in three-dimension.

7957-42, Poster Session

**Terahertz holographic interferometry**

A. A. Gorodetsky, V. G. Bespalov, Saint-Petersburg State Univ.
of Information Technologies, Mechanics and Optics (Russian Federation)

We present our new modeling and research results on terahertz holographic interferometry, a technique allowing to reconstruct changes in inner dielectric object structure, as terahertz radiation can penetrate through the majority of dielectric materials. For the last three years we’ve reported on our investigations in the field of pulse terahertz holography, going further, we present results of its application. Terahertz holographic interferometry technique is somehow alike the corresponding one in optics, but it allows as well managing optically opaque objects. Using the broadband pulse THz radiation with a spectrum in the range of 0.1-2.5 THz we can reconstruct object deformations up to several microns in the bulk 3d object after its two expositions. Using referenceless holographic reconstruction, available in terahertz, we can reconstruct both amplitude and phase change on an object. We use 1W Yb:KYW femtosecond laser as a pump source and InAs crystals put into magnetic field as THz generators in reflection way. For detection we use CdTe crystals, which suite best for Yb:KYW laser wavelength (1040nm)

7957-43, Poster Session
CUDA based holographic modeling software
A. A. Gorodetsky, Saint-Petersburg State Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

We present the result of an upgrade of previously described and used multithreaded software for modeling the process of holographic recording and reconstruction. The software allows 2d and 3d diffraction modeling for near- and far- field radiation of arbitrary spectral composition both for flat and 3d objects. The software was successfully applied to holographic nanolithography, terahertz pulse holography and diffraction of ultrashort optical pulses modeling. Today, a considerable upgrade is introduced, allowing referenceless iteration reconstruction of multiple wavelength intensity speckle patterns and GPU calculation functionality, which allows to accelerate calculation due to high parallelization and use more reasonable and compact systems. We present the comparison of results and performance of current and previous versions.

7957-44, Poster Session
Computer-generated “Alcova” hologram to display floating image with wide viewing angle
T. Yamaguchi, H. Ozawa, H. Yoshikawa, Nihon Univ. (Japan)

In this paper, we have investigated the floating image display with the computer-generated hologram (CGH).

As the 3D display, to make strong impression on the viewer, the display should reconstruct the floating image from the display plane.

However, there are few reports about the floating image display with the CGH.

Since the required spatial frequency to the display is very high compared with the rear image display, it is difficult to output the CGH which display the floating image.

Even if the CGH is output by the inadequate device, the viewing area and the image size of the CGH is not enough.

Therefore, to reduce the required spatial frequency for the fringe pattern of the CGH, the position of the object is placed at the behind of the hologram plane.

Also, the huge calculation amount of the fringe pattern is big problem.

In our work, since we developed our output device (named fringe printer) for the fringe pattern, the pixel pitch of the printed fringe pattern develops 0.44 um.

By using the fringe printer, we have achieved floating image with CGH.

The output CGH reconstructed the floating image, but the reconstructed image only had the narrow viewing angle and the small reconstructed objects.

Therefore, to change the CGH shape from the flat type to curve type, we investigate the wide viewing angle floating image display:

Also, to solve the huge calculation amount, we employ the GPU to make parallel calculation and calculation faster.

7957-45, Poster Session
New techniques for wave-field rendering of polygon-based high-definition CGHs
H. Nishi, K. Higashi, Y. Arima, K. Matsushima, S. Nakahara, Kansai Univ. (Japan)

Recently, we presented the polygon-based high-definition CGH (PBHD-CGH) that is a digitally synthetic hologram reconstructing virtual objects. The PBHD-CGH, whose size is more than several giga pixels, reconstructs a true fine spatial 3D image accompanied with a strong sensation of depth, because the CGHs reconstruct mutually occluded 3D scene constructed of surface-modeled objects. This feature is provided by the polygon method and the silhouette method. The polygon method, based on wave optics, is the technique for synthesizing the field of the surface-modeled virtual objects, while the silhouette method realizes light-shielding of hidden objects.

The polygon method also features an affinity with common computer graphics. Therefore, the technique for rendering PBHD-CGHS is called “Wave-field rendering”. In this paper, we report several CG-like techniques introduced into the wave-field rendering such as texture-mapping or smooth shading. In addition, we propose novel techniques for wave-field rendering; producing the feel of material, superimposing the 3D image of real objects on the virtual scene, and removing hidden surface in self-occluded objects.

These techniques remove various restrictions as to the design of PBHD-CGHs.

7957-46, Poster Session
Memory size reduction of the novel look-up table method using symmetry of Fresnel zone plate
S. Kim, D. Kwon, E. Kim, Kwangwoon Univ. (Korea, Republic of)

Recently, a novel look-up table (N-LUT) method to dramatically reduce the number of pre-calculated interference patterns required for generation of digital holograms was proposed. In this method, a 3-D object image is approximated as a set of discretely sliced image planes with different depth, and only the fringe pattern of the center object point on each image plane is pre-calculated, so-called a principal fringe pattern (PFP) and stored in the N-LUT, so that the size of the N-LUT can be significantly reduced by comparing to that of the conventional LUT method.

That is, the N-LUT contains only the fringe patterns of the object points with unity magnitudes located at each center of the depth-dependent image planes of the object. This PFP can be regarded as the Fresnel zone pattern (FZP) computed at each depth. In general, this FZP has reflection symmetry in geometry. That is, if we have the half of the full PFP, we can reconstruct the full size of PFP. Therefore, if we have only half of the PFP, we can generate the computer generated holography (CGH) without the loss of image quality. But the memory size of LUT could be reduced by half. Therefore, in this paper, we proposed the method to reduce the memory size of LUT using the reflection symmetry of PFPs. Some experiments are carried out and its results are comparatively discussed with those of the conventional methods in terms of computational speed and required memory space.
Hardware implementation of N-LUT method using field programmable gate array technology

S. Kim, D. Kwon, E. Kim, Kwangwoon Univ. (Korea, Republic of)

Recently, a novel look-up table (N-LUT) method to dramatically reduce the number of pre-calculated interference patterns required for generation of digital holograms was proposed. In this method, a 3-D object image is approximated as a set of discretely sliced image planes with different depth, and only the fringe pattern of the center object point on each image plane is pre-calculated, so-called a principal fringe pattern (PFP) and stored in the N-LUT, so that the size of the N-LUT can be significantly reduced by comparing to that of the conventional LUT method.

But, for real-time holographic 3D display, more reduction of calculation time is needed. One way to reduce the calculation time is the hardware implementation. And this hardware implementation for holographic 3D display application is researched by many researchers. Therefore, in this paper, we propose the hardware implementation method for N-LUT method using Field Programmable Gate Array (FPGA) technology. In the proposed method, calculation process is divided by some segment block for fast parallel processing of calculation of N-LUT method. That is, by using parallel processing by use of some segmented block based on FPGA technology, calculation speed of CGH can be increased. Some experiments are carried out and its results are comparatively discussed with those of the conventional methods in terms of computational speed and required memory space.
Four-dimensional coded optical OFDM for ultra-high-speed metro networks

I. B. Djordjevic, The Univ. of Arizona (United States)

The optical communication systems have been evolving rapidly in recent years in order to adapt to the continuously increasing demand on transmission capacity, coming mainly from the growing popularity of the Internet and multimedia in everyday life. In order to keep the system complexity reasonably low, the new optical communications solutions have to offer affordable upgrades of currently available optical communication systems operating at lower speeds to satisfy the required higher speeds. One such approach was based on multidimensional coded modulation. Namely, by increasing the number of dimensions (i.e., the number of orthonormal basis functions), we can increase the aggregate data rate of the system without degrading the BER performance as long as orthogonality among basis functions is preserved. All papers on multidimensional signal constellation for optical communications so far have been related to single carrier systems. In this paper, we describe how to map multidimensional signal constellation points in coherent optical OFDM systems. The key idea is to exploit all advantages of both of OFDM and multidimensional single carrier systems. The multidimensional mapper for OFDM can be described as follows. Let N-dimensional signal constellation point be represented as \( s = (s_0, s_1, \ldots, s_{N-1}) \), where \( s_j \) (\( j = 0, \ldots, N-1 \)) is the \( j \)-th coordinate. Let the duration of the signal be \( M \) signal constellation points. We can represent the signal constellation points in matrix form, by placing the coordinates of signal constellation points along the columns of signal matrix. We further apply two-dimensional inverse fast Fourier transform (2D-IFFT) to obtain 2D-IFFT array of complex numbers. The coordinates of complex numbers can be considered as in-phase (I) and quadrature (Q) channels, while the coordinates of two-dimensional array can be mapped to two orthogonal polarizations. The optical channel space is therefore four-dimensional. All other steps of this 2D-OFDM scheme are similar to conventional one-dimensional optical OFDM. On receiver side, we use the conventional polarization-diversity receiver, followed by 2D-FFT demapper. Therefore, this scheme can fully exploit the advantages of OFDM as an efficient way to deal with chromatic dispersion, PMD and PDL effects. At the same time we can exploit the advantages of multidimensional signal constellation to improve the OSNR sensitivity of conventional optical OFDM dramatically.

Real-time coherent OFDM transmission

N. Kaneda, T. Pfau, Alcatel-Lucent Bell Labs. (United States); Q. Yang, Wuhan Research Institute of Posts and Telecommunications (China); Y. Chen, Alcatel-Lucent Bell Labs. (United States)

We review the recent development in real-time coherent optical OFDM (CO-OFDM) transmission for their algorithm and implementation. The unique challenge of real-time implementation of OFDM for high speed optical data transmission including relatively large phase noise, frequency offset and dynamically changing optical channels are discussed. The fundamental digital signal processing (DSP) architectures of transmitter and receiver are presented in the manner achievable in state of the art field-programmable gate arrays (FPGAs) or application-specific integrated circuits (ASICs). Primary DSP components’ algorithm and implementations are presented and discussed. The successful demonstration of real-time CO-OFDM receivers includes a receiver with sampling rate of 2.5-Gsamples/s to receive a 3.55-Gb/s single channel and 53.3-Gb/s multi-band CO-OFDM signal.

Optimum signal constellations for high-speed optical metro networks and beyond

J. Zhang, Beijing Jiaotong Univ. (China); I. B. Djordjevic, The Univ. of Arizona (United States)

Telecommunication needs are increasing continuously thanks to the popularity of the Internet and multimedia in everyday life. The 100 Gb/s transmission is under standardization, and according to some industry experts 1Tb/s should be standardized by the year 2012-2013. Migrating to higher transmission rates comes along with numerous challenges including the degradation in the signal quality due to various linear and nonlinear channel impairments and increased installation costs. In order achieve beyond 400 Gb/s serial optical transmission using commercially available equipment, we propose the use of channel capacity achieving modulation formats. We propose the method to determine the optimum signal constellation for an arbitrary dispersion map. This method can be described by the following algorithm steps. (i) Determine the conditional probability density functions (PDFs) to be used in trellis optical channel description by evaluating of histograms. (ii) Start from arbitrary input source distribution to generate the state sequence and output sequence. (iii) Estimate the information rate by the forward-step of BJCR algorithm. (iv) Use the constrained stochastic Arimoto-Blahut algorithm to determine the optimum input distribution. (v) Determine the optimum signal constellation by minimizing the mean-square error of optimum source. (vi) Repeat steps above until convergence or until the maximum number of iterations is reached. We will study different dispersion maps currently in use and for each of them we will determine the optimum signal constellation. It will be shown that with optimum signal constellation for the dispersion map composed of periodically deployed SMF and DCF sections, we can achieve the spectral efficiency of 6 bits/s/Hz per single polarization for metro and medium-haul applications.
direct modulation of distributed feedback (DFB) lasers and coherent detection at 51.4 Gb/s and 64 QAM. A comprehensive theoretical model of the proposed system is developed. The proposed optical OFDM system concept and performance is based upon using electronic pre-compensation of laser frequency response, and electronic post compensation of DFB laser frequency chirp and chromatic dispersion. A numerical simulation of the transmission performance of the aforementioned system is conducted using different fiber lengths (40 km, 60 km, 120 km) and chirp parameters, which shows its attractiveness for access and metro applications.

7958-05, Session 1

Single-carrier versus sub-carrier bandwidth considerations for coherent optical systems

J. D. McNicol, Infinera Canada (Canada); V. Dangui, Infinera Corp. (United States); H. Sun, D. J. Krause, K. Wu, Infinera Canada (Canada); M. L. Mitchell, D. F. Welch, Infinera Corp. (United States)

Recently, 40 and 100 Gb/s Ethernet services have been defined. 400G and 1 Tb/s services can be anticipated in the future. Optical transport networks can enable a separation between the services provided and the underlying optical transport; service bandwidths may be larger or smaller than that carried on a single optical ‘wave’. In this work, we compare and contrast different arrangements for optical transport of systems having spectral efficiencies in the range of 2 - 5 bits/sec/Hz for sub-carrier bandwidths spanning 25 - 100 GHz. The analysis is made more challenging by variables such as fiber type, dispersion compensation arrangement, and traffic mix.

7958-06, Session 1

High order modulation format optical OFDM for access applications

D. Qian, T. Wang, NEC Labs. America, Inc. (United States)

Driven by both exponentially growing demand for broadband services and FSAN standardization activities, the transport capacity of next-generation optical access networks will migrate to 40-Gb/s per channel in the near future. OFDM has recently emerged as a very promising modulation format for high-speed optical transmission due to both high resistance to fiber dispersion and high spectral efficiency. By thus eliminating the need for dispersion compensation and reducing the transmission bandwidth, OFDM can significantly increase flexibility of access passive optical networks (PON) while reducing implementation cost. 40G and 100G downstream OFDMA-PON has been reported in the previous work. Limited by the DAC bandwidth and spectrum efficiency at that time, the Polarization-Multiplexing (POLMUX) OFDM signal and direct-detection has been proposed so that the required DAc bandwidth is reduced to half of the total bandwidth of the OFDM signal. However, in order to recover the signals from two orthogonal polarizations, one polarization beam splitter, two 20GHz photo-diodes and two ADC are used at the ONU receiver. Additionally, MIMO processing is needed which would also add more DSP complexity. As the rapidly increasing of the access and metro applications, such as filter, modulator, demodulator, switch and dispersion compensator. In this paper, we discuss some of our recent work on microring-resonator-based devices for advanced optical modulation formats including DPSK, DQPSK and Duobinary formats. Signal quality and power efficient operation of these devices are emphasized. It is shown that resonance-induced unique signal chirp could help extend the transmission distance with low signal quality penalties. The devices’ temperature sensitivity is also discussed.

7958-02, Session 2

Micro-resonator devices and optical broadband access application

A. Willner, L. Zhang, J. Yang, The Univ. of Southern California (United States)

Silicon micro-resonators play a key role in achieving compact, power-efficient and cost-effective devices and subsystems for optical broadband access applications, such as filter, modulator, demodulator, switch and dispersion compensator. In this paper, we discuss some of our recent work on microring-resonator-based devices for advanced optical modulation formats including DPSK, DQPSK and Duobinary formats. Signal quality and power efficient operation of these devices are emphasized. It is shown that resonance-induced unique signal chirp could help extend the transmission distance with low signal quality penalties. The devices’ temperature sensitivity is also discussed.

7958-03, Session 2

Inherent RF linearized bandwidth broadening capability of an ultra-linear optical modulator

B. Dingel, Nasfine Photonics, Inc. (United States); A. J. Prescod, Corning Inc. (United States); N. Madamopoulos, The City College of New York (United States)

We demonstrate these unique characteristics by contrasting IMPACC’s performance to the Resonator-Assisted Mach Zehnder (RAMZ) modulator. First, IMPACC can enhance its linearized RF bandwidth up to ~20% of central RF frequency (compared to ~1% for RAMZ). Second, unlike RAMZ, the RF bandwidth enhancement has a near-flat response characteristic across this bandwidth window. Third, IMPACC can maintain an excellent spurious free dynamic range (SFDR) capability (>130 dB at 1Hz bandwidth) across this window. The wide linear bandwidth capability is also demonstrated for modulation frequencies up to 75GHz.

7958-02, Session 2

Novel multicolor photodetectors for short- and long-distance optical communication

A. K. Dutta, R. Olah, G. Mizuno, Banpil Photonics, Inc. (United States); N. K. Dhar, Defense Advanced Research Projects Agency (United States)

No abstract available

7958-07, Session 2

Coherent optical component technologies for WDM transmission systems

S. Mino, K. Murata, T. Saida, I. Ogawa, NTT Photonics Labs. (Japan)

Our recent progress toward 100 Gbps and beyond is reviewed, focusing on integrated optical devices. Topics include our recently developed integrated optical receiver front-ends for 100Gbps PDM-OPSK based on multi-channel micro collimator optics and hermetically sealed O/E converters, and PLC-UNBO3 hybrid optical modulators for 100Gbps PDM-OPSK. We also show our recent activities toward beyond 100 Gbps, including 64 QAM modulators, modulation-level-selectable modulators, and high-speed digital-analog converter ICs for future multi-level transmissions.
**7958-08, Session 2**

**Enabling technologies for 100G coherent optical communication**

B. Zhang, Y. K. Lize, Opnext, Inc. (United States)

In this paper, we review the generation, detection and long-haul transmission of single-wavelength coherent PM-QPSK systems. The enabling technology of the 100G coherent transponder is first described from the systems attributes. Lab results then follow from various fiber-channel degrading effects, including cascading of more than ten 50GHz ROADMs over 1500km transmission testbed. We conclude with a recent field trial of upgrading an installed 10-Gb/s field system to 100-Gb/s using an FPGA-based real-time, single-carrier, coherent transponder prototype. Transmission over installed 1800km link was achieved with sufficient performance for error-free operation after FEC.

**7958-09, Session 2**

**Developing accurate simulations for high-speed fiber links**

S. M. Searcy, A. J. Stark, T. F. Detwiler, Y. Hsueh, Georgia Institute of Technology (United States); S. Tibuleac, ADVA Optical Networking North America, Inc. (United States); G. Chang, S. E. Ralph, Georgia Institute of Technology (United States)

Reliable simulations of high-speed fiber optic links are necessary to understand, design, and deploy fiber networks. Laboratory experiments cannot explore all possible component variations and fiber environments that are found in today’s deployed systems. Simulations typically depict relative penalties compared to a reference link. However, absolute performance metrics are required to assess actual deployment configurations. Here we detail the efforts within the Georgia Tech 100G Consortium towards achieving high absolute accuracy between simulation and experimental performance with a goal of ±0.25 dB for back-to-back configuration, and ±0.5 dB for transmission over multiple spans with different dispersion maps. We measure all possible component parameters including fiber length, loss, and dispersion for use in simulation. We also validate experimental methods of performance evaluation including OSNR assessment and DSP-based demodulation.

We investigate a wide range of parameters including modulator chirp, polarization state, polarization dependent loss, transmit spectrum, laser linewidth, and fiber nonlinearity. We evaluate 56 Gb/s (single-polarization) and 112 Gb/s (dual-polarization) DOPSK and coherent QPSK within a 50 GHz DWDM environment with 10 Gb/s OOK adjacent channels for worst-case XPM effects. We demonstrate good simulation accuracy within linear and some nonlinear regimes for a wide range of OSNR in both back-to-back configuration and up to eight spans, over a range of launch powers. This allows us to explore a wide range of environments not available in the lab, including different fiber types, ROADM passbands, and levels of crosstalk. Continued exploration is required to validate robustness over various demodulation algorithms.

**7958-05, Session 3**

**From Stokes measurements to PDF post-processing**

J. Max, S. O’Reilly, ITF Labs./Avensys Tech (Canada)

We present a robust post-processing technique to extract the polarization dependant frequency (PDF) and Polarization dependant loss (PDL) from stokes measurements of differential phase shift keying (DPSK) demodulators. The present method is based on sine-fitting on transmissions. It evaluates PDF and PDL from sinus parameters (phase, amplitude and amplitude offset) through a Müller matrix analysis. Mach-Zehnder (MZ) interferometer used for DPSK demodulation has a sinusoidal spectrum when illuminated with a sweeping source. However, since birefringence can not be totally avoided, the component response exhibits differences in polarization. PDF of an interferometer is the maximum shift in frequency at a given phase at every polarization. The most common technique consists of computing PDL data by using Müller analysis. PDF is then obtained basically by comparing wavelength at a given signal amplitude for orthogonal polarizations. This technique works well when PDF is of the order of several % of FSR, however, it becomes significantly less precise when PDF is less than 1% of FSR since it suffers from coupling between PDL and PDF along with different loss mechanisms. In this paper, we present a technique that separates phase measurements from amplitude measurements resulting in a more reliable post-processing technique for retrieving PDF.

Results confirm that this measurement technique is more precise on a wider range (actually no foreseen limits on the domain of validity) of PDL and PDF on tested demodulators.

**7958-06, Session 3**

**4G wireless networks: advances and research areas**

M. VenkatatAMLaham, Intel Corp. (United States)

The talk will cover the current status of 4G wireless networks and its evolution. We will touch upon some interesting developments and innovations to date. We will then talk about the key enhancements being considered in the 4G evolution. We will finally discuss some interesting research areas.
7958-07, Session 4

**Advances in fiber access networks development: efficient resource allocation and cost effective protection**

J. Chen, L. Wosinska, Royal Institute of Technology (Sweden)

Passive optical network (PON) is considered as the most promising fiber access network architecture, due to the relatively low deployment cost and high resource efficiency. Thus, this talk will focus on PON deployment and give an overview of our recent results related to dynamic resource allocation in PON and cost efficient reliability performance improvement of fiber access networks. It will be shown that among fiber access network architectures, PON is the one that offers solutions for providing protection at lowest cost. We will conclude with pointing out some selected research topics that are still open and need to be tackled.

7958-08, Session 4

**Crosstalk analysis of an extended reach hybrid tree-ring PON architecture**

S. C. Peiris, The City Univ. of New York (United States); D. Richards, N. Antoniades, College of Staten Island (United States); N. Madamopoulos, The City College of New York (United States)

A passive optical network (PON) is the leading technology being used for delivering last-mile connectivity without any active components in the distribution network. In this paper, we focus on an un-amplified hybrid tree-ring PON architecture that carries the benefits of both the tree and the ring architectures. Through simulation, we demonstrate the optical performance of the system and focus on the physical layer performance impact of interchannel and intrachannel crosstalk due to non-ideal WDM multiplexers/demultiplexers and optical switches in the system.

7958-09, Session 4

**A novel hybrid three-band transport system based on a DFB LD with multi-wavelength output characteristic**

H. Lu, P. Peng, H. Peng, C. Li, H. Su, National Taipei Univ. of Technology (Taiwan)

With the ubiquitous popularity of handheld devices, the demands on wireless and wired-line capacity have grown rapidly. The next generation communication systems require large data rate and broadband services highly. Radio-over-fiber (ROF), fiber-to-the-X (FTTX), and fiber optical CATV systems are promising candidates to meet the demands in wireless and wire-lined optical access networks. ROF transport systems have the ability to offer significant mobility, economic advantage, and large capacity due to the characteristics of broad bandwidth and low transmission loss. FTTX networks have offers the last mile solution in optical access networks. In addition, fiber optical CATV systems are deployed widely to provide broadband to subscribers. A hybrid three-band transport system that uses different optical wavelengths to deliver combined ROF RF/FTTX BB/CATV analog signals would be quite useful for a fiber networks providing telecommunication, Internet, and CATV services. However, it is a challenge to transmit RF, BB, and CATV signals simultaneously using one optical fiber in a cost-effective way. Hybrid multi-band transport systems are envisioned to have a multiple number of distributed feedback laser diodes (DFB LDs) which are wavelength-selected for each channel and controlled to operate at a specific wavelength, this process will increase the cost and complexity of the systems. Several approaches have been proposed to solve the problem. Lightwave transport systems employing spectrum-sliced light sources such as light-emitting diodes (LEDs) or amplified spontaneous emission (ASE) sources were proposed. Nevertheless, the output power of LED is insufficient to accommodate many channels. Moreover, although the spectrum-sliced ASE source provides much higher output power than that of the LED, it requires expensive erbium-doped fiber (EDF) and pumping LD. Recently, there has been a proposal of a multi-wavelength light source which is based on direct modulation of a DFB LD. When a DFB LD is directly modulated with large optical modulation index (OMI), the single wavelength characteristic of DFB LD will be changed into multi-wavelength one, and it can be used as a cost-effective light source in hybrid multi-band transport systems. In this report, we proposed and experimentally demonstrated a potentially cost-effective ROF/FTTX/CATV hybrid three-band transport system based on direct modulation of a DFB LD with multi-wavelength output characteristic. Transmission performances over an 80-km single-mode fiber (SMF) transport were studied. With the help of direct-detection technique and optical single sideband (SSB) scheme at the receiving site, low bit error rate (BER) and clear eye diagram were achieved for ROF and FTTX applications; as well as good performances of carrier-to-noise ratio (CNR), composite second-order (CSO) and composite triple beat (CTB) were obtained for CATV signals.

7958-10, Session 4

**Unified cost effective next-generation passive optical network and IEEE 802.16m network architecture**

S. Hussain, S. R. Zaidi, H. Erkan, The City College of New York (United States); A. Sana, Bronx Community College (United States)

This paper presents the key features of the emerging Next Generation Passive Optical Network (NG-PON) and IEEE 802.16m based Mobile Worldwide Interoperability for Microwave Access (WiMAX) networks to build a unified cost effective next generation hybrid Fiber-Wireless...
network. NG converged-access solutions can meet the demand for cost, mobility, bandwidth, reliability, security, and flexibility. NG-PON and 4th Generation (4G) Mobile WiMAX unified architecture enables differentiated bandwidth allocation to end users and can provide more network range and capacity at reduced operational cost. The concept of hybrid optical network unit and advanced base station (ONU-ABS) simplifies the network architecture and can save installation and operational costs.

7958-11, Session 5

Convergence of broadcasting and communications utilizing CATV network

K. Kumamoto, H. Hoshino, K. Yasukawa, Osaka Institute of Technology (Japan); T. Higashino, K. Tsukamoto, S. Komaki, Osaka Univ. (Japan); K. Inagaki, National Institute of Information and Communications Technology (Japan)

A so-called digital divide problem which is difference caused in information and communication service offered between regions is becoming social problems in Japan. Authors are investigating about a new solution of digital divide problem utilizing Radio over Fiber technology. The key point of our project is sub-carrier multiplexing (SCM) transmissions including broadcasting and communications. This paper will show overview of the project and propose a cost-effective system configuration. Moreover, some results of field trials will be demonstrated.

7958-12, Session 5

Performance analysis of IM/DD radio-on-fiber link for transmitting multicarrier RF signals

T. Higashino, S. Okumura, K. Tsukamoto, S. Komaki, Osaka Univ. (Japan); K. Kumamoto, K. Yasukawa, Osaka Institute of Technology (Japan); K. Inagaki, National Institute of Information and Communications Technology (Japan)

The Radio-on-fiber (RoF) technology is a strong candidate to construct cost-effective heterogeneous wireless access network for both urban and rural areas. Nowadays, the RoF technology can utilize to converge the broadcasting and the broadband wireless communications, because of their huge bandwidth, and protocol transparency. To distribute RF signals from control station to remote station, RF signals modulates the optical carrier intensity and it is detected by the use of photodetector. At the output of the RoF link, RF signals are radiated from the remote antenna that is quite limited by the radio regulations, such as spectrum mask, spurious power and adjacent channel leakage power (ACLR). Transmitting RF signals are deteriorated by the nonlinearity of the RoF link and following RF amplifier. Nonlinear distortion is especially related to the spectrum mask and ACLR regulation, and they are generally estimated by the two-tone test. Therefore, the nonlinear distortion estimation is taken as an important issue in the subcarrier multiplexing (SCM) system and to transmit multicarrier RF signal, because it increases by product of carrier number. Most of recent radio frequency (RF) signals in wireless service are employing multicarrier modulation whose subcarriers are densely located in frequency domain, such as orthogonal frequency division multiplexing (OFDM).

This paper provides analysis method of intermodulation distortion and peak factor of multicarrier RF signals including IEEE802.11g, ISDB-T and IEEE802.16e-2005 over intensity modulation / direct detection (IM/DD) RoF link. Experimental evaluation is also presented in terms of the error vector magnitude (EVM) and peak to average power ratio (PAPR).

7958-13, Session 5

Modulation of relaxation oscillation frequency of a DFB laser by using direct detection

A. García Juárez, Univ. de Sonora (Mexico); A. Baylón-Fuentes, P. Hernández-Nava, I. E. Zaldívar-Huerta, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); J. Rodríguez-Asumoza, Univ. de las Américas Puebla (Mexico); G. Aguayo-Rodriguez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); R. R. Gómez-Colín, Univ. de Sonora (Mexico)

Relaxation oscillation frequency (fr) in semiconductor lasers is a primarily important factor to investigate transmission capacity in multigigabit telecommunication systems as well as in subcarrier multiplexed (SCM) transmission systems. Infrared lasers (1.3 and 1.5 µm) are used as signal sources for the SCM transmission due to spectral characteristics as optical power and low phase noise, etc. Relaxation oscillation frequency is produced when a laser is operated in the low laser threshold current region. In this operation region, a semiconductor laser shows a smooth curve, where we can observe uncertainty about defining the onset of laser oscillation which are translated as relaxation oscillations in the laser intensity and can be seen as sidebands on both sides of the main laser line. In this context, we propose an optical communication system by using the relaxation oscillation frequency as an information carrier. The experimental setup used in this work is based on direct detection. In particular, we use a 1.5 µm wavelength distributed feedback (DFB) which is operated in the low laser threshold current region and the emission generated is detected by a fast photodetector (PD). The microwave signal obtained at the output of the PD is located on C band and it is modulated with analog TV signals. This technique has potential applications in SCM systems, such as CATV with many more channels, because frequency dependence of distortion and noise characteristics, which largely affect the quality in SCM transmission, are mainly determined by fr. Experimental results are validated by numerical simulations.

7958-14, Session 5

Development of broadband optical frequency resource over 8.4-THz in 1.0-um waveband for photonic transport systems

N. Yamamoto, National Institute of Information and Communications Technology (Japan); Y. Omigawa, Y. Kinoshita, Aoyama Gakuin Univ. (Japan); A. Kannno, K. Akahane, T. Kawanishi, National Institute of Information and Communications Technology (Japan); H. Sotobayashi, Aoyama Gakuin Univ. (Japan)

Constantly growing demand for greater photonic network capacities has necessitated the use of alternative wavebands and the development of methods for enhancing the transmission capacities. 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. We have recently focused on a use of a novel wavelength band such as a 1-µm waveband (Thousand-band: T-band) together with the conventional C- and L-bands for an enhancing usable optical frequency resources in a future photonic network employing wavelength division multiplexing (WDM) [1]. Therefore, here, we develop an ultra-broadband photonic transport system in the T-band to develop novel optical frequency resources in its waveband. In the proposed system, a holey fiber (HF) as a novel transmission line has been developed that is capable of data transmissions for the ultra-broadband. In this study, we demonstrated an ultra-broadband, 10-Gbps and error-free operation in the T-band photonic transport system using...
a wavelength tunable light source and a few-km long HF transmission line (Typical: >3.3-km). We successfully developed an ultra-broadband transmission capability, beyond the 8.4-THz bandwidth (1037-1068-nm), from usable optical frequency resources in the T-band. To construct the photonic network system of the future, we believe that the technologies of the demonstrated T-band photonic transport system using the HF transmission line represent a breakthrough in pioneering the use of ultra-broadband optical frequency resources. [1] N. Yamamoto et al., Opt. Express, 18, 4695 (2010).

7958-20, Poster Session
Next generation wireless technology WiMAX and its integration with EPON
S. R. Zaied, S. Hussain, H. Erkan, The City College of New York (United States); A. Sana, Bronx Community College (United States); A. Carranza, New York City College of Technology (United States)

Integration of next generation wireless technologies i.e., WiMAX (Worldwide Interoperability for Microwave Access) and or LTE (Long Term Evolution) with EPON is a brilliant concept that gives users the best of two worlds, wireless and wired. WiMAX gives users the convenience of mobility while integration with EPON gives theoretically unlimited bandwidth of fiber optic cable in backhaul. This paper investigates WiMAX and EPON technologies. At the end different scenarios of integration of EPON with WiMAX are discussed and optimal QoS mapping scheme is proposed for the integration of EPON and WiMAX.

7958-21, Poster Session
Techno-economic feasibility studies for solar-powered passive optical network
K. M. Ennser, S. Mangeni, S. Taccheo, Swansea Univ. (United Kingdom); S. Aleksić, Vienna Univ. of Technology (Austria)

The increasing demand for quality, quantity and speed in the telecommunication industry has been key drivers for the ongoing research, innovation and competition among services providers. It is generally believed now that the internet, on which many services depend, is poised to become truly pervasive providing services anywhere, anytime connectivity to people objects and things.

Among several technologies, passive optical network is one of the most promising high capacity low cost access network technologies. With the coming bandwidth hungry applications and increase of internet subscriber numbers the demand for PON is expected to grow rapidly. Considering the current green-technology trend, the power consumption of the network becomes a relevant issue. Although PON is considered a low power consumption access technology, the continuous broadband growth demand in the metropolitan area an alternative power supplier should be considered to address the energy need.

This paper presents a techno-economic feasibility study to use solar energy as a renewable energy to power the passive optical network. This discussion focuses on the requirements and sources of power for the active components of optical access networks. To ensure continuous reduction of the carbon footprint while advancing towards purely passive optical networks, we have emphasized the need for alternative, renewable and greener sources to supply the required power. Solar power would be used as the default power source while mains are used as backup or a standby source. This is because solar power can be harvested and stored with less carbon footprint.

7958-15, Session 6
WSS technology for the next generation ROADM networks
G. Cohen, K. Bala, Oclaro, Inc. (United States)

No abstract available

7958-15, Session 6
Ultra-wide tuning range of reconfigurable optical add-drop multiplexer using photorefractive polymer
Y. Wakayama, A. Okamoto, A. Tomita, Hokkaido Univ. (Japan); K. Sato, Hokkai-Gakuen Univ. (Japan)

Reconfigurable optical add-drop multiplexer (ROADM) systems promise to perform for green photonics by maximizing bandwidth capacity while enabling the reduction of capital and operational costs of equipment. For constructing ROADM systems with wide tuning range over 200nm, we focus on a transmission-type holographic wavelength filter with a photorefractive polymer because of the following great advantages. In our method, a wavelength for adding/dropping can be shifted easily by changing an incident angle of WDM signals. In addition, since the holographic grating is induced in the polymer as a real-time hologram, a filtering wavelength layer can be reassigned optically by rewriting the hologram with the change of grating spacing. The grating is static in long term by using a photorefractive polymer; however, it can be quickly erased and reconfigured with control beams. Thus, traffic can be remotely controlled with low power consumption because this type of grating is rewritable in pure optical operation. At the same time, circulators are unnecessary because its operation is based on Bragg diffraction through the transmission-type grating. In this work, we demonstrate on the
add-drop operation using a laser at 832 nm as a control beam source, and investigate diffraction efficiency and tuning range for different index modulation. From these results, we show the extra-wide tuning range from visible to infrared spectrum and short reconfiguration time estimated from the measured response time for erasing and writing the hologram. Furthermore, we show that diffraction efficiency can be increased by apodizing the distribution of the holographic grating.

7958-16, Session 6

Spectrum variable colorless, directionless and contentionless multi-degree ROADM node

P. N. Ji, NEC Labs. America, Inc. (United States); Y. Aono, NEC Corp. (Japan); T. Wang, NEC Labs. America, Inc. (United States)

Global communication traffic has been growing rapidly and is becoming more dynamic, leading to increased demands for better efficiency with respect to resources, scale, energy, and cost, especially in metro networks. As a result, metro optical networks can transmit WDM channels with mixed line rates simultaneously, and new services such as wavelength-on-demand are being offered. The current fixed grid WDM system cannot provide optimum spectrum utilization for such emerging networks, and the conventional ROADM nodes are facing color and direction issues.

We recently proposed a flexible optical WDM (FWDM) network architecture that is capable of dynamic allocation of network resources (in particular the optical spectrum), dynamic provisioning of connections, and automated network control to eliminate manual operation. A key network element in this FWDM network is a flexible ROADM node that can provide variable spectrum configuration dynamically.

In this work, we propose and experimentally demonstrate a multi-degree ROADM node that allows flexible spectrum configuration with colorless, directionless and contentionless switching operations. It uses liquid crystal on silicon (LCOS)-based switching platform to obtain fine spectral granularity and change passband widths for individual WDM channels. And it uses a transponder aggregator to perform centralized sharing of transponders for all add/drop signals. Experiment results show that inter-degree cross-connect and colorless and directionless add/drop operation on spectrum variable WDM signals can be achieved without incurring wavelength blocking in the node. This ROADM node enables spectrum and cost efficient switching compared to conventional fixed grid ROADM nodes.

7958-17, Session 6

PCE-based scalable dynamic path control for large-scale photonic networks

S. Araki, NEC Corp. (Japan); K. Shimada, H. Hasegawa, K. Sato, Nagoya Univ. (Japan); Y. Izawa, S. Ishida, I. Nishioka, NEC Corp. (Japan)

ASON (Automatic Switched Optical Network) / GMPLS (Generalized Multi-Protocol Label Switching) control plane technologies for automated path control of a photonic network have been developed for this decade. In the past few years, it has been deployed in service provider’s commercial networks, and their advantage in terms of OPEX (operational expenditure) reduction was reported by a service provider. Although, most of such networks are still relatively small, which are constructed by few tens of nodes, and they have to be expanded to nation-wide larger networks for more effective OPEX reduction. To control larger networks, typically thousands of nodes, multi-domain network configuration is advantageous to routing protocol scalability. Furthermore, the application of photonic network technology will continue to expand in the future, and optical paths will come to traverse multiple domains that are possibly under different carriers’ control and management.

We have studied qualitatively and concluded that the PCE (Path Computation Element) based routing is the most suitable model rather than other routing models, the per-domain routing and the ASON hierarchical routing for inter-domain path control over multi-domain photonic networks. For the inter-domain path control, the selection of domain sequences has a significant impact on the efficiency of networks. However, quantitative study of global optimization using a large network test environment has not been reported yet.

In the presentation, we will discuss the overall architecture of multi-domain photonic network control system, and also provide measured performance results for inter-domain path computation and path setups using global optimization scheme.

7958-18, Session 6

Linear formulation to avoid adjacent channel interference in LTD of optical networks

K. Day Rosario Assis, Federal Univ. do Recôncavo da Bahia (Brazil); A. F. Santana, Univ. Estadual do Sudoeste da Bahia (Brazil); M. Savasini, Univ. Estadual de Campinas (Brazil)

In this work, we propose a new optimization LP (Linear Programming)-complete formulation to block channel interference in links of optical fiber. To the best of our belief, the first linear formulation of a partial solution to the RWA problem avoiding the use of adjacent channels has been stated in other studies, where constraints are created using path formulation, where all possible paths are known beforehand. In this work, we propose a link formulation. Therefore, we do not know beforehand the set of alternative routes for any node pair. With all possible routes, the linear formulation that we propose can find effective results to avoid channel interference. Furthermore, our formulation is to the full logical topology design. We observe the effect of physical impairments in a higher layer, i.e., in virtual topology configuration.

7958-24, Session 6

Colorless and directionless multi-degree reconfigurable optical add/drop multiplexers for 100G network application

T. Wang, P. N. Ji, NEC Labs. America, Inc. (United States); Y. Aono, NEC Corp. (Japan)

The reconfigurable optical add/drop multiplexer (ROADM) has become one of the most important elements in 100G DWDM network. The next generation multi-degree ROADM requires two main features: colorless and directionless. Colorless means that add/drop ports are not wavelength specific, and directionless feature enables any transponder to be connected to any degree. In this paper we review and analyze different multi-degree ROADM node architectures that offer full colorless and directionless features with its network application. Their key characteristics and properties, including optical loss, size, cost, modularity and upgradability, are compared and discussed.

7958-16, Session 7

Broadband ubiquitous femto-cell network with MIMO distributed antenna system over WDM-PON

K. Iwatsuki, T. Tashiro, K. Hara, T. Taniguchi, J. Kani, N. Yoshimoto, NTT Corp. (Japan); K. Miyamoto, T. Nishiumi, T. Higashino, K. Tsukamoto, S. Komaki, Osaka Univ. (Japan)

This talk introduces a research on a convergence of WDM access and femto-cell MIMO antenna system which can provides next generation wireless accesses to realize higher bit-rate equivalent to that in current
All-optical demultiplexer based on dynamic multiple holograms for optical MIMO processing and mode division multiplexing

T. Oda, A. Okamoto, D. Soma, A. Tomita, Y. Wakayama, Hokkaido Univ. (Japan)

Optical MIMO processing and Mode Division Multiplexing (MDM) technique is attracting researchers’ attention recently. In MDM transmission technique, independent time series signal is modulated / demodulated for each spatial mode propagating in a multimode fiber. Therefore, MDM technique can be expected to bring a high-speed communication because of its dispersion-free characteristics. However, the separation technique which enables to split multiplexed spatial mode into each mode is needed. In previous reported MIMO systems, the separation of the multiplexed output signals has been realized by a micropositioning detection at different positions of the cross section of the multimode fiber. However, there is a problem that it is difficult to separate the spatial modes overlapped on the cross section of the fiber and to respond the mode change and fluctuation with fiber transmissions. In this study, we propose an all-optical demultiplexer based on dynamic multiple holograms by using a photorefractive material. This demultiplexer can adapt to distortion and temporal variation of spatial modes propagating in a multi-mode fiber caused by external environment. We evaluate a mode separation performance of this demultiplexer with various combinations of spatial modes including high-order LP modes and find out suitable combinations for MDM systems. We also consider the optical coupling between the fiber and demultiplexer. The diffraction efficiency and separation ratio is improved by inserting a random phase mask before demultiplexing and by adjustment of some optical parameters. Finally, the method of automatically rewriting the hologram to respond the change of the spatial mode is examined.

Optical wireless networked-systems: applications to aircrafts

M. Kavehrad, J. Fadlullah, The Pennsylvania State Univ. (United States)

This paper focuses on leveraging the progress in semiconductor technologies to facilitate production of efficient light-based in-flight entertainment (IFE), distributed sensing, navigation and control systems. We demonstrate the ease of configuring “engineered pipes” using cheap lenses, etc. to achieve simple linear transmission capacity growth. Investigation of energy-efficient, miniaturized transceivers will create a wireless medium, for both inter and intra aircrafts, providing enhanced security, and improved quality-of-service for communications links in greater harmony with onboard systems. The applications will seamlessly inter-connect multiple intelligent devices in a network that is deployable for aircrafts navigation systems, on-board sensors and entertainment data delivery systems, and high-definition audio-visual broadcasting systems. Recent experimental results on a high-capacity infrared (808 nm) system are presented. The light source can be applied in a hybrid package along with a visible lighting LED for both lighting and communications. Also, we present a pragmatic combination of light communications through “Spotlighting” and existing onboard power-lines. It is demonstrated in details that a high-capacity IFE visible light system communicating over existing power-lines (VLC/PLC) may lead to savings in many areas through reduction of size, weight and energy consumption. This paper addresses the challenges of integrating optimized optical devices in the variety of environments described above, and presents mitigation and tailoring approaches for a multi-purpose optical network.
Four-dimensional coded optical OFDM for ultra-high-speed metro networks

I. B. Djordjevic, The Univ. of Arizona (United States)

The optical communication systems have been evolving rapidly in recent years in order to adapt to the continuously increasing demand on transmission capacity, coming mainly from the growing popularity of the Internet and multimedia in everyday life. In order to keep the system complexity reasonably low, the new optical communications solutions have to offer affordable upgrades of currently available optical communication systems operating at lower speeds to satisfy the required higher speeds. One such approach was based on multidimensional coded modulation. Namely, by increasing the number of dimensions (i.e., the number of orthonormal basis functions), we can increase the aggregate data rate of the system without degrading the BER performance as long as orthogonality among basis functions is preserved. All papers on multidimensional signal constellation for optical communications so far have been related to single carrier systems. In this paper, we describe how to map multidimensional signal constellation points in coherent optical OFDM systems. The key idea is to exploit all advantages of both OFDM and multidimensional single carrier systems. The multidimensional mapper for OFDM can be described as follows. Let N-dimensional signal constellation point be represented as \( s=(s_0,s_1,...,s_{N-1}) \), where \( s_j \ (j=0,...,N-1) \) is the \( j \)th coordinate. Let the duration of the signal be \( M \) signal constellation points. We can represent the signal constellation points in matrix form, by placing the coordinates of signal constellation points along the columns of signal matrix. We further apply two-dimensional inverse fast Fourier transform (2D-IFFT) to obtain 2D-IFFT array of complex numbers. The coordinates of complex numbers can be considered as in-phase (I) and quadrature (Q) channels, while the coordinates of two-dimensional array can be mapped to two orthogonal polarizations. The optical channel space is therefore four-dimensional. All other steps of this 2D-OFDM scheme are similar to conventional one-dimensional optical OFDM. On receiver side, we use the conventional polarization-diversity receiver, followed by 2D-FFT demapper. Therefore, this scheme can fully exploit the advantages of OFDM as an efficient way to deal with chromatic dispersion, PMD and PDL effects. At the same time we can exploit the advantages of multidimensional signal constellation to improve the OSNR sensitivity of conventional optical OFDM dramatically.

Optimum signal constellations for high-speed optical metro networks and beyond

J. Zhang, Beijing Jiaotong Univ. (China); I. B. Djordjevic, The Univ. of Arizona (United States)

Telecommunication needs are increasing continuously thanks to the popularity of the Internet and multimedia in everyday life. The 100 Gb/s transmission is under standardization, and according to some industry experts 1Tb/s should be standardized by the year 2012-2013. Migrating to higher transmission rates comes along with numerous challenges including the degradation in the signal quality due to various linear and nonlinear channel impairments and increased installation costs. In order achieve beyond 400 Gb/s serial optical transmission using commercially available equipment, we propose the use of channel capacity achieving modulation formats. We propose the method to determine the optimum signal constellation for an arbitrary dispersion map. This method can be described by the following algorithm steps. (i) Determine the conditional probability density functions (PDFs) to be used in trellis optical channel description by evaluating of histograms. (ii) Start from arbitrary input source distribution to generate the state sequence and output sequence. (iii) Estimate the information rate by the forward-step of BJCR algorithm. (iv) Use the constrained stochastic Arimoto-Blahut algorithm to determine the optimum input distribution. (v) Determine the optimum signal constellation by minimizing the mean-square error of optimum source. (vi) Repeat steps above until convergence or until the maximum number of iterations is reached. We will study different dispersion maps currently in use and for each of them we will determine the optimum signal constellation. It will be shown that with optimum signal constellation for the dispersion map composed of periodically deployed SMF and DCF sections, we can achieve the spectral efficiency of 6 bits/s/Hz per single polarization for metro and medium-haul applications.

Real-time coherent OFDM transmission

N. Kaneda, T. Pfau, Alcatel-Lucent Bell Labs. (United States); Q. Yang, Wuhan Research Institute of Posts and Telecommunications (China); Y. Chen, Alcatel-Lucent Bell Labs. (United States)

We review the recent development in real-time coherent optical OFDM (CO-OFDM) transmission for their algorithm and implementation. The unique challenge of real-time implementation of OFDM for high speed optical data transmission including relatively large phase noise, frequency offset and dynamically changing optical channels are discussed. The fundamental digital signal processing (DSP) architectures of transmitter and receiver are presented in the manner achievable in state of the art field-programmable gate arrays (FPGAs) or application-specific integrated circuits (ASICs). Primary DSP components’ algorithm and implementations are presented and discussed. The successful demonstration of real-time CO-OFDM receivers includes a receiver with sampling rate of 2.5-Gsamples/s to receive a 3.55-Gb/s single channel and 53.3-Gb/s multi-band CO-OFDM signal.

Potential of OFDM for next generation optical access

D. Fritzsche, EICT GmbH (Germany); E. Weis, D. Breuer, Deutsche Telekom AG (Germany)

No abstract available

Low cost direct modulation and coherent detection optical OFDM for metro applications

N. Sheffi, D. Sadot, Ben-Gurion Univ. of the Negev (Israel)

High speed transmission systems (> 10 Gb/s) for cost-sensitive applications such as metropolitan network have attracted extensive interest due to the explosive data traffic growth in such applications. Optical orthogonal frequency division multiplexing (OFDM) based on direct modulation and direct detection for single-mode fiber (SMF) and multi-mode fiber (MMF) without optical amplification and dispersion compensation was proposed. Recent research has also shown that Optical OFDM can be used with electronic dispersion compensation using direct detection in SMF. However, laser frequency chirp has been
identified as a key limiting factor of capacity-versus-reach performance. In this paper, we present a novel concept of low cost optical OFDM with direct modulation of distributed feedback (DFB) lasers and coherent detection at 51.4 Gb/s and 64 QAM. A comprehensive theoretical model of the proposed system is developed. The proposed optical OFDM system concept and performance is based upon using electronic pre-compensation of laser frequency response, and electronic post compensation of DFB laser frequency chirp and chromatic dispersion. A numerical simulation of the transmission performance of the aforementioned system is conducted using different fiber lengths (40 km, 60 km, 120 km) and chirp parameters, which shows its attractiveness for access and metro applications.

7959-05, Session 1

Single-carrier versus sub-carrier bandwidth considerations for coherent optical systems

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Recently, 40 and 100 Gb/s Ethernet services have been defined. 400G and 1 Tb/s services can be anticipated in the future. Optical transport networks can enable a separation between the services provided and the underlying optical transport; service bandwidths may be larger or smaller than that carried on a single optical ‘wave’. In this work, we compare and contrast different arrangements for optical transport of systems having spectral efficiencies in the range of 2 - 5 bits/sec/Hz for sub-carrier bandwidths spanning 25 - 100 GHz. The analysis is made more challenging by variables such as fiber type, dispersion compensation arrangement, and traffic mix.

7959-06, Session 1

High order modulation format optical OFDM for access applications

D. Qian, T. Wang, NEC Labs. America, Inc. (United States)

Driven by both exponentially growing demand for broadband services and FSAN standardization activities, the transport capacity of next-generation optical access networks will migrate to 40-Gb/s per channel in the near future. OFDM has recently emerged as a very promising modulation format for high-speed optical transmission due to both its high resistance to fiber dispersion and high spectral efficiency. By thus eliminating the need for dispersion compensation and reducing the transmission bandwidth, OFDM can significantly increase flexibility of access passive optical networks (PON) while reducing implementation cost. 40G and 100G downstream OFDM-PON has been reported in the previous work. Limited by the DAC bandwidth and spectrum efficiency at that time, the Polarization-Multiplexing (POLMUX) OFDM signal and direct-detection has be proposed so that the required DAC bandwidth is reduced to half of the total bandwidth of the OFDM signal. However, in order to recover the signals from two orthogonal polarizations, one polarization beam splitter, two 20GHz photo-diodes and two ADC are used at the ONU receiver. Additionally, MIMO processing is needed which would also add more DSP complexity. As the rapidly increasing of the DAC sampling rate/bandwidth as well as the spectrum efficiency from higher order modulation format, a simple single-side band OFDM with a real single photodiode direct-detection becomes possible for 40G+ OFDM-PON. We propose and experimentally demonstrate a simple OFDM-PON architecture for downstream that benefits from all these technical development by exploiting SSF-OFDM with direct-detection to realize 40-Gb/s transmission over 20 km SSMF plus 15dB attenuation. The 64/32/16-QAM modulation formats are used respectively, enabling total 43.6-Gb/s transmission.

7959-02, Session 2

Micro-resonator devices and optical broadband access application

A. Willner, L. Zhang, J. Yang, The Univ. of Southern California (United States)

Silicon micro-resonators play a key role in achieving compact, power-efficient and cost-effective devices and subsystems for optical broadband access applications, such as filter, modulator, demodulator, switch and dispersion compensator. In this paper, we discuss some of our recent work on microring-resonator-based devices for advanced optical modulation formats including DPSK, DQPSK and Duobinary formats. Signal quality and power efficient operation of these devices are emphasized. It is shown that resonance-induced unique signal chirp could help extend the transmission distance with low signal quality penalties. The devices’ temperature sensitivity is also discussed.

7959-03, Session 2

Inherent RF linearized bandwidth broadening capability of an ultra-linear optical modulator

B. Dingel, Nasfine Photonics, Inc. (United States); A. J. Prescod, Corning Inc. (United States); N. Madamopoulos, The City College of New York (United States)

We demonstrate these unique characteristics by contrasting IMPACC’s performance to the Resonator-Assisted Mach Zehnder (RAMZ) modulator. First, IMPACC can enhance its linearized RF bandwidth up to – 20% of central RF frequency (compared to ~1% for RAMZ). Second, unlike RAMZ, the RF bandwidth enhancement has a near-flat response characteristic across this bandwidth window. Third, IMPACC can maintain an excellent spurious free dynamic range (SFDR) capability (>130 dB at 1Hz bandwidth) across this window. The wide linear bandwidth capability is also demonstrated for modulation frequencies up to 75GHz.

7959-05, Session 2

Novel multicolor photodetectors for short- and long-distance optical communication

A. K. Dutta, R. Olah, G. Mizuno, Banpil Photonics, Inc. (United States); N. K. Dhar, Defense Advanced Research Projects Agency (United States)

No abstract available

7959-07, Session 2

Coherent optical component technologies for WDM transmission systems

S. Mino, K. Murata, T. Saida, I. Ogawa, NTT Photonics Labs. (Japan)

Our recent progress toward 100 Gbps and beyond is reviewed, focusing on integrated optical devices. Topics include our recently developed integrated optical receiver front-ends for 100Gbps PDM-OPSK based on multi-channel micro collimator optics and hermetically sealed O/E converters, and PLC-LiNbO3 hybrid optical modulators for 100Gbps PDM-OPSK. We also show our recent activities toward beyond 100 Gbps, including 64 QAM modulators, modulation-level-selectable modulators, and high-speed digital-analog converter ICs for future multi-level transmissions.
7959-08, Session 2

Enabling technologies for 100G coherent optical communication

B. Zhang, Y. K. Lize, Opnext, Inc. (United States)

In this paper, we review the generation, detection and long-haul transmission of single-wavelength coherent PM-QPSK systems. The enabling technology of the 100G coherent transponder is first described from the systems attributes. Lab results then follow from various fiber-channel degrading effects, including cascading of more than ten 50GHz ROADMs over 1500km transmission testbed. We conclude with a recent field trial of upgrading an installed 10-Gb/s field system to 100-Gb/s using an FPGA-based real-time, single-carrier, coherent transponder prototype. Transmission over installed 1800km link was achieved with sufficient performance for error-free operation after FEC.

7959-09, Session 2

Developing accurate simulations for high-speed fiber links

S. M. Searcy, A. J. Stark, T. F. Detwiler, Y. Hsueh, Georgia Institute of Technology (United States); S. Tibuleac, ADVA Optical Networking North America, Inc. (United States); G. Chang, S. E. Ralph, Georgia Institute of Technology (United States)

Reliable simulations of high-speed fiber optic links are necessary to understand, design, and deploy fiber networks. Laboratory experiments cannot explore all possible component variations and fiber environments that are found in today’s deployed systems. Simulations typically depict relative penalties compared to a reference link. However, absolute performance metrics are required to assess actual deployment configurations. Here we detail the efforts within the Georgia Tech 100G Consortium towards achieving high absolute accuracy between simulation and experimental performance with a goal of ±0.25 dB for back-to-back configuration, and ±0.5 dB for transmission over multiple spans with different dispersion maps. We measure all possible component parameters including fiber length, loss, and dispersion for use in simulation. We also validate experimental methods of performance evaluation including OSNR assessment and DSP-based demodulation. We investigate a wide range of parameters including modulator chirp, polarization state, polarization dependent loss, transmit spectrum, laser linewidth, and fiber nonlinearity. We evaluate 56 Gb/s (single-polarization) and 112 Gb/s (dual-polarization) DQPSK and coherent QPSK within a 50 GHz DWDM environment with 10 Gb/s OOK adjacent channels for worst-case XPM effects. We demonstrate good simulation accuracy within linear and some nonlinear regimes for a wide range of OSNR in both back-to-back configuration and up to eight spans, over a range of launch powers. This allows us to explore a wide range of environments not available in the lab, including different fiber types, ROADM passbands, and levels of crosstalk. Continued exploration is required to validate robustness over various demodulation algorithms.

7959-06, Session 3

Bidirectional data transmission over multimode fiber using integrated transceiver chips

R. Michalzik, A. Kern, M. Stach, F. Rinaldi, D. Wahl, Univ. Ulm (Germany)

No abstract available

7959-07, Session 3

Tuneable VCSEL aiming for the application in interconnects and short haul systems

C. Gieri, K. Zogal, S. Jatta, H. A. Davani, Technische Univ. Darmstadt (Germany); F. K üppers, Technische Univ. Darmstadt (United States); P. Meissner, Technische Univ. Darmstadt (Germany); T. Gründl, C. Grasse, M. Amann, Walter Schottky Institut (Germany); A. J. Daly, B. Corbett, Tyndall National Institute (Ireland); B. W. Kögel, Á. Haglund, J. Gustavsson, P. Westbergh, A. Larsson, Chalmers Univ. of Technology (Sweden); P. Debernardi, Istituto di Elettronica e di Ingegneria dell’Informazione e delle Telecomunicazioni (Italy); M. Ortsiefer, Vertilas GmbH (Germany)

No abstract available

7959-08, Session 3

Inexpensive 3dB coupler for POF communication by injection-molding production

M. Haupt, U. H. P. Fischer, Hochschule Harz (Germany)

POFs (polymer optical fibers) replace traditional communication media such as copper and glass step by step within short distance communication systems, mostly because of their cost-effectiveness and easy handling.

POFs are used in various fields of optical communication, e.g. the automotive sector or in-house communication. But for now only a few key components for a POF communication network are available. Even basic components, such as splices and couplers, are fabricated manually. This leads to high costs and fluctuations in the performance of the component.

That means, that “state-of-the-art” couplers have high insertion losses due to their manufacturing method. This can be only compensated by higher power budgets.

To produce couplers with better performances new fabrication methods are indispensable. A cheap and effective way to produce couplers for POF communications system is injection molding.

The paper gives an overview over couplers available on market and compares their performance. The paper shows an easy way to produce 3dB couplers by injection molding. First prototypes are presented and characterized. Also an overview of different coupler types (1:3, 1:4) is presented and how these kinds of couplers can be produced easily.

7959-07, Session 4

Advances in fiber access networks development: efficient resource allocation and cost effective protection

J. Chen, L. Wosinska, Royal Institute of Technology (Sweden)

Passive optical network (PON) is considered as the most promising fiber access network architecture, due to the relatively low deployment cost and high resource efficiency. Thus, this talk will focus on PON deployment and give an overview of our recent results related to dynamic resource allocation in PON and cost efficient reliability performance improvement of fiber access networks. It will be shown that among fiber access network architectures, PON is the one that offers solutions for providing protection at lowest cost. We will conclude with pointing out some selected research topics that are still open and need to be tackled.
Crosstalk analysis of an extended reach hybrid tree-ring PON architecture
S. C. Peiris, The City Univ. of New York (United States); D. Richards, N. Antoniadis, College of Staten Island (United States); N. Madamopoulos, The City College of New York (United States)

A passive optical network (PON) is the leading technology being used for delivering last-mile connectivity without any active components in the distribution network. In this paper, we focus on an un-amplified hybrid tree-ring PON architecture that carries the benefits of both the tree and the ring architectures. Through simulation, we demonstrate the optical performance of the system and focus on the physical layer performance impact of interchannel and intrachannel crosstalk due to non-ideal WDM multiplexers/demultiplexers and optical switches in the system.

A novel hybrid three-band transport system based on a DFB LD with multi-wavelength output characteristic
H. Lu, P. Peng, H. Peng, C. Li, H. Su, National Taipei Univ. of Technology (Taiwan)

With the ubiquitous popularity of handheld devices, the demands on wireless and wired-line capacity have grown rapidly. The next generation communication systems require large data rate and broadband services highly. Radio-over-fiber (ROF), fiber-to-the-X (FTTX), and fiber optical CATV systems are promising candidates to meet the demands in wireless and wire-line optical access networks. ROF transport systems have the ability to offer significant mobility, economic advantage, and large capacity due to the characteristics of broad bandwidth and low transmission loss. FTTX networks have offers the last mile solution in optical access networks. In addition, fiber optical CATV systems are deployed widely to provide broad bandwidth to subscribers. A hybrid three-band transport system that uses different optical wavelength to deliver combined ROF RF/FTTX BB/CATV analog signals would be quite useful for a fiber networks providing telecommunication, Internet, and CATV services. However, it is a challenge to transmit RF, BB, and CATV signals simultaneously using one optical fiber in a cost-effective way. Hybrid multi-band transport systems are envisioned to have a multiple number of distributed feedback laser diodes (DFB LDs) which are wavelength-selected for each channel and controlled to operate at specific wavelength, this process will increase the cost and complexity of the system. Several approaches have been proposed to solve the problem. Lightwave transport systems employing spectrum-sliced light sources such as light-emitting diodes (LEDs) or amplified spontaneous emission (ASE) sources were proposed. Nevertheless, the output power of LED is insufficient to accommodate many channels. Moreover, although the spectrum-sliced ASE source provides much higher output power than that of the LED, it requires expensive erbium-doped fiber (EDF) and pumping LD. Recently, there has been a proposal of a multi-wavelength light source which is based on direct modulation of a DFB LD. When a DFB LD is directly modulated with large optical modulation index (OMI), the single wavelength characteristic of DFB LD will be changed into multi-wavelength one, and it can be used as a cost-effective light source in hybrid multi-band transport systems. In this report, we proposed and experimentally demonstrated a potentially cost-effective ROF/FTTX/CATV hybrid three-band transport system based on direct modulation of a DFB LD with multi-wavelength output characteristic. Transmission performances over an 80-km single-mode fiber (SMF) transport were studied. With the help of direct-detection technique and optical single sideband (SSB) scheme at the receiving site, low bit error rate (BER) and clear eye diagram were achieved for ROF and FTTX applications; as well as good performances of carrier-to-noise ratio (CNR), composite second-order (CSO) and composite triple beat (CTB) were obtained for CATV signals.

New concept for a regenerative amplifier for passive optical networks
A. Tervonen, M. Mattila, Luxdyne, Ltd. (Finland) and Aalto Univ. (Finland); W. Weiershausen, Luxdyne, Ltd. (Finland); T. von Lerber, Luxdyne, Ltd. (Finland) and Darmstadt Univ. of Technology (Germany); R. Parsons, H. Chaouch, College of Optical Sciences, The Univ. of Arizona (United States); F. Kueppers, College of Optical Sciences, The Univ. of Arizona (United States) and Darmstadt Univ. of Technology (Germany); S. K. Honkanen, Aalto Univ. School of Science and Technology (Finland)

Photonic balancing - a scheme where logically opposite pulses derived from the two outputs of a delay-line demodulator for phase shift keyed (PSK) signals counter-propagate in the saturated regime of a semiconductor optical amplifier (SOA) - has proven to enhance the receiver performance, e.g. in terms of decreased optical signal-to-noise-ratio (OSNR) requirements for a given target bit error ratio (BER). Here, we extend the photonic balancing scheme towards a new concept for a regenerative amplifier targeted at extending the reach and/or the number of subscribers in passive optical networks (PON) in order to support major operators’ plans to reduce the number of central offices and access areas by approximately 90%. For a given target BER, we demonstrate experimentally three different set-ups, exhibiting (a) an 8-dB (or 6x more subscribers) higher post-amplifier loss tolerance compared to a conventional SOA implementation (compared to unamplified PON the improvement is about 40 dB), (b) an extended feeder line length (75 km) combined with high splitting ratio (10 layers) for a pre-amplified version, and (c) high input power variation tolerance (< 30 dB burst-to-burst) in upstream direction as needed for highly asymmetric tree structures.

Unified cost effective next-generation passive optical network and IEEE 802.16m network architecture
S. Hussain, S. R. Zaidi, H. Erkan, The City College of New York (United States); A. Sana, Bronx Community College (United States)

This paper presents the key features of the emerging Next Generation Passive Optical Network (NG-PON) and IEEE 802.16m based Mobile Worldwide Interoperability for Microwave Access (WiMAX) networks to build a unified cost effective next generation hybrid Fiber-Wireless network. NG converged-access solutions can meet the demand for cost, mobility, bandwidth, reliability, security, and flexibility. NG-PON and 4th Generation (4G) Mobile WiMAX unified architecture enables differentiated bandwidth allocation to end users and can provide more network range and capacity at reduced operational cost. The concept of hybrid optical network unit and advanced base station (ONU-ABS) simplifies the network architecture and can save installation and operational costs.

Field trials of 100G and beyond: an operator’s point of view
S. Vorbeck, M. Schneider, W. Weiershausen, H. Mayer, A. Schippel, P. Wagner, A. Ehrhardt, R. Braun, D. Breuer, U. Drafz, Deutsche Telekom AG (Germany); D. Fritzsche, EICT GmbH (Germany)

No abstract available
7959-11, Session 5

Scaling 100G QPSK links for reliable network development

A. J. Stark, S. Searcy, Y. Hsueh, T. Detwiler, Georgia Institute of Technology (United States); S. Tibuleac, M. Filer, ADVA Optical Networking North America, Inc. (United States); G. Chang, S. Ralph, Georgia Institute of Technology (United States)

Nonlinearities are a performance limitation in coherent optical links, and efforts have been made to understand the tradeoffs between launch power and the penalties related to nonlinearities. Using both simulation and experimental results from our 100G testbed we investigate the use of a nonlinear phase criterion that quantifies the total nonlinear phase accumulation within a 112 Gb/s PDM-QPSK link. We examine the nonlinear effects of self-phase (SPM) and cross-phase modulation (XPM) on a 112 Gb/s PM-QPSK channel propagating between four 10 Gb/s OOK aggressor channels on a 50 GHz grid and quantify the launch power and span count scaling behavior. In order to assess the applicability of a nonlinear phase criterion on real-world links, we determine the launch power that yields a 1.5 dB OSNR penalty at a BER of 10^-3 for each configuration. This launch power then allows the identification of a Nonlinear Threshold Power (number of spans times launch power) that fully incorporates the increasing nonlinear penalties with further transmission distance. This metric allows for the determination of a set of engineering rules for deployment of 100 Gb/s PDM-QPSK in linear links with arbitrary numbers of spans and span distances. These experimental results are validated with simulations.

7959-12, Session 5

Chromatic dispersion analysis and partially compensation for tunable liquid crystal optical interleaver

S. A. Alboon, Yarmouk Univ. (Jordan); A. S. Abu-Abed, Univ. of Central Oklahoma (United States); A. N. AL-Omari, Yarmouk Univ. (Jordan)

Flat-top liquid crystal tunable optical interleavers have shown a great potential to perform in the DWDM systems. In this paper, Chromatic dispersion analyses are conducted for a flat-top liquid crystal tunable optical interleaver based on Combined Michelson and Gires-Tournois interferometers. In order to try to reduce the dispersion associated with the interleaver’s operation. Initial simulation results show a 30% reduction in the chromatic dispersion (from 420 [ps/nm] to 280 [ps/nm]) for the simulated interleaver configuration. This reduction is achieved without any additional components or design modifications but only with the tuning capability of the liquid crystal. More analyses will be conducted to achieve more reduction in order to have more reliable performance for the interleaver.

7959-13, Session 5

Electrical PMD equalization methods for intensity modulated optical polarization multiplex transmission systems

D. Goelz, F. Pohl, P. Meissner, Technische Univ. Darmstadt (Germany)

Today's large capacity photonic network systems use bit rates of 10 Gbit/s, 40 Gbit/s and higher. Polarization mode dispersion (PMD) is the limiting factor since it causes intersymbol interference (ISI) especially at high data rates. When polarization multiplex (PoMUX) is employed to increase spectral efficiency, the distortions caused by PMD get even stronger due to the additional polarization crosstalk. Employing coherent detection (CD) these mitigations can be fully compensated with linear filters, since CD delivers amplitude, phase and polarization information of the electrical field. As a drawback we have to take into account a high complexity of the receiver, causing high overall cost. At the other hand we have direct detection (DD) systems where the receiver complexity can be kept low. Furthermore maximum likelihood sequence estimation (MLSE) detection has been successfully demonstrated for standard direct detection systems. In a first step the MLSE for standard intensity modulated (IM) DD systems is adapted to work in an IM PoMUX DD system. The performance of the method is assessed by simulations. And it is compared with least mean squares based equalizers which are employed to equalize signal distortions in CD transmission systems.
green photonics technology based on self-organized optical networks realizing an autonomous peer-to-peer electric power transmissions without centralized control for the power grid. In this optical network, we introduced an adaptive algorithm for concurrent peer-to-peer communications, by utilizing optical nonlinearity depending on the signal strength passing through the network. This method is applicable for autonomous organization of functions for ad-hoc electric power distribution systems for the power grid. For this purpose, a simple optical-electrical hybrid bistable circuit composed of such light emitting diode (LED) and photo diode (PD), has been incorporated into the network node. In the experiment, the method uses a simple, local adaptation of transmission weights at each network node, which enables self-organizing functions of the network, such as self-routing, self-optimization, self-recovery and self-protection. Based on this method, we have demonstrated experimentally a new smart grid model applicable for ad-hoc electric power distribution systems mediated by power consumptions. In this model, electric power flow is controlled autonomously through the self-organized network nodes associated with individual power facilities having photovoltaics and electric storage devices, etc., and the nodes convert the amounts of electric power supply and/or consumption to the light intensity values using above mentioned transmission weights at each node. As a consequence, we have experimentally demonstrated a simple short-haul system model for ad-hoc electric power distribution with a self-organized optical network as a novel green photonics technology application for smart grid.

7959-15, Session 6

WSS technology for the next generation ROADM networks

G. Cohen, K. Bala, Oclaro, Inc. (United States)

No abstract available

7959-15, Session 6

Ultra-wide tuning range of reconfigurable optical add-drop multiplexer using photorefractive polymer

Y. Wakayama, A. Okamoto, A. Tomita, Hokkaido Univ. (Japan); K. Sato, Hokkai-Gakuen Univ. (Japan)

Reconfigurable optical add-drop multiplexer (ROADM) systems promise to perform for green photonics by maximizing bandwidth capacity while enabling the reduction of capital and operational costs of equipment. For constructing ROADM systems with wide tuning range over 200nm, we focus on a transmission-type holographic wavelength filter with a photorefractive polymer because of the following great advantages. In our method, a wavelength for adding/dropping can be shifted easily by changing an incident angle of WDM signals. In addition, since the holographic grating is induced in the polymer as a real-time hologram, a filtering wavelength layer can be reassembled optically by rewriting the hologram with the change of grating spacing. The grating is static in long term by using a photorefractive polymer; however, it can be quickly erased and reconfigured with control beams. Thus, traffic can be remotely controlled with low power consumption because the grating is rewritable in pure optical operation. At the same time, circulators are unnecessary because its operation is based on Bragg diffraction through the transmission-type grating. In this work, we demonstrate on the add-drop operation using a laser at 633nm as a control beam source, and investigate diffraction efficiency and tuning range for different index modulation. From these results, we show the ultra-wide tuning range from visible to infrared spectrum and short reconfiguration time estimated from the measured response time for erasing and writing the hologram. Furthermore, we show that diffraction efficiency can be increased by apodizing the distribution of the holographic grating.

7959-16, Session 6

Spectrum variable colorless, directionless and contentionless multi-degree ROADM node

P. N. Ji, NEC Labs. America, Inc. (United States); Y. Aono, NEC Corp. (Japan); T. Wang, NEC Labs. America, Inc. (United States)

Global communication traffic has been growing rapidly and is becoming more dynamic, leading to increased demands for better efficiency with respect to resources, scale, energy, and cost, especially in metro networks. As a result, metro optical networks can transmit WDM channels with mixed line rates simultaneously, and new services such as wavelength-on-demand are being offered. The current fixed grid WDM system cannot provide optimum spectrum utilization for such emerging networks, and the conventional ROADM nodes are facing color and direction issues.

We recently proposed a flexible optical WDM (FWDM) network architecture that is capable of dynamic allocation of network resources (in particular the optical spectrum), dynamic provisioning of connections, and automated network control to eliminate manual operation. A key network element in this FWDM network is a flexible ROADM node that can provide variable spectrum configuration dynamically.

In this work, we propose and experimentally demonstrate a multi-degree ROADM node that allows flexible spectrum configuration with colorless, directionless and contentionless switching operations. It uses liquid crystal on silicon (LCOS)-based switching platform to obtain fine spectral granularity and change passband widths for individual WDM channels. And it uses a transponder aggregator to perform centralized sharing of transponders for all add/drop signals. Experiment results show that inter-degree cross-connect and colorless and directionless add/drop operation on spectrum variable WDM signals can be achieved without incurring wavelength blocking in the node. This ROADM node enables spectrum and cost efficient switching compared to conventional fixed grid ROADM nodes.

7959-17, Session 6

PCE-based scalable dynamic path control for large-scale photonic networks

S. Araki, NEC Corp. (Japan); K. Shimada, H. Hasegawa, K. Sato, Nagoya Univ. (Japan); Y. Iizawa, S. Ishida, I. Nishioka, NEC Corp. (Japan)

ASON (Automatic Switched Optical Network) / GMPLS (Generalized Multi-Protocol Label Switching) control plane technologies for automated path control of a photonic network has been developed for this decade. In the past few years, it has been deployed in service provider’s commercial networks, and their advantage in terms of OPEX (operational expenditure) reduction was reported by a service provider. Although, most of such networks are still relatively small, which are constructed by few tens of nodes, and they have to be expanded to nation-wide larger networks for more effective OPEX reduction. To control larger networks, typically thousands of nodes, multi-domain network configuration is advantageous to routing protocol scalability. Furthermore, the application of photonic network technology will continue to expand in the future, and optical paths will come to traverse multiple domains that are possibly under different carriers’ control and management.

We have studied qualitatively and concluded that the PCE (Path Computation Element) based routing is the most suitable model rather than other routing models, the per-domain routing and the ASON hierarchical routing for inter-domain path control over multi-domain photonic networks. For the inter-domain path control, the selection of domain sequences has a significant impact on the efficiency of networks. However, quantitative study of global optimization using a large network test environment has not been reported yet.

In the presentation, we will discuss the overall architecture of multi-domain photonic network control system, and also provide measured
performance results for inter-domain path computation and path setups using global optimization scheme.

7959-18, Session 6
Linear formulation to avoid adjacent channel interference in LTD of optical networks
K. Day Rosario Assis, Federal Univ. do Recôncavo da Bahia (Brazil); A. F. Santana, Univ. Estadual do Sudoeste da Bahia (Brazil); M. Savasini, Univ. Estadual de Campinas (Brazil)

In this work, we propose a new optimization LP (Linear Programming)-complete formulation to block channel interference in links of optical fiber. To the best of our belief, the first linear formulation of a partial solution to the RWA problem avoiding the use of adjacent channels has been stated in other studies, where constraints are created using path formulation, where all possible paths are known beforehand. In this work, we propose a link formulation. Therefore, we do not know beforehand the set of alternative routes for any node pair. With all possible routes, the linear formulation that we propose can find effective results to avoid channel interference. Furthermore, our formulation is to the full logical topology design. We observe the effect of physical impairments in a higher layer, i.e., in virtual topology configuration.

7959-24, Session 6
Colorless and directionless multi-degree reconfigurable optical add/drop multiplexers for 100G network application
T. Wang, P. N. Ji, NEC Labs. America, Inc. (United States); Y. Aono, NEC Corp. (Japan)

The reconfigurable optical add/drop multiplexer (ROADM) has become one of the most important elements in 100G DWDM network. The next generation multi-degree ROADM requires two main features: colorless and directionless. Colorless means that add/drop ports are not wavelength specific, and directionless feature enables any transponder to be connected to any degree. In this paper we review and analyze different multi-degree ROADM node architectures that offer full colorless and directionless features with its network application. Their key characteristics and properties, including optical loss, size, cost, modularity and upgradability, are compared and discussed.

7959-19, Session 7
Efficient elastic optical path network for transmission beyond 100G
B. Kozicki, H. Takara, K. Yonenaga, M. Jinno, NTT Corp. (Japan)

No abstract available

7959-20, Session 7
Multi-layer photonics modeling framework for the design, analysis, and optimization of devices, links, and networks
A. Richter, H. Louchet, C. Arellano, I. Koltchanov, J. Farina, VPIsystems GmbH (Germany)

- overview of design challenges and corresponding modeling requirements on different abstraction levels (devices, transmission systems, networking aspects)
- exemplary design applications and modeling studies with focus on aggregation and metro networks

7959-21, Session 7
Dynamic routing, wavelength assignment, and spectrum allocation in transparent flexible optical WDM networks
A. N. Patel, P. N. Ji, NEC Labs. America, Inc. (United States); J. P. Jue, The Univ. of Texas at Dallas (United States); T. Wang, NEC Labs. America, Inc. (United States)

Due to emerging heterogeneous applications, the traffic in the metro optical networks is getting more dynamic with diverse granularity. To support such increasing traffic demands in the future, we have proposed the Flexible Optical WDM (FWDM) network architecture which is capable of dynamic allocation of network resources and dynamic provisioning of connections using the automated control plane. Unlike the conventional fixed grid WDM networks in which channels are provisioned with fixed spectral spacing, the FWDM networks can support line rates with finer granularity by provisioning channels with flexible spectrum allocation to leverage the spectral and wavelength efficiencies.

One of the open problems in the FWDM networks is that for a given transparent network and dynamic arrival of traffic with various line rates, how to establish lightpaths, route the lightpaths over physical topology, assign line rates to the lightpaths, assign wavelengths, and allocate the spectrum such that minimum spectrum is utilized. We refer to this problem as dynamic routing, wavelength assignment, and spectrum allocation problem (D-RWSA). In this paper, we propose a greedy algorithm and evaluate the performance of the FWDM architecture with the conventional fixed grid WDM network architecture in terms of spectral efficiency, blocking probability, and cost. Simulation results show that the proposed architecture improves spectral and cost efficiencies with lower blocking probability compared to the fixed grid networks.

7959-24, Session 7
Network transformations through packet optical convergence
H. Schmidtke, Juniper Networks, Inc. (United States)

No abstract available
Novel fibers for next generation parametric devices

H. L. Fragnito, J. Amilton Mores, Jr., Univ. Estadual de Campinas (Brazil); L. Heitzmann Gabrielli, Cornell Univ. (United States); H. E. Hernandez-Figueroa, Univ. Estadual de Campinas (Brazil)

One major limitation for scaling the capacity of optical networks for the future demands is the bandwidth of optical amplifiers. The ideal amplifier should be efficient, have bandwidth of 400 nm to fully cover the high transparency region of silica fibers (1250-1650 nm), and the gain spectrum should be as flat as possible. Available technologies such as rare-earth doped fibers, Raman and semiconductor based optical amplifiers are limited to ~100 nm bandwidths due to the nature of the materials (i.e., phonon broadening of the spectral resonances). The bandwidth, gain ripple and operational spectral region of Fiber Optical Parametric Amplifiers (FOPAs), on the other hand, are determined by the fiber chromatic dispersion, which is something that can be engineered with proper waveguide design.

Flat-broadband FOPAs were reported exhibiting 115 nm bandwidth in a single fiber [1] and 150 nm [2] by concatenating fibers with different zero dispersion wavelengths. While impressive, these results are rather modest when compared to theoretical expectations. What limits the achievement of better FOPAs in practice is the lack of optical fibers specifically designed for FOPA applications. In real fibers, the dispersion parameters fluctuate, mainly due to variations of the geometry during the manufacturing process of the fiber. Thus the efficiency of the parametric processes fluctuates along the fiber length, resulting in a device that requires more pump power for a given gain, and that exhibits more noise [3] and spurious four wave mixing [4] than in an uniform fiber.

We discuss several fiber designs that should be easy to fabricate and that are optimized for FOPAs. Following the design criteria elaborated in [5] for conventional highly nonlinear fibers, we analyze solid-core photonic crystal fibers. We use a genetic algorithm to generate races of fibers that are robust against geometrical fluctuations for flat-broadband FOPAs.

References
Four-dimensional coded optical OFDM for ultra-high-speed metro networks
I. B. Djordjevic, The Univ. of Arizona (United States)

The optical communication systems have been evolving rapidly in recent years in order to adapt to the continuously increasing demand on transmission capacity, coming mainly from the growing popularity of the Internet and multimedia in everyday life. In order to keep the system complexity reasonably low, the new optical communications solutions have to offer affordable upgrades of currently available optical communication systems operating at lower speeds to satisfy the required higher speeds. One such approach was based on multidimensional coded modulation. Namely, by increasing the number of dimensions (i.e., the number of orthonormal basis functions), we can increase the aggregate data rate of the system without degrading the BER performance as long as orthogonality among basis functions is preserved. All papers on multidimensional signal constellation for optical communications so far have been related to single carrier systems. In this paper, we describe how to map multidimensional signal constellation points in coherent optical OFDM systems. The key idea is to exploit all advantages of both OFDM and multidimensional single carrier systems. The multidimensional mapper for OFDM can be described as follows. Let N-dimensional signal constellation point be represented as \( s=(s_0,s_1,...,s_{(N-1)}) \), where \( s_j \), \( j = 0,...,N-1 \), is the jth coordinate. Let the duration of the signal be M signal constellation points. We can represent the signal constellation points in matrix form, by placing the coordinates of signal constellation points along the columns of signal matrix. We further apply two-dimensional inverse fast Fourier transform (2D-IFFT) to obtain 2D-IFFT array of complex numbers. The coordinates of complex numbers can be considered as in-phase (i) and quadrature (Q) channels, while the coordinates of two-dimensional array can be mapped to two orthogonal polarizations. The optical channel space is therefore four-dimensional. All other steps of this 2D-OFDM scheme are similar to conventional one-dimensional optical OFDM. On receiver side, we use the conventional polarization-diversity receiver, followed by 2D-FFT demapper. Therefore, this scheme can fully exploit the advantages of OFDM as an efficient way to deal with chromatic dispersion, PMD and PDL effects. At the same time we can exploit the advantages of multidimensional signal constellation to improve the OSNR sensitivity of conventional optical OFDM dramatically.

Real-time coherent OFDM transmission
N. Kaneda, T. Pfau, Alcatel-Lucent Bell Labs. (United States); Q. Yang, Wuhan Research Institute of Posts and Telecommunications (China); Y. Chen, Alcatel-Lucent Bell Labs. (United States)

We review the recent development in real-time coherent optical OFDM (CO-OFDM) transmission for their algorithm and implementation. The unique challenge of real-time implementation of OFDM for high speed optical data transmission including relatively large phase noise, frequency offset and dynamically changing optical channels are discussed. The fundamental digital signal processing (DSP) architectures of transmitter and receiver are presented in the manner achievable in state of the art field-programmable gate arrays (FPGAs) or application-specific integrated circuits (ASICs). Primary DSP components’ algorithm and implementations are presented and discussed. The successful demonstration of real-time CO-OFDM receivers includes a receiver with sampling rate of 2.5-Gsamples/s to receive a 3.55-Gb/s single channel and 53.3-Gb/s multi-band CO-OFDM signal.

Optimum signal constellations for high-speed optical metro networks and beyond
J. Zhang, Beijing Jiaotong Univ. (China); I. B. Djordjevic, The Univ. of Arizona (United States)

Telecommunication needs are increasing continuously thanks to the popularity of the Internet and multimedia in everyday life. The 100 Gb/s transmission is under standardization, and according to some industry experts 1 Tb/s should be standardized by the year 2012-2013. Migrating to higher transmission rates comes along with numerous challenges including the degradation in the signal quality due to various linear and nonlinear channel impairments and increased installation costs. In order achieve beyond 400 Gb/s serial optical transmission using commercially available equipment, we propose the use of channel capacity achieving modulation formats. We present the method to determine the optimum signal constellation for an arbitrary dispersion map. This method can be described by the following algorithm steps. (i) Determine the conditional probability density functions (PDFs) to be used in trellis optical channel description by evaluating of histograms. (ii) Start from arbitrary input source distribution to generate the state sequence and output sequence. (iii) Estimate the information rate by the forward-step of BJCR algorithm. (iv) Use the constrained stochastic Arimoto-Blahut algorithm to determine the optimum input distribution. (v) Determine the optimum signal constellation by minimizing the mean-square error of optimum source. (vi) Repeat steps above until convergence or until the maximum number of iterations is reached. We will study different dispersion maps currently in use and for each of them we will determine the optimum signal constellation. It will be shown that with optimum signal constellation for the dispersion map composed of periodically deployed SMF and DCF sections, we can achieve the spectral efficiency of 6 bits/s/Hz per single polarization for metro and medium-haul applications.

Potential of OFDM for next generation optical access
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No abstract available

Low cost direct modulation and coherent detection optical OFDM for metro applications
N. Sheffi, D. Sadot, Ben-Gurion Univ. of the Negev (Israel)

High speed transmission systems (> 10 Gb/s) for cost-sensitive applications such as metropolitan network have attracted extensive interest due to the explosive data traffic growth in such applications. Optical orthogonal frequency division multiplexing (OFDM) based on direct modulation and direct detection for single-mode fiber (SMF) and multi-mode fiber (MMF) without optical amplification and dispersion compensation was proposed. Recent research has also shown that Optical OFDM can be used with electronic dispersion compensation using direct detection in SMF. However, laser frequency chirp has been identified as a key limiting factor of capacity-versus-reach performance. In this paper, we present a novel concept of low cost optical OFDM with
The 64/32/16-QAM modulation formats are used respectively, enabling the realization of 40-Gb/s transmission over 20 km SSMF plus 15 dB attenuation. OFDMA-PON architecture for downstream that benefits from all these high-speed optical transmission due to both the high resistance to fiber dispersion and high spectral efficiency. By thus, the Polarization-Multiplexing (POLMUX) OFDM signal and the contrast different arrangements for optical transport of systems having spectral efficiencies in the range of 2 - 5 bits/sec/Hz for sub-carrier bandwidths spanning 25 - 100 GHz. The analysis is made more challenging by variables such as fiber type, dispersion compensation arrangement, and traffic mix.

**7960-05, Session 1**

**Single-carrier versus sub-carrier bandwidth considerations for coherent optical systems**

J. D. McNicol, Infinera Canada (Canada); V. Dangui, Infinera Corp. (United States); H. Sun, D. J. Krause, K. Wu, Infinera Canada (Canada); M. L. Mitchell, D. F. Welch, Infinera Corp. (United States)

Recently, 40 and 100 Gb/s Ethernet services have been defined. 400G and 1 Tb/s services can be anticipated in the future. Optical transport networks can enable a separation between the services provided and the underlying optical transport; service bandwidths may be larger or smaller than that carried on a single optical 'wave'. In this work, we compare and contrast different arrangements for optical transport of systems having spectral efficiencies in the range of 2 - 5 bits/sec/Hz for sub-carrier bandwidths spanning 25 - 100 GHz. The analysis is made more challenging by variables such as fiber type, dispersion compensation arrangement, and traffic mix.

**7960-06, Session 1**

**High order modulation format optical OFDM for access applications**

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Driven by both exponentially growing demand for broadband services and FSAN standardization activities, the transport capacity of next-generation optical access networks will migrate to 40-Gb/s per channel in the near future. OFDM has recently emerged as a very promising modulation format for high-speed optical transmission due to both high resistance to fiber dispersion and high spectral efficiency. By thus eliminating the need for dispersion compensation and reducing the transmission bandwidth, OFDM can significantly increase flexibility of access passive optical networks (PON) while reducing implementation cost. 40G and 100G downstream OFDM-ON has been reported in the previous work. Limited by the DAC bandwidth and spectrum efficiency at that time, the Polarization-Multiplexing (POLMUX) OFDM signal and direct-detection has been proposed so that the required DAC bandwidth is reduced to half of the total bandwidth of the OFDM signal. However, in order to recover the signals from two orthogonal polarizations, one polarization beam splitter, two 20GHz photo-diodes and two ADC are used at the ONU receiver. Additionally, MIMO processing is needed which would also add more DSP complexity. As the rapidly increasing of the DAC sampling rate/bandwidth as well as the spectrum efficiency from higher order modulation format, a simple single-side band OFDM with a real single photodiode direct-detection becomes possible for 40G+ OFDM-ON. We propose and experimentally demonstrate a simple OFDM-ON architecture for downstream that benefits from all these technical development by exploiting SSB-OFDM with direct-detection to realize 40G-Gb/s transmission over 20 km SSMF plus 15dB attenuation. The 64/32/16-QAM modulation formats are used respectively, enabling total 43.6-Gb/s transmission.
Enabling technologies for 100G coherent optical communication

B. Zhang, Y. K. Lize, Opnext, Inc. (United States)

In this paper, we review the generation, detection and long-haul transmission of single-wavelength coherent PM-QPSK systems. The enabling technology of the 100G coherent transponder is first described from the systems attributes. Lab results then follow from various fiber-channel degrading effects, including cascading of more than ten 50GHz ROADMs over 1500km transmission tested. We conclude with a recent field trial of upgrading an installed 10-Gb/s field system to 100-Gb/s using an FPGA-based real-time, single-carrier, coherent transponder prototype. Transmission over installed 1800km link was achieved with sufficient performance for error-free operation after FEC.

Developing accurate simulations for high-speed fiber links

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Reliable simulations of high-speed fiber optic links are necessary to understand, design, and deploy fiber networks. Laboratory experiments cannot explore all possible component variations and fiber environments that are found in today's deployed systems. Simulations typically depict relative penalties compared to a reference link. However, absolute performance metrics are required to assess actual deployment configurations. Here we detail the efforts within the Georgia Tech 100G Consortium towards achieving high absolute accuracy between simulation and experimental performance with a goal of ±0.25 dB for back-to-back configuration, and ±0.5 dB for transmission over multiple spans with different dispersion maps. We measure all possible component parameters including fiber length, loss, and dispersion for use in simulation. We also validate experimental methods of performance evaluation including OSNR assessment and DSP-based demodulation. We investigate a wide range of parameters including modulator chirp, polarization state, polarization dependent loss, transmit spectrum, laser linewidth, and fiber nonlinearity. We evaluate 10 Gb/s (single-polarization) and 112 Gb/s (dual-polarization) DOPSK and coherent QPSK within a 50 GHz DWDM environment with 10 Gb/s OOK adjacent channels for worst-case XPM effects. We demonstrate good simulation accuracy within linear and some nonlinear regimes for a wide range of OSNR in both back-to-back configuration and up to eight spans, over a range of launch powers. This allows us to explore a wide range of environments not available in the lab, including different fiber types, ROADM passbands, and levels of crosstalk. Continued exploration is required to validate robustness over various demodulation algorithms.

Rate-adaptive modulation and coding for optical fiber transmission systems

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Rate-adaptive optical transmission techniques trade off information bit rate for transmission distance and other factors affecting signal quality. These techniques enable increased bit rates over shorter links, while enabling transmission over longer links when regeneration is not available. They are likely to become more important with increasing network traffic and a continuing evolution toward optically switched mesh networks, which make signal quality more variable. We propose a rate-adaptive scheme using variable-rate forward error correction (FEC) codes and variable constellations with a fixed symbol rate, quantifying how available bit rates vary with distance. The scheme uses serially concatenated Reed-Solomon codes and an inner repetition code to vary the code rate, combined with single-carrier polarization-multiplexed quadrature amplitude modulation with variable constellation sizes and digital coherent detection. A rate adaptation algorithm uses the signal-to-noise ratio (SNR) or the FEC decoder input bit-error ratio (BER) estimated by a receiver to determine the FEC code rate and constellation size that maximizes the information bit rate while satisfying a target FEC decoder output BER and an SNR margin, yielding a peak rate of 200 Gbit/s in a nominal 50-GHz channel bandwidth. We simulate single-channel transmission through a long-haul fiber system incorporating numerous optical switches, evaluating the impact of fiber nonlinearity and bandwidth narrowing. With zero SNR margin, we achieve bit rates of 200/100/50 Gbit/s over distances of 650/2000/3000 km. Compared to an ideal coding scheme, the proposed scheme exhibits a performance gap ranging from about 6.4 dB at 650 km to 7.5 dB at 5000 km.
is avoided through tap settling constraints. The method is applicable to QPSK transmissions and many other modulation formats as well, including general QAM signals, offset-QPSK, and CPM, or a combination thereof. We present the architecture and its performance under several different formats and link conditions. Comparisons of complexity and performance are drawn between the proposed architecture and conventional receivers.

7960-13, Session 3
Polarization demultiplexing using independent component analysis

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Independent component analysis has been applied to polarization demultiplexing for coherent optical fiber communications. Polarization multiplexed QPSK signals were successfully demultiplexed using the tensor based algorithm without any knowledge of the modulation format.

7960-14, Session 4
Interchannel nonlinear impairment compensation by advanced split-step method

F. Yaman, E. Mateo, T. Wang, NEC Labs. America, Inc. (United States); G. Li, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Nonlinear impairments are one of the major limitations to the channel capacity and transmission distance. Compensation of nonlinear impairments by digital signal processing is the next logical step following the compensation of linear impairments such as dispersion and polarization-mode dispersion. Algorithms for removing nonlinear impairments require higher complexity and resources compared to linear impairments, since in the case of nonlinear impairments the channel becomes signal dependent. Therefore in addition to the inverting the channel impairments, the channel itself has to be computed or estimated based on the signal itself. Recently, digital backward propagation (DBP) has proved to be an efficient way to remove nonlinear impairments for both intra-channel and inter-channel nonlinear impairments. Advanced DBP algorithms have been proposed to radically reduce the complexity of DBP compared to the conventional split-step Fourier transform method. With the help of these advanced algorithms, inter-channel impairments can be compensated with complexities close to what is required for intra-channel impairments. The differences that arise in the implementation of the advanced algorithms in the case of polarization-multiplexed systems are also discussed in detail.

7960-16, Session 4
Comparison of 8 Tb/s optical transport systems using different modulation formats

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In this work we compare and contrast the performance of an 8 Tb/s optical transport system implemented with various modulation formats. The modulation format assumes variants of a PM-QPSK modulation with coherent detection and digital signal processing (DSP) with equal FEC performance for each scenario. For the same total 8 Tb/s capacity in the C band, we analyze the several approaches from the point of view of: (a) WDM Kerr nonlinear impairments over SMF and LEAF, (b) electronic requirements and complexities, (c) ASIC complexities and heat, and (d) laser line width requirements. We find differences in the approach results in substantially different tolerances in launch power (integrated over the C band) for both SMF and LEAF fiber resulting in varied reach performance. The significant changes to the baud rate, electrical bandwidth and thermal profile can be achieved with further advanced modulation structures as compared to a standard PM-QPSK modulation format. Finally, advanced modulation formats are shown to perform better relative to tolerances to local oscillator linewidth in the presence of high values of digital dispersion compensation. Further scenarios including mixed traffic with 10 Gb/s signals are analyzed and will be presented.

7960-17, Session 4
Analysis and mitigation of Mach-Zehnder modulator nonlinearity in coherent optical OFDM system in the presence of high peak power

Y. London, D. Sadot, Ben-Gurion Univ. of the Negev (Israel)

The nonlinear effect of Mach-Zehnder modulator (MZM) in optical fiber under the presence high peak power of optical orthogonal frequency division multiplexing (OFDM) is investigated. A full optical coherent communication system is presented and analyzed numerically. A method to mitigate the nonlinear effect by means of digital pre-distortion is proposed. Inclusive quantitative analysis of the effect of peak to average power (PAPR) reduction on the performance of the proposed Optical-OFDM system is presented.
The need for speed: 100 Gb/s and its utility beyond fiber efficiency
R. Wilcox, Huawei Technologies Co., Ltd. (China)

In fiber optic transmission systems, network economics have traditionally driven the deployment of technologies enabling higher per wavelength transmission speeds. For bit rates up to 10 Gb/s the decision point for a system upgrade was governed by the transponder cost break point of four times the bandwidth for 2.5 times the cost. Starting with 40 Gb/s systems, other factors started to influence deployment decisions. With 100 Gb/s starting to become commercially available, there are indications that the economics over 40 Gb/s systems will be much improved. However, other factors will again be the driving force for installation of this new transmission rate. These include fiber bandwidth efficiency, latency, packet switching efficiency and operational costs. This presentation will explore these factors including the economics to outline a service provider’s motivation to install 100 Gb/s line systems.

High-order QAM transmission for the future optical transport network beyond 100Gb/s
T. Kobayashi, NTT Network Innovation Labs. (Japan)

As PDM-QPSK has been recognized as a very promising candidate for the long-haul transport of 100G Ethernet, research interest is focusing on transmission systems beyond 100Gb/s/ch. Higher-order multi-level modulation formats are very attractive for achieving the high spectral efficiency and high speed channels needed to accommodate ultra-high speed client signals on the optical transport network (OTN). In particular, quadrature amplitude modulation (QAM) is a promising modulation technique; high spectral efficiency of 10G/b/s/Hz has been reported from the combination of 128-QAM and polarization division multiplexing (PDM). However, there is a trade-off between the number of signal points and OSNR tolerance, thus transmission distance is restricted as the signal constellation expands. Moreover, system requirements, such as laser line-width, ADC/DAC resolution, and circuit linearity, become severe. We recently demonstrated the 3000-km class long-haul transmission of a single channel 160 Gb/s 16-QAM signal. We employed three key technologies; optical 16-QAM signal synthesis by superposing two optical QPSK signals, proposed pilot-less detection scheme with digital PLL-based frequency offset compensator and OSNR improvement using digital low-loss fiber and EDFA/distributed Raman amplification. In this paper, we review several system configurations for higher-order QAM, and then discuss transmission performance focusing on the tolerance to OSNR, nonlinearity, carrier frequency offset, and laser line-width. In particular, experiments investigate the impact of laser line-width for three different line width combinations of transmitter laser and local oscillator; the test lasers are 15-kHz, 100-kHz external cavity laser and 3-MHz distributed feedback laser.

Advances in coherent optical modems and 16-QAM transmission with feedforward carrier recovery
R. Noé, S. Hoffmann, C. Wördehoff, A. Al-Bermani, M. El-Darawy, Univ. Paderborn (Germany)

Polarization multiplexing and quadrature phase shift keying (QPSK) each double spectral efficiency. Combined with synchronous coherent polarization-diverse intradyne receivers this modulation format is ultra-robust and cost-efficient. A feedforward carrier recovery is required in order to tolerate phase noise of normal DFB lasers. Signal processing in the digital domain permits compensation of at least chromatic and polarization mode dispersion. Some companies have products on the market, others are working on them. For 100 GbE transmission, 50 GHz channel spacing is sufficient.

16QAM quadrature amplitude modulation (16-QAM) is attractive to double capacity once more, possibly in a modulation format flexible transponder which is switched down to QPSK only if system margin is too low. For 16-QAM the phase noise problem is sharply increased. However, also here a feedforward carrier recovery has been implemented. A number of carrier phase angles is tested in parallel, and the recovered data is selected for that phase angle where squared distance of recovered data to the nearest constellation point, averaged over a number of symbols, is minimum. An intradyne/self-homodyne synchronous coherent 16-QAM experiment (2.5 Gb/s, 81 km) will be presented.

spectrally efficient polymer optical fiber transmission
S. Randel, Alcatel-Lucent Bell Labs. (United States); C. Bunge, Hochschule für Telekommunikation Leipzig (Germany)

The polymer optical fiber (POF) made of poly(methyl methacrylate) (PMMA) is an attractive transmission medium for high speed communication links in home networks, in automotive information networks, and in industrial automation.

Growing demands for quality of service, e.g., for IPTV distribution in homes and for Ethernet based industrial control networks will necessitate gigabit speeds in near future.

The authors will present an overview on recent advances in the design of spectrally efficient and robust gigabit over POF transmission systems.

Polymeric optical waveguide polarization beam splitters incorporating low loss birefringent polymers
J. Kim, N. Son, M. Oh, Pusan National Univ. (Korea, Republic of); J. Seo, J. Lee, Y. Noh, H. Lee, ChemOptics Inc. (Korea, Republic of)

The rapid increase of the internet traffic has led the optical communication system development continuously. In the 100 Gbps optical communication system, the transmission bandwidth was increased by utilizing various polarization states. In order to control the polarization of the light source accurately, various polarization controlling devices have been necessary. The optical polarization beam splitters are the essential components to separate the mutually orthogonal polarizations used for the coherent optical communication system. In this study, we propose a polarization beam splitter fabricated by using UV crosslinkable fluorinated polymers and birefringent polymers with low optical loss for the wavelength around 1550 nm. It consists of Y-branch polymeric waveguide with one of the two arms formed with a birefringent polymer. By the adiabatic mode evolution, TE/TM mode splitting occurs at the branch. The device was designed by performing a two-dimensional beam propagation method. The polarization beam splitter was fabricated on a silicon substrate by using conventional fabrication process of polymeric waveguide such as spin coating, photolithography, and oxygen plasma etching. For the device with a branch angle of 1/300 rad and a thickness of birefringent polymer of 5 µm, a crosstalk of less than -20 dB and insertion loss of 1.63 dB was achieved for the wavelength of 1550 nm.
Photonic generation of RF multiple carriers using a mode-locked laser and a single photodiode

P. Ghelfi, Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy); G. Serafino, F. Fresi, Scuola Superiore Sant’Anna (Italy); G. Villanueva, P. Perez-Millan, J. L. Cruz Munoz, Univ. de Valencia (Spain); F. Berizzi, Univ. di Pisa (Italy); A. Bogonia, Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy)

The generation of mm-wave signals for radar applications by means of purely electrical architectures needs to face several issues, mainly related to electromagnetic interference, distortions and high phase noise. Spectral purity of electronic microwave generation is mainly limited by the noisy frequency multiplication of stable local oscillators, that worsens the signal quality as the required frequency increases. State-of-the-art electronic oscillators cannot generate highly stable RF signals above few tens of GHz.

Recently new generations of radar systems are under development, employing multiple RF carriers to improve the target detection, the clutter decorrelation and the signal-to-clutter ratio. The use of multiple carriers will also allow the realization of multi-input multi-output radar systems. In this paper we propose a novel architecture for the optical generation of multiple RF signals, based on the beating of couples of modes from a Mode-Locked Laser (MLL) in a single photodiode, filtering them by means of very narrow optical filters and ad-hoc designed fibre Bragg gratings.

The scheme is experimentally evaluated generating simultaneously two carriers at 10GHz and 30GHz, showing their very low phase noise, limited amplitude fluctuations and negligible interference (~30dB) between each other. Moreover, measurements prove that the time jitter keeps low and constant even increasing the filtered modes detuning, i.e. the RF carrier frequency.

The obtained results show that the proposed architecture is a promising scheme for the generation of single or multiple high purity carriers up to extremely high frequency (W band), far beyond the limits of electronic oscillators.

Fiber-coupled superconducting nanowire single photon detector for quantum key distribution

L. Zhang, Z. Yuan, L. Kang, J. Chen, P. Wu, C. Cao, Nanjing Univ. (China)

In this paper, the fabrication details and optimization of micro-fabrication process were presented for developing superconducting nanowire single-photon detectors (SNSPD). Besides, the devices failure analysis was also introduced. With those methods, we successfully fabricated high-quality SNSPDs whose maximum system efficiencies were up to 30% for 660 nm wavelength and 4.2% for 1550 nm wavelength according to the single-photon detection experiment. At the dark count rate of 10 c/s, the detection efficiencies were 20% (660 nm) and 3% (1550 nm) with the SNSPD fabricated with above mentioned methods.

Coherent state statistics from time-resolved photon counting

A. Prabhakar, H. Ravishankar, Indian Institute of Technology Madras (India)

The presence of multi-photon states affects the security of quantum communication channels. Estimating the number of photons in the optical pulse train also helps determine the stability of laser sources in coherent optical systems. We resolve the number of photons in a pulse by connecting the pulse train to a single photon detector through a 3-dB coupler. The second arm of the coupler is fed back to the input to form a ring cavity. By ensuring that the repetition rate of the input pulse train is less than 8 times that of the cavity round-trip time, we effectively attenuate each input pulse 256 times (though we observe that we attenuate the coherent pulse to single photon levels by 5 round trips).

Our gated avalanche photodetector (GAPD) is synchronized to the arrival times of the pulses in the cavity by using a combination of electronic and optical delay lines. We collect detection statistics for all 8 round trips, as bits in a SRAM, and repeat the experiment 2^18 times. The probability estimates. The efficiency of the detector can be estimated from a log-log plot of the probability of having zero photons versus the dark count. In addition, by comparing the arrival patterns of the photon pulses after 3, 4 and 5 round-trips, we are able to accurately establish the Poissonian characteristics of the input coherent state.

WSS technology for the next generation ROADM networks

G. Cohen, K. Bala, Oclaro, Inc. (United States)

No abstract available

Ultra-wide tuning range of reconfigurable optical add-drop multiplexer using photorefractive polymer

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Reconfigurable optical add-drop multiplexer (ROADM) systems promise to perform for green photonics by maximizing bandwidth capacity while enabling the reduction of capital and operational costs of equipment. For constructing ROADM systems with wide tuning range over 200nm, we focus on a transmission-type holographic wavelength filter with a photorefractive polymer because of the following great advantages. In our method, a wavelength for adding/dropping can be shifted easily by changing an incident angle of WDM signals. In addition, since the holographic grating is induced in the polymer as a real-time hologram, a filtering wavelength layer can be reassigned optically by rewriting the hologram with the change of grating spacing. The grating is static in long term by using a photorefractive polymer; however, it can be quickly erased and reconfigured with control beams. Thus, traffic can be remotely controlled with low power consumption because the grating is writable in pure optical operation. At the same time, circulators are unnecessary because its operation is based on Bragg diffraction through the transmission-type grating. In this work, we demonstrate on the add-drop operation using a laser at 633nm as a control beam source, and investigate diffraction efficiency and tuning range for different index modulation. From these results, we show the extra-wide tuning range from visible to infrared spectrum and short reconfiguration time estimated from the measured response time for erasing and writing the hologram. Furthermore, we show that diffraction efficiency can be increased by apodizing the distribution of the holographic grating.
Spectrum variable colorless, directionless and contentionless multi-degree ROADM node

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Global communication traffic has been growing rapidly and is becoming more dynamic, leading to increased demands for better efficiency with respect to resources, scale, energy, and cost, especially in metro networks. As a result, metro optical networks can transmit WDM channels with mixed line rates simultaneously, and new services such as wavelength-on-demand are being offered. The current fixed grid WDM system cannot provide optimum spectrum utilization for such emerging networks, and the conventional ROADM nodes are facing color and direction issues.

We recently proposed a flexible optical WDM (FWDM) network architecture that is capable of dynamic allocation of network resources (in particular the optical spectrum), dynamic provisioning of connections, and automated network control to eliminate manual operation. A key network element in this FWDM network is a flexible ROADM node that can provide variable spectrum configuration dynamically.

In this work, we propose and experimentally demonstrate a multi-degree ROADM node that allows flexible spectrum configuration with colorless, directionless and contentionless switching operations. It uses liquid crystal on silicon (LCoS)-based switching platform to obtain fine spectral granularity and change passband widths for individual WDM channels. And it uses a transponder aggregator to perform centralized sharing of transponders for all add/drop signals. Experiment results show that inter-degree cross-connect and colorless and directionless add/drop operation on spectrum variable WDM signals can be achieved without incurring wavelength blocking in the node. This ROADM node enables spectrum and cost efficient switching compared to conventional fixed grid ROADM nodes.

PCE-based scalable dynamic path control for large-scale photonic networks

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ASON (Automatic Switched Optical Network) / GMPLS (Generalized Multi-Protocol Label Switching) control plane technologies for automated path control of a photonic network has been developed for this decade. In the past few years, it has been deployed in service provider’s commercial networks, and their advantage in terms of OPEX (operational expenditure) reduction was reported by a service provider. Although, most of such networks are still relatively small, which are constructed by few tens of nodes, and they have to be expanded to nation-wide larger networks for more effective OPEX reduction. To control larger networks, typically thousands of nodes, multi-domain network configuration is advantageous to routing protocol scalability. Furthermore, the application of photonic network technology will continue to expand in the future, and optical paths will come to traverse multiple domains that are possibly under different carriers’ control and management.

We have studied qualitatively and concluded that the PCE (Path Computation Element) based routing is the most suitable model rather than other routing models, the per-domain routing and the ASON hierarchical routing for inter-domain path control over multi-domain photonic networks. For the inter-domain path control, the selection of domain sequences has a significant impact on the efficiency of networks. However, quantitative study of global optimization using a large network test environment has not been reported yet.

In the presentation, we will discuss the overall architecture of multi-domain photonic network control system, and also provide measured performance results for inter-domain path computation and path setups using global optimization scheme.

Linear formulation to avoid adjacent channel interference in LTD of optical networks

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In this work, we propose a new optimization LP (Linear Programming)-complete formulation to block channel interference in links of optical fiber. To the best of our belief, the first linear formulation of a partial solution to the RWA problem avoiding the use of adjacent channels has been stated in other studies, where constraints are created using path formulation, where all possible paths are known beforehand. In this work, we propose a link formulation. Therefore, we do not know beforehand the set of alternative routes for any node pair. With all possible routes, the linear formulation that we propose can find effective results to avoid channel interference. Furthermore, our formulation is to the full logical topology design. We observe the effect of physical impairments in a higher layer, i.e, in virtual topology configuration.

Colorless and directionless multi-degree reconfigurable optical add/drop multiplexers for 100G network application

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The reconfigurable optical add/drop multiplexer (ROADM) has become one of the most important elements in 100G DWDM network. The next generation multi-degree ROADM requires two main features: colorless and directionless. Colorless means that add/drop ports are not wavelength specific, and directionless feature enables any transponder to be connected to any degree. In this paper we review and analyze different multi-degree ROADM node architectures that offer full colorless and directionless features with its network application. Their key characteristics and properties, including optical loss, size, cost, modularity and upgradability, are compared and discussed.