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Contents

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6468-43, Session 1

Small-footprint InGaSb/AlGaAsSb multiple quantum well light-emitting diodes

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No abstract available

6468-44, Session 1

Design analysis of lattice-matched AlInGaN-GaN quantum wells for optimized intersubband absorption in the mid-IR regime

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Mid-IR optoelectronics play important roles in free space communications, medical, biological, environmental and military applications. Existing III-Nitride intersubband QW for mid-IR applications are based on AlGaN-GaN materials. The large conduction band offset (~2eV) in AlGaN-GaN allows suppression of thermionic escape and thermal-assisted tunneling of electrons, thus leading to suitability in realizing low-dark-current detectors and high-performance lasers. Femtosecond carrier dynamics in the III-Nitride also confirms its suitability for ultrafast switchers. However, AlGaN is grown under tensile condition (-2.5 %) on GaN, thus resulting in large dislocation density and challenges to grow high-quality thick high Al-content AlGaN layers, which are necessary for realizing AlGaN-GaN multiple-QWs for intersubband absorption and gain media.

Here we present and analyze a comprehensive design analysis of lattice-matched AlInGaN-GaN QW systems for optimized intersubband absorption in the mid-IR regimes. The utilization of lattice-matched AlInGaN-GaN QW systems leads to higher crystal quality for higher bandgap AlInGaN material systems, as well as the ability to grow high-quality multiple stages of AlInGaN-GaN QWs systems for intersubband photodetectors, switchers, and lasers. Lattice-matched structure also leads to reduced polarization field in the materials, due to the removal of piezoelectric polarization, which leads to improved transition dipole matrix element. Our studies indicate strong intersubband absorption in the 3-6 micron regimes is obtainable for optimized lattice-matched AlInGaN-GaN QW systems, with transition dipole matrix element (~9-10 Å) of approximately 50% larger than those reported (~5-6 Å) for AlGaN-GaN QW systems. Optimization for QWIP and optical switcher using the lattice-matched AlInGaN-GaN QW systems will also be discussed.

6468-45, Session 1

Intersubband relaxation dynamics in short-wavelength InGaAs/AlAsSb quantum well structures

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Intersubband transitions in semiconductor quantum wells (QW) are crucial for mid-infrared lasers, detectors, and modulators. New compound materials such as lattice matched InGaAs/AlAsSb and strain compensated InGaAs/AlAs, both grown on InP, feature large conduction band discontinuities (>1eV) and allow the extension of the available wavelength range into the near infrared. Such short wavelengths require narrow QWs (<3 nm) where the first excited state inside the QW may be raised above indirect (X or L) valleys within the Brillouin zone.

We have studied intersubband relaxation dynamics in In0.53Ga0.47As/AlAs0.56Sb0.44 multiple QWs with thicknesses between 2 and 4.6 nm (corresponding to absorption wavelengths of 1.9 to 3.2 μm) by femtosecond pump-probe experiments. The high repetition rate (78 MHz) of our 280 fs pulses in combination with a rapid-scanning technique results in a detectable transmission change as low as 10^-5. At early delay times, all samples show an exponential decay of the transient transmission occurring with time constants of 1 to 1.5 ps. The relaxation dynamics at later delay times strongly depends on the QW thickness and doping. For very narrow QWs the observed bi-exponential decay indicates several competing relaxation channels. Here transfer of electrons to X- and L-states in the wells or in the barriers is energetically possible. States localized in the barrier exist due to strong band bending resulting from the n-type modulation doping. Finally, we will also show rate-equation simulations to study possible relaxation scenarios within a three level system.

6468-46, Session 1

Microscopic theory of light-intersubband-excitation coupling in semiconductors

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This papers shows that the coupling between light and intersubband excitations in semiconductors is fundamentally different from the well understood coupling to interband transitions that leads to excitonic polaritons. It is shown that bosonic approximations required for a Hamiltonian theory can be manipulated and turned “on/off” in the regime of excitations where the signatures of the coupling are best defined. Thus, bosonic effects can be in principle controlled by manipulating the intersubband carrier injection. Furthermore, the evolution of the quasiparticle with injected carrier density is opposite to that of the conventional polariton. Numerical results for III-V quantum wells and quantum cascade lasers under realistic nonequilibrium operating conditions are given by direct evaluation of analytical approximations obtained from a nonequilibrium Keldysh Green’s functions formalism. The approach consistently describes dispersions found experimentally if light is absorbed due to intersubband transitions and predicts anomalous dispersions under population inversion conditions.

6468-05, Session 2

Graphics-processor-units-based accelerated 2D and 3D FDTD solvers

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Our group has employed the use of modern graphics processor units (GPUs) for the acceleration of finite-difference based computational electromagnetics (CEM) codes. In particular, we accelerated the well-known Finite-Difference Time-Domain (FDTD) method, which is commonly used for the analysis of electromagnetic phenomena. This algorithm uses difference-based approximations for Maxwell’s Equations to simulate the propagation of electromagnetic fields through space and materials. The method is very general and is applicable to a wide array of problems, but runtimes are long enough that acceleration is highly desired. In this paper we present GPU-based accelerated solvers for the FDTD method in both its 2D and 3D embodiments.

6468-06, Session 2

Simulation of various configurations of single-pump dispersion-compensating Raman/EDFA hybrid amplifiers

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Dense Wavelength Division Multiplexing (DWDM) and Raman technologies allows for higher bandwidths, longer amplifier spans and closer channel spacing, but imposes very tight spectral and optical specifications in optical fiber communication systems. Raman amplifiers can be distributed, lumped or discrete, or hybrid, thus, either Raman amplifiers can serve as low-noise preamplifiers for EDFA or they can meet the full amplifier needs in “all-Raman” systems. Hybrid Raman amplifiers utilizing distributed Raman amplification (DRA) in transmission fibers in conjunction EDFA are an enabling and promising technology DWDM systems. Also, in Raman amplifiers, the amplification and dispersion compensation (DC) can be combined in the same fiber. The DC fiber ends up having net gain rather than loss, which leads to a wider system margin and the ability to insert other elements such as optical ADD-DROP multiplexers. DC modules based on Raman amplification in DC fiber have been considered to be attractive means as an enabling tool for the future long-haul high capacity optical communication systems, and their system applications have been successfully demonstrated.

In this work, numerical simulations are performed and the performance comparison of three types of DC Raman/EDFA hybrid amplifiers configurations in terms of gain, noise figure and nonlinear effect induced penalty is presented. A numerical simulator is presented for the analysis and design optimization of Raman/EDFA hybrid amplifiers for multi-wavelength operation. This simulator combines a steady-state model of a DRA with a spectrally resolved model for the EDFA. The numerical simulator allow us to calculate the overall gain, the noise figure (NF), the optical signal-to-noise ratio (OSNR) and the signal and ASE spectrum at the output of a Raman/EDFA hybrid amplifier. We concluded that performance tradeoffs should be considered when an optimum hybrid amplifier configuration for a given fiber optic transmission system is to be decided.

6468-07, Session 2

Simplified gain calculation in erbium-doped LiNbO3 waveguides

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The combination of excellent electro-optical, acousto-optical and nonlinear optical properties makes lithium niobate (LiNbO3) an attractive host material for integrated optical components such as electro-optical modulators, acousto-optically tunable wavelength filters and Bragg gratings. In the last few years Erbium doped LiNbO3 waveguide optical amplifiers (EDWA’s) have attracted increasing interest. The optical gain achievable in Ti:Er:LiNbO3 waveguides by optical pumping could compensate or even over compensate these scattering, absorption and insertion losses leading to “zero loss” devices with net optical gain. The analysis of Er-doped diffused channel waveguides is, hence, required for design of amplifying integrated optical circuits in order to optimize the performance of these gain devices. The coupled differential equations, which govern the evolution of, pump power (1484nm), signal power (1.5 to 1.6mm) and amplified spontaneous emission involve integrals, which depend explicitly on the modal fields at the pump and signal wavelength in the diffused channel waveguide and have to be evaluated numerically. In-fact, in general, it is not possible to obtain analytical forms for the modal fields and propagation constant, hence, to obtain them various approximate or numerical methods (BPM, finite difference or finite element) are used. In this paper the modal field profiles are obtained by the variational analysis and then approximated to an appropriately chosen rectangular function, which leads to analytical forms of coupled differential equations with no integrals for the calculation of gain and ASE characteristics of the amplifying waveguide. Thus, computations are simplified and computation time is also reduced. The gain characteristics obtained by the analysis are also compared with exact calculations and available experimental results, showing adequate accuracy.

6468-08, Session 3

Influence of refraction dispersion on the Sagnac effect in semiconductor ring lasers

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No abstract available

6468-09, Session 3

Rb-saturated-absorption-profile-based enhancement of semiconductor laser frequency stability

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Maintainance of semiconductor lasers’ frequency stability is crucial to their proper function as light sources in interferometric applications and coherent optical communications systems. Numerous reports describe the use of atomic absorption lines and Fabry-Perot etalons as frequency references. The satellite-to-satellite tracking laser interferometers used to measure fluctuations in earth’s gravity field accurately gauge infinitesimal variations in the relative velocity of satellites flying in tandem, at better than 10 nm/s; a feat that requires frequency stability greater than 10-13 in the square root of the Allan variance σ.

Taking advantage of the Fabry-Perot etalon’s short-term stability and tunability over a wide frequency range, and the Rb absorption line’s stability over the long term, we succeeded in stabilizing the frequency of a semiconductor laser.

Where in earlier trials, overall frequency stability was enhanced by optimizing the modulation frequency, this experiment involved the alteration of the modulation frequency, from 770Hz to 20kHz. The result: stability of $\sigma = 2 \times 10\text{-}12$ at 7.77kHz. It should be noted that when we adjust the modulation-frequency, the -width is also affected, so in the follow-up, we will set the modulation-width constant in changing modulation frequency, obtaining improved stability in the process.

6468-10, Session 3

Laser diode frequency stabilization by means of optical feedback and the magneto-optical effect

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A method of detecting gravitational-field variations using laser diode is described. While the GRACE project is currently using the Doppler microwave system for measuring the velocities of satellites flying in tandem, in the future, more advanced laser interferometry will be employed. In so doing, it is hoped that we will be able to measure infinitesimal changes in their velocities, by using frequency stabilized lasers rated at better than 10-13 in the square root of the Allan variance (σ) for $1s < \tau < 100s$. As laser light sources, these devices will be notable for their compactness, energy efficiency, light weight and high frequency stability.

So, this thesis describes the improved frequency stabilization obtained through the use of the magneto-optical effect of the Rb-D2 absorption line, and the adaptation of the PEAK method, in order to obtain a precise control signal. The method allows us to modulate the reference frequency of the stabilization system (the absorption spectrum of the Rb-D2 absorption line) by modulating the magnetic field applied to the Rb absorption cell, instead of the oscillation frequency of the laser diode. Thus, we were able to achieve a frequency stabilized laser diode ($\sigma = 9 \times 10\text{-}12$) without its linewidth broadening, at an integration time of 40 s.

Investigations are ongoing, into the use of the optical feedback method to narrow the laser diode's oscillation spectrum, as well as the use of a thermostat, to control the temperature of Rb-cell in magnetic fields, to stabilize laser diode oscillation frequencies. It is our strong belief, that by using those methods, we will achieve greater frequency stability.

6468-11, Session 3

Compact double optical feedback external-cavity diode laser system and its frequency stabilization

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External cavity diode laser (ECDL) systems are presently experiencing a surge in popularity as laser light-sources, in precision-measurement applications such as gravitational-field variation measurements. Because such systems require that their external reflectors be precisely controlled to eliminate low-frequency fluctuations (LFF) in optical output, we conducted experiments with a new type compact ECDL system, i.e., a double cavity version, under the assumption that it would help eliminate LFF. This technique brings the added advantages of a narrower linewidth than would be achievable via a single optical feedback. However, the ECDL's oscillation frequency is susceptible to the influences of the driving current, changes in the refractive index, and the expansion/contraction of the length of the external reflector that results from fluctuations in atmospheric temperature. We made every effort to maintain the length of the ECDL cavity, while evaluating oscillation-frequency stability. We used a super-invar board as the platform for our compact ECDL system, in order to minimize the influence of thermal expansion. Moreover, in ECDL systems, there is, in the short term, deterioration caused by mechanical vibrations, as well as fluctuations in atmospheric pressure. So, ECDL systems need to be miniaturized, to decrease these factors' influence. To that end, we created the compact double optical feedback ECDL system. We used the square root of the Allan variance to evaluate oscillation frequency stability, observing, in the process, that it improved stability.

6468-21, Session 4

Optimization on the design of an ultra-high-power multisection tunable laser gain epilayers

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Great efforts and vast investments have been put into the research and develeopment of widely tunable lasers in the last 25 years. Tunable lasers have become critical components in the implementation of next generation telecommunication networks and systems, to provide dynamic wavelength provision for channel restoration, reconfiguration and protection. Some stringent requirements have been imposed on tunable lasers by telecom applications. Consequently, ultra-high optical output power (>100 mW), wide tunability (tuning range around 40nm), narrow linewidth (< 2MHz), and side-mode suppression ratio (SMSR > 40dB) have become the main objectives for the development of the future telecom tunable lasers. Facet output power is the fundamental decisive factor among these targets. Original design ideas and novel approaches to the design of ultra-high power InGaAsP/InP based multi-section widely-tunable laser gain section have been reported by the authors previously, which are mainly comprised of two parts: firstly, an InP spacer layer is placed below the ridge and above the multiple quantum wells (MQWs) stack, so as to introduce extra freedom in the control of widening the single mode ridge width. Secondly, a bulk balance layer structure is placed above the InP buffer layer and below the MQWs stack, which enables a large reduction of free-carrier loss by greatly shifting the optical power distribution to the intrinsic and n-doped sides, with lower free-carrier absorption losses. This paper will focus on the implementation optimization of the above design ideas and approaches, regarding output power, threshold current, slop efficency and other related optical and electrical properties.

6468-22, Session 4

Gain eigenvalue calculations for antiguided VCSELs and arrays

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Antiguided cavities, arrays, and antiresonant reflecting optical waveguides are useful for achieving high-power single-mode output from a vertical cavity surface emitting laser (VCSEL) structure [1]. The standard procedure for optical simulation of semiconductor lasers is to obtain the passive cavity modes, which neglects the influence of the spatial gain distribution. However, this is clearly inappropriate for an antiguided structure, where we expect the gain distribution to have a strong influence on the optical modes. Therefore, antiguided structures are ideally suited for gain eigenvalue analysis [2].

The gain eigenvalue modes are the eigenfunctions of an integral equation enforcing the self-consistency of a lasing mode. The modal electric field multiplied by the susceptibility representing the gain distribution is a polarization current. Using the tensor Green's function of the planar VCSEL structure, the electromagnetic field emitted by this polarization current is obtained. To enforce self-consistency, we set the electric field emitted by the polarization current equal to the modal electric field.

In practice, the gain eigenvalue equation is discretized using Galerkin's method: the electric field inside the active region is expanded and tested using a set of cylindrical pulse functions [2]. The matrix elements of the discretized Green's function are obtained in k-space using Fourier transformed basis and testing functions. In order to simulate an array of coupled cavities, the matrix elements between cavities are obtained by spatially shifting the testing functions. The Fourier transform of the testing function then becomes an infinite Bessel series. Sample results from these calculations will be presented.

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6468-23, Session 4

Investigation of optical far-field stability in long-wavelength VCSELs: Thermal and carrier-induced effects

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In recent years long-wavelength vertical-cavity surface-emitting lasers (VCSELs) have started to enter transceiver applications in place of edge-emitting lasers. Due to the lower output power of VCSELs, the coupling efficiency of optical power into optical fibers becomes an important issue. VCSELs have good circular far-fields but for high coupling efficiency a narrow and stable far-field (over ambient temperature and driving current) is essential. This contribution aims to investigate the optical far-field by means of a state-of-the-art technology computer aided design (TCAD) tool. Measurements of far-fields for the simulated device are available at different ambient temperatures and bias currents.

The fully-coupled electro-opto-thermal multi-dimensional simulations use a microscopic physics-based model. The optical modes are obtained by solving the vectorial Helmholtz equation, using a finite element approach. The impact of temperature, free carrier absorption and gain on the refractive index is accounted for. The far-field is calculated using Green's functions. The equations are solved self-consistently.

The comparison of simulated and measured L-I, V-I characteristics and far-field as well as the wavelength-shift show good agreement for different ambient temperatures as well as driving current values. The influence of the turn-on of a higher order mode on the far-field angle is investi-

gated. The simulations reveal the impact of gain-guiding, temperature effects and free-carrier absorption (plasma effect) on the (multi-mode) far-field. The design of optical guiding structures (such as oxides or tunnel junctions) and its effect on the farfield behaviour over ambient temperature and bias current is investigated.

6468-62, Session 4

Size reduction of a semiconductor nanowire laser by using metal coating

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No abstract available

6468-01, Session 5

Active photonic lattices: The physics of coupled microlaser arrays

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An important feature of coupled laser arrays is that the gain in one cavity is modulated by the radiation from another cavity. This is a generic characteristic with many forms of coupling, including fringe field interactions in closely packed arrays and reflection feedback from external mirrors. Cross-cavity gain depletion can occur in many types of laser arrays, including edge emitting semiconductor lasers, VCSELs and fiber laser bundles. It is what sets the behavior of active photonic lattices apart from the well known passive photonic lattices involving radiation interference due to real index variations.

The case of planar VCSEL arrays is chosen as generic example for studying the physics of active photonic lattices. Results of theoretical calculations and numerical simulations will be presented, addressing the following issues:

a) Non-linear phase-locked Bloch eigenmodes and boundary layer formation for finite arrays

b) Lattice defects, including sites that fail to lase, and defect tolerance

c) Excitation of stable, slow-light, lattice waves and photonic sound propagation

d) Unstable lattice behavior at high coupling strengths, with self-excited array oscillations and chaotic transitions

e) Phase locking in realistic arrays, with random variations in the cold-cavity parameters (manufacturing tolerances), via self-regulated frequency pulling

f) Existence and properties of randomly phase-locked arrays with “fuzzy” eigenmodes

6468-02, Session 5

Optical simulation of photonic crystal patterned layer lasers

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A fast and accurate round-trip transfer matrix technique is developed to assist the optical design of multilayer photonic crystal based lasers. First, a complete set of propagating and evanescent modes for each patterned layer is obtained, assuming periodic boundary conditions in the in-plane directions and uniformity in the out-of-plane direction. Next, the scattering matrix method [1] is used to calculate reflection and transmission coefficients between layers. For the layer representing the laser cavity, a round-trip transfer matrix is obtained using the reflection coefficients at the layer boundaries. The eigenfunctions of this round-trip matrix are the resonant modes of the cavity.

Using this round-trip transfer matrix technique, we obtained the dispersion relation of a double grating slab waveguide laser cavity. For this problem, the modes of the grating are calculated using a quasi-analytical technique, which is accurate for arbitrary grating index contrast. We observed pseudo-bandgaps at Brillouin zone edges as expected. The round-trip technique is extended to 2d photonic crystal layers through the use of a hybrid method for efficiently calculating the propagating and evanescent modes of 2d photonic crystals. In addition, the round-trip technique is applied to woodpile structures [2] by treating each layer as a 1d grating oriented perpendicular to the layer before. One advantage of our method is the incorporation of open boundaries at the top and bottom layers, which allows us to model the finite height of the layered structure. Also, defects can be introduced and analyzed in any layer.

6468-03, Session 5

Effective index perturbation: Correlations between the photonic bandgap and the donor-like defect mode in photonic crystal slab

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Two-dimensional photonic-crystal-slab (2D PCS) microcavities have been a good candidate to form single photon sources [1]-[4], biosensor, and high-sensitivity filters [5], due to their ultra-small mode volume V, high quality factor Q, and enhanced spontaneous emission. Significant progresses have been made in the computational techniques for the design of photonic crystal slab based microcavity, and in the understanding of these cavity characteristics. Works reported to date are mostly based on three-dimensional (3D) finite-difference time-domain (FDTD) technique [6]-[8], which can accurately simulate the characteristics of these devices. However, the fully vectorial 3D FDTD approach is extremely time and computer memory consuming. Effective index method (EIM) [6], [9], has proved to be very effective and efficient in predicting the cavity properties with reduced dimensionality (from 3D to 2D), where only the effective index of fundamental guided mode of the unperturbed slab is considered. EIM is most effective for the low-index-contrast PCS. However, it becomes less accurate when it is applied to high index contrast PCSs, where high index contrast is favorable for reduced vertical cavity loss and better mode confinement. Efforts have been reported to adjust the effective index by matching the photonic band diagram (dispersion plot) with frequency offset [10] and effective index modification [11]. However, to the best of our knowledge, no work has been reported in effective index method based approaches, on the correlation of shifted photonic band diagram with the cavity defect mode and the corresponding quality factor Q.

We introduce an effective index perturbation (EIP) technique in determining the suitable effective index for accurate prediction of cavity modal property and defect mode locations based on 2D and 3D plane wave-expansion (PWE) techniques and 2D FDTD method. In donor-like defect mode cavities formed in air-column based photonic crystal slabs, very good agreement in defect mode locations with less than 2% computational error was obtained with the EIP technique by matching the dielectric band edges simulated from 2D and 3D PWE techniques. The highest Q mode can also be correctly predicted, which is also very important in photonic crystal microcavity design, where the mode with the highest cavity Q could be most important in determining the cavity characteristics, including lasing and sensing.

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6468-04, Session 5

Design and simulation of an ultra compact integrated waveplate using 2D photonic crystal slab waveguide

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We have numerically investigated the optical path of the TE and TM waves propagating through a two-dimensional triangular based photonic crystal (PC) slab waveguide. The PC slab waveguide is formed by removing one row of the air holes along ΓK direction. The radius of the air holes is 0.3 a, where a is the lattice constant of the PC. The thickness of 0.75 a for the PC slab waveguide provides a strong index guiding for the TE polarization and PBG guiding for the TM polarization over a wide wavelength range. The plane wave expansion and three-dimensional finite-difference time domain (3D-FDTD) methods were employed for design and simulation of the 2D PC slab waveguide. Spatial Fourier transform of the field distribution along the guiding direction was used for the analysis of the dispersion properties of the guided mode of the waveguide.

For the wavelength range of a/0.26-a/0.29, the propagation loss was less than 2 dB/mm for both TE and TM polarizations. In this range of wavelength, it was found that the effective refractive index for the TE polarization was substantially larger than that of the TM polarization. The large birefringence of this structure suggests that the 2D PC slab waveguide is useful for the construction of compact waveplates. The refractive indices for the TE and TM polarization were calculated over the wavelength range of a/0.26 - a/0.29. The results showed that the PC crystal slab waveguide with the length of 7a would act as a first-order waveplate at the input wavelength of 1.55 μm.

6468-12, Session 6

Analysis of substrate modes in GaN/InGaN lasers

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In this contribution, substrate modes in edge-emitting lasers in the material system Gallium-Nitride are analyzed by means of comprehensive measurements and simulations. The simulations are complex vectorial optical mode calculations using a finite-element method. The simulation domain comprises the ridge waveguide and the full substrate with open boundary conditions on the sides. Therefore, the coupling mechanisms of the waveguides formed by the ridge and the substrate can be analyzed in a realistic setup. The characterization data include the optical loss spectrum obtained from Hakki-Paoli measurements, optical near field, and farfield measurements. The devices used for characterization are ridge waveguide quantum well lasers grown on GaN and SiC substrates. This allows a direct comparison of different substrate materials. A comparison of the measurement data with the simulations explains the characteristics of the substrate modes in a consistent way, and shows very good agreement for the optical loss oscillations, farfield angle, and nearfield pattern. It is shown that material losses, material dispersion and optical diffraction are important for the analysis of substrate modes. In addition, the absence of optical nearfield intensity for SiC substrates is explained by a waveguide analysis. Finally, the impact of substrate modes for the laser design is demonstrated by measurements from optimized devices.

6468-13, Session 6

Comparison of the simulation and experiments of the nitride-based UV-light-emitting diodes

K. Iida, H. Watanabe, K. Takeda, T. Nagai, K. Nagamatsu, K. Balakrishnan, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan); A. Bandoh, Showa Denko K.K. (Japan)

No abstract available

6468-14, Session 6

Comparative study of the crystalline quality and performance of the nitride-based light-emitting diodes with c-plane, a-plane, and m-plane heterostructures

T. Kawashima, T. Nagai, D. Iida, A. Miura, Y. Tsuchiya, Y. Okadome, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan)

No abstract available

6468-24, Session 7

Implications of injection current and active layer length on the performance of reflective semiconductor optical amplifiers

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In order to solve the last-mile bottleneck problem, passive optical access networks are being deployed worldwide by service providers. Reflective semiconductor optical amplifier (RSOA) is an attractive solution for optical network units (ONUs) in WDM passive optical networks. GPON standard requires ONUs operating up to 2.5 Gb/s, but the modulation speed of currently available RSOAs is limited to 1.5 Gb/s. Designing RSOAs for high speed modulation is a challenging issue.

In this paper, a time-domain model for RSOA is built based on carrier rate equation. In this model, the gain saturation effect and the dependence of spontaneous carrier lifetime on carrier density are explicitly included, and the evolving of carrier density and the optical power in time and space under current modulation is considered in detail. Using this time-domain model, the small signal frequency response and the Q-factor of the output signal under large signal modulation are calculated, and the effect of the injection current and the active layer length on RSOA performance is investigated. The simulation results demonstrate that the carrier spontaneous lifetime is the most important limiting factor of the modulation speed of RSOA. Increasing the injection current of RSOA improves the small signal frequency response and the Q-factor of the output optical signal. The active layer length of RSOA also has a significant impact on its modulation speed. With fixed modulation current, increasing active layer length of RSOA results in a better frequency response. 2.5 Gb/s operation of RSOAs is possible with higher injection current and/or longer active layer. The simulation also shows that the input optical power has small effect on the modulation speed of RSOAs.

6468-25, Session 7

A simple analytical model to determine gain in 1064-nm pumped Tm-doped 1470-nm amplifier

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Recently, much attention has been paid to the Tm-doped fiber amplifier (TDFA) for 1470 nm amplification because of its potential application in the S-band optical fiber communication. In this paper, we present a simple analytical model to approximately analyze the TDFA regardless of the host

glass composition. We have verified the validity of the method using the in-house fabricated Tm-doped silica glass fiber as well as the reported results for the fluoride fiber. Although there are total six levels involved for the emission in the Tm-doped optical fiber, we simplified the solution of rate equations by considering a low signal power regime and defining a simple definition for the gain coefficient of the TDFA.

The spectral variation of the gain obtained with the silica glass fiber TDFA after pumping with pump power of 275 mW at 1064 nm showed good agreement between the simulated and the measured values. To verify the validity of the procedure for the non-silicate glass fibers such as fluoride glass fiber, the experimental results reported earlier[1] were considered. The pump power dependence of the gain in the fluoride glass fibers calculated by our method showed a very good agreement with the experimental results reported. The error was found to increase as the gain approached saturation because the model did not consider the effect of ASE in the fluoride fibers and was valid in the non-saturated regime. The maximum error in determination of gain was limited to 12%.

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6468-26, Session 7

Vertical-illumination InGaAs/InP quasi-unipolar photodetector with high-bandwidth, quantum efficiency, and resistance to bandwidth collapse

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Vertical-illumination PIN photodetectors with InGaAs absorption regions enjoy wide application in long-wavelength (1.3 and 1.55 micron) optical receivers for high-speed telecommunications systems [1], where they must meet challenging demands on quantum efficiency (QE) and bandwidth (BW). High QE detectors require very thick (>2 micron) absorbers, which not only place limitations on bandwidth, but also contribute to the phenomenon of bandwidth collapse at input power levels intolerably low for some systems [2,3]. In this work we demonstrate the use of doping strategy to achieve quasi-unipolar operation [4], in which velocity overshoot and non-linear self-biasing are exploited to satisfy system requirements of high quantum efficiency, high bandwidth, low voltage, and high optical saturation power. The device structures studied, grown on an n+ InP substrate via MOCVD, consist of a 1.5 micron n- InP buffer region followed by an InGaAs absorption region of various thicknesses, and a very thin InGaAsP cap layer. In-process specifications for InGaAs absorber and InP buffer doping are optimized, enabling BW, QE and saturation intensity to be determined by design. Results of device characterization are presented, and numerical simulations reconcile high bandwidths with what would seem otherwise fatal limitations of transit time and incomplete electrical depletion.

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6468-27, Session 7

Tailoring the transmission spectrum of the long period fiber gratings by variation in the length of the grating

R. Singh, E. K. Sharma, Univ. of Delhi (India)

A long period grating couples power from the guided core mode to the forward propagating cladding modes. Complete power transfer takes place from the core mode to the cladding mode for the wavelength that satisfies the phase matching condition and requires an interaction length equal to the coupling length. In this paper we present the anomalous behavior of the transmission spectrum of long period grating for lengths greater than the coupling length. We have obtained analytical expressions for the position of occurrence of peaks and amount of power retained in the cladding mode for overcoupled gratings. If the grating length is greater than the coupling length the power starts returning to the core mode and is fully coupled back at twice the coupling length. For such a grating our calculations show that there is zero power in the cladding mode at resonance wavelength but, two analytically predicted, peaks appear in the transmission spectrum on either side of the resonance wavelength, each carrying 0.465Po. Gratings of lengths four or six times the coupling length exhibit similar behavior but the two peaks become sharper and shift towards zero detuning wavelength as the length increases. However, for intermediate values of coupling length, e.g., 1.5 or 3.5 times the coupling length, the spectrum has one peak appearing at the resonance wavelength along with two side peaks, all with equal power. Thus the spectrum of overcoupled gratings forms an interesting study and can be tailored for specific filtering applications like an efficient gain flattening filter.

6468-29, Session 8

Comparative analysis on the observed non-linear dynamics between single diode lasers and lateral coupled diode lasers

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Lateral coupled diode lasers (LCDL) are two twin laser ridges electrically isolated and optically coupled. These devices are characterised by a second resonance frequency, beyond the relaxation oscillation frequency, which appears due to interaction of the emitted fields of each one of the laser stripes [1]. The dynamics of these devices depend significantly on the location the frequency of the second resonance and on its locking conditions [1]. Further studies have found that the second resonance frequency matched in both the frequency response and RIN spectrum of the device [2].

From the analysis of the RIN spectrum of the LCDL devices a study of its nonlinear behaviour is achieved. In this study, it was found that, under certain bias conditions, the second resonance frequency is at double the relaxation oscillation frequency and, for the first time, a period doubling is observed . This effect is similar to a single diode laser when is current modulated at the double the relaxation oscillation frequency, as experimentally observed by Liu and Ngai [3] and Bennet et al. [4] and theoretically studied in ref [5].

In this work a study of the period doubling evolution as a function of the relative bias applied to the LCDL device is made by analysing the RIN spectrum of these devices. Also in this paper an analysis of the previous results with the evolution of the period doubling of one of the ridges of the LCDL with external current modulation is made in order to compare these with the results reported in Refs. 3, 4 and 5.

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6468-30, Session 8

Radio-over-fiber transmission from an optically injected semiconductor laser in period-one state

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Nonlinear dynamics of semiconductor lasers has found many interesting applications in microwave photonics technology. In particular, a semiconductor laser under an optical injection of proper strength and optical frequency detuning can enter into the dynamical period-one (P1) state through Hopf bifurcation. The resulting optical output carries a broadly tunable high-speed microwave modulation without employing any expensive microwave electronics. It is therefore a desirable source for radio-over-fiber (RoF) applications. The P1 state can also be adjusted to have a nearly single sideband (SSB) optical spectrum. It is an advantageous property for long distance fiber transmission because it minimizes the microwave power penalty that is induced by chromatic dispersion. In this work, we investigate in detail the properties of the P1 state and the effect of fiber dispersion as a function of the injection conditions. Based on a well established rate equation model, the results show that the generated microwave frequency can be several times higher than the intrinsic relaxation resonance frequency of the laser. With a strong injection strength and an injection detuning higher than that required for Hopf bifurcation, the generated microwave power is nearly constant and the optical spectrum is close to SSB. We simulate the effect of fiber chromatic dispersion and the result shows a maximum microwave power penalty of less than 2 dB. The characterization of the P1 state is useful in guiding the design of RoF systems based on optically injected semiconductor lasers.

6468-31, Session 8

All-optical noninvasive chaos control of a semiconductor laser

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No abstract available

6468-32, Session 8

Excitability of chaotic transients in a semiconductor laser

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No abstract available

6468-33, Session 8

Excitability in a quantum dot semiconductor laser with optical injection

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We analyse experimentally the dynamics of a quantum dot semiconductor laser operating under optical injection. We demonstrate a stable synchronisation region in parameter space and an unstable unlocking boundary where we observe excitable pulses and chaos via period doubling. We report the first experimental observation of multipulse excitability in a semiconductor laser and provide a theoretical analysis of the system.

The experiment was carried out on samples of 1.5 mm long InAs QD lasers grown on a GaAs substrate emitting around 1310nm. The master laser was a commercial external cavity tunable device with linewidth < 100 kHz and tunable in steps of 0.1 pm. The slave laser output was coupled to a 12 GHz photodiode or an optical spectrum analyser via a single mode fibre. The photodiode was either connected directly to a real-time oscilloscope of 6 GHz bandwidth, or amplified and connected to a electrical spectrum analyser to provide high sensitivity spectral analysis with a bandwidth limited by the photodiode. The experimental parameters available are the master power, the slave current and the master-slave detuning. We find within the experimentally accessible range single excitable pulses, double excitable pulses, bistability between a stable fixed point and a limit cycle and bistability between two stable points. We model this system using quantum-dot rate equations and obtain good agreement with the experimental results. This is the first observation of which we are aware, of multipulse excitability in a semiconductor laser. The high relaxation oscillation damping of quantum-dot lasers delays the onset of chaos and enables many dynamical features to be observed.

6468-34, Session 8

A secure encryption scheme using chaotic self-pulsating laser diodes

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The synchronization of chaotic non-linear systems has led to the realization of the use of chaos to mask a signal in a secure information communication channel. Secure communication has been demonstrated in electronic circuits and using erbium doped fiber ring lasers. This was extended to the use of synchronized chaotic laser diodes using external optical feedback that allows higher speed message encoding.

It is well known that modulating a semiconductor laser under certain conditions can generate chaotic emission. Particularly suited for these kinds of application are self-pulsating laser diodes which emit regular optical pulses under dc electrical bias. Under external modulation of the bias current the output pulse magnitude and timing becomes chaotic.

The critical component of any chaotic communication protocol is the synchronization of a transmitter and receiver system in order to determine the signal from the chaotic carrier. It has recently been demonstrated theoretically that it is possible to synchronize two chaotic self-pulsating laser diodes.

In this presentation we propose a secure data transmission protocol using chaotic self-pulsating laser diodes. We present a theoretical analysis of different methods of data encryption and investigate the bit error rates of such systems and any issues of security.

6468-35, Session 9

Quantum kinetic approach to electron-LO-phonon relaxation: Is there a phonon bottleneck problem in optoelectronic devices?

P. Gartner, J. Seebeck, F. Jahnke, Univ. Bremen (Germany)

No abstract available

6468-36, Session 9

Maximizing the gain: Optimizing the carrier distribution in InGaAs quantum dot lasers

P. M. Smowton, I. C. Sandall, Cardiff Univ. (United Kingdom); D. J. Mowbray, H. Liu, M. Hopkinson, Univ. of Sheffield (United Kingdom)

The performance of lasers with self assembled quantum dot active regions is significantly affected by the presence of the two dimensional wetting layer and the other states necessary for carrier injection due to the manner in which carriers are distributed amongst the various states. In this work we describe three approaches to overcome the low value of

maximum saturated gain, which has been observed by many groups worldwide, and explain the approaches in terms of the impact on the distribution of carriers within the available states.

We present results of direct measurements of the modal gain and measurements that indicate the form of the carrier distribution within the samples to justify our argument. The structures examined include the use of a high growth temperature to smooth the matrix layer, the use of p-type modulation doping and the use of InAlAs capping layers and all have been grown by solid source molecular beam epitaxy.

We demonstrate CW operation at 1.3μm for 1mm long devices with uncoated facets and very low threshold current density (< 40Acm-2) in longer devices. We also demonstrate that the negative T0 (reducing threshold current density with increasing temperature) obtained around room temperature in our p-doped devices is due to the temperature dependence of the gain.

6468-37, Session 9

A microscopic theory for optical gain in semiconductor quantum dots

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For practical application of quantum dots (QDs) in light emitters as well as for fundamental studies of their emission properties, dephasing processes due to carrier-carrier and carrier-phonon interaction play a critical role. They determine the homogeneous linewidth of the QD resonances, limit the coherence properties of QD lasers and their ultrafast emission dynamics, and have a strong influence on coherent optical nonlinearities.

We apply a microscopic theory to study optical absorption and gain spectra of semiconductor QDs. The dephasing of a coherent excitation and energy shifts of the interband transitions due to carrier-carrier Coulomb interaction and carrier-phonon interaction are determined from a quantum kinetic treatment of correlation processes which includes non-Markovian effects. In general we observe a strong broadening of the QD resonances with homogeneous linewidths of several meV at room temperature. Comparable results have been found in recent photoluminescence spectroscopy measurements of single QDs.

Our quantum kinetic theory predicts a new effect, not found in other gain materials. For large carrier densities, the maximum gain can decrease with increasing carrier density. This behavior arises from a delicate balancing of state filling and dephasing, so that a appropriate treatment of the carrier density dependence of dephasing is necessary. The microscopic theory is also used to determine the alpha-factor for QD systems.

6468-38, Session 9

Multi-section gain-lever quantum dot lasers

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The “gain-lever” effect has been studied previously to improve the modulation efficiency of both amplitude modulation and optical frequency modulation of semiconductor lasers. The gain lever device usually consists of two electrically-isolated sections in which one, the modulation section, is biased at a low gain level with high differential gain. The other, the gain section, is biased at a high gain level with low differential gain. Due to gain clamping and the sub-linear relationship between gain and carrier density in low dimensional media such as quantum wells (QW), any small change in injection current in the modulation section will lead to larger changes in the gain section. The outcome is that the modulation efficiency and the 3-dB bandwidth depend on the differential gain and damping rate ratios between the two sections. Most previous research has been done on QW gain lever lasers, while quantum dot (QD) emitters are expected to demonstrate more significant gain lever action due to their stronger gain saturation with carrier density. In this work, we study the modulation efficiency and 3-dB bandwidth in gain lever quantum dot lasers with multiple sections. The added benefit of the multi-section layout is that one can vary the ratio of the modulation and gain section lengths without switching to another device. Also, the modal gain versus current density, which is the most important relationship for gain lever devices, can be directly obtained from the actual device using the segment-contact method.

6468-39, Session 9

Lateral mode dynamics in high-power wide-aperture quantum dot laser

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Recent advancements in epitaxial growth technology have opened up the possibility of fabricating high quality quantum dot active material for CW high power semiconductor lasers. Quantum dot active medium is known to be beneficial for high power generation owing to a low linewidth-enhancement (alpha) factor and inhibited carrier diffusion in the active region. A low alpha factor suppresses the possible filamentary lasing in wide aperture lasers whereas inhibited carrier diffusion in the active layer can result in a lower facet temperature at high power regimes. Both these properties have a profound influence in the formation and order of lateral modes sustained in these devices.

In this paper, we simulate and analyze the lateral mode dynamics in wide-aperture high-power quantum dot lasers taking into account the thermal and carrier contributions to the lateral index variation in CW operation. The field and carrier equations are solved in one space dimension (lateral direction) and time using the finite element method (FEM) in the mean-field approximation. This single longitudinal mode approximation is valid in the limit of strong inhomogeneous broadening as encountered in a quantum dot active material where inter-longitudinal mode intereaction can be neglected. Carrier diffusion from wetting and spacer layer is also into account. A 2D FEM thermal model including current spreading is designed to self consistently account for the thermal contribution to the lateral index variation.

The intrinsic instabilities associated with wide aperture devices are investigated and the possibility of a single lobed far field is predicted through lateral index profiling. The fundamental analysis reveals the underlying physical processes and indicates advantages and limitations of these quantum dot devices.

6468-16, Session 10

Pattern formation in multistacked-quantum-dot-based microcavities: Modelization and role of gain asymmetries in the alpha factor

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No abstract available

6468-17, Session 10

Quantum-confined Stark effects in interdiffused semiconductor quantum dots

Y. Wang, D. E. Negro, H. S. Djie, B. Ooi, Lehigh Univ.

Quantum-confined Stark effect in zero-dimensional semiconductor quantum dot (QD) has attracted considerable interest due to the potential applications in electro-optic modulation and quantum computing. Composition interdiffusion occurs easily during the high temperature epitaxial growth or ex situ annealing treatment, therefore understanding the effects of interdiffusion is essential for device design and modeling. However, relatively little attention has been devoted to a systematic study of

this effect. In this paper, the effects of isotropic interdiffusion on the optical transition energy of self-assembled InAs/GaAs and InAs/InP quantum-dot (QD) structure under an electric field have been investigated theoretically. Our three-dimensional (3D) QD calculation is based on coupled QDs with different shapes arranged periodically in a tetragonal superlattice, taking into account the finite band offset, valence-band mixing, strain, and effective mass anisotropicity. The electron and hole Hamiltonians with the interdiffusion effect are solved in the momentum space domain. Our results show that isotropic 3D In-Ga (As-P) interdiffusion will not introduce a negative electron-hole separation in InAs/GaAs (InAs/InP) QD, suggesting the inverted alignment depends on the diffusion profile and is not an inherent property of the self-assembled QDs. The uniform interdiffusion makes the Stark shift become more symmetry about in lens-shaped QDs, implying the reduced build-in dipole momentum. The interdiffusion also leads to enhanced Stark shift with more prominent effects to QDs that are under larger electric fields.

6468-18, Session 10

Quantum 3D finite-difference-time-domain (Q-FDTD) analysis of InGaAs-GaAsP and InN-GaN quantum-dot nanostructures

Y. Ee, Y. P. Gupta, R. A. Arif, N. Tansu, Lehigh Univ.

Self-assembled quantum dots (QD) nanostructures have been extensively studied for lasers and QD intersubband photodetectors applications. The shape engineering of the self-assembled QDs structures relies heavily on epitaxy conditions during the SK growth mode. Typical MBE-grown QDs assume pyramidal shape, while MOCVD-grown QDs have either tapered-pyramidal or disk-like shape. One of the challenges is to accurately analyze the QDs nanostructures provided by the complex arbitrary shapes from the self-assembly epitaxy. Accurate numerical modeling for 3-D nanostructures with complex shape is required for analyzing the device physics of QDs active region, as well as for optimizing the QDs active media realized by experiments.

In this work, we present a full 3-D numerical model based on 3-D Quantum-Finite-Difference-Time-Domain (Q-FDTD) method, with Perfectly Matched Layer boundary condition, as a versatile tool to accurately analyze 3-D QD nanostructure with arbitrary shape. Model solid theory has been utilized to determine the 3-D band lineup of the QD heterostructure. The effects of strain distribution, effective mass distribution, and polarization field on the band structure of the QD nanostructure are also taken into account in the model. The Q-FDTD computation has been applied for analyzing 1) MOCVD-grown InGaAs QDs with GaAsP barriers on GaAs, and 2) MOCVD-grown InN QDs with GaN barriers. The Q-FDTD simulation, using the QDs shape measured by TEM and AFM, shows good agreement with the experimental results obtained from the as-grown InGaAs QDs with GaAsP barriers. Comparison of the Q-FDTD simulation results with experimental results of interdiffused InGaAs-GaAsP QDs will also be discussed.

6468-19, Session 10

Simulation of p-n junction properties of nanowires and nanowire arrays

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The unique properties of semiconductor nanowires enable promising optoelectronic applications such as photodetectors and laser sources [1]. Due to the increased surface/volume ratio, nanowire-based p-n junctions exhibit properties different from those of bulk junctions, including weaker screening property and stronger fringe field effect. This work employs PROPHET [2] to numerically investigate the unique electrical properties of p-n junctions in single nanowire and nanowire arrays.

We examined the reduction of the screening effects as the nanowire radius shrinks [3].PROPHET is used to solve the semiconductor Shockley equations for a p-n junctions in silicon nanowires surrounded by dielectric. The junction depletion width increases abruptly for devices with moderate doping concentrations for wire radius below 50 nm. Such size effect is associated with the finite cross section of nanowires ,absent in bulk junctions. This effect is particularly beneficial to photodetector applications, where the increased depletion width is desired for longer photon absorption region. We also simulated the capacitance of such systems. The results strongly suggest that the fringe capacitance increases dramatically as wire radius decreases; it is the underlying cause of the increased depletion width in nanowires.

We further investigated the fringe-field effects in nanowire arrays. It is observed that the fringe effect can increase the total capacitance by more than forty times when the wires are sparsely distributed. The increase of the depletion width saturates when the wire spacing is greater than the wire length, indicating that the fringe-field is also limited by the wire length.

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6468-20, Session 10

Solution of the 3D Schrödinger equation with tensor effective mass based on perfectly matched layer and spectral element methods

C. D. Cheng, J. H. Lee, K. H. Lim, H. Z. Massoud, Q. H. Liu, Duke Univ.

A simple and systematic algorithm based on the perfectly matched layer (PML) method and spectral element method (SEM) is introduced to solve the 3-D Schrödinger equation with tensor effective mass. This algorithm extends the lead regions of a device into artificial PML media, where a modified Schrödinger equation with complex stretched coordinates is satisfied. The interface between the physical and PML media has zero reflection, and waves attenuate rapidly into the PML region before transmitting to the contact boundary. This algorithm provides a highly effective open boundary condition when solving both bounded and unbounded states in quantum devices. The additional PML region can be designed such that less than -100 dB incoming waves are reflected by this artificial material with the implementation of the spectral element method. Consequently, the solution of the Schrödinger equation and thus the current in the original device region do not deviate from the correct solution. In this algorithm, the total wavefunction contributed from all ports and all modes are directly calculated, thus significantly simplifying the problem in comparison with conventional open boundary conditions. The implementation of the tensor effective mass provides an excellent tool to study strain effects along any arbitrary orientation. Within this PML implementation, the spectral element method has been applied to achieve an error that exponentially decreases with the increase of the polynomial order and sampling points. This accuracy has been demonstrated by comparing the numerical and analytical results from waveguide and plane-wave examples, and its utility has been illustrated by solving nanowire semiconductor devices.

6468-40, Session 11

Quantum light generation with a semiconductor quantum dot

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No abstract available

6468-41, Session 11

Optical manipulation of semiconductor quantum dots in superfluid helium

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No abstract available

6468-42, Session 11

Advances in GaN-based quantum dots and photonic crystals for nanophotonic devices

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No abstract available

6468-15, Poster Session

Optical and electrical investigations of junction temperature effects in green InGaN/GaN multiple-quantum-well light-emitting diodes

W. Chen, D. Kuo, C. Hung, C. Ke, H. Shen, J. Wang, Y. Wu, T. Nee, Chang Gung Univ. (Taiwan)

With recent advances in nitride-based light-emitting diodes (LEDs) and laser diodes (LDs), the importance for the development of high brightness as well as high temperature devices is profound. The effects of temperature variation on the characteristics of LEDs inherent leads to a deterioration in the light output power constancy, internal quantum efficiency, and device reliability. In this work, thermal effects on the optoelectrical characteristics of green InGaN/GaN multiple quantum well (MQW) LEDs have been investigated in detail for a broad temperature range, from 30 oC to 100 oC. The current-dependent electroluminescence (EL) spectra and current-voltage (I-V) curves have been measured to characterize the thermal-related affects on the optoelectrical properties of the InGaN/GaN MQW heterostructures.

Experimentally, both the forward voltages decreased with slope of -2.6 mV/K and the emission peak wavelength increased with slope of +4.5 nm/K with increasing temperature, indicating a change in the contact resistance between the metal and GaN layers and the band gap shrinkage effect. With increasing injection current, it has been found the strong current-dependent blueshift of -0.048 nm/mA in EL spectra. It was attributed to not only the stronger band-filling effect but also the enhanced quantum confinement effect, resulted from the piezoelectric polarization and the spontaneous polarization in InGaN/GaN heterostructures. A comprehensive theoretical model for the dependence of forward voltage and emission peak shift on junction temperature was developed to examine the abnormal optical and electrical properties of InGaN/GaN MQW heterostructures. All the calculations are agreement with the experimental observations. The temperature-dependent optoelectrical evolutions for the LEDs studied will be discussed in detail as well.

6468-54, Poster Session

Analysis of power harmonic content and relaxation resonant frequency of a diode laser

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We have performed an analysis of harmonic contents of optical output power for a diode laser and described the results in details. In the first step the absolute value of power for each harmonic is obtained in terms of various diode laser parameters, and the variations of external parameters such as modulation current, bias current and frequency are discussed. The analysis is done by direct solution of rate equations of an arbitrary diode laser for carrier and photon densities. We conclude that the maximum power occurs at isolated peaks and their loci have been investigated and shown to be predictable by theory. It is known that the optical power has a nonlinear dependence on frequency, and the maximum optical power of each harmonic attained in its resonance frequency. The resonant frequency is shown to be tunable by bias current; thus in the next step we obtain the transfer function for different harmonic contents and have achieved exact expression for each, allowing better optimization to gain improved results. We extend the approach to higher harmonics and numerically calculate the THD (Total Harmonic Distortion) versus related parameters such as frequency, bias current and modulation current. Furthermore we found an effective approach to reduce SHD (Second Harmonic Distortion). The sequence for every arbitrary laser structure is also possible to be developed by the approach presented in this work.

6468-55, Poster Session

New results of InGaN LED simulation

O. I. Rabinovich, Moscow State Institute of Steel and Alloys/ Technological Univ. (Russia); S. G. Nikiforov, ATV Outdoor Systems (Russia); V. P. Sushkov, Moscow State Institute of Steel and Alloys/Technological Univ. (Russia) and Acol Technologies S.A. (Switzerland); A. V. Shishov, Acol Technologies S.A. (Switzerland)

Blue and green InGaN Light-Emitting Diodes (LED) with different quantity of quantum wells were simulated. We simulated changing LED's performance characteristics depending on In concentration and at different temperatures. Our results and the model describing them [1] gave us the possibility to forecast the LED's work at different situations.

All this also exactly corresponds with our experimental results of LEDs degradation investigation during 10 000 hours.

Reference:

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6468-56, Poster Session

Optimization of GaAs PIN diodes for neutron detection

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GaAs-based PIN detectors with mesa sizes 1 to 10 mm were fabricated and characterized for alpha particle response using a Po-210 alpha source. By decoupling the neutron conversion process of a proximity moderator, we were able to directly probe the alpha response characteristics of the PIN detectors as a function of device area. Dark current levels in the PIN detectors were low (~6 to 9 pA at zero bias). A linear relationship between mesa size and dark current was observed. The PIN detectors were found to have a strong alpha response (4 nA/mm^2) with a linear relation between the response current and mesa area. Using the measured alpha response properties of the GaAs PIN diodes one is able to select the optimal device area for a given moderator and application specific neutron fluency.

The alpha response of the detectors as a function of distance from the source was measured for each mesa size. We have a theoretical model of the expected detector response which includes the system geometry and losses due to attenuation of the alpha particles in air. The results of the measurements and a comparison of the theory and experiments will be presented.

6468-57, Poster Session

A novel approach for the analysis of Ti-PE:LiNbO3 distributed parameter waveguides

G. Bou Abboud, B. E. Benkelfat, Institut National des Télécommunications (France); N. Grossard, Photline Technologies (France)

Proton exchanged is becoming widely accepted as a complementary technique to titanium indiffusion for the fabrication of integrated optical waveguides in LiNbO3.

In this paper, we propose, for the first time to our knowledge, a novel method to analyze the optical distributed waveguides formed by local index variation, combining two processes, titanium indiffusion (Ti), and a localized patterned proton exchange (PE), yielding to the Ti-PE: LiNbO3 distributed parameter waveguides.

The effective index/impedance-matching technique has been used to analyze the propagation through this device, due to its simplicity and robustness. The traditional dispersion equation has been used before to compute the effective index of the diffused or the proton exchanged waveguides. For an arbitrary index profile, with a periodic or an almost-periodic corrugated waveguides, a new dispersion equation is derived for the Ti-PE:LiNbO3 waveguide, which yield to compute the corresponding effective index .

The efficiency of the method is shown by varying many parameters, like the index modulation or the proton exchanged depth for example. The simulation's result proves that the evolution of the reflectivity's spectrum has been found to be in a good agreement with prediction.

These numerical results and the experimental investigations, which we had carried out previously, show that the optimization of the different waveguide's parameters could yield to realize a predefined spectral response and more precisely the tailored optical filters.

Investigations are being carried out to determine the different waveguide's parameters, given a specification of the filter's characteristics, especially the reflection coefficient.

6468-58, Poster Session

Optical properties of subwavelength nanoholes in metal films

V. N. Minasyan, K. Adamyan, Yerevan State Univ. (Armenia)

We predict that the highly unusual transmission properties the metal films with nanoholes for the visible and the shorter wavelength infra red light perforated with periodic array subwavelength holes at room temperature is connected with the existence a new substance of matter within holes. This effect cames to view due to the Richardson-Dushman effect of thermionic emission due to which on the surface of vacuum-metal is formed the layer in the vacuum which in turn is a skin of metal.

6468-59, Poster Session

Discrimination characteristics of a wire-grid polarizer for polarimetric detection of multiple polarized beams

D. Kim, S. Moon, Yonsei Univ. (South Korea)

The presence of multiple polarized beams can limit the polarimetric discrimination capability of a wire-grid polarizer (WGP). In this study, the effect of linearly polarized background on the polarimetric performance of a WGP has been investigated and compared with that of a perfect polarizer. Simulation results based on rigorous coupled-wave analysis indicate that while a WGP mimics a perfect polarizer in discrimination characteristics, the range of the object polarization angle that can be discriminated against polarized background is fairly limited. The negative impact of Rayleigh anomaly is also discussed. The detectability of the object polarization can be strongly enhanced by employing a multi-cell WGP with multiple polarization orientations.

6468-60, Poster Session

Solitons in multicomponent dense media

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This work is devoted to soliton regimes of propagation of light beams in a co-doped crystal, crystalline matrix of which possesses Kerr nonlinearity. The dopant densities are supposed to be high enough so that the near dipole-dipole (DD) interaction between all impurity atoms becomes significant. Co-doping is known to make the laser cooling more effective and to amplify the photorefractive effect. Moreover in multicomponent media local field can lead to new effects such as cooperative decay and coherent exchange.

In dependence on relation between pulse duration and relaxation times we consider coherent and incoherent solitons. The group velocity dispersion (GVD) and diffraction influence is taken into account. As analysis shows, the soliton solutions can be found only at certain relations between concentrations and dipole moments of the impurity transitions. The coherent soliton shape strongly depends on the effective DD coupling constant (DDCC), magnitude and sign of the GVD as well as cubic susceptibility value. At the same time, the velocity of the solitons depends on the DDCC only. These solitons are characterized by nonlinear phase modulation. The coherent soliton area can be less than 2pi. It's possible to obtain a new type of the soliton solution providing GVD and Kerr nonlinearity values are quite high. As for incoherent solitons, such a propagation regime is realisable only when the input intensity is not very high, as the conditions of cubic approximation are fulfilled. At this the incoherent soliton area can differ from 2pi, and its velocity depends on the pulse duration, dephasing, detuning from the resonance, DDCC. We analyse also the conditions for the realisation of spatial solitons.

6468-51, Session 12

Monolithic passively mode-locked lasers using quantum-dot or quantum-well materials grown on GaAs substrates

Y. C. Xin, A. Stintz, H. J. Cao, CHTM/Univ. of New Mexico; L. Zhang, A. L. Gray, Zia Laser, Inc.; S. R. Bank, Stanford Univ.; M. Osinski, CHTM/Univ. of New Mexico; J. S. Harris, Jr., Stanford Univ.; L. F. Lester, CHTM/Univ. of New Mexico

There is renewed interest in semiconductor mode-locked lasers (MLLs) as sources for multi-gigahertz, ultra-short optical pulse generation. The compact size, low power consumption, and direct electrical pumping of monolithic semiconductor MLLs make them promising candidates for optical interconnects, clock distribution, time division multiplexing and arbitrary waveform generation. Operating wavelengths between 1250 and 1550 nm are desirable for compatibility with silicon-based waveguides and detectors and optical fiber-based components. These wavelengths are now accessible using GaAs-based materials technologies, which are desirable for MLL components because of their large-scale manufacturing capability and ultra low-loss GaAs/AlGaAs waveguides. In this work, the optical characteristics and physics of passive MLLs fabricated from 1.3-μm InAs dots-in-a-Well (DWELL), 1.25-μm InGaAs single quantum well (SQW), and 1.55-μm GaInNAsSb SQW structures grown using elemental source molecular beam epitaxy (MBE) are described. Result highlights are described next.

With a 5 GHz InAs DWELL mode-locked laser, an ultra-low jitter of 300 fs is achieved. The shortest pulse width is 2.5 ps and the peak power is up to 400 mW. For the 42% indium InGaAs SQW and the GaInNAsSb SQW MLLs, we hypothesize that the low density of states due to high compressive strain and narrow QW thickness explains why these devices have

similar pulsewidth performance to the DWELL MLLs. However, the SQW MLLs are much more sensitize to the gain/absorber length ratio. With the InGaAs SQW MLL, a record high-temperature performance for a monolithic passively mode-locked semiconductor laser is found. Compared with the typical operating range of the InAs DWELL devices (<60C), the operation is in excess of 100 °C, making the InGaAs QW MLL suitable for applications in uncooled environments. The first 1.55-μm GaInNAsSb SQW MLL operates at a repetition rate of 5.8 GHz and has a 170 kHz in the RF spectrum indicating respectable jitter.

6468-52, Session 12

Experimental and theoretical analysis of stable operation in monolithic quantum dot passively mode-locked lasers

K. C. Brown, V. I. Kovanis, D. Murrell, M. L. Fanto, Air Force Research Lab.; Y. C. Xin, L. F. Lester, CHTM/Univ. of New Mexico

Quantum dot semiconductor mode-locked lasers have attracted considerable attention recently from the fundamental physics and technology points of view. Combining an ultra-low linewidth enhancement factor, very low transparency, ultra-fast gain recovery time, and a high saturation power, quantum dot active regions have the potential to provide significantly reduced pulse width and higher peak power compared to their quantum well counterparts. Potential applications include optical clocking, on-chip optical interconnect, sources for wavelength division multiplexing, optical sampling, optical coherence tomography, and methods of arbitrary waveform generation. In this paper, two-section mode-locked lasers consisting of monolithic quantum dot gain and absorber sections are studied as a function of absorber voltage, injected current to the gain region, and relative section lengths. We map the regions of stable mode-locking as measured by the electrical and optical spectra and propose a theoretical model whose features are influenced by the Lang-Kobayashi equations and are consistent with the experimental results. In particular, the relative advantages of increasing the absorber length compared to increasing the absorber reverse bias voltage are analyzed. Initial data indicate that doubling the absorber length from 1.4 to 2.8-mm in a 5 GHz repetition rate device increases the region of stable mode-locking by at least 25%, while increasing the absorber reverse bias can more than double the mode-locking regime. Nonetheless, in these devices, stable mode-locking over greater than a 100 mA bias range is realized with a grounded absorber making single bias control of a passively mode-locked semiconductor laser feasible.

6468-53, Session 12

If EM fields do not operate on each other, why do we need many modes and large gain bandwidth to generate short pulses?

C. Roychoudhuri, Univ. of Connecticut and Femto Macro Continuum

No abstract available

6468-47, Session 13

Novel concepts for ultrahigh-speed quantum-dot VCSELs and edge-emitters

N. N. Ledentsov, Technische Univ. Berlin (Germany)

No abstract available

6468-48, Session 13

Femtosecond carrier transport analysis of terahertz radiation from InAs and InN

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It has been demonstrated that narrow bandgap semiconductors, such as InAs and InN, generate terahertz radiation more effectively than wide bandgap semiconductors, such as InP and GaAs, because of the lighter electron effective mass in the narrow bandgap semiconductors. To understand the ultra-fast carrier transport in these semiconductors, a momentum conservation and relaxation equation with a k-dependent effective mass is used to simulate the photo-generated hot electrons. Background electrons are treated separately due to their different carrier temperature. Hole currents are calculated using regular drift-diffusion equations assuming their temperatures are invariant at room temperature. By applying Poisson's equation, these equations are coupled self-consistently. The emitted THz radiation is then calculated.

Modeling shows that the dominant currents in narrow bandgap semiconductors are due to diffusion of the photo-generated hot electrons and redistribution of the background electrons (n-type) under drift. As doping increases, the drift current associated with the background electrons cancels the diffusion current and significantly reduces the THz radiation, especially for n-type materials due to higher electron mobility as compared to holes. Modeling also shows that the Dember field, created by the ultrafast separation of photo-generated carriers at an early time, slows down the diffusion of the photo-generated carriers at a later time. This result manifests itself as a saturation effect when the number of photo-generated carriers exceeds the background doping. In addition, the decreasing photo-excited electron temperature with increasing excitation wavelength lowers the THz amplitude, despite the increasing photon number.

The above modeling results agree well with experimental results.

6468-49, Session 13

Investigation of photodetector structures for THz emission by photomixing using numerical simulation

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No abstract available

6468-50, Session 13

Optimum design of nonlinear-optical-loop mirrors for compression of low power gain-switching pulses

C. de Dios Fernández, H. Lamela, Univ. Carlos III de Madrid (Spain)

Short pulsed laser sources have recently been under study for applications in Optical Communications. Several pulsed laser sources have been studied so far. Gain-Switching diode lasers are one of them [1]. These pulsed laser sources are easy and cheap to implement but offer higher pulse widths and lower pulse time stability. The use of a nonlinear shaper device can improve the quality of these short laser pulses and make them suitable for high speed optical communication applications. Nonlinear Optical Loop Mirrors (NOLM) are nonlinear compression devices that also offer pulse shaping capabilities [2][3], as well as noise reduction [4][5].

This work presents a novel design of Nonlinear Optical Loop Mirror optimized for the compression of optical pulses obtained by means of a Gain-Switching diode laser source. The proposed NOLM is based on an amplifier and a nonlinear photonic crystal optical fiber. The use of photonic crystal optical fibers is interesting since its high nonlinearity help constructing a NOLM with short loop length. The use of an amplifier is also

important, since it is the element that makes the same loop configuration suitable for compression of optical pulses in a wider range of widths, input peak power values or initial chirp conditions.

The methodology followed to obtain an optimized design of NOLM for compression of Gain-Switching optical pulses is based on two studies. A first approach to the design is made by means of a simplified analytical study of the dispersion and nonlinear phenomena that launch the compression performance of the loop. This study is made considering that the group velocity dispersion (GVD) and the self phase modulation (SPM) influence the pulse propagation separately. In addition to this, each element is characterized by a net GVD, SPM and, in the case of the amplifier, a gain. This simplified approach offers the possibility of considering several optical loop mirror configurations and comparing their compression characteristics in a short computing time. Given an optical pulse, this study helps identifying the important parameters and its values to achieve highest compression ratio by means of the analysis of the transfer function maps.

For maximum compression, we seek for a NOLM with a transfer function whose first peak appears at low input power levels. Gain-Switching laser pulses obtained from a diode laser are in the miliwatts range. On the other hand, a short fiber loop is also interesting. This first analysis gives us a broad understanding of the NOLM under investigation and helps us focus on a range of values of the several parameters that influence the device performance.

The shape of the transfer function is crucial for understanding the compression performance of the loop, since the sharpest it gets, the higher the compression ratio is. For exploring these characteristics we have to go deeper into the NOLM dynamic. Thus, the second approach is the detailed simulation of the NOLM performance following the Nonlinear Schrödinger Equation to present an optimum design of the shaper device. This study gives the ranges of the input pulse characteristics for which the design is suitable for compression. The results obtained are the basis for the development of an experimental NOLM for Gain-Switching laser pulses, which is under development in our Research Group.

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6468-61, Session 13

Generation of terahertz radiation using semiconductor heterostructures

S. W. Koch, M. Kira, Philipps-Univ. Marburg (Germany); M. R. Hofmann, Ruhr-Univ. Bochum (Germany); J. V. Moloney, L. Fan, M. Fallahi, College of Optical Sciences/The Univ. of Arizona

No abstract available

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6469-01, Session 1

Plasmonic metamaterials and devices

X. Zhang, Univ. of California/Berkeley

No abstract available

6469-02, Session 1

Design of wideband optical polarizing films for visible region using oblique metal island films

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Oblique metal island (OMI) films are composed of prolate metal nanoclusters (i.e., islands) inclining to one side. The OMI films exhibit resonance-type absorption in visible region and large optical anisotropy as the resonance wavelengths for the polarization along the shorter and longer axes of the prolate metal nanoclusters are different from each other. In the previous paper (OPTO 2006), we proposed an optical polarizing films consisting of the multilayer of the OMI layers and thin glass layers in which we utilize the optical anisotropy of the OMI films. The proposed optical polarizing films have high heat resistivity in comparison with commercially available polarizing films consisting of dichromatic polymer film as those are made of glass and metal. We theoretically evaluated the extinction ratio of 30 dB and insertion loss of 0.03 dB at the wavelength of 720 nm for the optical polarizing films designed by using silver as metal. However, the bandwidths of the designed polarizing films are narrow (about 50nm) as the multilayers consist of the OMI films with the same structure. In this work, we demonstrate the designs of wideband optical polarizing films for visible region. Aluminum is chosen as metal since the resonance wavelength of aluminum is shorter than that of silver from larger plasma frequency of aluminum. The resonance wavelength depends not only on the choice of metal but also on the aspect ratio of the prolate islands and distance between the centers of the islands. We have designed the optical polarizing films for 400-700 nm by using several OMI layers with various aspect ratio of the prolate islands. The extinction ratio of designed optical polarizing films is greater than 20 dB.

6469-03, Session 1

Optical switching with a thermochromic film

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Materials for optical switching are highly sought for applications in optical devices. On the other hand, for applications in photonic crystals, optical lithography, and ultrahigh density optical data storage, continued efforts are being expended in trying to achieve smaller optical microfabricated features to meet the device design requirements. However, due to the diffraction of light, which limits the attainable spot diameter, it is difficult to reduce the feature size any further through conventional optical process. Microfabrication techniques, including lithography and reactive ion etching, can produce microstructures. However, these processes are costly and tend to be either limited in their resolution or slow in their throughput. Optical near-field effects have been reported to be capable of achieving resolution exceeding the diffraction limit. However, generation of optical near-field through a near-field scanning optical microscope has the inherent difficulty in the fabrication and fragility of the tapered fiber and lack of reproducibility. In this article, optical switching effect of a thermochromic thin film is reported. The optical properties of the film have a strong dependence on the temperature. By using a pump-probe configuration, the time response of the thermochromism of the material is revealed, which ensures the instantaneous realization of the effect. Applying the thermochromic film as a mask layer, optical super-resolution effect is experimentally demonstrated with the optical switching effect of the thermochromism. The effect, which produces a light-induced aperture as a result of change in the optical properties of the thermochromic material, effectively reduces the laser beam size. Details will be discussed.

6469-04, Session 1

Time dependence of internal stress and optical characteristics of SiO2 optical thin film

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Recently, optical thin films have been increasingly needed in optical components. SiO2 is most frequently used as a low- refractive-index material of optical thin films. The stress of the film is an important parameter that relates to the adhesion of the film. However, the long-term time dependence of the stress has not been thoroughly discussed for SiO2 optical thin films. In this report, the time dependence of the stress of SiO2 optical thin film is discussed in terms of optical characteristics in the infrared region. The optical characteristic and structure of SiO2 optical thin films prepared by vacuum deposition (using an EB gun) and ion-assisted deposition (IAD) were observed by FT-IR, XRD and SEM. The stress of the SiO2 optical thin films was measured using an interferometer to determine the change in the substrate shape. The SiO2 thin films prepared by vacuum deposition and IAD exhibited compression stress. Decreases in the stress of the films for vacuum deposition were observed to continue for more than 1000 hours. This result is different from that of the conventional stress model in which the stress changes stop after about one week. The stresses of the films prepared by IAD were observed to hardly change. Absorption by Si-O bonds was observed at 1100cm-1. The change in bonds from Si-O to Si-OH was observed in the film prepared by vacuum deposition. It is thought that this result of the change in bonds was related to the decrease in the stress of the films.

6469-05, Session 1

Active resonant subwavelength grating for scannerless range imaging sensors

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We present the design and initial fabrication results for a wavelength-agile, high-speed modulator that enables a long-term vision for the THz Scannerless Range Imaging (SRI) sensor. This modulator takes the place of the currently utilized SRI micro-channel plate which is limited to photocathode sensitive wavelengths (primarily in the visible and near-IR regimes).

The new component is an active Resonant Subwavelength Grating (RSG). An RSG functions as an extremely narrow wavelength and angular band reflector, or mode selector. Theoretical studies predict that the infinite, laterally-extended RSG can reflect 100% of the resonant light while transmitting the balance of the other wavelengths. Previous experimental realization of these remarkable predictions has been impacted primarily by fabrication challenges. Even so, we have demonstrated large-area (1.0mm) passive RSG reflectivity as high as 100.2%, normalized to deposited gold. In this work, we transform the passive RSG design into an active laser-line reflector.

Two of Sandia's successful technologies - subwavelength diffractive optics and THz sources and detectors - are poised to extend the capabilities of the SRI sensor. The ultimate goal is to drastically broaden the SRI's sensing waveband - all the way to the THz regime - so the sensor can see through image-obscuring, scattering environments like smoke and dust.

Surface properties, such as reflectivity, emissivity, and scattering roughness, vary greatly with the illuminating wavelength. Thus, objects that are difficult to image at the SRI sensor's present near-IR wavelengths may be imaged more easily at the considerably longer THz wavelengths (0.1 to 1mm).

6469-06, Session 2

Challenges in the fabrication of transparent laser ceramics

R. Gaume, J. A. Wisdom, R. K. Route, R. L. Byer, Stanford Univ.

No abstract available

6469-07, Session 2

Novel photonics materials for broadband lightwave processing

Y. Ohishi, Toyota Technological Institute (Japan)

We are engaged in developing glass-based photonics materials for practical functional devices in future optical networks. We are focusing on the following two research items, (1)Broadband optical amplification media, (2)Efficient optical signal processing materials. Glasses and glass ceramics doped with new active ions including transition metal ions, and heavy metal oxide waveguide glasses for optical signal processing are researched. I will present status of our research and prospect of photonics device materials in my talk.

6469-08, Session 2

Ceramization of erbium activated planar waveguides by bottom up technique

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Erbium doped materials have been widely investigated as Er3+ ions exhibit emission at 1500nm, which coincides with the minimum-loss transmission window of silica based optical fibers telecommunication systems [1]. Transparent glass ceramics materials are of great importance in photonics, because they combine the glass mechanical and optical properties with a crystal-like rare-earth ion environment where their higher cross-sections can be exploited in order to fabricate more efficient and compact optical waveguide amplifiers.

A simple method to incorporate nanocrystals in erbium activated planar waveguides based on the bottom up method is reported.

Hafnia nanocrystal were first prepared from a suspension of hafnium oxichloride in ethanol where the mixture was kept under reflux for 2 h resulting a colloidal suspensions. The nanocrystals were incorporated in a 80 SiO2-20 HfO2 solution activated by 1 mol% Er3+ ions made by sol-gel route. Planar waveguides were prepared using dip-coating deposition on v-SiO2 substrates and densified at 900°C [2].

The waveguides, monomode at 1500nm, were characterized by photoluminescence (PL) spectroscopy in function of the time of heat treatment. In this case we can observe a structuration of the PL spectra indicating the embedding of erbium ions in a crystalline structure [3], and a lifetime enhancement of the 4I13/2 metastable level. Losses measurements of 0.3 dB.cm-1 at 1500nm have demonstrated the excellent quality of the system, suitable for successful OPWA applications.

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6469-09, Session 2

Spectroscopic studies and AFM analysis of Ho3+ and Tm3+ doped yttrium oxide nanoparticles

D. N. Patel, C. C. Perry, S. Kennedy, Oakwood College

Y2O3 nanocrystals doped with rare-earth ions have attracted considerable interest because of their chemical and thermal stability and their possible application in the light emitting devices and three-dimensional displays. Two trivalent-rare-earth ion singly doped Y2O3 nanoparticles have been synthesized using the co-precipitation technique, and their thorough room temperature spectroscopic studies have been carried out using visible and infrared laser excitation. The size estimation of the nanoparticles using x-ray diffractometry and atomic force microscope will be presented. The concentrations of the trivalent rare-earth ions have been determined using the microanalysis technique. The upconversion mechanisms and laser power studies for the different emissions from Tm3+ doped and the Ho3+ doped nanocrystals will also be presented.

6469-10, Session 2

A hybrid sol-gel reverse-mesa waveguide using lanthanide phosphate nanoparticles for optical amplification

H. Gan, L. Li, C. T. DeRose, R. A. Norwood, C. R. De Silva, Z. Zheng, N. N. Peyghambarian, The Univ. of Arizona

Organic-inorganic hybrid sol-gel materials have been widely used for the fabrication of optoelectronic devices due to many advantages. However the residual OH like groups after low temperature treatment have hindered the development of the erbium doped polymer waveguide amplifiers working at ~1550nm. Variety of means have been tried to overcome this problem. Doping the erbium ions, along with ytterbium ions to increase the pumping efficiency, in lanthanum phosphate nanoparticles may be a promising way since (i) the emission lifetime can be good; (ii) at ~1550nm the nanoparticles are transparent and the refractive index is very close to that of the optical fibers; and (iii) the nanoparticles are highly dispersible in many organic media. Here we demonstrate how the erbium and ytterbium containing lanthanum phosphate nanoparticles can be used in a reverse mesa waveguide to achieve optical signal enhancement. Erbium and ytterbium containing lanthanum phosphate nanoparticles have been synthesized with a molar ratio of La:Yb:Er = 76:21:3 and dispersed in cyclopentanone with 30wt% hydrolyzed MAPTMS. The composite has been incorporated into a 4mm reverse mesa waveguide prepared using organic-inorganic hybrid sol-gel material based on MAPTMS and zirconium n-propoxide. An optical signal enhancement of ~2dB/cm at 1527nm has been obtained using a 200mW 980nm pump laser. Modeling analyses have shown that the overall performance can be further improved. The results indicate that the hybrid sol-gel reverse mesa waveguides using erbium and ytterbium containing lanthanum phosphate nanoparticles are promising as optical amplifiers in integrated optical systems.

6469-11, Session 2

2.6-watt average-power mode-locked ceramic Nd:YAG laser

J. A. Wisdom, D. Hum, M. J. F. Digonnet, M. M. Fejer, R. L. Byer, Stanford Univ.; A. Ikesue, Poly-Techno Co., Ltd. (Japan)

We report a mode-locked 1064-nm ceramic Nd:YAG oscillator producing multiple watts of output power. The laser consists of a 1.2 at. % Nd:YAG ceramic gain medium pumped with an 808-nm laser diode, placed in a 1.92-m cavity, and passively mode-locked with a SESAM of 1% modulation depth. At a pump power of 11.1 W, the laser produced 2.6 W of average power with a slope efficiency of 27%. The pulse length was 25 ps at a repetition rate of 78 MHz. The ceramic exhibited no peak power degradation during a 20-hour test of doubling efficiency with periodically poled stoichiometric lithium tantalate.

6469-12, Session 3

Concentration dependence of the fluorescence decay profile in transition metal doped chalcogenide glass

M. A. Hughes, D. W. Hewak, Univ. of Southampton (United Kingdom); R. J. Curry, Univ. of Surrey (United Kingdom)

In this paper we present the fluorescence decay profiles of vanadium and titanium doped gallium lanthanum sulphide (GLS) glass at various doping concentrations between 0.01 and 1% (molar). We demonstrate that below a critical doping concentration the fluorescence decay profile can be fitted with the stretched exponential function: exp[-(t/t)ß], where t is the fluorescence lifetime and ß is the stretch factor. At low concentrations the lifetime for vanadium and titanium doped GLS was 30 μs and 67 μs respectively. We validate the use of the stretched exponential model and discuss the possible microscopic phenomenon it arises from. We also demonstrate that above a critical doping concentration of around 0.2% (molar) the fluorescence decay profile can be fitted with the double exponential function: a*exp-(t/t1)+ b*exp-(t/t2), where t1and t2 are characteristic fast and slow components of the fluorescence decay profile, for vanadium the fast and slow components are 5 μs and 30 μs respectively and for titanium they are 15 μs and 67 μs respectively. We also show that the fluorescence lifetime of vanadium and titanium at low concentrations in the oxide rich host; gallium lanthanum oxy-sulphide (GLSO) is 43 μs and 97 μs respectively, which is longer than that in GLS. From this we deduce that vanadium and titanium fluorescing ions preferentially substitute into high efficiency oxide sites until at a critical concentration they become saturated and low efficiency sulphide sites start to be filled.

6469-13, Session 3

Mid-infrared fiber laser application: Er3+ doped chalcogenide glasses

V. Moizan, V. Nazabal, F. Smektala, P. Houizot, J. Troles, J. Adam, Univ. de Rennes I (France); J. Cariou, ONERA (France); J. Doualan, R. Moncorgé, ENSICAEN (France)

Mid-infrared (IR) lasers are of interest for a variety of applications including environmental sensing, LIDAR and military counter measures. However, this wavelength range lacks powerful, coherent, robust and compact sources. A solution can lie in chalcogenide glasses as host materials for rare-earth ions. Rare earth ions possess numerous transitions in IR that can be potentially exploited for lasing or amplification. To date, many radiative transitions in near- as well as mid-IR- were observed in bulk chalcogenide glasses mainly doped with Pr3+, Tb3+, Dy3+, Ho3+, Er3+, and Tm3+. However, infrared emissions originating from rare earth ions doped amorphous chalcogenide fiber are reported more rarely. Besides excellent heat dissipation, the fibre geometry offers high pump intensity and good overlap of pump and laser modes what reduce the threshold and increase the laser efficiency.

Indeed, with an extended infrared transparency, low phonon energy limiting the non radiative multiphonon relaxation rates and suitable rare-earth solubility, sulphide glasses based on Ge-Ga-Sb-S system make available radiative transitions in the 3-5 μm range. The glasses with nominal composition of Ge20Ga5Sb10S65 (2S2G) doped with Er3+ (1000 to 15000 ppm) were prepared by means of conventional melting and quenching method. High purity elements (5-6 N) were weighted in a dry glove box, put in a fused silica ampoule and pumped under vacuum of 10-5 mbar for few hours. To minimize non radiative transitions and to decrease the optical losses, purification steps are essential. Therefore, dynamic and static distillations were performed on sulphur to reduce the hydrogen and carbon level in the glass. Then, the sealed tubes are heated in a rocking furnace to ensure the homogenization of the melt and quenched in order to obtain the glass rods used for fiber drawing or spectroscopic studies.

The Er3+, widely studied in glass fibers for near-IR amplification, was initially selected for the transition 4I9/2?4I11/2 emitting at around 4.5 μm -in spite of a branching ratio unfavourable to a strong quantum efficiency- in order to demonstrate the suitability of this sulphide composition for mid-infrared fibre lasers application. The impact played by the presence of -SH impurities and the possible influence of rare earth pairs was investigated following the photoluminescence of Er3+ doped 2S2G glasses elaborated with different level of purification and Er3+ concentration. In these objectives, emission and absorption spectra have been recorded. More precisely, the fluorescence and radiative decay lifetimes for the four energy levels 4F9/2, 4I9/2, 4I11/2 and 4I13/2 were measured and compared with those derived from Judd-Ofelt theory. The fibre drawing of the Er3+ doped 2S2G glasses and measurements of optical losses in mid-IR were carried out. As example, a monoindex sulfide fiber (400μm) doped with 1000ppm of Er3+ gave at minimum attenuation wavelength a value of about 0.8dB/m. The luminescence properties in mid-IR are currently in progress.

6469-14, Session 3

Recent advances in laser-induced cooling in rare-earth doped low phonon materials

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The recent finding of new low phonon materials (both glasses and crystals) as rare-earth (RE) hosts which may significantly decrease the nonradiative emissions from excited state levels have renewed the interest in investigating new RE anti-Stokes emission channels. In this work, we present the first experimental demonstration of anti-Stokes laser-induced cooling in two different erbium-doped matrices: a low phonon KPb2Cl5 crystal and a fluorochloride glass. In order to asses the presence of internal cooling in these systems we employed the photothermal deflection technique, whereas the bulk cooling was detected by means of a calibrated thermal sensitive camera. The cooling was obtained by exciting the Er3+ ions at the low energy side of the 4I9/2 manifold with a tunable Ti: sapphire laser. It is worthwhile to mention that this excited state, where cooling can be induced, is also involved in infrared to visible upconversion processes nearby the cooling spectral region. On the other hand, it is also noticeable that the laser induced cooling can be easily reached at wavelengths and powers at which conventional laser diodes operate, which renders these systems very convenient for applications, such as compact solid-state optical cryo-coolers.

The cooling efficiencies are found to be about 0.4% and 0.7% for the crystal and glass samples, respectively. These figures are remarkable if one takes into account the fact that the concentration of the optically active ions in our materials are about 0.5% of Er3+ and that our experiments are performed in a single pass configuration. From a fundamental perspective, these results are quite important, as this ion comes to engross the small list of rare earth ions that are amenable of cooling (Yb3+ and Tm3+ ions being the other two known so far). Moreover, they open a wide field of applications related with the possibility to use cooling by anti-Stokes emission to offset the heat generated by the laser operation in Er3+-based fiber lasers -the so called radiation-balanced lasers- that would allow to use dual wavelength pumping to take advantage of the cooling processes occurring at a given wavelength. This technique could allow to scale up the power of Er3+ based fiber lasers. On the other hand, the use of Er3+-doped nanoparticles for bioimaging and/or phototherapy could also take advantage of a dual wavelength pumping (at a nearby wavelength) in order to balance the thermal damage produced in a soft tissue by the infrared pumping wavelength at which the upconversion process occurs.

6469-15, Session 3

Systematic and material independent variation of electrical, optical, and chemical properties of Ln-materials over the Ln-series (Ln=La,Ce,Pr,..,Lu)

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Lanthanide (Ln) doped or stoïchiometric Ln-materials play an increas-

ingly important role in photonic applications such as lasers, wide band-gap electroluminescent devices, LED phosphors and scintillator detectors. Considerable progress has been made in the past few years in developing models describing the energy of the Ln 4f and 5d states, both ab initio based [1,2] as well as empirical based [3,4]. These models predict Ln-material properties by considering the energy of the 4f and 5d states as a function of the type of Ln-ion of the Ln-series (La,Ce,Pr,..,Lu).

In this contribution a empirical model for lanthanide materials is presented that describes a systematic and material independent variation of the electronic structure over the Ln-series. The model is derived from experimental data on 4f and 5d energies of Ln-ions as impurities in luminescent materials [5,6] but, as will be shown, can fruitfully be applied to stoïchiometric Ln-materials as well [7]. The validity and usefulness of the model is demonstrated by application to the Ln-sulphides and the well known Ln-oxides LnO, Ln2O3, and LnO2 for which the model correctly predicts insulating, semi-conducting or metallic behavior, nature and magnitude of band-gap energies and chemical stability of Ln-materials as well as valence and valence changes of Ln-ions. The model may serve as a reliable tool to accelerate design of a broad range of Ln-materials with deliberately chosen properties.

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6469-16, Session 4

Fiber design for high power fiber lasers

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There have been significant efforts on developing high power fiber lasers with narrow line-width and good beam quality. Such high power lasers pose significant challenges on fiber designs to reduce nonlinear effects such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), and achieve simultaneously single mode operation. This paper reviews different fiber design approaches for high power lasers. First, we review the conventional step index profile design and discuss its limitations. Then we present new design approaches for reducing the SBS through profile and glass composition designs. We also discuss fiber designs to achieving single polarization and at same time to mitigate the SRS effect. Finally, we discuss design concepts for achieving single mode operation in high power lasers such as index profile designs, Yb dopant profile designs and helical core fiber designs.

6469-17, Session 4

Power budget of Er-doped fiber evaluated with integrating sphere

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It is known that the power conversion efficiency of Er-doped fiber amplifier is as much as 60%, although the quantum efficiency of 4I13/2 level is more than 90% in most of the fiber materials. In this study, the spectral power of side spontaneous emissions of Er-doped fibers at 1.55um, 1um, 0.55um, etc. were evaluated quantitatively with an integrating sphere as well as an optical spectrum analyzer for the fiber end output. It was found that the side spontaneous emission power at 1.55um was much larger than the ASE power and nearly saturated at the lower pump power. Although the optical power at 0.55um was much smaller, the nonradiative loss after upconversion process was significant especially for EDFs with higher Er concentration, by taking into account the low quantum efficiency of the 4S3/2 level, almost 0.1% in silica glasses. The side-spontaneous emission power and ASE power decreased with increasing power of the input signal at around 1.55um, while the 0.55um upconversion power increased. The signal wavelength variation of these three powers showed similar tendencies against the wavelength variation of the output signal power or gain spectrum; i.e., a negative correlation for the two 1.55um spontaneous emissions and a positive correlation for the 0.55um upconversion. It is suggested that some part of the signal photons contributes to the second and third excited state absorption to the upper levels, resulting in the increase of green emission with increasing power of the amplified signal. We report various spectroscopic aspects of EDFs, which was not detected only by the data of fiber end.

6469-18, Session 4

Advanced waveguide lasers fabricated by femtosecond laser writing in an Er:Yb-doped phosphate glass

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Recently, a great effort has been devoted to waveguide lasers, because of their inherent simplicity and ease of integration into photonic integrated circuits. Due to their compactness, such lasers are expected to achieve on the one hand a high temporal coherence, making them attracting for fiber optical reflectometry, distribute sensing, and range finding applications; on the other hand, these lasers will provide low-noise and inexpensive pulsed sources for applications in optical communications, optically sampled analog-to-digital converters, and spectral line-by-line pulse shaping. An innovative technology for fabrication of waveguide devices is direct writing by femtosecond laser pulses. We report here on advanced waveguide lasers, operating both in continuous wave and pulsed regimes, based on active waveguides fabricated with optimal writing parameters in a phosphate glass substrate using an industrial oriented femtosecond oscillator. Stable single mode operation was obtained by using a high gain per unit length waveguide and narrow bandwith fiber bragg gratings to compose an ultra-short linear laser cavity. The laser provided more than 50 mW in single longitudinal and transverse mode operation with 21% slope efficiency. With respect to the pulsed regime, a mode-locked ring laser, providing transform limited 1.6-ps pulses, was also demonstrated by combining a high gain waveguide and an innovative fiber-pigtailed saturable absorber based on carbon nanotubes.

6469-19, Session 4

Ultra-broadband Raman gain media for photonics device applications

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Raman gain coefficient up to ~30 times that of the silica glass, a widely used glass fiber currently used in the telecom industry, has been recently reported in the 85TeO2-15WO3 (TW) glass system. However, usable gain bandwidth of the TW glass (≥ 170 cm-1) is lesser than that of the silica glass (~210 cm-1). We have now developed glasses in the TeO2-BaO-SrO-Nb2O5 (TBSN) system with additives such as WO3 and P2O5 that have higher glass stability against crystallization, gain coefficients, and bandwidths compared to the TW glass. The difference between the first crystallization temperature (Tx) and glass transition temperature (Tg) ($\Delta T = Tx - Tg$) of the new glasses are as high as 250 oC as against 120 oC of the TW glass. This higher ΔT of the new glasses makes it easier to draw optical fibers without any crystallization. The WO3 and P2O5 addition affected the optical properties of the TBSN glasses oppositely. The WO3 addition increased the refractive indices, whereas the P2O5 addition decreased it. Also, the WO3 addition red-shifted the optical band gap of TBSN glasses, whereas the P2O5 addition blue-shifted it. Raman scattering characteristics of the new glasses were studied extensively using lasers of wavelength ranges from 488 to 785 nm and evaluated the ex-

pectable Raman gain coefficients and bandwidths at communication bands. The Raman gain coefficients of the new glasses are as high as ~42 times that of silica glass for a 633 nm excitation. More importantly, the gain bandwidths of the new glasses were as high as ~357 cm-1. This bandwidth is 1.7 times higher than that of the silica glass and more than twice that of the TW glass. The new glasses would be promising candidates as ultra-broadband Raman amplifiers.

6469-20, Session 4

Yb-doped phosphate fiber laser

Y. Lee, Stanford Univ.

No abstract available

6469-21, Session 5

Large aperture tunable ultra narrow band Fabry-Perot-Bragg filter

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A novel type of filters based on a combination of a Fabry-Perot etalon and a volume Bragg grating is demonstrated.

The proposed solid-spaced Fabry-Perot etalon consists of a high quality fused silica window with both faces having identical dielectric mirrors coatings. The transmission of this Fabry-Perot etalon is a discrete channel spectrum consisting of narrow lines (typically a few tens of picometers) which are separated by gaps with constant width defined as the free spectral range (typically between 0.1 and 10 nm). These discrete resonances define the addressable wavelengths.

The second element of the complex filter is a volume Bragg grating. This component is obtained by recording of a sinusoidal refractive index modulation into the volume of a photo-thermo-refractive glass plate. Central wavelength of such element can be tuned over several tens of nanometers by rotating the Bragg grating and therefore changing the incidence angle. This element is thus used to select one of the Fabry-Perot resonances and switch between them.

We present the modeling and an experimental demonstration of a Fabry-Perot-Bragg filter centered at 1064 nm. It consists of the combination of a 25 pm bandwidth, 0.8 nm free spectral range high transmission solid-spaced Fabry-Perot etalon and a 97% diffraction efficiency reflecting Bragg grating. The resulting filter has high throughput (> 80%), a single transmitting band with ultra-narrow width (25 pm), broad rejection band and more than 10 nm tunability.

6469-22, Session 5

A diffractive lens for matter-wave beams

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A simple focusing device is proposed for de Broglie matter-waves - a diffractive lens, based on the optical effect of diffractive multifocal focusing of radiation. This matter-wave lens consists of two co-axial circular apertures, in which the second aperture of smaller diameter is located where the Fresnel number of the first aperture is unity. It is shown that diffraction of a de Broglie matter wave by a system of two pinholes on an optical axis exhibits the multifocal focusing effect of matter waves in the near-field (Fresnel zone). The focusing, defocusing and refocusing phenomenon is explained as resulting from periodic phase changes at singular points, which are points where the intensity is zero and the phase is undefined. It is shown that the proposed matter-wave lens could create a very intense, spatially-localized beam of atoms. Theoretical predictions for the focusing efficiency of a neutral atomic beam by the diffractive lens are: the spot diameter is ~ 0.1 microns, the ratio of focal and incident intensities is ~ 15, the focal length of the diffractive lens is in the range ~ 0.13 - 6 cm, the focusing depth is in the range ~ 15 - 30 cm, and the energy transmitting efficiency is ~ 30%. For the relatively-large diameters of the pinholes, larger than 5.0 microns, the proposed configuration acts as a matter-wave lens with a large focal length and a long focusing depth.

6469-23, Session 5

A single crystal photo-elastic-modulator

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We present theoretical and experimental data and possible applications of a photo-elastic-modulator (PEM) made of LiNbO3. PEMs modulate the polarization of a light beam and are mainly used in ellipsometry in the form of Kemp-modulators. They are made of a piece of optical glass which is glued to a quartz-crystal. Both pieces are tuned to the same longitudinal eigenfrequency on which the crystal is electrically excited such that the whole assembly starts to oscillate with a significant resonance rise due to sympathetic resonance. A polarized light beam that travels through the glass will experience a modulated polarization due to stress induced birefringence. One disadvantage is that both pieces must be fine-tuned to have the same resonance frequency, which is cumbersome, since the eigenfrequency of the glass cannot be determined directly by its electrical answer like for the crystal. The use of the quartz-crystal itself for the modulation of polarization has the drawback, that in all directions the natural birefringence would have to be compensated by another crystal. We present now a cut of LiNbO3, where the desired longitudinal oscillations can be excited by a transversal electrical field and where the light travels along the optical axis such that no compensation of natural birefringence is necessary. Due to its high piezo-electricity it can be excited to oscillate with low electrical power. The proposed configuration is outstanding in its simplicity and efficiency when compared to the use of other piezo-electric crystals, which will be discussed as well.

6469-24, Session 5

Semiconductor saturable absorbers with recovery time controlled by lattice mismatch

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Semiconductor saturable absorber mirrors (SESAMs) are increasingly used to passively mode-lock a large variety of lasers. For efficient and self-starting mode-locking, the absorption recovery time should attain values in the range from few picoseconds to few tens of picoseconds depending on the properties of the gain medium and the laser cavity design. The recovery time of absorption in lattice-matched materials, typically used in SESAM growth, is of few hundreds picoseconds or even nanoseconds. Therefore, the fabrication process of SESAMs should include special measures to reduce the recovery time (e.g. low-temperature growth or ion-irradiation).

In this paper we demonstrate a fast 1060 nm SESAM structure for which the amount of nonradiative recombination centers, and hence the recovery time, is controlled through lattice-mismatch engineering. The structure comprises an 80-nm thick InGaP layer with 2.2% lattice-mismatch to GaAs, which is responsible for generating non-radiative recombination centers through misfit and threading dislocations. The defect density within the InGaAs/GaAs quantum-well absorbing region could be controlled by the thickness of a GaAs buffer layer grown between the InGaP and the quantum-wells. For thickness of the GaAs buffer of 110 nm and 570 the absorption recovery time was 5 and 10 ps, respectively. It is important to note that the structures did not show degradation of the optical properties when compared to standard SESAMs (without InGaP layer). Self-starting mode-locked operation of an Yb-doped fiber laser has been successfully achieved by using the fast SESAMs comprising InGaP lattice reformation layer.

6469-25, Session 5

Low-loss, low-voltage, AlGaAs/GaAs high speed optical switch with doping and composition graded heterojunction interfaces

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Carrier-injection-type high-speed semiconductor optical switches have been of interest in recent years due to their nanosecond switching times, their immunity to variations in temperature, wavelength, polarization, etc, and the ease with which they can be monolithically integrated with other components. Their drawbacks, however, have been high insertion loss and excessive power dissipation. To overcome these limits, a novel, large cross-section, single-mode AlGaAs/GaAs optical switch has been designed and fabricated. The switch's strip-loaded waveguide uses a five-layer W-shaped heterostructure and a 1.7um-thick core layer which provides high fiber-coupling efficiency. Since the constituent heterojunction band discontinuities can impede the current across the junction, the addition of 20nm-40nm-thick compositionally graded interfaces significantly reduces the switching voltage. The doping was also graded to further compensate the built-in potential of the heterojunction. In addition, using lightly doped core layer can reduce the series resistance of the switch, which is important in heat reduction. The core doping needs to be low otherwise it will cause increased free-carrier absorption, which contributes to high insertion loss. We have fabricated switches with different core doping levels using both abrupt and graded heterojunctions. The measured on-chip optical propagation losses are 0.3dB/cm for unintentionally doped core, 2.5dB/cm for 2E16/cm^3 doped core, and 26dB/cm for 2E18/cm^3 doped core. The measured switching voltage is reduced from 7.5V to 3.4V by changing abrupt heterojunctions to graded ones without substrate thinning. We have calculated the theoretical I-V curves for switches with abrupt/graded heterojunctions based on thermionic emission. These predictions agree well with the measured data.

6469-26, Session 6

Fiber AOTF with record large FSR and its application as an NIR spectrometer

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An all-fiber acousto-optic tunable filter (AOTF) is developed for near infrared (NIR) spectroscopy applications. The AOTF is built on a 7-cm long cladding etched high numerical aperture (NA) single mode fiber. Acoustic energy is launched into the fiber through a piezo-electric transducer to couple the light from core mode into cladding mode at a resonant wavelength. The cladding mode is finally absorbed by the fiber jacket to form a narrow band notch filter. By tailoring the dispersion of the fiber, the core mode to higher order cladding mode coupling is completely suppressed, leaving only LP01 mode (the core mode) to LP11 mode (the first order cladding mode) coupling enabled. This technique enables the fiber AOTF to operate with a record large free spectral range (FSR) of >700nm, which is required by NIR spectroscopy applications. Other features of the fiber AOTF include a large wavelength tuning range of >500nm (from 1700nm to 2200nm), a narrow bandwidth of <5.5nm, a low insertion loss of <0.2dB, and a small electrical power consumption of <100mW. For test purposes, the fiber AOTF spectrometer is utilized to measure the output spectrum of a super-luminescence diode (SLD) light source emitting at around 2100nm. In comparison with the same spectrum measured with a PbS array spectrometer, the spectrum acquired with the AOTF spectrometer shows much better resolution and reveals fine spectral features of the SLD light source.

6469-27, Session 6

A novel optical tuning technology

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A novel optical tuning technology based on non-resonant interferometer - Optune technology and interferometer are described. This interferometer has one totally reflective layer parallel with one partially reflective layer, separated by an adjustable air gap. An input fiber optic collimator delivers a free space collimated beam which is incident first on the partially reflective layer at a small incidence angle. This beam bounces many times between the two reflective layers. All the beams going through the partially reflective layer are collected by an output fiber optic collimator, which makes all the beams to interfere at the entrance aperture of the output fiber. The optical configuration has no resonant frequencies. A certain wavelength at the input is available at the output for certain gap size within a gap range. Any arbitrary input wavelength can be selected (filtered) by adjusting the gap size with a PZT nanotranslation stage. 90 nm tuning range requires 10 ∝m change of the gap. Optune interferometer has 240 nm tuning range, 0.2 ms / 100 nm tuning speed, 0.15 nm bandwidth, 1 dB insertion loss, 45 dB contrast, no tuning holes, 0.2 dB flatness, 0.2 dB polarization dependent loss, 6 ps/nm chromatic dispersion and 0.5 ps differential group delay. Optune interferometer can be used either for filtering or for generating optical wavelengths in a broad range of applications such as: optical monitoring by using FBG and Brillouin technologies, and optical communications. Optune optical tuning technology comprising also the interferometer is covered by U.S. Patent No. 7,002,696.

6469-28, Session 6

Nonlinear mixing in nanowire subwavelength waveguides

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We report nonlinear mixing in nanowire subwavelength waveguides. Nanowires with diameters smaller than the optical wavelength can radially confine optical modes and waveguide light along the nanowire length, therefore acting as a subwavelength waveguide. The high quantum efficiency and large refractive index make direct-gap semiconductor nanowires a unique class of materials for photonic devices. In addition, CdS nanowire crystals provide a large nonlinear coefficient (Chi^2) well suited for nonlinear mixing in a waveguide geometry defined by the nanowire axis. To investigate nonlinear mixing and phase matching in subwavelength waveguides, finite-difference time-domain (FDTD) calculations were used. In particular, we have studied the critical role played by the coherence length in subwavelength waveguides to achieve phase matching in a one-dimensional structure. We successfully demonstrate the generation of nonlinear signals in active semiconductor nanowires. The ability to efficiently generate and waveguide nonlinear signals offers new opportunities for coherent all-optical switching in integrated nanoscale photonic systems.

6469-29, Session 6

Development of soft-glasses photonic crystal fibers made by stacking-and-draw technique

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Photonic Crystal Fibers (PCF) show better attenuation and stronger light confinement by increasing the number of periods. These desirable aspects can be used to produce better optical fiber amplifiers, nonlinear optics devices, gas and biological sensors, and others. On the other hand the PCF light guiding becomes more sensitive to defects. Therefore, only silica optical fibers made with high quality silica capillaries have been produced. The main difficulty to produce several periods PCF with soft-glasses is the abrupt viscosity variation with temperature that decreases the accuracy of fiber diameter control. By careful control of capillaries quality and of the fiber drawing process we have been able to produce up to five periods soft glass (borosilicate and tellurite) PCF. For that we used a Heathway drawing tower with a N2 flow and controlled temperature. The optical attenuation of these soft-glass PCFs was measured by the cut back method and the effect of light confinement on the fiber core was observed by optical microscopy.

6469-30, Session 6

Star cross section polymer open photonic crystal fibers

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Photonic Crystal Optical Fibers can be used to build highly sensitive chemical and biochemical optical sensors due to long optical paths provided by the fibers. For that, the evanescent field of the guided light must overlap the region with the substance to be sensed. This would be difficult with usual geometry of today's Photonic Crystal fibers even for gases, which would have to be pumped into the fiber. An open to the air optical fiber would be ideal for this application. We demonstrate this possibility by drawing a polymer (PMMA) open optical fiber with a star shape cross section by extrusion. To do that we filled a cylindrical stainless steel chamber with granular PMMA and extruded the material at 230o C with 5 kg/cm2 pressure through a 9 mm star shaped die in a Chemat fiber drawing tower until a 0.5 mm diameter fiber was obtained. For this kind of fiber the refractive index of the "clad", composed by PMMA/air, is lower than the refractive index of the "core", composed by PMMA only. We showed good efficiency light guiding by coupling the 633 nm HeNe laser light into this fiber. We then painted the fiber surface with the Europium chelate [Eu(DBM)3phen], where DBM and phen are dibenzoylmethane and 1,10-phenanthroline respectively, dissolved in heptane and observed the 613 nm typical Eu3+ luminescence when excited with 390 nm light. This show the potential of this fiber for optical sensing using the Eu3+ energy transfer to other molecules in its neighbourhood.

6469-31, Session 6

Photosensitivity of optical fiber gratings and sensing applications

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Optical fiber gratings, in particularly, fiber Bragg gratings (FBGs), are one of the most important components in telecommunications with applications such as dispersion compensators and add/drop multiplexers. Currently, hydrogen loading is applied in the fabrication of FBGs to improve the ultraviolet photosensitivity response of telecommunication fibers. Thermal post annealing is required to outgas the residual hydrogen and to stabilize the FBG spectrum, which diminishes the process control owing to a variable resonance wavelength shift (~2 nm) and a reduced grating strength. Post ultraviolet-laser trimming of thermally annealed FBGs has therefore been proposed to precisely tune the final grating characteristics. While such trimming has been most promising in high-germanium-content fibers, application in standard telecommunication fibers such as Corning SMF-28 (3% GeO2) is scarce due to its inherently weak photosensitivity in the absence of hydrogen loading. New technique to realize enhancement and controllable tuning of the photosensitivity is highly desired. In this article, we demonstrate a new, versatile approach to realize the precise wavelength tuning of fiber gratings in standard telecommunication fibers. Post laser trimming will be applied to achieve precise wavelength tuning. The influence of the pulse widths and wavelengths of the trimming lasers will be compared and analyzed. The pulse width of the trimming laser significantly alters the characteristics of the fiber gratings. The performance of the fiber gratings is monitored under different environmental conditions, which serves as the basis for the applications as sensors. Details on the photosensitivity of the fiber gratings and their applications will be discussed.

6469-32, Session 6

Electric-arc-induced long period fiber gratings for gain equalization of erbium-doped optical amplifiers

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We fabricated Long-Period Fiber Gratings (LPFGs) in single mode fibers (SMF28) using electric arc discharges, produced from a commercial splicer.

In our experimental set-up, we observed that the fiber becomes slighty tapered due to longitudinal tension during the arc: this effect depends on the arc power and time length. We experimentally investigated how these characteristics can influence grating's performances, especially in view of employing the LPFG as gain equalizer for an erbium-doped optical amplifier.

As expected, we found that, with periods typically of few hundreds microns, the spectral response of the grating depends on the period, the intensity of the perturbation, the grating length and the type of mode-coupling induced. Since the latter parameter cannot be estimated directly from the transmission spectra, we propose a method to determine the mode-coupling occurring in the device and to assess the index modulation induced by the electric arcs. This method combines both experimental and simulated data, and can be used to characterize LPFGs made-up by any method.

6469-49, Session 6

A study of silver-film ion-exchanged glass waveguides in phosphate glass

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Silver-sodium thin-film ion exchange is a powerful method for fabricating waveguides for integrated optics components. Being a dry process, the Ag thin-film ion exchange is particularly well suited for fabricating components in phosphate glass that is known to have chemical durability issues when used with molten salt processes. In spite of this, phosphate glass is an attractive choice for waveguide lasers due to its high solubility of rare earth ions enabling high gain values in short cavity lengths. Quite recently, many waveguide lasers for telecommunications and sensors have been realized in phosphate glass, either using Ag+ - Na+ or K+ - Na+ ion exchange.1-4 Compared with K+ - Na+ ion exchange, Ag+ - Na+ ion exchange produces higher maximum refractive index change in the glass resulting in much more flexibility in tuning the mode profile dimensions.

In this work, properties of Ag thin-film ion exchange with Er/Yb-codoped and undoped Schott IOG-1 phosphate glass has been studied. Emphasis has been put on finding the proper glass parameters (diffusion coefficient for Ag+ ions and the mobility ratio between the participating ions) at the process temperatures. Knowledge of these parameters is crucial for the design and modeling of new components. In order to extract the diffusion parameters we utilized the following procedure: We ion-exchanged a slab waveguide using the same process conditions as in the case of a two-dimensional waveguide fabrication. We then measured the effective refractive indices of the propagating modes by prism coupling. Thereafter, a smooth refractive index profile was constructed by a method suggested by Chiang.5 This refractive index profile was compared with the Ag+ ion concentration profile calculated from the diffusion equation by Crank-Nicolson method. The self-diffusion coefficient for Ag+ ions and the mobility ratio M were varied until convergence between the refractive index profile and the concentration profile was found. Using the diffusion parameters obtained from these experiments, two-dimensional waveguide mode profiles were calculated by finite difference method. These theoretically obtained mode profiles were compared with the measured channel waveguide mode profiles for different mask opening widths. In this paper, we will also present our recent results on UV-imprinted Bragg gratings in these waveguides.

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6469-34, Poster Session

Characterization of light scattering and film structure of TiO2 thin film

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The structure of optical thin films was changed by some conditions. There conditions were materials, coating methods and coating parameters (ion beam output etc.). For example, titanium dioxide thin films prepared by IAD method (Ion Assisted beam Deposition), which have column structure. Foggy levels depend on film structure. Recently, the foggy levels are measured using haze mater. But weak foggy sample of haze value didn?ft correspond to visual inspection. Therefore, in this work, optical thin films were evaluated by not only light intensity of scattered light but also angles parameter. As a result, it was considered the estimation of film structure of optical thin films was possible by using angle dependence of the scattered light.

6469-36, Poster Session

Simple chromatic dispersion measurement method using a spectral interferometer

J. Lee, I. H. Shin, D. Y. Kim, Gwangju Institute of Science and Technology (South Korea)

We present a novel chromatic dispersion measurement method using a spectral domain interferometer for single mode optical fiber over a wide spectral range (200 nm). This technique is based on the Mach-Zehnder interferometer using a white light source and spectrometer. A phase was directly retrieved from a measured spectral interferogram to obtain relative group velocity, chromatic dispersion and dispersion slope. The measured results with the proposed method were compared with those obtained using a conventional measurement method. Those results have good agreement with each other. Our proposed method can simply, accurately, and quickly (< 500 ms) measure chromatic information for a short length of optical fiber as well as optical devices.

6469-37, Poster Session

Graded porous silicon optical filter fabricated with the aid of diffusion-limited etch

K. Hwang, Y. Park, H. Jeon, Seoul National Univ. (South Korea)

Spectrum slicing is a method of sharing incoherent sources such as amplified spontaneous emission (ASE), superluminescent diodes by allocating a spectrally sliced signal to each channel. Utilizing the standard photolithography and wet etch technique only, we have realized a porous silicon optical filter which has a wide spectral tuning range in the near optical communication wavelength region. The etch window on the p+-Si wafer was intentionally tapered in width along one direction. Since the etching nature is partially diffusion-limited, etch depth is to be differentiated along the taper direction. For the completion into a device, the thin film of optical filter was detached from the Si substrate, and bonded onto a transparent glass substrate.

Using a fiber-coupled ASE source, we measured the transmission spectrum of the filter structure as a function of probe position. The measurements revealed that the transmission peak, which was as narrow as ~2 nm, monotonically shifts as the probed location is scanned along the taper direction. The tuning range extends from 1500 to 1600 nm, fully covering both the C and L bands in optical communication wavelength range.

6469-38, Poster Session

Codoped materials for high power fiber lasers: diffusion behaviour and optical properties

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Optical fibers for high power lasers and amplifiers are fabricated on the basis of quartz glass which has outstanding properties concerning high fiber strength, high power hardness and low optical losses compared with other glasses such as heavy metal fluoride or oxide glasses. It is well known, however, that the host properties of pure silica regarding the active rare earth ions are insufficient and the laser medium has to be improved by the incorporation of co-dopants.

Here we present new investigations of material and fiber properties for phosphorus/aluminium and germanium/aluminium co-doping, additional to the rare earth ions ytterbium, thulium and erbium/ytterbium, which are today most important for the realization of cw and pulsed high power devices. The diffusion behaviour in the complex systems shows characteristic interaction effects, which influence dopant concentration and spatial distribution. The refractive index in the co-doped systems and the basic attenuation deviate remarkably from additivity relations. The absorption spectrum in the UV/VIS/NIR region depends on co-dopant concentration and on preparation conditions, with influence on the fluorescence properties of the rare earths and the laser efficiency.

Examples of solid and microstructured double-clad laser fibers with optimized co-dopant concentration are demonstrated.

6469-39, Poster Session

Stable system technique for measuring the refractive index profile of an optical fiber by modified fiber-type confocal microscope method

S. B. Cho, Y. Youk, D. Y. Kim, Gwangju Institute of Science and Technology (South Korea)

A conventional refractive index profiling technique for an optical fiber depends on the sample structure. On the other hand, the reflection method is applicable to specialty fibers with complex and axially non-symmetric structures as well as general optical fibers because it can take 3D image profiling without considering sample structures. By using a modified fiber-optic confocal scanning optical microscope system, we have obtained a stable and simple refractive index measurement system. We could acquire high-level spatial resolution and good index precision by using a stable SLD source with 680nm wavelength and a visible single mode fiber with 4μm core width instead of a pinhole structure. Although this system is stable and simple, it is very sensitive to the roughness of a sample surface because of using the optical fiber as a pinhole system. Actually there is somewhat roughness in an end surface of a sample fiber cut by a common cleaver. To solve this problem, another synch-detector and a polarizing beam splitter (PBS) added in the fiber-optic confocal microscope system. The reflected light from the sample surface is divided by a PBS; one ray go back through the optical fiber in order to obtain a confocal point and another ray go through the new detector in order to obtain reflected power. The power detected by new detector is insensitive to the surface roughness because of no pinhole system. We could implement the simple and robust index measurement system by using a fiber-optic system and a new synch-detector.

6469-40, Poster Session

Effects of CsCl to enhance the thermal stability range of tellurite glasses for Er3+ doped optical fiber drawing

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Tellurite glasses are important as a host of Er3+ ions because of their large solubility and because it presents a broader gain bandwidth than Er3+ doped silica, with promises to increase the bandwidth of the communication systems. But the small thermal stability range (TSR) of tellurite glasses compromises the quality of the optical fibers. We show that the addition of CsCl to tellurite glasses can increase its thermal stability range making it easier to drawn good quality optical fibers. We therefore investigated the role of the CsCl on the thermal stability range. We observed that CsCl acts like a net modifier in glass systems, weakening the net by forming Te-Cl bonds. We show that the thermal expansion coefficient mismatch is in the right direction for optical fiber fabrication purposes and that Bi2O3 content can be used to control the refractive index of clad and core glasses. Finally we produced singlemode and multimode Er3+ doped optical fibers by the rod-in-tube method using highly homogeneous Te2O3-ZnO-Li2O-Bi2O3-CsCl glasses.

6469-41, Poster Session

Equilibrium-state emission of electron-trapping material thin-film for applications in nonlinear-dynamics

R. Pashaie, N. H. Farhat, Univ. of Pennsylvania

Optical signal processing (OSP), which is motivated by the parallelism and massive interconnectivity of optics is a promising methodology for the implementation of computational machines with applications in higher order systems such as chaotic neural networks. Dynamics of higher order systems, for instance one-dimensional maps, includes fixed, periodic and chaotic attractors. Optical realization of these nonlinear dynamical systems requires nonlinear optical devices whose degree of nonlinearity is more than saturation. In the current paper, it's shown that the equilibrium-state emission of a particular type of stimulable phosphor, the so called electron-trapping material (ETM), under simultaneous blue light and near-infrared illumination is considered as a potential candidate for the realization of such a nonlinear device. The main advantage of the present approach, besides its flexibility in realization of a variety of nonlinear curves, is that all the processes are electronic processes which can be done much faster, in comparison with liquid crystal where the speed of the device is restricted by the physical movement of molecules.

6469-44, Poster Session

A reconsideration of the birefringent interleaver

C. Cheng, Miami Univ.

The wavelength interleaver has become an important component of dense wavelength division multiplexing (DWDM) systems. Various approaches are proposed to implement the wavelength interleaver. Among these approaches, the one based on the birefringent crystal might be the first one ever been proposed and manufactured. The birefringent wavelength interleaver has a de facto standard structure which consists of n pieces of birefringent crystal with designed rotation angles. One important yet often overlooked issue regarding this structure is worthy of discussion. It is well known that the lossless finite impulse response (FIR) filter can be used to model a "standard" birefringent interleaver without material loss, and a "standard" interleaver consisting of n pieces of birefringent crystals can be represented with an nth-order Z-transform transfer function. However, it is seldom mentioned that, this popular birefringent interleaver diagram can not represent arbitrary nth-order Z-transform function of a lossless FIR filter. In other words, for an nth-order lossless FIR filter whose transfer function is derived from signal processing theory, it might not be feasible with the standard birefringent wavelength interleaver diagram. This fact makes it difficult to apply signal processing techniques to the birefringent wavelength interleaver design. In this article, we proposed an alternative birefringent wavelength interleaver diagram which consists of n pieces of birefringent crystals with same rotation angle and (n+1) pieces of half-wave plates whose angles can be changed. It will be shown that, by adding one more degree of freedom, this alternative interleaver diagram can represent arbitrary nth-order lossless FIR filter.

6469-45, Poster Session

Rare earth doped tellurite glasses for fiber lasers in the 2-micron wavelength region

D. Milanese, M. Vota, G. Liao, M. Ferraris, Politecnico di Torino (Italy); N. Coluccelli, S. Taccheo, Politecnico di Milano (Italy)

Tellurite glasses are promising materials for fiber lasers emitting in the 2 micron region, thanks to their low phonon energy and require a less complex fabrication route than fluoride.

In this paper Tm doped tellurite glasses were prepared and characterized and codoping with Yb and Ho was investigated in order to improve pump efficiency and wavelength emission range. Optical properties of Tm3+ ions in the glass were studied. Different concentration of Tm2O3 were added in the glass in order to investigate their effects on the glass properties and efficiency. Samples were all prepared by melting 30g batches of well-mixed reagents in platinum crucible at 900°C for 1h using an electric furnace in air. The melts were cast on a preheated brass plate and samples were annealed at a temperature 10°C below the Tg for 2 hours and then slowly cooled down to room temperature.

The glass transition temperatures (Tg) were determined by differential scanning calorimetry (Perkin-Elmer DSC7), at a heating rate of 10°C/min. The density was determined at room temperature following the Archimedes' principle using water as an immersion liquid. The refractive index n was measured by the prism coupling method (Metricon 2010).

The absorption spectra were measured in the wavelength range from 180 to 2000 nm and by means of a UV-VIS-IR spectrophotometer (Varian Cary 500) using optically polished samples with a thickness of approximately 2 mm.

Raman spectroscopy of glasses was also carried out in the wavelength range of 200-1400 (cm-1).

Fluorescence spectra were also measured

6469-47, Poster Session

Analysis into different multi-photon processes participating in upconversion luminescence of Er: NaY (WO4) 2 crystal

F. Song, K. Zhang, L. Han, J. Su, J. Tian, Nankai Univ. (China)

The exciting power dependency of upconversion luminescence participated by different multi-photon processes is deduced in this paper and applied to analyze the upconversion luminescence of Er3+ doped NaY(WO4)2 crystal. After careful inspection into the log-log plots of the upconversion emission intensities as a function of the excitation power, this paper explains the saturation phenomena emerges when the exciting power is relatively high.

6469-48, Poster Session

A miniature electro-optic switch array

X. Lu, Univ. of Massachusetts/Lowell; M. Li, PICC Property and Casualty Co., Ltd. (China)

We present a miniaturethat electro-optic (EO) switche design. A low insertion loss < 0.2dB and high extinction ratio of > 30dB can be obtained. The innovative device structure enables easy scale-up to N by N array with a size of a few millimeter square with a low insertion loss and extremely small power consumption.

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6470-01, Session 1

Nonlinear optics for nanophotonics and biophotonics

P. N. Prasad, Univ. at Buffalo

No abstract available

6470-03, Session 1

New organic molecular nanoprobes for in vivo two-photon fluorescence microscopy

P. L. Baldeck, Univ. Joseph Fourier (France); C. Andraud, École Normale Supérieure de Lyon (France); A. Attias, Ctr. National de la Recherche Scientifique (France); C. Barsu, École Normale Supérieure de Lyon (France); J. Bernard, Univ. Joseph Fourier (France); F. Bolze, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Y. Bretonnière, F. Darbour, École Normale Supérieure de Lyon (France); A. Duperray, A. Grichine, Institut Albert Bonniot (France); A. Hayek, Institut de Physique et Chimie des Matériaux de Strasbourg (France); T. Huault, Univ. Joseph Fourier (France); D. Kréher, Ctr. National de la Recherche Scientifique (France); G. Lemercier, École Normale Supérieure de Lyon (France); F. Mathevet, Ctr. National de la Recherche Scientifique (France); O. Maury, École Normale Supérieure de Lyon (France); J. Nicoud, Institut de Physique et Chimie des Matériaux de Strasbourg (France); C. Ricard, B. P. J. van der Sanden, Inst. Nat'l de la Santé et de la Recherche Médicale (France); O. Stephan, L. Vurth, J. A. Vial, Univ. Joseph Fourier (France)

During the last ten years, two-photon fluorescence microscopy has become a turnkey in vivo imaging technique in biology. The use of near-infrared femtosecond lasers for fluorescence imaging has premium avantages for easy 3D sectioning, deep penetration in diffuse tissues, and simultaneous excitation of multicolor probes. Most labelling fluorophores are selected from commercially probes that have been developped and well-characterized for one-photon fluorescence microscopy. They have modest two-photon cross-sections that are several orders of magnitude lower than molecules optimized for their nonlinearities.

In this paper we will present an overview of our research on new TPA fluorescent probes for in vivo microscopy: bistibene-based blue fluorophores and boron containing chromophores synthetisized by IPCMS group, styrylpyridine-based multi-branched molecules synthetisized by LCP group, push-pull molecules for membrane imaging synthetisized by ENS group, organic nanodots synthetisized by SPECTRO group.

We will report on their two-photon absorption properties and imaging applications in living cells and model small animals.

6470-04, Session 2

Nonlinear microscopy of collagen fibers

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We used intrinsic Second Harmonic Generation (SHG) by fibrillar collagen to visualize the three-dimensional architecture of collagen fibrosis at the micrometer scale using laser scanning nonlinear microscopy. We showed that SHG signals are highly specific to fibrillar collagen and provide a sensitive probe of the micrometer-scale structural organization of collagen in tissues. Moreover, recording simultaneously other nonlinear optical signals in a multimodal setup, we visualized the tissue morphology using Two-Photon Excited Fluorescence (2PEF) signals from endogenous chromophores such as NADH or elastin.

We then compared different methods to determine quantitative indexes of collagen fibrosis using nonlinear microscopy, given that most collagen fibrils are smaller than the microscope resolution and that second harmonic generation is a coherent process. In order to define a robust method to process our tri-dimensional images, we either calculated the fraction of the images occupied by a significant SHG signal, or averaged SHG signals after thresholding. We showed that these scores provided an estimation of the extension of renal and pulmonary fibrosis in murine models, and clearly sorted out the fibrotic mice.

6470-05, Session 2

Organic nanofibers from thiophenes, phenylenes and thiophene-phenylenes

F. Balzer, Humboldt-Univ. zu Berlin (Germany); M. Schiek, Carl von Ossietzky Univ. Oldenburg (Germany); A. Lützen, Univ. Bonn (Germany); K. H. B. Al-Shamery, Carl von Ossietzky Univ. Oldenburg (Germany); H. Rubahn, Syddansk Univ. (Denmark)

Single crystalline organic nanofibers from, e.g., phenylene or thiophene oligomers have already demonstrated their application potential in photonics and optoelectronics as well as model systems for basic research [1,2]. Phenylene fibers, e.g., are assembled from organic nanoclusters into mutually parallel entities on anisotropic silicate substrates like muscovite mica because of the interaction with strong electric surface fields. Such fibers emit polarized blue light and show nonlinear optical activity, after functionalization of the molecular building block with electron push-pull groups in para-positions [3]. Single crystalline fibers are also formed by green- and orange-light emitting oligo-thiophenes, but they assemble into domains of at least eight different needle directions on a single mica domain because of a slightly different crystal structure as compared to the phenylenes. Nonetheless the emitted light is polarized along only two directions. The transition between the two regimes (single parallel fibers vs. multiple aligned ones) will be clarified using newly synthesized molecules consisting of various combinations of phenylene and thiophene groups. Their growth will be compared to that of rubrene and POPOP, two other prototypical organic molecules for electronic and photonic applications.

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2: F. Balzer, L. Kankate, H. Niehus, R. Frese, Ch. Maibohm, H.-G. Rubahn, Nanotechnology 17 (2006) 984.

3: J. Brewer, M. Schiek, A. Lützen, K. Al-Shamery, H.-G. Rubahn, Nano Letters, accepted for publication (2006).

6470-06, Session 2

Development and study of hybrid organic: colloidal quantum dot systems

K. N. Bourdakos, D. M. N. M. Dissanayake, R. J. Curry, Univ. of Surrey (United Kingdom)

The hybrid organic-inorganic system of C60 fullerenes and PbS nanocrystals has been studied with the aim of determining the constituents interactions following photoexcitation. The system was studied using optical techniques including standard absorption and photoluminescence spectroscopy as a function of constituent concentration in an optically inactive host matrix. The excitation energy used to obtain photoluminescence was varied to allow the selected excitation of the constituents. Typically the 458 nm line of an Ar+ laser was chosen to excite both species whilst a 800 nm diode laser was used to excite only the PbS. At high relative concentrations of the nanocrystals within the sample the photoluminescence of the PbS is similar to that observed from the pure solutions on PbS nanocrystals. However, as the concentration of the C60 fullerene is increased to match that of the PbS nanocrystals a shift of the PbS photoluminescence towards shorter wavelengths is observed. The exact mechanism behind this behaviour is being explored in continuing studies including time-resolved ultra-fast pump-probe spectroscopy. The results of this work have implications on ongoing related work studying organic solar cell devices based on these material systems.

6470-42, Session 2

Molecular design for two-photon absorption: from the visible to telecommunication wavelengths

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Applications related to the two-photon absorption (TPA) process are now well-known and concerns different fields: 3D-fluorescence imaging, 3D optical data storage, 3D lithographic microfabrication, photodynamic cancer therapy, and optical limiting. Different approaches for the design of efficient TPA chromophores, which depend on the incident wavelength and/or applications, will be considered. This presentation will report our molecular engineering work for the design of systems for optical limiting applications (OL) and biology.

Organic and coordination complexes oligofluorenes are of great interest for the design of molecules with enhanced TPA cross-sections. Their high TPA efficiency have been interpreted in terms of coherent coupling of transition dipole moments in oligomers (i); the effect of the metal on TPA properties will be discussed. OL properties of these systems will be presented.

Promising molecules (in terms of synthesis facilities, solubility, TPA efficiency) will be presented for applications in the 1400-1600 nm range; their OL properties at telecommunications wavelengths will be also shown.

TPA properties of long-lived luminescent rare-earth complexes will be presented; these properties, which arise from an efficient light harvesting process between the organic ligand and the metal, will be used in effects related to studies of proteins.

Chromophores, with a high photochemical stability, interesting solubility and spectroscopic properties, have been designed for biological imaging (ii); their behavior in biologic cells will be discussed.

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(ii) C. Barsu, R. Fortrie K. Nowika, J.-C. Vial, P. Baldeck, A. Barsella, A. Fort, M. Hissler, Y. Bretonnière, O. Maury, C. Andraud Chem. Comm. 2006, 4744-4746.

6470-08, Session 3

Using DNA to organize organic nonlinear optic chromophores

B. H. Robinson, Univ. of Washington

No abstract available

6470-09, Session 3

Photoelectric effect and current-voltage characteristics in DNA-metal Schottky barriers

D. Zang, IPITEK, Inc.

No abstract available

6470-10, Session 3

DNA biotronics

J. G. Grote, Air Force Research Lab.

No abstract available

6470-11, Session 3

Dielectric and electrical transport properties of DNA-CTMA thin-films

C. M. Bartsch, Univ. of Dayton

Using a new capacitive test structure, the dielectric properties of deoxyribonucleic acid-based films (DNA-CTMA) were measured over a wide frequency range (from 1 to 20 GHz), various temperatures (25 and 100C), and at different DC bias voltages. The capacitance of the Au/DNA-CTMA/Au structure was found to be tunable by more than 50% at room temperature. The current-voltage curves were also obtained for the Au/DNA-CTMA/Au structure. The electrical characteristics of DNA-CTMA thin films were compared with those of amorphous polycarbonate (APC), a standard commercial polymer.

6470-12, Session 4

New paradigm for ultrahigh electro-optic activity: through supramoleculars self-assembly and novel lattice hardening

A. K. Jen, Univ. of Washington

No abstract available

6470-13, Session 4

Nonlinear optical properties of functionalized DNA thin films

O. Krupka, R. Czaplicki, A. El-Ghayoury, B. Sahraoui, Univ. d'Angers (France); F. Kajzar, CEA Saclay (France); J. G. Grote, Air Force Research Lab.; I. Rãu, Univ. d'Angers (France)

Nucleic acids and their derivatives attract a lot of attention of researchers due to their biological role. At the same time DNA, which exhibits charge migration is a subject of interest for its physical properties, and particularly for a great potential of application in photonics and in molecular electronics1,2. However for this kind of applications it has to be functionalized with active molecules.

It is well knows that the purified DNA dissolves only in water. Therefore, we performed additional processing in order to make DNA processable into thin films and more suitable for optoelectronics device fabrication with improved optical quality2. The water soluble DNA was complexed with an appropriate cationic surfactant giving in this way a new type of nanocomposites, which is insoluble in water, but soluble in most of organic solvents. The obtained DNA-lipid complex can be processed into thin films by solution cast techniques. It can be also functionalised with active chromophores by doping and/or intercalation.

In this work we report the processing of this complex into thin films and the preliminary results of our studies of linear and non-linear optical properties of thin films of functionalized DNA with active NLO molecules. The films were characterized by the UV-VIS spectroscopy. Their nonlinear optical properties were studied by optical third harmonic generation (THG) and degenerate four wave mixing (DFWM). This comparative studies allowed us to get information on the rotational contributions to cubic susceptibilities in these supramolecular structures.

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2. Vijayender Bhalla, Ram P.Bajpai, Lalit M. Bharadwaj, DNA electronics, EMBO reports vol. 4, No. 5, pp. 442, 2003

6470-14, Session 4

Optical modulation from an electro-optic polymer based hybrid Fabry-Perot etalon using transparent conducting oxides

H. Gan, H. Zhang, C. T. DeRose, R. A. Norwood, M. Fallahi, The Univ. of Arizona; J. Luo, A. K. Jen, Univ. of Washington; B. Liu, S. Ho, Northwestern Univ.; N. N. Peyghambarian, The Univ. of Arizona

Fabry-Perot etalons using electro-optic (EO) organic materials can be used as spatial light modulators (SLM's) for wavelength division multiplexing (WDM) communication systems. High performance SLM's require: (1) low insertion loss, (2) high speed operation, and (3) large modulation depth with low drive voltage. Three developments can enhance the SLM performance to a new level. First, low loss distributed Bragg reflector (DBR) mirrors are now used in SLM's to replace thin metal mirrors for reduced transmission loss and high finesse. Second, EO polymer materials have shown excellent properties for wide bandwidth optical modulation for information technology due to their fabrication flexibility, compatibility with extremely high speed operation, and possibility of being engineered to demonstrate large EO coefficients at the telecommunication wavelengths. Last, very low loss transparent conducting oxide (TCO) electrodes, e.g. indium oxide (In2O3) with an absorption coefficient ~1000/cm, have drawn increasing attention for use in optoelectronic devices. Here we report how the low loss In2O3 electrodes can help improve the optical modulation performance of a Fabry-Perot etalon using electro-optic (EO) polymer AJL8/APC. The electrodes used to apply voltage include one highly conductive indium tin oxide (ITO) electrode outside the etalon cavity and one low-absorption indium oxide (In2O3) electrode inside the etalon cavity. High finesse (~215) and a low insertion loss (~4dB) have been obtained. 10dB isolation ratio and ~10% modulation depth at 200kHz with 5V applied voltage have been achieved. These results indicate EO polymer etalons are promising as spatial light modulators (SLM's) for information technology.

6470-15, Session 4

Improvement of electro-optic effect and novel waveguide structure in hybrid polymer/sol-gel modulators

Y. Enami, C. T. DeRose, C. L. Loychik, D. L. Mathine, R. A. Norwood, The Univ. of Arizona; J. Luo, A. K. Jen, Univ. of Washington; N. N. Peyghambarian, The Univ. of Arizona

We report on latest results for hybrid electro-optic (EO) polymer-solgel modulators with low half-wave voltage (Vpi) and low insertion loss. Larger EO coefficient r33 results from high poling field for EO polymer sandwiched between low conductive sol-gel cladding layers. The reduced inter-electrode distance (d) resulting from the elimination of the sol-gel core layer in the active region further reduces Vpi. Straight channel phase modulators operate with Vpi = 4.2V at 1550nm using a reduced d of 11.5micron, which corresponds to an r33 of 78pm/V, among the highest r33 reported.

6470-16, Session 4

Highly efficient organic thin films for second order nonlinear optics

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No abstract available

6470-17, Session 5

Photonics polymer for fiber to-the-display

Y. Koike, Keio Univ. (Japan) and Japan Science and Technology Agency, ERATO-SORST (Japan)

The concept of "Fiber to-the-Display" is proposed, where the high bandwidth plastic optical fiber with more than 10 Gbps is directly connected with high quality display. We have proposed novel photonics polymers; Graded-Index Plastic Optical Fiber (GI POF) that achieved more than 10 Gbps data transmission, Highly Scattered Optical Transmission (HSOT) Polymer for LCD backlight of which brightness is almost twice as that of conventional "transparent" backlight ,and Zero-Birefringence Optical Polymer. As the birefringence disturbs polarized waves, it is an undesirable phenomenon for high performance optical devices that handle polarized light. We have noted this phenomenon and proposed the Zero-Birefringence Optical Polymers.

The concept of "Fiber to-the-Display" is based on these photonics polymers. As GI POF network is directly connected to the high definition display of homes and offices, the real time face to face communication with clear motion picture can be realized. We demonstrated the multipoint digital video conferencing over the gigabit GI POF network for medical consultation and a business conference and confirmed the level of its quality. When elderly people get sick late at night, it would be a great relief if they could consult doctors online with such real-time clear motion picture in large sized display without hitting keyboard. The photonics polymer will realize the concept of "Fiber to-the-Display".

6470-18, Session 5

Hard and flexible optical printed circuit board

E. Lee, Inha Univ. (South Korea)

We report on the design, fabrication, and integration of optical printed circuit boards using micro/nano-scale polymer/organic optical wires and devices. The objective is to realize generic and application-specific O-PCBs, either in hard form or flexible form, that are compact, light-weight, low-energy, high-speed, intelligent, and environmentally friendly, for low-cost and high-volume universal applications. The O-PCBs consist of 2-dimensional planar arrays of micro/nano-scale optical wires, circuits and devices that are interconnected and integrated to perform the functions of sensing, storing, transporting, processing, switching, routing and distributing optical signals on flat modular boards. For O-PCB fabrication, the polymer and organic optical wires and waveguides are first fabricated on a board and are used to interconnect and integrate micro/nano-scale photonic devices. The micro/nano-optical functional devices include lasers, detectors, switches, sensors, directional couplers, multi-mode in-

terference devices, ring-resonators, photonic crystal devices, plasmonic devices, and quantum devices. We also use active polymer wires for active device applications. We discuss uses of O-PCBs for telecommunications, computers, transportation systems, space/avionic systems, and bio/sensor-systems.

6470-19, Session 5

Preparation of graded-index plastic optical fiber by co-extrusion process

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Poly(methyl methacrylate) (PMMA) based graded-index plastic optical fibers (GI POFs) are expected to be a medium for very-short-reach networks because its large core diameter and great flexibility allow an easy network installation. In this paper, a novel preparation method of GI POFs called 'co-extrusion process' is proposed. Compared with the conventional method (preform method), manufacturing cost could be remarkably reduced by the new method.

In the co-extrusion method, PMMA homopolymer (for cladding) and PMMA including aromatic molecules that have higher refractive index (for core) were fed into a die, then, a concentric core-cladding structure was formed. Subsequently, the dopant in the core region diffused into the cladding layer. Thus, a parabolic refractive index profile in radial direction was formed.

By controlling the extruding temperature, the diffusion conditions (i.e., the diffusion temperature, the diffusion time), and the molecular weight of PMMA, a PMMA-based GI POF was prepared for the first time by this method. The refractive index profile obtained by this method showed show a tailing of refractive index profile at the core-cladding boundary, which is a typical profile obtained by Fickian diffusion. The bandwidth degradation by the tailing in the index profile has been of a concern. However, it was confirmed experimentally that the GI POFs with refractive index profiles without tailing could be obtained even by the co-extrusion method under appropriate diffusion conditions. As a result, the refractive index profile that was precisely fitted to the power-law profile with an index exponent g=2.7(optimum g=2.49) was obtained by adjusting the diffusion condition. It is indicated that the GI POF obtained by the co-extrusion process is expected to have a high-bandwidth similar to the one prepared by the conventional interfacial-gel polymerization method.

6470-20, Session 5

Perfluorinated polymer based multi-core polymer optical fiber

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Along with the spread of Internet, high-data transmission media are expected. In particular, graded-index plastic optical fibers (GI-POFs), which can be used with good facility, are expected.

In this study, the multi-core POF which has a 350 um diameter and includes 127 cores of 20 um diameter each is successfully fabricated by a novel co-extrusion process for the first time. Each core has a graded index profile. Therefore, the bandwidth of optical signal transmitting through each core is much higher than of step index POF, and excellent bending performance is expected. The observed bandwidth of a signal through one core was over 2 GHz through 300-m length. And also it was confirmed that the optical signal could be independently transmitted through each core without leakage of light.

Perfluorinated polymer called CYTOP® (manufactured by Asahi Glass Co., ltd) are used as fiber materials. Therefore, very low loss attenuation from visible to 1.5 um can be achieved, science there is no C-H bonding in this material.

The parts of these results have been obtained from the research entrusted by the New Energy and Industrial Technology Development Organization.

6470-21, Session 6

Polymers with unprecedented NLO response

N. N. Peyghambarian, Optical Sciences Ctr./The Univ. of Arizona

No abstract available

6470-22, Session 6

Styrylpyridine derivatives as lego building blocks for electroluminescence and two photon processes

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In the first part, we will describe a general approach for the synthesis of 6,6'-(disubstituted)-3,3'-bipyridine based chromophores. All these compounds exhibit a high electron affinity and are strongly fluorescent. As an application, blue-and green-emitting LEDs were fabricated.

In the second part, we will report on the design, synthesis, and structural as well nonlinear optical characterizations of a new class of disclike molecules based on tristyrylpyridine cores. Measurements of TPA using the two-photon fluorescence method in the fs regime indicate that these chromophores exhibit two-photon absorption. The results indicate that (i) a change of the substitution either of the electron-acceptor core or of the peripheral electron-donating groups, and (ii) of the number of branches influence significantly the TPA cross sections. Moreover, upon protonation, the TPA properties are greatly enhanced in the 700-900 nm range. Thus, these molecules can serve as pH-sensitive TPA dyes. Preliminary results related to biological applications will be also presented.

6470-23, Session 6

Observation of optical dispersion effects in metallic nanostructures fabricated by laser illumination of an organic polymer matrix doped with metallic salts

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Chemical reactions induced by two photon induced absorption is a powerful technique to fabricate micro and nano structures. In our case we are using a polymer containing metallic salts which are reduced after an electro-chemical process initiated by two-photon absorption. In the experimental arrangement femtosecond laser pulses are sent through a microscope objective. By scanning the focal point in the polymer matrix this technique allows us to fabricate at-the-demand two dimensional and three dimensional metallic structures. It is then possible to remove the polymer host to obtain free standing and stable metallic structures. Although interaction with laser light is rather complex we were able to obtain reproducible nanostructures such as lines, arrays, spots, rings, etc... which can be as small as 200 nm.

Such metallic structures exhibit interesting optical properties. Metallic double lines and gratings exhibit bright diffraction effects. Rings and dots have been found to show strong and unusual dispersion and focusing effects which seems to be due to plasmon resonances occurring in the metallic structures.

6470-24, Session 7

Liquid crystal frequency selective surfaces for tunable negative-zero index optical materials and devices

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In this invited paper, we will present an overview of recent work on the feasibility of designing frequency selective surfaces that possess refractive indices that are electrically or optically tunable from negative-zero-positive values.

6470-25, Session 7

On the importance of rotational contributions to cubic susceptibility in catenanes and rotaxanes

I. Rãu, R. Czaplicki, A. Humeau, B. Sahraoui, G. Boudebs, O. Krupka, Univ. d'Angers (France); D. A. Leigh, J. Berna Canovas, Univ. of Edinburgh (United Kingdom); F. Kajzar, CEA Saclay (France)

Catenanes and rotaxanes [1,2] are a new class of functional organic molecules, designed for use in various types of practical applications. Catenanes are built up from macrocycles which may rotate independently, whereas in rotaxanes the macrocycle is located on a tread and can either rotate or shuttle between two (or more) stations. A clipping movement in rotaxanes is possible too in the case of a flexible thread, made e.g. from photoisomerizable chemical bonds. The shuttling movement of macrocycle on the thread is limited by two bulky stoppers [3]. Because of these different movement degrees of freedom the catenanes and rotaxanes have attracted a great attention as promising candidates for the development of prototypical structural units for device applications, and particularly in swtching. For these reasons they have been proposed as nanoscale devices such as switchable molecular brakes [5], shuttles [6], ratches [7] and electronically configurable logic gates [8]. This different degrees of freedom of movement present in these molecules are expected to contribute significantly to the cubic susceptibility.

In this paper we will present and discuss a systematic study of the rotational contributions to the cubic susceptibility as observed by z-scan and polarization dependent DFWM experiments on solutions of these molecules, compared with optical third harmonic generation, measuring the electronic contribution only. The results show importance of this contribution.

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6470-26, Session 7

Resonance enhancement of two-photon cross section for optical storage in the presence of hot band absorption

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For the two-photon absorption- (2PA) based applications it is important to have materials with high values of two-photon cross-section. It is well known that the cross-section is resonancely enhanced by tuning the laser wavelength close to one-photon absorption (1PA) resonance. However, for some applications (such as 3D memory) 1PA poses a serious problem because it makes molecules to absorb light not only in the beam focus, but rather in the whole illuminated volume.

Here we show that for resonance enhancement one can find the optimal set of parameters: laser wavelength, intensity, temperature etc. to avoid destructive influence of 1PA. We study a new class of asymmetrical phtalonaphtalocyanine chromophores, which characterized by strong and narrow 1PA line with full width at half maximum 200-400 1/cm. This allows for high values of 2PA cross-sections (10000-20000 GM) at detuning about 1000-3000 1/cm. At temperatures near 110K these molecules also possess two metastable tautomer forms, which can be switched by 2PA. At higher temperatures one of two forms is dominant, however the deuteration helps to increase stability temperature. We measure 1PA and 2PA line shape in a series of chromophores as the function of the detuning frequency, sample temperature and excitation pulse intensity. Based on our measurements we introduced a model, which allows us to study tradeoff between 1PA and 2PA. For the first time we showed, that in some compounds the existence of sharp shifted from resonance peak in 2PA spectrum provides the range of optimal frequencies where 1PA influence can be greatly reduced.

6470-27, Session 7

Theoretical and experimental approaches to enhanced two-photon absorption

K. Kamada, K. Ohta, National Institute of Advanced Industrial Science and Technology (Japan)

In this paper, we review theoretical and experimental approaches to intense two-photon absorption (TPA) of molecular systems such as breaking of the alternancy symmetry, resonance enhancement, and control of molecular orientation in nanoscopic low dimension space. It is widely accepted that introduction of electron donors (D) and/or acceptors (A) enhances TPA of a molecular system. This is explained by large transition dipole moments for the D/A system, but it has not been well understood why it is so. Recently we found that the alternancy symmetry, which result in pair splitting by coupling between the degenerate electronic configurations, gives a good perspective to this issue. On the other hand, considerable enhancement is possible without modifying the molecular structures. One of the cases is resonance enhancement, where the two-photon transition path is promoted by wavelength dispersion of the one-photon resonance term. Also control of molecular orientation can enhance the TPA for linear shape molecules. Some theoretical outlines and experimental results for the above mentioned issues are presented.

6470-28, Session 8

Aggregation- and crystallization-induced light emission

Y. Hong, Y. Dong, H. Tong, Z. Li, M. Häussler, J. W. Y. Lam, B. Z. Tang, Hong Kong Univ. of Science and Technology (Hong Kong China)

A group of organic chromophoric molecules including siloles, fulvenes, pyrans and tetraphenylethenes are designed and synthesized. Light emis-

sions of conventional luminescent materials are often quenched by aggregate formation. These molecules, however, become stronger lumiophors when aggregated although they are practically nonemissive in their dilute solutions. By varying their packing structures in the aggregation states, emission color ranging from blue to red can be achieved. The emission of fulvenes can also be controlled by changing their morphology. While they emit a faint light in the amorphous state, their crystal forms are strongly luminescent. Intermolecular interaction or restriction of intramolecular rotation in different states may be responsible for such behaviors. Further modification of their structures by molecular engineering endeavors may generate materials that can find an array of applications in optical display systems and as biological probes.

6470-29, Session 8

Cantilevers with integrated organic LEDs for scanning probe microscopy

K. H. An, Y. Zhao, B. O'Connor, W. Loh, K. P. Pipe, M. Shtein, Univ. of Michigan

Organic thin films which are based on Van der Waals-bonded molecular organic compounds can be deposited onto a variety of substrates including scanning probe cantilevers without the lattice-matching constraints of conventional covalently-bonded semiconductors. Here we demonstrate organic light-emitting devices (OLEDs) fabricated on scanning probe cantilevers using thermal evaporation of molecular organic compounds and metallic electrodes. Ion beam lithography was used to define the emissive region in the shape of a ring having a diameter of 5 micrometers. The width of the ring emission was less than a micron as measured in the far field. Stable light emission was observed from the device at forward bias, with a current-voltage response similar to that of archetypal OLEDs. Such a probe can enable a new form of electrically-pumped SNOM compatibile with existing atomic force microscopy tools and techniques. The emission wavelength can be tuned across the entire visible spectrum, including white light emission, by altering the composition of the emissive layer with a wide range of luminescent dyes. Should the ring-shaped light emission be used for imaging, the sample image can be deconvolved using a ring filter to achieve high resolution. The OLED probe can also be used to transfer excitons through the cathode to a sample via plasmon-assisted energy transfer; such a probe would be valuable for studying exciton dynamics in organic or organic/inorganic hybrid photovoltaic devices. By demonstrating the first active organic device on a scanning probe cantilever, this work opens the door to a wide range of new scanning probe techniques based on this class of materials for areas such as biological imaging.

6470-30, Session 8

Stimulated emission of sulforhodamine 640 doped DNA distributed feedback laser device

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Optical properties of DNA thin film were studied. It is found that DNA material has very low optical loss (<0.5dB/cm) and is suitable for thin film device applications. Sulforhodamine 640 (SRh) laser dye was doped into DNA material. Amplified spontaneous emission was observed from DNA:SRh.

Second order distributed feedback (DFB) laser device was fabricated on this material by using Interference Lithography technique. SRh doped polymethyl-methacrylate (PMMA:SRh) thin film was fabricated and tested for comparison. Stimulated emission was observed when the device was optically pumped by a frequency doubled Nd:YAG laser at 532 nm. Both peak narrowing and intensifying were experimentally examined to prove stimulated emission. Threshold energies for both DFB lasers were observed. Device output energy versus input energy was studied at different pump energy beyond threshold. A linear relationship was plotted and energy efficiencies were calculated from experimental results. The peak FWHM beyond threshold for both DNA:SRh and PMMA:SRh DFB devices was less than 0.5 nm. DNA DFB device has a lower threshold and higher slope efficiency than PMMA DFB device. Both devices have a threshold much lower than semiconductor lasers.

6470-32, Session 9

Pentacene-quantum dot polymeric nanocomposite for infrared photodetection

K. Lee, Hannam Univ. (South Korea)

An organic/inorganic polymeric nanocomposite thin film device, consisting of poly-N-vinyl carbazole as host matrix, lead selenide quantum dots as photosensitizer and the organic semiconductor pentacene as conductivity boosters, is fabricated. Because of the inherent insolubility of pentacene, it is incorporated in the form of a soluble precursor which is made to undergo thermal conversion into pentacene. The device exhibits dramatic enhancement of infrared photocurrent due to pentacene. Efficient photogeneration of carriers coupled with enhanced conductance results in high photoconductive quantum efficiency.

6470-33, Session 9

Submicron patterning of conductive polymers for use in infrared polarizers

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Conductive polymers have become an extremely useful class of materials for many optical applications. Additionally, advanced fabrication methods have led to the development of metal based micro-wiregrid polarizers utilizing submicron features. Adapting these fabrication approaches for use with polymer materials leads to optical polarizers with unique properties. The patterning of conductive polymers with the small features required for wiregrid polarizers leads to several challenges. First, the deposition of the polymer must provide a layer thick enough to provide a polarizer with a useful extinction ratio that also has high conductivity and environmental stability. Two deposition approaches have been investigated, spin coating and electrochemical growth, and results of this work will be presented. Also, the polymers considered here are not compatible with basic photoresist processes. Various tactics have been examined to overcome this difficulty including the use of hard bakes of the polymer, protective overcoats and patterned growth. The adaptations required for successfully patterning the polymer will be reviewed. Finally, fabricated devices will be shown and their optical characterization presented.

6470-34, Session 9

Photobleaching microfabrication of polymer microring resonators

A. L. Pyajt, J. Zhou, A. Chen, J. Luo, S. K. Hau, A. K. Jen, L. R. Dalton, Univ. of Washington

Photobleaching as a new method of fabrication of electro-optic (EO) polymer waveguide micro-ring resonator is presented. The device consists of two polymer layers spin-coated on Si substrate - a bottom cladding with the refractive index 1.5 and the EO layer with the refractive index 1.6. Photolithographic mask with opaque waveguide lines is used for the direct patterning of EO layer. Non-protected areas in the film on both sides of the lines were photobleached and the refractive index decreased down to 1.55, for both TE and TM polarizations, providing lateral confinement of the channel waveguides. Direct patterning of EO polymer in one step has better resolution than traditional techniques, for example, Reaction Ion Etching (RIE), where the patterns need to be first transferred to photoresist and then etched. Resonance in microring resonators is very sensitive to the gap between the waveguide and the ring, which has to be on the order of several hundreds of nanometers with 50 nm precision. This technique allows resolving this gap using UV exposure. Therefore, stan-

dard photolithographic equipment - mask aligner with UV lamp and a photomask can be used for resolving of very small features. Resonators made with this simple, one-step fabrication technique have shown high resonance contrast of better than 15 dB and low total insertion loss of 9 dB, most of which is mainly caused by fiber coupling in and out of the chip. Microring resonators fabricated this way can be used to make chemical and biological sensors of very small size and high sensitivity. They also can be used for photonic on-chip components - switches, modulators, filters and reflectors. This method does not involve use of solvents, any other chemicals or dry etching by traditional fabrication methods. Therefore, photobleaching is a valuable complement to the traditional micro-fabrication and especially useful to polymers that are not compatible to solvents and wet chemical processes.

6470-35, Session 10

Optical storage through second harmonic signals in organic films

A. F. Fort, A. Barsella, L. Mager, D. Gindre, G. Taupier, K. D. Dorkenoo, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

We report on the possibility to make large capacity optical memories for mass data storage using polymeric or sol-gel materials that have been functionalized with non linear optical push-pull molecules of the diazobenzene family. The principle of the approach rests upon the inscription of patterns of molecular orderings and their detection through their ability to generate second harmonic signals from micro-areas. Provided that the polymer film has been previously corona poled to become, in essence, a blank or white page, the writing step now consists to locally decrease the degree of alignment of the chromophores in microscopic volumes in the bulk of the sample and, consequently, to cancel the second harmonic generation from these areas.

The local arrangement of the NLO azo-molecules is broken with a focalized laser beam promoting two-photon absorption (TPA) in the very vicinity of the focal point. In this restricted volume TPA leads to a redistribution of the chromophore orientation through cis-trans isomerisation. A standard multi-photon microscopy set-up is used to pick-up the second harmonic generation signals, to study the dynamics of the phenomenon, and also to serve as a feedback to control the writing process. The results, obtained on a film of methylmethacrylate copolymer where one monomer out of ten carries a Disperse Red 1 guest molecules demonstrate the validity of this approach. By combining the two processes, SHG and TPA, depending quadratically on the intensity of the exciting beam, an intrinsic spatial selectivity as high as 300 nm x 300 nm x1000 nm can be obtained, depending on the microscope objectives used. These characteristics for the individual bits of information allow predicting storage capacities of the order of 1012/cm3 of active material.

6470-36, Session 10

Charge carrier transport and trapping in disordered organic materials

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No abstract available

6470-37, Session 10

Light induced processes in thin films of indandione type organic molecules

I. Muzikante, M. A. Rutkis, E. Fonavs, Latvijas Univ. (Latvia); B. Stiller, D. Neher, Univ. Potsdam (Germany); V. Kampars, P. Pastors, Riga Technical Univ. (Latvia)

No abstract available

6470-39, Poster Session

Polyvinyl alcohol as photoluminescent conductive polymer

J. B. R. Ruiz-Limón, G. Wetzel, A. Olivares-Pérez, E. L. Ponce-Lee, S. Toxqui-López, M. P. Hernández-Garay, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We synthesized a photoluminescent conductor polymer composed of polyvinyl alcohol, which was doped with nickel chloride to increase its conductivity and benzalkonium chloride to obtain photoluminescence properties, when it is radiated with a green laser beam (532 nm). We compared its absorbance curve and its energy emitted curve to observe the amount energy that is taken advantage of this process. Besides we research the photoluminescence behavior when an electric currant is applied in our conductor polymer, obtaining a modulation capacity.

6470-40, Poster Session

Photoluminescence of glucose with currant colorant

E. L. Ponce-Lee, A. Olivares-Pérez, J. B. R. Ruiz-Limón, M. P. Hernández-Garay, S. Toxqui-López, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Photoluminescence light line emitted at 640 nm is observed on glucose doped with currant colorant Deiman when it is radiated by a green laser at 532nm. The absorbance behavior versus photoluminescence spectra, the profile pumping modulated versus emission and different intensity pumping versus amplitude emission were compared to get the kind of luminescence (phosphorescence or fluorescence) and determine the possible mechanism, that produce this phenomenon.

6470-41, Poster Session

Multi-objective optimization of microcavity OLEDs with DBR mirror

A. W. Lu, J. C. S. Chan, A. D. Rakic, The Univ. of Queensland (Australia); A. M. C. Ng, A. B. Djurisic, The Univ. of Hong Kong (Hong Kong China)

In this work, the emission efficiency and spectral shift with respect to viewing angle were optimized by optimizing the design of the multi-layer top mirror of a microcavity OLED device. We first calculated the electroluminescence emission spectra of a microcavity OLED consisting of widely used organic materials, N,N-di(naphthalene-1-yl)-N,N-diphenyl¬benzidine (NPB) as a hole transport layer and tris (8-hydroxyquinoline) (Alq3) as emitting and electron transporting layer. LiF/Al was considered as a cathode, while Ag anodes was used. Dielectric layers were stacked on top of the cathode to alter the properties of the top mirror. Once the optimum structure has been determined, the microcavity OLED devices were fabricated and characterized. The experimental results have been compared to the simulations and the influence of the thickness of the mirror layers, emission region width and position on the performance of microcavity OLEDs was discussed.

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6471A-01, Session 1

Ultrafast carrier dynamics in self-organized InGaAs quantum dots

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Carrier dynamics in InGaAs/GaAs quantum dots is analyzed with highly sensitive femtosecond transmission spectroscopy. In a first step, measurements on a large ensemble of nanoislands reveal the dynamical electronic filling of quantum dots from the surrounding wetting layer. Most interestingly, we find a spin-preserving scattering into fully localized states within a few picoseconds. Moreover, the scattering mechanism is found to be predominantly phonon mediated. Then, individual artificial atoms are isolated with metallic shadow masks. For the first time, a single self-assembled quantum dot is addressed in an ultrafast transmission experiment. We find relative transmission changes of the nanostructure in the order of 0.00001 directly revealing individual interband transitions of one quantum dot. Comparing the bleaching signals with photoluminescence results, different multiexciton configurations are identified in the transmission changes. The nonlinear optical response of the artificial atom exhibits a pronounced picosecond dynamics corresponding to ultrafast carrier relaxation in the quantum dot. As a result, we have developed an ultrafast optical tool for both manipulation and read-out of a single self-assembled quantum dot.

6471A-02, Session 1

Ultrafast near-field microscopy of single gold nanoparticles

K. Imura, H. Okamoto, Institute for Molecular Science (Japan)

We investigated ultrafast thermal effect on collective oscillation of electrons, known as surface plasmon, for gold nanoparticles. It is of fundamental importance to know how the electron-electron (e-e) and electron-phonon (e-ph) scattering processes after photoexcitation depend upon size and shape of nanoparticles and how the thermal propagation proceeds inside the particle. Dynamical spectroscopy of a single particle with high temporal and spatial resolution is informative for this purpose. We applied ultrafast scanning near-field optical microscope (SNOM) to image the electromagnetic local density of states (LDOS) inside the nanorods and nanoplates, and also to investigate dynamic behavior of LDOS after photoexcitation in a space- and time-resolved manner.

We found that transmission and two-photon excitation images of nanorods show characteristic spatial oscillating features reflecting the SP modes excited. These images agree qualitatively with the calculated ones of the electromagnetic LDOS. Time-dependent behaviors of transient transmission of single gold nanorods were also measured. From the transient transmission images, reduction and enhancement of transmission were found, respectively, at the central part and both sides of the rod. The image is ascribed to a LDOS change due to the elevation of electronic temperature in the rod upon the photo-excitation. A fast rise and a slow decay were found at the both sides of the rod. These temporal responses can be fit to double exponential functions. The time constant for the faster component (e-e scattering) is 0.6±0.1 ps and the slower one (e-ph scattering) 2.8-1.5 ps. The e-ph scattering is found to become faster toward the end-edge of the nanorod. Origin of this finding will be discussed.

6471A-03, Session 1

Quantum light emission of two lateral tunnel-coupled (In,Ga)As/GaAs quantum dots controlled by a tunable static electric field

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We demonstrate direct control over the level of lateral quantum coupling between two self-assembled InGaAs/GaAs quantum dots (QDs). This coupled system, which we also refer to as a lateral quantum dot molecule (QDM), was produced using a unique technique which combines molecular beam epitaxy and in-situ atomic layer etching [1]. Atomic force microscopy measurements show that each QDM consists of two structurally distinct QDs, which are aligned along the [1-10] direction. Electrodes were processed on the sample surface in order to allow for the application of lateral electric fields.

Each QDM exhibits a characteristic photoluminescence spectrum consisting primarily of two neutral excitonic and two biexcitonic transitions. Photon statistics measurements between the excitonic emission lines display strong antibunching in the second-order cross-correlation function which confirms that the two QDs are quantum coupled. Cascaded emission between corresponding biexcitonic and excitonic emission has also been observed.

Using a parallel electric field we can control the quantum coupling between the dots [2]. This control manifests itself as an ability to reversibly switch the relative intensities of the two neutral excitonic transitions. Furthermore, detailed studies of the emission energies of the two neutral excitonic transitions as a function of parallel lateral electric field show a clear anomalous Stark shift which further demonstrates the presence of quantum coupling between the dots. In addition, this shift allows for a reasonable estimate of the coupling energy. Finally, a simple 1-D model, which assumes that the coupling is due to electron tunnelling, is used to qualitatively describe the observed effects.

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6471A-05, Session 2

Pulse duration dependence of the third order optical nonlinearity of a cadmium sulfide dendrimer nanocomposite

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Open and close aperture Zscans were performed on various CdS quantum dots embedded in either generation 4 (G4) and G5 poly(propyleneimine) dendrimer or a G6 PAMOH dendrimer films using picosecond and femtosecond pulses between 350 nm and 1 ?m. The films had an average thickness of 400nm. The measured values of the third order nonlinear coefficient were among the highest off-resonance nonlinearities reported for organic and/or hybrid composites materials. However, the nonlinear response with picosecond pulses were about an order of magnitude higher than the femtosecond counterpart. We show that the nonlinear response in these materials is also a function of the dynamics of the excited states involved and that measurements of the nonlinear optical coefficient with pulses of different duration is directly correlated to the excited states dynamics. For example the difference in bleaching effects from short and longer pulses can substantially change the nonlinear optical response of a material.

6471A-06, Session 2

Extreme ultrafast dynamics at metal and semiconductor surfaces

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Impulsive excitation of semiconductor and metal surfaces by 10 fs near-UV laser pulses creates highly nonequilibrium distributions of single particle and collective excitations. Rapid scattering of the prepared nonequilibrium e-h plasma brings the surface to a local thermal equilibrium on few picosecond time scale. We present several examples where extreme excitation density and time resolution reveal unexpected phenomena that provide new insight into the nonlinear optical response of solids. 1) 2nd to 4th order time-resolved photoemission of Cu(100) surface reveal the origins of the nonlinear response of metals. We observe unambiguous evidence for the above threshold photoemission (ATP), which occurs for a certain range of electron parallel momenta through image potential intermediate states that surprisingly are bound even above the vacuum level. 2) Impulsive excitation of graphite leads to the generation of coherent optical phonons involving the C-C stretching (47.5 THz) and interplane shear (1.3 THz) modes, which we detect by transient E-O sampling measurements. Surprisingly, the interaction of the lattice with the nonequilibrium e-h plasma stiffens of the C=C stretching mode immediately after the excitation. DFT calculations show this to be a manifestation of the interaction of the photoinduced the plasma with the semimetal lattice. 3) Finally, we describe the excitation and imaging of surface plasmon polaritons on epitaxial Ag films. By interferometric time-resolved photoelectron emission microscopy we record movies of surface plasmon polariton wave propagation and interference with a delay interval of 330 attoseconds/frame and 50 nm spatial resolution.

6471A-07, Session 2

Metallic colloids and their plasmonic properties

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Colloidal growth of plasmonic nanostructures may present some advantages such as shape control at the nm scale with atomic smoothness of the surfaces and possibly reduced damping.

We show that the seed-mediated growth of gold nanostructures is strongly dependent on the gold seed nanocrystal structure. Starting with gold seed solutions prepared such that they are either single crystalline or twinned, growth yields either nanorods with good control over the aspect ratio (~ 10%) or elongated bipyramidal nanoparticles. The nanorods are single crystalline while the gold bipyramids are penta-fold-twinned. The gold bipyramids are also strikingly monodisperse in shape with the sharpest ensemble surface plasmon resonance reported so far.

Silver can be coated onto the gold nanostructures leading to a large blue-shift of the longitudinal plasmon resonance. Surprisingly, even a thin silver layer introduces much additional damping explained as scattering at the Au/Ag interface. Silver can be converted to silver sulfide yielding a large red-shift. The metal-semiconductor composite materials may present interesting nonlinear optical properties which are being currently investigated.

Finally, the nonlinear optical scattering from individual Au nanorods was measured under excitation by ultrafast laser pulses on resonance with their longitudinal plasmon mode. Surprisingly, the ultrafast nonlinearity can be attributed entirely to the heating of conduction electrons and does not exhibit any response associated with coherent plasmon oscillation. This indicates an unanticipated damping of strongly driven plasmons.

6471A-08, Session 3

Ultrafast dynamics of photoexcited charge and spin currents in semiconductor nanostructures

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The ultrafast dynamics of optical excitations in semiconductors and semiconductor nanostructures is analyzed on the basis of a microscopic many-body theory. Solutions of the semiconductor Bloch equations (SBE) provide a detailed description of the time-dependent material excitations, i.e., the polarizations and the carrier occupations. For the case of coherent photocurrents excited by two-color laser pulses, the SBE allow one to nonperturbatively evaluate light-field-induced intraband and interband excitations and this set of equations is also well suited for the analysis of many-body effects such as excitonic resonances and carrier-carrier and carrier-phonon scattering processes.

Numerical solutions of the SBE including many-body correlations on the second Born-Markov level predict an enhanced damping of the spin current relative to that of the charge current. This result which is a consequence of Coulomb scattering between carriers with opposite spin is remarkable since the spin of each particle is conserved in the considered scattering processes. The SBE are further used to study the dependence of the generation and the decay of the charge and spin currents on the temperature, the excitation intensities, and the frequencies of the incident light fields.

Interesting effects are obtained when the scattering processes are computed beyond the Markov approximation. Such quantum-kinetic calculations show that the overall decay of the currents is basically correctly described already within the Markov approximation. However, depending on the excitation conditions, memory effects which reflect the finite duration of scattering events may lead to additional oscillatory signatures in the current transients.

6471A-09, Session 3

Quantum complementarity of microcavity polaritons

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Cavity-polaritons in planar semiconductor microcavities are two-dimensional eigenstates which result from the strong resonant coupling between the cavity-photons and the excitons in the embedded quantum wells [1]. The photonic part of cavity polaritons makes them easy to access by optical means, while their excitonic part enables strong mutual non-linear interaction. These properties together with their peculiar in-plane dispersion lead to the occurrence of wave-mixing phenomena and stimulated emission processes already at relatively low excitation intensities, which was recently exploited for producing both parametric amplification and spontaneous parametric emission (SPE) [2]. In these processes the nonlinear interactions between polaritons cause the scattering of two pump polaritons generated by a resonant optical excitation of given in-plane momentum into pairs of polaritons, the signal and idler modes. SPE is already at moderate excitation intensities a self-stimulated process, expected to produce states of many polariton pairs exhibiting quantum correlation.

The polariton dynamics is investigated experimentally in a III-V microcavity using ultrafast time-resolved imaging of the directional space, achieved combining multiple measurements with a streak-camera. Parametric scattering of polaritons is found at higher polariton densities [3]. To investigate the theoretically expected non-classical pair correlations between the signal and idler polaritons, the fundamental principle of quantum complementarity is exploited. According to this principle, interference between two possible paths of a quantum particle cannot be observed if it is possible in principle to obtain information about which path the particle followed. Specifically, the emission of different polariton paths is superimposed in an experiment employing two mutually coherent pump beams. As predicted by the quantum complementarity principle, the experimental results show that two idler polaritons interfere if and only if they share the same signal-mode, so that a measurement performed in coincidence on the signal-mode could not be used to gather “which-path” information. A theoretical description in terms of multi-particle quantum correlated states reproduces the experimental results in detail, and

demonstrates that pair correlations created by the polariton-polariton interaction are at the origin of the experimental findings [4].

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6471A-10, Session 3

Ultrafast pump-probe spectroscopy with an extremely broad probe spectrum for studying the exciton relaxation process in an InGaN thin film

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The non-degenerate pump-probe experiments in the UV-visible range are important because of the needs for understanding the optical properties of many novel wide-band-gap semiconductor compounds, such as AlInGaN and MgCdZnO, and many light-emitting organic/polymers. Those materials are used for the developments of display and lighting applications. Because of the lack of ultra-short pulsed laser in the UV-visible range, the pump-probe studies of wide-band-gap materials require the second-harmonic generation (SHG) of a fs Ti:sapphire laser for excitation. Recently, for studying the carrier dynamics in AlInGaN, both the degenerate and non-degenerate approaches have been widely employed. In this paper, we report a non-degenerate pump-probe experiment with an extremely broad probe spectrum (up to 90 nm) in the UV-blue range. We use an InGaN thin film as the sample for demonstrating the operation of this pump-probe system and the carrier relaxation process in the nanostructures of the sample. Previously, we have demonstrated a non-degenerate operation by using two BBO crystals for independently tuning the pump and probe. In such an operation, the BBO crystal in the probe branch needs to be rotated or even replaced for achieving a broad spectral range. Hence, the measurement is quite time consuming and unstable. In the new development, we implement an extremely broad SHG spectrum for the probe based on a 7-fs mode-locked Ti:sapphire laser. With the operation of this non-degenerate system, the time-resolved probe spectral evolution at a particular pump wavelength can be obtained with one measurement. We use the non-degenerate pump-probe scheme to monitor the ultrafast carrier relaxation process from the excitation levels down to the free-carrier and the localized states in an InGaN thin-film sample, in which indium-rich nano-clusters exist to form the localized states. From the time-resolved differential transmission profiles at various spectral positions of infinitesimal spectral width and the temporal evolution of probe spectrum, one can observe the following two points: First, once carriers are excited, only a small portion of carriers relaxes into the free-carrier and localized states independently within 1 ps. Second, the major part of carriers starts to relax into the two groups of states not until several ps after excitation. Such a relaxation process does not seem to be completely cascading, i.e., relaxation into the localized states through the free-carrier states.

6471A-11, Session 4

Extra enhancement of luminance decay rate near the boundary of a silver thin-film region on an InGaN/GaN quantum well through the resonance coupling of surface plasmon polariton

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Enhancements of photoluminescence (PL) intensity and carrier recombination rate through the resonance coupling of surface plasmon polariton (SPP) with carriers in a quantum-well (QW) structure have been demonstrated recently as a potential scheme to increase light emission efficiencies of a light emitting device. In this paper, we report the results of using three single-QW samples of different cap layer (barrier) thicknesses for studying the resonance coupling effects of carriers in the QW with the SPPs on metal surfaces. The three barrier thicknesses are 10, 20 and 100 nm. The PL photon energy of those QW samples is designated to be about 2.8 eV, which is close to the resonance energy of SPP of silver on GaN. First, we coated the samples with 50nm silver films such that rough boundaries existed between the coated and uncoated regions. We observed the increase of the carrier recombination rate from time-resolved PL (TRPL) measurements. More than 10 times increase in decay rate for the 10 and 20nm-barrier samples were recorded. The 100nm-barrier sample shows little difference between the coated and uncoated regions. Near the coating boundaries, where the transmittance of PL intensity is almost the same as that in the uncoated region, we observed a tremendous increase of PL decay rate (more that 100 and 50 times) in the 10nm-barrier and 20nm-barrier samples, respectively. Then, we used the photolithography and lift-off methods to define the silver coating region. In this situation, boundaries are microscopically sharp. We measured again the TRPL decay rate for observing the difference between the boundary regions and the uncoated regions. Unlike what observed previously, no differences were observed. We therefore attribute this extra enhancement phenomenon to the modification of SPP density of states with the gradient change of silver coating thickness at the boundary.

6471A-12, Session 4

Ultrafast spatio-temporal dynamics of polariton condensates in semiconductor microcavities

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In recent years, the formation of coherent populations of exciton-polaritons in semiconductor microcavities has opened up connections with the fields of both superconductivity and cold atom condensates. Ultrafast pump-probe measurements on semiconductor microcavities previously show enormous nonlinear optical interactions induced by the strong coupling of light and matter modes.[1] These experiments reveal that macroscopic occupation of polaritons at particular energies and wavevectors strongly modify the dispersion of the system.[2] This renormalized dispersion relation is formally analogous to the Bogoliubov dispersion expected from the lowest energy excitations in Bose condensates. However, current models do not consider at the same level the spatial extent and dynamics of polaritons in the microcavity.[3]

In order to further investigate the spatial properties, a two-beam ultrafast imaging experiment has been devised. A streak camera is coupled to piezo-controlled collection optics, allowing movies to be made of the real-space emission, with picosecond time resolution. Experiments on the effect of the overlap between pump and the kick beams on such a strong-coupled microcavity have been performed. The results show fascinating and rich dynamics dependent on power and wavelength including temporal ripples and real-space dragging of the polaritons. These effects are compared to both classical and super-fluid behaviour.

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6471A-36, Session 4

Fast carrier dynamics in GaAs deep-centers for novel high-efficiency light-emitters for 1.3um-1.5um fiber optics

J. L. Pan, Yale Univ.

Achieving fiber-optic components on the same substrate as integrated circuits is important for future high-speed systems. This has led to a costly push to develop InP electronics. However, for reasons of reliability and cost, GaAs remains the established technology for integrated optoelectronics.

Recently, much interest has focused on the use of deep-centers in either gallium arsenide (GaAs) or silicon (Si) for obtaining long wavelength emission (greater than the bandgap wavelength). However, this deep-center optical emission has had very small internal radiative efficiencies of much less than 1 percent, and a total radiative output which is much less than that from a direct bandgap semiconductor.

We have demonstrated an important breakthrough: the first high (greater than 50 percent) radiative-efficiency light-emitting-diodes (LEDs) at the 1.3-1.5 micron wavelengths using native defects (As-antisite, Ga vacancies, and their complexes) in GaAs. In our talk, we will report the fast carrier dynamics associated with the efficient luminescence from these GaAs deep-centers. Significantly, we show these GaAs deep-centers to have a total radiative output which is much higher than that from bulk InGaAs and is as high as that from high-quality InGaAs quantum wells.

Moreover, we show these GaAs deep-centers to have internal radiative efficiencies which were substantially greater than 50 percent. (Thus, our GaAs deep-centers showed a total radiative output and internal efficiency which is much larger than that exhibited by other deep-centers in either GaAs or Si). This is an enabling technology for fiber-optic components lattice-matched to GaAs integrated circuits. Our high radiative efficiencies were made possible by fast (subpicosecond) trapping of holes by deep-centers, followed by a conduction-to-deep-level transition. Since our GaAs deep-center materials are fundamentally new, we also made the first measurement of several lifetimes (radiative and nonradiative) associated with valence-band-to-deep-level and conduction-band-to-deep-level transitions in our GaAs deep-level materials. Our high material quality was made possible by: (1) significant advances in the understanding of the thermodynamics and kinetics of incorporation of large concentrations of native defects during the growth of GaAs for the purpose of light emission of high radiative efficiency (greater than 50 percent) below the bandgap energy;(2) an engineered shift of absorption bands to above the bandgap energy, and of luminescent bands to below the bandgap energy. A significant result is that, in our material, the luminescence is not self-absorbed by the GaAs deep-centers.

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6471A-14, Session 5

Generating and manipulating spins in semiconductors

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There is a growing interest in exploiting electron and nuclear spins in semiconductor nanostructures for the manipulation and storage of information for emergent technologies based upon spintronics and quantum logic. Here we provide an overview of recent developments in the area through a discussion of temporally- and spatially-resolved optical measurements that focus on all-electrical schemes for the local generation and manipulation of spins in conventional semiconductor heterostructures. The results provide a compelling proof-of-concept that quantum spin information can be controlled within high-speed electrical circuits. Using magneto-optical spectroscopies, current-induced spin polarization and the spin Hall effect have been observed in semiconductors. These studies have led to the recent demonstration of electrically-generated spin currents that travel macroscopic distances in the solid state. The results suggest opportunities for tuning spin sources using quantum confinement, strain and device engineering in non-magnetic materials. In addition, semiconductor microcavities offer unique means of controlling light-matter interactions in confined geometries, resulting in a wide range of applications in optical communications and inspiring proposals for quantum information processing and computational schemes. Here we present emerging opportunities for manipulating and communicating coherent spin states with semiconductor microcavities through the study of electron spin dynamics in optically-pumped microdisk lasers with quantum wells and interface-fluctuation quantum dots. Electron spin dynamics are modified by the stimulated emission in the disks, and reveal an enhancement of the spin coherence time when the optical excitation is in resonance with a high quality lasing mode. This resonant enhancement is manipulated by altering the cavity design and dimensions. In analogy to devices based on excitonic coherence, this ability to engineer coherent interactions between electron spins and photons may provide novel pathways towards spin dependent quantum optoelectronics.

6471A-15, Session 5

Spin-dependent dynamics of individual CdTe/ZnTe quantum dot states studied by correlation spectroscopy

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Semiconductor quantum dots (QDs) attract attention as non-classical light sources and potential systems for quantum information processing. Both types of applications require a thorough knowledge of excitation and relaxation mechanisms in the QDs. Most of QD studies have been performed on canonical III-V GaAs-based systems. II-VI semiconductor compounds are particularly interesting due to their robust excitonic states, allowing observation of strong photoluminescence up to higher temperatures.

This work is devoted to photon correlation studies of individual II-VI CdTe/ZnTe QDs in view to determine non-resonant excitation mechanisms and provide information on spin relaxation of QD states. Second order photon autocorrelations and cross-correlations were measured in a Hanbury-Brown and Twiss setup for neutral and charged exciton and biexciton transitions, excited by frequency-doubled femtosecond pulses of a Ti:Sapphire laser. Part of the measurements were circular- or linear polarization resolved and performed in magnetic field. The results of non-polarized measurements were interpreted using a simple rate equation model and allowed us to establish the dominant role of single carrier capture in the non-resonant excitation of the QD. Polarization-dependent correlation measurements were used to study the magnetic field controlled transition between anisotropic QD exciton eigenstates active in linear polarization and those active in circular polarization. The same measurements provided information on spin relaxation of the QD excitonic states and of the carriers left in the dot after charged exciton recombination.

6471A-16, Session 5

Coherent nuclear spin dynamics in n-GaAs quantum wells probed by an optical pump-probe technique

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In order to elucidate the roles of nuclear spins in spin-dependent electrical and optical properties of semiconductor nanostructures, much effort has been devoted to exploit a new class of nuclear magnetic resonance (NMR) technique with high sensitivity and high spatial resolution. Optical approaches are considered to be suitable for local manipulation and detection of such nuclear spin dynamics. However, there have been only a few reports in which the coherent feature of nuclear spins is observed by optical detection [1, 2]. In this study, we demonstrate detection nuclear spin coherence in semiconductor quantum wells (QWs) by a time-resolved Kerr rotation (TRKR) technique combined with manipulation by pulse rf NMR [3].

The sample we studied here is n-GaAs/AlGaAs (110) QWs, in which conduction electrons excited by circular polarized light have long spin life-

time (> 1 ns) enough for enhancement of dynamic nuclear polarization [4]. In the TRKR measurements, we used a mode-locked Ti:Al2O3 laser with a pulse duration of 110 fs and repetition rate of 76 MHz. The photon energy was tuned at the resonant excitation of the lowest electron-heavy-hole absorption peak. Under a transverse magnetic field, the Larmor precession of the electron spins was monitored at 5.5 K as a measure of nuclear magnetic field acting on the electron spins via hyperfine interaction. The temporal nuclear polarization after the irradiation of a single-pulsed resonant rf magnetic field was observed by measuring the change of the Kerr rotation Δ K at a fixed time delay Δt between pump and probe pulses. We traced the oscillation of Δ K, i.e. the Rabi oscillation, as a function of the pulse width of the resonant rf magnetic field for 71Ga (8.18 MHz at 0.630 T). We also employed a spin-echo technique to evaluate the intrinsic coherence time, which reveals the dependence on the orientation of the magnetic field with respect to the crystalline axis as expected by the nearest neighbor dipole-dipole interaction.

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6471A-17, Session 6

Coherence control of electron spin currents in semiconductors

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We review some of our recent work on the use of one or two color optical techniques to generate and control electronic spin currents in semiconductors for which a spin orbit interaction exists. The generation process relies on the quantum interference between different absorption pathways between single and two photon absorption of harmonically related beams or right and left circularly polarized components of a monochromatic beam. For different crystal orientations and/or beam polarizations it is possible to generate a spin current with or without an electric current, and an electrical current with or without a spin current. In our experiments, which are conducted either at 80K or 295K, we typically employ nominally 100 fs pulses centered near 1500 and 750 nm. The currents generated are quasi-ballistic and the carriers typically move distances of ~ 1-10 nm, determined by the momentum relaxation time, which is of the order of 100 fs. Pure spin currents can be detected by taking advantage of the accumulation of up and down spins on opposite sides of tightly focused pump beams. The spin states are detected through differential transmission measurements of tightly focused right and left circularly polarized, near-band-edge probe pulses, delayed by several picoseconds from the pump pulses to allow carrier thermalization to occur. By spatial scanning across the differential spin profiles and determining the amplitude of the response we are able to translate this into nm spatial resolution of spin displacement. Finally, the ability to generate ballistic currents using purely optical techniques allows us to generate transverse Hall-like currents, with transverse charge currents generated from pure spin currents and transverse spin currents generated from pure charge currents.

6471A-18, Session 6

Ultrafast spin injection into self-assembled quantum dots

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Electronic spin states in semiconductor quantum dots (QDs) are one of the most promising material candidates for the future quantum information technology. Long spin-relaxation times of the carriers have been reported in the QDs. This is an important advantage of the use of QD for semiconductor spintronic devices, where the manipulation of the spin degree of freedom of the carriers is needed. Spin injection, which is the transport of spin-polarized carriers into a non-magnetic semiconductor, is a crucial research subject for the manipulation of the carrier spins in semiconductor quantum structures. The spin-split levels of the carriers in the QD are discrete under magnetic fields resulting from the strong quantum confinement effects. Therefore, quantum tunneling of carriers should play an important role in the spin injection processes in the QD system.

We have studied the electron-spin injection from a diluted magnetic semiconductor quantum well (DMS-QW) into non-magnetic QDs of CdSe through a tunneling barrier in the coupled structures, where the spins of photo-excited carriers can fully be polarized in the DMS-QW under magnetic fields resulting from the giant Zeeman effects. Time-resolved circularly polarized photoluminescence (PL) was measured for the coupled structures. We show an efficient electron-spin injection from the DMS-QW into the QDs, where the circularly polarized PL is observed with the polarization degree up to 40% from the non-magnetic QDs. A rise time of the polarization degree indicates that the electron-spin injection time is as short as 20 ps. The PL energy also shows that the electron-spin injection is assisted by LO-phonon scattering in the QDs. The electron-spin injection via LO-phonon-assisted resonant tunneling opens possibilities of spin control in the QDs exhibiting strong quantum confinement effects.

6471A-19, Session 6

Charging and spin-polarization effects in InGaAs quantum dots under bipolar carrier injection

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III-V semiconductor quantum dots (QDs) are currently a subject of an active research for device applications in both conventional and quantum opto-electronics, with the device range from lasers and photo-detectors to quantum logic and single-photon emitters. In both fields of opto-electronic applications, the performance of the QD-based devices relies on dynamics of charge carriers and also their spins. Therefore, an understanding of these dynamical processes, especially in structures employing electrical injection, is crucial for the design and optimization of such devices.

In this work we develop ultrafast polarization-resolved pump-probe techniques based on the exciton polarization properties to study carrier and spin dynamics in InGaAs/GaAs QDs. We demonstrate that charged quantum dots give rise to novel spin memory effects, stable up to T>150K and on timescales of several nsec. Due to notable differences in the dynamical response of neutral and charged excitons, our techniques allow precise measurement (<10%) of the fraction of charged dots in a dot ensemble and, in addition, determination of the spectral distribution of charges across the ensemble, i.e. the charging profile as a function of dot energy.

We then apply our method to study QDs under electrical injection in p-i-n diodes, where we find that there is a high probability of independent capture of electrons and holes, resulting in dot charging. Our findings are likely to be particularly relevant for low injection applications, such as single-photon QD emitters, where both the wavelength and polarization properties of the emitted light will depend strongly on the number and sign of the carriers captured by the dot.

6471A-20, Session 7

Optical properties of n- and p-type doped ZnO films grown by laser molecular-beam epitaxy

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Optical and electrical properties of doped ZnO are reported. Photoluminescence spectroscopy has been used to study carrier recombination in n(gallium)- and p(nitrogen)-type doped ZnO epitaxial films grown on lattice-matched ScAlMgO4 substrates. Our samples were deposited by a laser -molecular-beam epitaxy method. A bright near-band-edge photoluminescence (PL) could be observed even at room temperature for Ga-doped thin films. The peak position of PL showed a systematic blue-shift, consistent with the Burstein-Moss effect. Donor concentration dependence of a Stokes shift and of broadening in the PL band was explained

in terms of potential fluctuations caused by the random distribution of donor impurities.

Two strong donor-acceptor pair (DAP) emission peaks were observed for the first time in N-doped ZnO at 3.18 (DdAP) and 3.24 eV (DsAP) at 5 K as shown on the right-hand side. The spectrum also includes a PL line assigned to neural-donor bound exciton (D0X) recombination.

As the investigation on electrical properties, we compare the results of calculation with our experimental data to discuss how much the electron mobility of undoped and Ga-doped epilayers is approaching their physical limit. theoretical calculation was performed which took all major scattering mechanisms into consideration. Since it is inappropriate to adopt the relaxation time approximation for polar optical phonons, the variational method was used for the calculation. The calculated mobility at nondegenerate concentration region is about 430 cm2/Vs. The theoretical value is in good agreement with the experimental value.

6471A-21, Session 7

Ultrafast multiphoton absorption spectroscopy of wide-gap materials

W. Ji, J. He, H. I. Elim, Y. Qu, National Univ. of Singapore (Singapore)

Multiphoton absorption (MPA) manifests itself in transparent materials which are exposed to high-intensity, ultrafast laser pulses. Recently, MPA in both organic materials and semiconductor quantum dots has received great attention because of potential technological applications. However, the attainment of answers to basic questions like how to reveal a particular underlying mechanism and how to enhance MPA for a given material, require a comprehensive picture on the wavelength dependence of MPA. In this talk, the speaker will present their recent investigation on the spectral dependence of two-photon or three-photon absorption in a variety of wide-gap semiconductors like CdS, CdSe, CdTe, ZnSe, ZnS, ZnO, etc., in forms of bulk crystals or quantum dots, with using both femtosecond Z-scans and transient absorption measurements in the wavelength range from 600 nm to 960 nm. The speaker will also report their observation of saturation in MPA, and MPA-generated charge carrier absorption and dynamics in the high-intensity regime. This presentation is largely based on their recent publications, namely, (1) “Three-photon absorption in water-soluble ZnS nanocrystals”, Appl. Phys. Lett. 88, 18114 (2006); (2) “Three-photon absorption in ZnO and ZnS crystals”, Opt. Exp. 13, 9235 (2005); and (3) “Observation of interband two-photon absorption saturation in CdS nanocrystals”, J. Phys. Chem. B 109, 19184 (2005).

6471A-22, Session 7

High field transport in GaN and AlGaN/GaN heterojunctions

S. Yamakawa, Arizona State Univ.; M. Saraniti, Illinois Institute of Technology; S. M. Goodnick, Arizona State Univ.

Here we report on high field transport in GaN and GaN field effect devices, based on the rigid-ion model of the electron-phonon interaction within the Cellular Monte Carlo (CMC) approach. Using the rigid pseudo-ion method for the hexagonal wurzite structure, the anisotropic deformation potentials are derived from the electronic structure, the atomic pseudopotential, and the full phonon dispersion and eigenvectors for both acoustic and optical modes. Piezoelectric as well as anisotropic polar optical phonon scattering is accounted for as well. In terms of high field transport, the peak velocity is primarily determined by deformation potential scattering described through the rigid pseudo-ion model. The calculated velocity is compared with experimental data from pulsed I-V measurements. While good agreement with experiment is found for the peak velocity, the low field characteristics are not reproduced by electron-phonon scattering alone. The further inclusion of dislocation, piezoelectric and impurity scattering provides good overall agreement with experiment.

We simulate the effects of non-equilibrium hot phonons on the energy relaxation as well, using a detailed balance between emission and absorption during the simulation, and an anharmonic decay of LO phonons to acoustic phonons, as reported previously. Non-equilibrium phonons are shown to result in a significant degradation of the velocity field characteristics for high carrier densities, such as those encountered at the AlGaN/GaN interface due to polarization effects. We also compare to hot electron luminescence measurements in AlGaN/GaN structures where hot phonons play an important role in the steady state electron temperature.

6471A-23, Session 8

Terahertz isotropic photonic magnetoresistance

C. A. Baron, K. J. Chau, A. Y. Elezzabi, Univ. of Alberta (Canada)

Recently, it has been demonstrated that the photonic analog of anisotropic magnetoresistance (AMR) can be realized in the terahertz (THz) transmission properties of ferromagnetic microparticle ensembles. Here, THz transmission through the particle ensembles is mediated by near field coupled particle plasmons, and hence the optical properties of the ensemble are sensitive to the resistivity modulation caused by electrical AMR intrinsic to the ferromagnetic particles. However, despite the similarities between electrical anisotropic magnetoresistance and photonic anisotropic magnetoresistance, photonic magnetoresistance is in general an effect not solely governed by the electrical properties of the constituent medium. Rather, in mesoscopic ensembles of ferromagnetic particles it is dependent on extrinsic structural effects in addition to the electronic properties of the metal.

We report on a new form of magnetoresistance, isotropic photonic magnetoresistance (IPMR), in the THz transmission through porous Ni microparticle ensembles mediated by induced surface charge on the particles. Unlike PAMR, the THz pulse amplitude shows striking isotropy in its magnetic field directionality dependence. To our knowledge, such magnetic isotropy has not been observed in the counterpart electrical transport configuration. Furthermore, examination of the arrival times of the THz pulses transmitted through the porous microparticle ensemble reveals strong magnetic field orientation dependence. We attribute the magnetically induced isotropic amplitude attenuation to the extrinsic particle geometry, whereas the magnetic field orientation dependent THz pulse arrival times are attributed to intrinsic AMR associated with the surface of ferromagnetic Ni. Such concurrent amplitude insensitivity and temporal sensitivity to magnetic field configuration in IPMR opens the door for investigating novel magnetic phenomena, such as phase-sensitive magnetic circuits.

6471A-24, Session 8

Ultrafast terahertz spectroscopy of electronic correlations: from exciton gases to cooper-pair condensates

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Coulomb interactions between the large number of constituents in a many-particle system can generate correlated states with fundamentally new physical properties. Time-resolved spectroscopy is a powerful tool to study key microscopic quantum processes that occur on ultrafast timescales in bulk and nanoscale materials. Here, I will discuss our recent experiments that employ coherent terahertz (THz) pulses and direct field-resolved detection to probe time-varying correlations of charge carriers in semiconductors and superconductors. In bulk and nanostructured semiconductors, the THz electromagnetic response of metastable excitonic states reveals characteristic inter-level transitions in analogy to atoms. We can trace intra-excitonic absorption as a function of temperature, density, excitation energy, and time. The formation and ionization of excitons is directly resolved and is accompanied by a transition between conducting and insulating states. Intra-excitonic spectroscopy provides new tools to measure pair densities and map out excitonic phase diagrams directly. Moreover, in high-Tc superconductors (such as Bi-2212) the THz-frequency

electromagnetic response couples directly to the Cooper pair condensates and to quasiparticle excitations. We observe transient changes in the THz conductivity that occur after ultrafast depletion of the superconducting condensate. The temporal decay reveals a bimolecular kinetics of charge pair formation that occurs after transient depletion of the condensate. Such experiments trace correlated states via their transient low-energy response and motivate further THz studies of microscopic processes and collective excitations in nanoscale and correlated-electron materials.

*Work performed in collaboration with M. A. Carnahan, D. Hägele, B. A. Schmid, R. Huber, S. Oh, J. Eckstein, and D. S. Chemla

6471A-25, Session 8

Ultrafast terahertz electric field polarization dynamics in metallic metastructures

A. Y. Elezzabi, K. J. Chau, Univ. of Alberta (Canada)

The manner in which light interacts with materials can yield substantial information about their underlying microstructure. This is particularly relevant for mesoscopic materials possessing an underlying micro- or nanostructure between the atomic and wavelength scale. While the optical properties of a bulk medium are solely dependent on the constituent atoms, the optical properties of mesoscopic media strongly depend on both the intrinsic material response and the extrinsic structure of the medium. In this work, we explore the interaction of terahertz radiation with various complex mesoscopic metallic structures. In contrast to conventional continuous wave experiments conducted in the visible and microwave regimes, time-domain THz spectroscopy enables direct measurement of the time-domain electric field and polarization dynamics of the electromagnetic waves propagated through the structures. With this experimental methodology, we discover that the radiation scattered from various mesoscopic metallic structures possess complex phase and polarization effects which are otherwise not found in light interaction with the constituent medium. The results show that on mesoscopic scales, extraordinary phase and polarization modulation can be engineered that is not otherwise achievable with bulk media. Understanding light behaviour in these structures is not only of fundamental significance, but could potentially lead to the development of entirely new materials to improve communication and information technology.

6471A-26, Session 8

Probing transient photoconductivity in nanostructured materials using time-resolved terahertz spectroscopy

C. A. Schmuttenmaer, J. B. Baxter, Yale Univ.

The microscopic details of carrier transport in nanocrystalline colloidal thin films is required for complete understanding of a variety of photochemical and photoelectrochemical cells utilizing interpenetrating networks. Measuring the photoconductivity and charge transport properties in these materials, however, is a challenging problem because of the inherent difficulty of attaching wires to nanometer-sized objects. Furthermore, picosecond (ps) carrier dynamics play an important role in efficient charge separation and transport, but the low temporal resolution of traditional methods used to determine the photoconductivity precludes their use in studying sub-ps to ps dynamics. Time-resolved THz spectroscopy (TRTS), on the other hand, is a non-contact electrical probe capable of measuring the photoconductivity on a sub-ps to nanosecond (ns) timescale. In this paper, TRTS is employed to determine the transient photoconductivity of ZnO nanowires, polycrystalline, and nanoparticle films, as well as dye-sensitized nanocrystalline colloidal TiO2 films. Electron injection occurs on sub-ps time scales. Decay kinetics (on hundreds of ps to ns time scales) indicate that surfaces and interfaces are the dominant sources of recombination. The photoconductivity deviates strongly from Drude behavior and is explained by disorder-induced carrier localization and/or backscattering of the photogenerated carriers. Trends as a function of material and morphology will be discussed.

6471A-27, Session 8

Interaction of THZ radiation with semiconductor lasers

M. R. Hofmann, C. Brenner, S. Hoffmann, Ruhr-Univ. Bochum (Germany); M. A. Salhi, M. Koch, Technische Univ. Braunschweig (Germany)

We analyze the potential of diode lasers for terahertz (THz) technology, namely for the generation and detection of THz radiation.

The generation of THz radiation is achieved with a diode laser operated in a special external cavity which supports tunable two color emission. We unambiguously detect direct THz emission at the difference frequency of the two laser modes and discuss the underlying physical mechanisms. On the basis of this discussion we suggest concepts for an increase of the emitted THz power level to application relevant values.

The detection of THz radiation is achieved by coupling the emission of a THz gas laser into the active region of a diode laser. We observe a voltage variation over the p-n-junction that scales with the injected THz power. The voltage variation is only observed when the laser is pumped with injection current. Therefore we conclude that the free carrier plasma mediates a THz absorption which leads to a variation of the quasi Fermi level splitting that is measured. We discuss possibilities to extend this THz detection scheme even towards spectral resolution.

6471A-28, Session 9

Ultrafast laser nanoprocessing and intreactions with semiconductor nanostructures

C. P. Grigoropoulos, D. J. Hwang, N. Misra, Univ. of California/ Berkeley

Results on the nanoscale laser-induced surface modification will be presented. Ultra-fast pulsed lasers have been coupled to near-field-scanning optical microscopes (NSOMs) in apertureless configurations as well as through apertured bent cantilever fiber probes. Calculations of the electromagnetic field show effective enhancement of the near-field intensity distribution on the target surface. The feature size depends on the pulse length, and the near-field absorption distribution. Experiments have been conducted on the surface modification of metals, polymers and semiconductor materials in both ambient air and controlled gas environments. By combining nanoscale ablative material removal with subsequent chemical etching steps, ablation nanolithography and patterning has been demonstrated. Confinement of laser-induced crystallization to nanometric scales has also been shown. Nanoscale chemical vapor deposition of semiconductr nanodots will be presented. Applications on nanoscale chemical analysis will be discussed. Pulsed laser radiation is also utilized to activate dopants in Si nanowires employed in the fabrication of low contact resistance flexible macro-electronics. The fundamental interactions of nanosecond and femtosecond pulsed laser radiation with the wires are probed experimentally and analyzed theoretically.

6471A-29, Session 9

Autocorrelation measurements of the FELBE free-electron laser and photocurrent saturation study in two-photon QWIPs

H. Schneider, O. Drachenko, S. Winnerl, M. Helm, Forschungszentrum Rossendorf (Germany); M. Walther, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

The two-photon quantum well infrared photodetector (QWIP) comprises three equidistant subbands, two of which are bound in the quantum well, and the third state in the continuum. The intermediate subband causes a resonantly enhanced optical nonlinearity, which is about six orders of magnitude stronger as compared to usual semiconductors. In addition, temporal resolution is only limited by the sub-ps intrinsic time constants of the quantum wells, namely the intersubband relaxation time and the

dephasing time of the intersubband polarization [1]. Both properties make this device very promising for quadratic autocorrelation measurements of pulsed mid-infrared lasers.

We have performed autocorrelation measurements of ps optical pulses from the free-electron laser (FEL) facility FELBE at the Forschungszentrum Rossendorf. Using a rapid-scan autocorrelation scheme at a scan frequency of 20 Hz, high-quality quadratic autocorrelation traces are obtained, yielding ratios close to the theoretically expected value of 8:1 between zero delay and large delay for interferometric autocorrelation, and 3:1 for intensity autocorrelation. Thus, two-photon QWIPs provide an excellent new technique for online pulse monitoring of the FEL. In addition, we have investigated the saturation mechanism of the photocurrent signal, which is due to internal space charges generated in the detector.

[1] H. Schneider et al., Optics Lett. 30, 287 (2005).

6471A-30, Session 9

Near-field microwave diagnostics with nonlinear-optical sensors

J. Whitaker, Univ. of Michigan

Semiconductor devices with the capability of operating at very high digital switching speeds and analog amplifier bandwidths are enabling new opportunities for the development and widespread application of high-frequency microwave and millimeter-wave circuits and systems. Radars, including automotive collision-avoidance systems at 77 GHz as well as military phased arrays at W-band, along with a wide variety of communications systems, immediately come to mind as examples. As concepts are advanced to reduce the size of systems while increasing their bandwidth, there are mounting challenges associated with interference and cross-talk that may only be addressed with novel techniques such as near-field characterization. Nonlinear optical probes that are interrogated by ultrashort optical pulses and that are often based on semiconductor materials can play a key role in the measurement of electric and magnetic fields that are not only guided within microwave circuits, but that are also radiated both from leaky circuits and from systems such as phased-array antennas.

This paper will present the concept and implementation of a near-field microwave measurement system that relies on the Pockels effect in fiber-coupled, semi-insulating GaAs probes to acquire polarization-sensitive maps of electric-field patterns in close proximity to antenna arrays, integrated circuits, and packaged components. The evolution of the electro-optic field-mapping technique, which has subsequently addressed magnetic-field characterization via magneto-optic sensing and temperature measurement through semiconductor band-gap modulation, will also be discussed. The use of emerging materials, such as diluted magnetic semiconductors, and novel structures, such as multi-element resonant cavities, will be considered.

6471A-31, Session 10

Removal of laser-induced non-equilibrium longitudinal-optical phonons

Y. J. Ding, Lehigh Univ.

We give an overview of our recent progress on the removal of longitudinal-optical (LO) phonons in type-II superlattices (SL's) and quantum wells (QW's). We recently demonstrated that LO phonons could efficiently pump electrons from the quasi-X states to the quasi-Γ states in short-period type-II GaAs/AlAs SL's. As a result, peculiar behaviors on these SL's were observed. For example, photoluminescence (PL) intensity for the quasi-direct transition dramatically increased as temperature or pump power was increased. On the other hand, for a specific structure of the InAs/GaSb type-II QW's, we measured the dependence of the integrated PL intensity on temperature. As a result, the integrated PL intensity first decreased and then increased dramatically as the temperature of the cold finger was increased. The minimum PL intensity occurred at around 120 K. When the pump intensity was increased within a certain range a broad shoulder appeared on the short-wavelength side of the dominant PL peak. Therefore, the effect of increasing the pump intensity was essentially the same as that of increasing the temperature. Since the electrons in this type-II QW structure have a much longer lifetime, the PL upconversion is much more efficient than that for a typical type-I QW or SL structure. As the temperature was increased, the PL upconversion rate was significantly enhanced. This is due to the fact that more and more LO phonons become available for up-transferring the electrons from the acceptor states in the GaSb layers to the ground state in QW's, as the temperature of the cold finger was increased.

6471A-32, Session 10

Non-equilibrium optical phonon dynamics in bulk and low-dimensional semiconductors

G. P. Srivastava, The Univ. of Exeter (United Kingdom)

Theoretical investigations of long-wavelength non-equilibrium optical phonon intrinsic dynamics in bulk and low-dimensional semiconductors will be presented. The theory is based on the application of Fermi's golden rule formula, with phonon dispersion relations as well as crystal anharmonicity considered in the framework of isotropic continuum model [1]. Up to four different decay channels for the decay of optical modes will be identified [2]: Klemens's channel (into two acoustic daughter modes), generalized Ridley channel (into one acoustic and one optical mode), generalized Vallee-Bogani channel (into a lower mode of the same branch and an acoustic mode), and Barman-Srivastava channel (into two lower-branch optical modes).

For bulk semiconductors important channels for the decay of LO and TO modes will be identified in a selected number of cases, including cubic (diamond and zincblende structures) and hexagonal (wurtzite structure) phases. The investigation also highlights the role of crystal structure and cation/anion mass ratio in determining lifetime of modes. As a new route of dynamics we will consider decay of surface localized modes into two lower energy surface localized modes. Nanowires and nanotubes are characterized by the presence of low-frequency optical modes. Estimates of the intrinsic life-times of such modes in silicon nanowires and carbon nanotubes will be presented. The results will be used to support and explain available experimental data, and to make predictions in some cases.

[1] G. P. Srivastava, The Physics of Phonons (Adam Hilger, Bristol, 1990)

[2] S. Barman and G. P. Srivastava, Phys. Rev. B 69, 235208 (2004)

6471A-33, Session 10

Studies of LO phonons in GaN by subpicosecond time-resolved Raman spectroscopy

K. Tsen, Arizona State Univ.; J. G. Kiang, Walter Reed Army Institute of Research; D. K. Ferry, Arizona State Univ.; H. Morkoc, Virginia Commonwealth Univ.

A large non-equilibrium phonon population created in a semiconductor under the relaxation of carriers after excitation by an intense laser pulse, in particular with the application of an electric field, not only causes a decrease of energy loss rate of the electronic system (the so-called "hot-phonon effects") but also reduces the electron drift velocity. These have been demonstrated and well understood in a variety of semiconductors such as GaAs and Si. However, for some not so well established semiconductors, a case in point being GaN, the effects of the presence of a large non-equilibrium phonon population are less well understood, and sometimes the results are even contrary to our general belief.

The accumulation of a large non-equilibrium phonon population is a result of efficient electron-longitudinal optical (LO) phonon coupling and a relatively long phonon lifetime. In this presentation, we shall demonstrate a novel experimental technique - time-resolved Raman spectroscopy to interrogate the electron-LO phonon scattering rate and LO phonon population relaxation time in GaN. Our experimental results not only shed light on the possible decay channel of zone-center LO phonon in GaN but also

resolve some controversy over the LO phonon lifetime in the literature.

References:

1. For a review, see “Ultrafast Spectroscopy of Semiconductors and Semiconductor Nanostructures”, J. Shah (Springer-Verlag, New York, 1996), p. 161-224.

2. K.T. Tsen in “Ultrafast Physical Processes in Semiconductors”, published by Academic Press as the book Volume #67 (Ed. K.T. Tsen) in the series - “Semiconductors and Semimetals”, edited by R.K. Willardson and E.R. Weber (Boston, 2001), p. 109.

3. K.T. Tsen, Juliann G. Kiang, D.K. Ferry and H. Morkoc, Appl. Phys. Lett. in press.

6471A-34, Session 10

Mitigating hot phonons in high power optoelectronic devices based on wide gap semiconductors

J. B. Khurgin, Johns Hopkins Univ.

In this talk I will discuss critical role played by hot phonons in limiting high speed performance of electronic and optical devices based on wide gap nitride semiconductors. I will introduce a simple model that explains velocity saturation in the wide bandgap semiconductors and, based, on the experimental data, show that hot phonons in nitrides present unique challenge. I will discuss the various methods of mitigating the effects of hot phonons - ranging from creating conditions for stimulated phonon emission to use of disorder.

6471A-35, Session 10

Hot-phonon effects in III-V nitride heterostructure devices

D. Jena, K. A. Wang, J. Simon, Y. Cao, Univ. of Notre Dame

The III-V nitride semiconductors (AlN, GaN, InN) and their alloys have delivered stellar performance in various optoelectronic and high-speed high-power electronic devices. The performance levels of such devices (for example HEMTs) are, however, still far below the limits posed by fundamental physical processes. One of the reasons put forward for this inconsistency is the extremely strong electron-LO phonon interaction in the nitrides. For example, the mean time for generation of a LO phonon by high energy electron-lattice collision is in the ~10fs range, whereas the mean decay time for LO phonons is ~100 times longer. Therefore, there is a large accumulation of non-equilibrium LO phonons in III-V nitride in regions of high carrier density and high fields. Two fundamental questions therefore arise -

a) How do these non-equilibrium phonons affect the transport properties of carriers?

b) Are there ways by which such high non-equilibrium carrier densities can be controlled?

Both these questions are addressed from a combined experimental and theoretical investigation. We have measured the dependence of the PL peak upon applied electric field in donor-doped GaN to extract a hot-phonon lifetime of ~4ps. Similar measurements have been performed on bulk InN, and in Al(Ga)N/GaN heterostructures to explore the effect of Frohlich interaction in the entire III-V nitride family. Novel epitaxial design paradigms will be presented as proposed solutions to the deleterious effects of non-equilibrium carriers on saturation velocities in III-V nitride semiconductor HEMTs at present, and for LO-phonon assisted quantum cascade lasers in the future.

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6471B-36, Session 11

Delta-doped active pixel sensor imaging arrays with high quantum efficiency and 100% fill factor

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In this paper, we report the development and demonstration of delta-doped, thinned, back-illuminated active pixel sensor imaging arrays (APS). Fabricated using standard CMOS processes, APS imaging arrays offer on-chip signal processing and flexible readout architectures. Thinning and back-illumination promise to enable APS imaging arrays with the high quantum efficiency required of scientific imagers, but as with back-illuminated charge-coupled devices (CCDs), back surface passivation and electrical contact are essential to performance. Delta doping, a low temperature epitaxial growth technology developed at JPL for scientific CCDs, has been demonstrated to achieve high, stable, and uniform quantum efficiency across the entire spectral range from the extreme ultraviolet through the near infrared. Quantum efficiencies greater than 90% have been demonstrated with antireflection-coated, delta-doped CCDs. In addition, delta-doping passivates the back surface and provides an electrical contact suitable for biasing, enabling full depletion with low dark current. Delta-doped APS devices exhibit the high quantum efficiency that has become the standard for scientific-grade CCDs. Together with new circuit designs for low-noise readout currently under development, delta-doping expands the potential scientific applications of APS imaging arrays, and brings within reach important new capabilities, such as fast, high-sensitivity imaging with parallel readout and real-time signal processing.

6471B-37, Session 11

Linearity of the photocurrent response with light intensity for silicon PIN photodiode array

I. O. Goushcha, B. Tabbert, A. O. Goushcha, Semicoa

The properties of the back-illuminated, thin pin photodiode arrays (PDA) for medical imaging application were reported recently. Among the most important features of the arrays were the high quantum efficiency, fast signal rise time, very small AC and DC crosstalk (< 0.01%) within the spectral range 400 to 800 nm, very low leakage currents and high shunt resistance (> 10 G-Ohm). The current work discusses the photo-sensitivity linearity of the back-illuminated, pin photodiode arrays built on 75-um thick single silicon dies. This work describes also the automatic probe system for opto-electrical testing of the front- and backside illuminated photodiode arrays. The system allows 100% testing of wafers and dies before die attach. The system is configured to work on wafers up to 150 mm in size or single multi-pixel dies. PDA photosensitivity linearity measurements were performed in the range of input light fluxes above ~1nW/pixel and the linearity was found to be better than 0.01% within the spectral range from 450 to 1000 nm. For lower light fluxes, the non-linearity of the photo-sensitivity was smaller than the noise current of the array pixels and different methods should be applied to measure the photosensitivity linearity with an accuracy of better than 0.1%. This work also gives an estimate for the theoretical limit for this kind of sensitivity linearity measurements.

6471B-38, Session 11

Tiled silicon photomultipliers for large area, low light sensing applications

P. J. Hughes, D. Herbert, A. Stewart, J. C. Jackson, SensL Technologies Ltd. (Ireland)

Large area optical detection systems are required for applications including spectro photometric systems, nuclear medical systems, biomedical systems, biodiagnostics systems, and high energy physics. Each of these applications requires that a detector or detector arrays be closely coupled with scintillators blocks and other light sources.

In this paper, the scaling of novel Silicon Photomultiplier detectors (SPM) to tile across a large area is presented. In particular, a method is discussed for compact packaging of SPM detectors into a tiled NxN array. The SPM detector has performance characteristics comparable to photon multiplier tubes (PMT's) detectors used in these applications today but offers several performance and system design advantages including spatial resolution, small form factor, weight, magnetic insensitivity and low bias operation. Examples presented in the paper include high spatial resolution Positron Emission Tomography (PET) and electromagnetic calorimeter detection systems for high energy physics.

6471B-40, Session 11

Optical and x-ray characterization of two novel CMOS image sensors

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A UK consortium (MI3) was formed in 2004 under an RC-UK Basic Technology Programme to develop CMOS active pixel sensors for a broad range of scientific applications including space science, particle physics and medical imaging. The key image sensor performance parameters for both optical and x-ray illumination have been evaluated for two new sensors produced by this consortium.

The first, an 'On-Pixel Intelligent CMOS' (OPIC), is a digital pixel sensor test structure designed for high speed imaging. The test structure consists of three arrays, two of which have different readout shift register designs. Each 30μm pixel contains two 8-bit DRAM memories to store both the pixel value after integration and the time at which the pixel crossed a threshold voltage. A 1-bit "hit flag" is also included on-pixel for sparse readout. Frame speeds can reach 3,700fps. The second sensor, 'Vanilla', is a 512x512 array capable of high speed region of interest readout for object location and tracking. Six regions of interest of 6x6 pixels are available at 20kHz readout rate with 10-bit resolution. Full frame readout achieves 100fps at 12-bit resolution. This sensor utilizes a 'flushed' reset scheme to overcome the problems of image lag with soft reset and the increased noise of hard reset.

Measurements include linearity, photon transfer, spectral response, modulation transfer function and detective quantum efficiency. X-ray performance parameters are evaluated by optically coupling a layer of CsI:Tl scintillator to the sensor. A comparison of the performance parameters for both sensors will be presented.

6471B-41, Session 11

Design and fabrication of a linear array PIN photodiode for computed mammo-tomography(CmT) system

S. W. Park, Y. Yi, Korea Univ. (South Korea)

While mammography is the standard for breast cancer screening worldwide, it is widely recognized that mammography has limitations, espe-

cially for women with dense breasts. In response to the need for a more sensitive approach to breast cancer screening, a PIN photodiode-based detector module specifically for use is a Computed mammo-Tomography (CmT) using a fan-beam type X-ray source, was designed, fabricated, and evaluated.

The calculated penetration depth derived from absorption coefficient is about 7um with a wavelength of 700nm. Because the light is just can be collected in signal by the p- active layer with the quantity of 1/e, for about 67%, it is necessary for adequate depletion depth of about 15um to acquire all of the incident light. So far, our chosen the wafer with 1500 Ohm-cm resistivity offers about 17um depletion depth. The pixel pitch of the photodiode is 0.4mmÅ~3.0mm. One module has 64-channels in its linear array. The depth of the p-layer, depletion region as an intrinsic layer, and neutral region as a resistor are 0.3, 17, and 360 um with zero bias. The measured leakage current, using a semiconductor parameter analyzer-HP 4155A, is under 0.5nA/cm2. The measured capacitance using a LCR meter-HP 4284A is 200pF with zero bias. The spectral response and rising time is also measured and response test for X-ray was carried out.

In conclusion, the developed photodiode module has suitable performance characteristics for low energy X-ray detection as need in a Computed mammo-Tomography (CmT). The detector module consists of the PIN photodiode and the GOS with 300um thickness is applicable to a CmT system.

6471B-42, Session 11

Improvement of crosstalk on 5M CMOS image sensor with 1.7x1.7μm2 pixels

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Crosstalk of CMOS Image Sensor (CIS) causes degradation of spatial resolution, color mixing and leads to image noise. Crosstalk consists of spectral, optical and electrical components, but definition of each component is obscure and difficult to quantify. For the first time, quantifiable definition of each component is proposed to perform crosstalk analysis in this paper. Contribution of each component to the total crosstalk is analyzed using opto-electrical simulation. Simulation is performed with an internally developed 2D finite difference time domain (FDTD) simulator coupled to a commercial device simulator. The simulation domains consist of sets of three pixels. Plane wave propagation from micro-lens to the photodiode is analyzed with FDTD and the optical simulation result is transformed into the photo-current in the photodiode using electrical simulation. Spectral crosstalk constitutes 84% of total crosstalk while optical and electrical crosstalk each contributes 8% to the total crosstalk at the normal incident light. Spectral crosstalk is suppressed through careful selection of color filter (CF) materials that have good selectivity of color spectrum. The CIS's cell with improved CF is simulated in full visual spectrum of light to obtain the cell's photosensitivity in addition to the crosstalk simulation. The characteristics of crosstalk and sensitivity show contrary trend to one another as a function of CF thickness. Therefore, the crosstalk target is fixed and simulation is performed to determine the minimum CF thickness that satisfies the crosstalk target. With optimal CF material and thickness, sensitivity increases by 10% and spectral crosstalk decreases by 30%.

6471B-43, Session 12

Fully integrated sub 100ps photon counting platform

S. J. Buckley, S. J. Bellis, J. C. Jackson, SensL Technologies Ltd. (Ireland)

Previous high resolution counting modules, specifically designed for TCSPC applications, have tended to be based on a computer card format such as PCI. This has tended to result in a costly solution that is restricted to the computer it resides in. We describe a four channel timing module that interfaces to a computer via a USB port and operates with a resolution of less than 100 picoseconds. The core design of the system is an advanced FPGA interfacing to a precision time interval measurement module, mass memory block and a high speed USB 2.0 serial data port. The FPGA design allows the module to operate in a number of modes allowing both continuous recording of photon events (time-tagging) and repetitive TCSPC time binning. In time-tag mode the system reports, for each photon event, the high resolution TCSPC time along with the chronological time (macro time) and the channel ID. The time-tags are uploaded in real time to a host computer via a high speed USB port allowing continuous storage to computer memory of up to 4 millions photons per second. In time-bin mode, TCSPC is carried out with count rates up to 10 million photons per second. Each curve resides in a block of 128,000 time-bins each with a resolution programmable down to less than 100 picoseconds. Each bin has a limit of 65535 hits allowing autonomous curve recording until a bin reaches the maximum count or the system is commanded to halt. Due to the large memory storage, several curves/experiments can be stored in the system prior to uploading to the host computer for analysis. This makes this module ideal for integration into high timing resolution specific applications.

6471B-44, Session 12

High-accuracy and cost-effective photodiode spectral response measurement system

G. Chang, C. Liao, Y. Lin, National Taiwan Normal Univ. (Taiwan)

With the rapid growth of optoelectronics technologies, photodiodes (PDs) has been widely used in optical measurement systems, color measurement and analysis systems, etc. In particular, to perform precise color measurement, the spectral response of PDs is a very important and essential characteristic. The goal of this paper is to develop a high-accuracy and cost-effective spectral response measurement system for PDs. In this paper, the proposed system contains a grating-based spectral filtering module, a digital signal processing (DSP) module, and a DSP-based platform. In the spectral filtering module, the one-grating and double-grating configurations used in monochromators are first analyzed and simulated, and then experiments are conducted, to check if which one can meet the system specifications (e.g., cost and measurement accuracy). To effectively increase the signal to noise ratio, a digital lock-in amplification technique is devised to process the signal acquired from the amplifier of PDs under test. To communicate and manipulate the measured data, a DSP-based platform is developed in the proposed system. Experimental results indicate that this approach gives quite satisfactory results.

6471B-47, Session 13

Delta doped high purity p-channel silicon CCDs with near 100% QE from the UV-NIR

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Delta doping applied to high purity silicon imagers enables coverage of a wide spectral range, from the UV-NIR, in a single detector design. These detectors are ideal in applications requiring low level light detection, for example astronomical telescopes, where dark current, noise, and broadband quantum efficiency (QE) are of primary importance. Fully-depleted, back-illuminated high purity silicon CCDs offer extended red response, with 100% internal QE up to 1000 nm. However, an electrode is required on the back surface that satisfies two conditions for optimal performance. First, absorption by the electrode must be minimized for high short wavelength (UV) QE; second, the silicon surface must be passivated to minimize surface-generated dark current. Because delta doping creates a highly conducting layer confined within several monolayers of the back surface it can achieve both purposes.

We have developed n-type delta doping as a back surface process, and have demonstrated near 100% internal QE from 200 to 1000 nm with dark current as low as 0.5 e-/pixel/hr at -135 ºC. Antimony delta doping by molecular beam epitaxy (MBE) is used to achieve very high dopant incorporation in a thin, surface-confined layer. Optimization of this pro-

cess has enabled the growth of a delta-doped layer with > 10^14 cm^-2 antimony. The temperature is kept below 450 ºC throughout the entire process, which is required for compatibility with fully processed and functional Al-metallized devices. We will present our latest results on delta-doping high purity CCDs, including QE, imaging, dark current, and uniformity. Emphasis will be placed on performance of large format delta doped CCDs. We will also present results on broadband antireflection coatings for tailored wavelength sensitivity.

6471B-48, Poster Session

Estimations on the photo-response characteristics of the non-fully depleted silicon PIN photodiode for near infrared spectral range and its experimental results

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We have estimated the responsivity and the rise time of the non-fully depleted silicon p-i-n photodiode and determined optimum intrinsic layer resistivity for the best photo-response characteristics at a given condition. The estimation of the rise time was done with considering undepleted intrinsic layer resistance and drift velocity at low electric field. Our research shows that the maximum responsivity is 0.72 A/W and the fastest rise time is 14 ns at 24 V operation voltage for 900 nm wavelength, when 80 um depletion width was formed on the high resistive n-type wafer of 380 um thickness. Based on our considerations, we have fabricated the high performance silicon p-i-n photodiode for near-IR spectrum of 900 nm and analyzed its characteristics. In spite of optical loss caused by IR filter, the responsivity for 900 nm wavelength is 0.67A/W and the rise time is about 20 nsec at 24 V. These values are well consistent with our estimation works when the parasitic capacitance by the package is considered, and excellent results compared with conventional ones.

6471B-50, Poster Session

Study on metal/p-GaN contacts on p-i-n GaN-based detectors

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The contact of p-GaN was formed under the different annealing condition, and its effect on p-i-n GaN-based detectors was studied by current-voltage (I-V) measurements and response spectra. The parameters of metal/p-GaN interface were obtained by fitting the forward I-V curves. The results show ideal factor of M-S contacts annealed at 550C for 3min is about 1.19, which means the formation of the good ohmic contacts at the M-S interface and leads the lower open voltage and the smaller series resistance. But metal/p-GaN contacts have no obvious effect on response spectra of detectors.

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6472-01, Session 1

The quasi-optical performance of CMB astronomical telescopes

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Optical design in the terahertz (THz) waveband can be challenging, especially for high-precision applications. In this paper we summarise our experience with the quasi-optical design and subsequent performance of astronomical telescopes designed to measure the faint temperature and polarisation properties of the Cosmic Microwave Background Radiation, in particular QUaD[1] and the Planck Surveyor[2]. These telescopes contain a range of quasi-optical components including corrugated feed horns, on- and off-axis conic mirrors and lenses. Knowledge of their optical performance and beam patterns is critical for understanding systematic effects in the reliable extraction of feeble polarisation signals.

Although Physical Optics can be used to characterise electromagnetic systems to high accuracy, it is computationally intensive at these frequencies and often not suitable for the initial design or preliminary analysis of large multi-element optical systems. In general there is a lack of dedicated software tools for modelling the range of components and propagation conditions encountered in typical systems and we have employed a variety of commercial and in-house software packages. We describe the techniques used, their predictions and the performance of the telescopes that have been measured to-date.

[1] Cahill, G., O'Sullivan, C., Murphy, J.A., Lanigan, W., Gleeson, E., et al., Proceedings of the SPIE, Volume 5498, pp. 396-406, 2004.

[2] Yurchenko V.B. and Lamarre J.-M., JOSA A, 22, 12, 2838-2846, 2005.

6472-02, Session 1

Studies of the critical electric field and L valley offset of a semiconductor by terahertz radiation

J. Hwang, H. Lin, C. Chang, L. S. Chang, Y. Lu, National Cheng Kung Univ. (Taiwan)

The amplitude of terahertz radiation (THz) is measured for a series of GaAs and InAlAs surface intrinsic-N+ (SIN+) structures with various built-in surface electric fields which are used as the bias fields for the radiation. It is found that as the surface field is lower than the so called "critical electric field", the amplitude is proportional to the product of the surface field and the number of photo-excited carriers. As the surface field exceeds the critical field, the amplitude is independent of the surface field but proportional to the product of the critical field and the number of the photo-excited carriers. The critical field corresponds to the field at which the drift velocity is at maxima in the semiconductor and depends on the energy difference between the Γ to L valley of the semiconductor.

6472-03, Session 1

Comparative analysis of key physical mechanisms limiting the efficiency of intersubband and interband THz lasing nanostrutures

L. D. Shvartsman, B. Laikhtman, The Hebrew Univ. of Jerusalem (Israel)

We present a comparative analysis of various mechanisms providing selective depopulaton and controlling the gain in THz lasers. These mechanisms include electron-electron scattering and electron-phonon scattering. We show that even for perfectly selective pumping there is rather strong limitation to the gain in intersubband lasers. Different kinds of wave function engineering, such as resonant tunneling and so called resonant LO phonon scheme can lead to only a very limited progress. We compare our conclusions with the current situation in the THz laser research. As a much more prospective way we suggest using bipolar structures. According to our estimates the gain in bipolar structures can by many times exceed the gain reachable in intersubband lasers.

6472-04, Session 1

Quantum frequency transformer of radiation

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The quantum mechanical system consisting from a planar wave guide from a bismuth and alloys bismuth - antimony located in a magnetic field up to 25 Tl is generated. The electronic energy spectrum of crystals is quantized, and the ultra quantum limit of a magnetic field is reached in fields about 2 Tl. As a result of an irradiation the monochromatic infrared radiation with energy of a quantum 119 meV happens quantum jumps of electrons on Landau levels of a conduction band. The relation of reference energies is those, that the spontaneous transitions of electrons from an inversely occupied Landau level on below lying free from electrons Landau levels of a conduction band are possible, the energy distances between which correspond to a frequency band from 4 up to 10 THz. The magnetooptical oscillations are watched in a broad band of temperatures from 80 up to 280 K on crystals of a bismuth and alloys bismuth - antimony in a range of concentrations of antimony up to 20 atomic %. It happens because the processes of a dispersion of electrons on phonons essentially diminish for system located in a quantizing magnetic field. The electrons can dissipate on free from charge carriers Landau levels. The structure of a phonon spectrum of a bismuth and alloys bismuth - antimony is those, that in fields of an above ultra quantum limit the relaxation time will increase together with degeneration of Landau levels sharply. It gives in a peaking of resonant features in magnetooptical spectrums.

6472-05, Session 1

Artificial plasmonic materials for THz applications

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Artificial, or meta-, materials have attracted considerable attention in the recent literature. These have the potential to provide the emerging fields of THz microscopy and bio-sensing with new types of filter and lens technologies. The dimensions of the THz metamaterials (where 300 microns = 1 THz) make them ideally suited to micromachining fabrication processes. In surface micromachining, conventional integrated circuit techniques are used to create three dimensional structures.

A surface micromachining process has been developed which uses, the commercially scalable, backside UV exposure to produce very high aspect ratio SU8 pillars. This allows the periodicity and diameter, or even pillar angle, to be readily changed on the micron level. The band structure of the filter is determined by these parameters and extremely sensitive to sub-wavelength variations. Arrays of the high aspect pillars have been fabricated which act as artificial plasmonic crystals. These are demonstrated here with up to 98% relative transmission in their pass bands.

The high pass band transmission of these structures is sufficient to enable multiple filter designs to be combined. This provides the ability to combine the filter characteristics, leading to narrower transmission peaks.

Furthermore, we report on an enhanced fabrication process which enables the high aspect ratio pillars to be transferred to a flexible polymer, such as PDMS. This facilitates the variation of the periodicity, and hence, filters characteristics of the devices through mechanical deformation.

6472-06, Session 1

Theory of optical-to-terahertz conversion in a slab of nonlinear zinc-blende material

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Optical rectification of femtosecond laser pulses in nonlinear crystals is a proven way to generate terahertz radiation. We developed a theory that describes the optical-to-terahertz conversion in a slab of finite thickness made of a zinc-blende material. We consider two typical experimental situations: a) phase-matched case (ZnTe and 0.8 um optical wavelength) and b) nonphase-matched case (GaAs and 1.56 um optical wavelength). The theory accounts for the transverse size and two photon-absorption of the laser beam. We trace the temporal dynamics of the optical-to-terahertz conversion inside the slab and study the angular distribution of the terahertz emission from the slab. The theory allows us to explain experimental dependence of the conversion efficiency on laser focusing. The optimal parameters (such as laser transverse size and crystal thickness) maximizing the terahertz yield for GaAs and ZnTe are calculated.

6472-07, Session 2

Sub-wavelength THz plastic fibers

C. Sun, J. Lu, H. Chen, L. Chen, National Taiwan Univ. (Taiwan)

In this presentation, we will review our recent development on the sub-wavelength plastic fiber for THz waveguiding. The proposed and demonstrated terahertz single-mode sub-wavelength waveguide is similar to an optical taper fiber, having a low attenuation constant (~ 0.01 cm-1), a high coupling efficiency, and a free-space direct coupling capability, comprised with a sub-wavelength PE fiber core with air cladding. The spectral characteristic of the sub-wavelength THz fiber will be discussed, with an effective attenuation minimum of THz waves on the order of or less than 0.001 cm-1 at a specific wavelength range which depends on the fiber diameter. More over, the application of the sub-wavelength plastic fiber will also be discussed, including a first demonstration of a single-mode fiber-based THz directional coupler.

6472-08, Session 2

Using channel waveguides for efficient THz parametric generation and detection

Y. J. Ding, Lehigh Univ.

It is obvious that we can take advantage of waveguide structures to significantly improve the conversion efficiencies for THz generation and the sensitivities for THz detection. Among different waveguide structures, we propose to use a new type of the channel waveguides, i.e. metallic-dielectric hybrid (MDH), to further enhance the interaction strengths for the THz parametric conversion. Since such a waveguide can suppress the radiation losses, it was intensively used to confine the millimeter waves at the wavelengths of around 6 mm (50 GHz). In addition, such a waveguide can be also used as a platform hosting a class of the THz waveguide devices such as sources, filters, and IR detectors to perhaps construct the first THz integrated circuits. Even an array of the 2-D waveguide devices are feasible. Furthermore, the entire structure consisting of a large number of the THz waveguide devices could be fabricated using the well-established fabrication procedure. Due to the waveguide confinement, new phase-matching configurations can be tailored. Since such a structure allows us to modulate the THz signal based on electro-optic effects, the signal-to-noise ratio for the THz detection may be further improved.

6472-09, Session 2

Electromagnetic scattering calculations for terahertz sensing

L. M. Zurk, B. Orlowski, G. Sundberg, Portland State Univ.; D. P. Winebrenner, E. I. Thorsos, A. Chen, Univ. of Washington

There has been a recent growth in interest in the application of terahertz (THz) sensing to a variety of problems, including the detection of explosive devices. The THz regime has many advantages, including a safe (non-ionizing) screening modality and a wavelength that has the potential to provide high-resolution 3D imaging. For detection of explosives, it has the further advantage of potentially exhibiting spectral peaks for several classes of explosive material.

However, in addition to the quantum mechanical response due to the chemical structure, materials also have the potential of producing a classic electromagnetic scattering response due to the presence of volume scatterers and/or rough interfaces present in the object. This response can serve to alter or obscure the identifying resonances, and thus it is critical to understand the nature of the scattering. In this work, random media models are devised for explosives to quantify the classical scattering response due to embedded volume inhomogeneities (in the form of spherical inclusions) and a rough surface interface. For explosives, volume scattering may result from the presence of micron-scale air gaps (or voids) that are typically a few percent by volume and from explosive grains that are tens of microns in diameter. The response due to these particles is calculated using a Quasi-Crystalline Approximation (QCA) that rigorously accounts for multiple scattering effects. Results of the QCA calculations are compared with THz measurements for materials with differing void radii, and are shown to correctly predict the increased transmission loss for larger inclusions.

Scattering from a rough surface interface is calculated using both an analytical approach (Kirchhoff theory) and a numerical calculation (Finite Difference Time Domain, FDTD) for surfaces with a roughness spectrum following a Gaussian distribution. The importance of the volume versus surface scattering for different classes of explosives is presented and discussed in the context of THz sensing of explosive devices.

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6472-10, Session 2

Analysis of standing waves in submillimeter-wave optics

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In this paper, we describe on a theoretical method based on Gaussian Beam Mode Analysis for modelling standing waves in submillimetre optical systems. Standing waves or multiple reflections have been traditionally been difficult to model but this analytical method proves to be very versatile in first order predictions. This technique can be applied to reflections between optical components such as lenses and apertures and mirrors [1].

As our method uses a full multi-moded scattering matrix description of the feed horn (typically a corrugated horn), which are then transformed to equivalent free space Gaussian modes, multiple reflections between the source/detector device, located at the back of the horn, and any arbitrary surface in the optical path can be accurately analyzed. An in-depth overview of the technique is presented along with experimental verification at a frequency of 100 GHz were many common causes for standing waves

in receiver systems are investigated; including apertures, stops and the influence of off-axis optics.

[1] N. Trappe et al. "Gaussian beam mode analysis of standing waves between two coupled corrugated horns", IEEE Trans Antennas Propagat, 53, 1755 - 1761, 2005.

6472-11, Session 2

Gaussian beam mode analysis of millimeter-wave imaging and detection

W. P. Lanigan, E. Butler, E. Duffy, I. McAuley, L. Young, R. May, R. J. Mahon, J. A. Murphy, C. M. O'Sullivan, National Univ. of Ireland/Maynooth (Ireland)

We report on various optical schemes that can be used for imaging and detection, including both near-field lens-less schemes and also techniques from Fourier optics. A feature of the work is the use of Gaussian beam mode analysis in the design of such systems and in the efficient extraction of useful data concerning the characteristics of the object being detected or imaged. Near field lens-less millimetre-wave imaging (both transmission and reflection) has been found to be useful for extracting high resolution information (in terms of the wavelength) from biological samples, in which internal structure can be recovered, while holography involving near-field wave-front reconstruction has be used for extracting phase information of a beam of radiation reflected or transmitted by an object. Holography can be also used for imaging the phase centre of non-standard feed antennas or determining the refractive index of non-uniform materials, for example. Fourier optics techniques in the millimetre and terahertz bands can be utilized to improve image quality or extract spatial frequency information about the field of view. Such approaches allow for the possibility of spatial filtering to either enhance or suppress features of the image. The masks can be designed using Gaussian beam analysis. A novel application of directly using information from the Fourier plane would be in the detection of objects of a given size anywhere in a cluttered field of view with just a few detectors, thus eliminating the necessity for scanning in an image plane.

6472-12, Session 2

Modelling of the optical performance of millimeter-wave instruments in MODAL

M. L. Gradziel, C. M. O'Sullivan, National Univ. of Ireland/Maynooth (Ireland); G. Curran, Institute of Technology Blanchardstown (Ireland); J. A. Murphy, G. A. Cahill, National Univ. of Ireland/Maynooth (Ireland); C. Pryke, The Univ. of Chicago; W. K. Gear, Cardiff Univ. (United Kingdom); S. E. Church, Stanford Univ.

MODAL is an optical design and analysis package targeting the millimetre and sub-millimetre region of the electromagnetic spectrum. It is being developed at NUI Maynooth with the aim of integrating advanced modelling techniques and access to High Performance Computing into a user-friendly and yet very powerful tool for an (quasi-)optical designer. In this paper we present an application of MODAL in modelling of an existing instrument (QUaD), with the goal of optimising its performance.

The QUaD telescope is a ground-based experiment designed to measure the polarisation of the CMB, that began observations from the South Pole in March 2005. Measurements have shown that there is a small stigmatic distortion of the primary mirror which causes the far-field beam to be elliptical away from best focus. The fast beam between the primary and secondary mirrors means that changes in their separation on the order on a millimetre will have a significant effect on the beam shape. Early observations have shown this to be the case. It is important that the observed beam profiles are understood in terms of likely changes in the optical configuration before any adjustments are made.

Here we present new results from analysis of the predicted performance of the QUaD telescope, with particular emphasis on polarisation information. They were obtained by using MODAL to model the whole telescope, with the distortion of the primary accounted for, for a range of component tilts and separations. We also present preliminary work on the design and performance characterisation of an interferometric CMB instrument.

6472-13, Session 2

High finesse scanning Fabry-Perot filter for millimeter and sub-millimeter wave spectroscopy

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A scanning Fabry-Perot transmission filter composed of a pair of high reflectivity dielectric mirrors has been demonstrated at millimeter and sub-millimeter wavelengths. The mirrors are formed by alternating quarter-wave layers of silicon and air in the usual Bragg configuration. Characterization was performed at sub-mm wavelengths using a gas laser together with a Golay cell and at mm-wavelengths using a backward wave oscillator and crystal detector or microwave power meter. High resistivity in the silicon layers was found important for achieving high peak transmittance, especially at the longer wavelengths. A finesse value of 860 for a scanning Fabry-Perot cavity composed of three-period Bragg mirrors was experimentally demonstrated, and this implies achieved mirror reflectivity of 99.63%. Measured finesse values are in reasonable agreement with values calculated assuming ideal Bragg mirrors using available data for silicon's complex refractive index. Finesse values of several thousand are considered to be within reach. This suggests the possibility of a compact terahertz Fabry-Perot spectrometer that can operate in low resonance order to realize high free spectral range while simultaneously achieving a high spectral resolution. Such a device is directly suitable for airborne/satellite and man-portable sensing instrumentation.

6472-14, Session 3

Terahertz science and applications based on poled electro-optic polymers

L. M. Hayden, X. Zheng, C. V. McLaughlin, Univ. of Maryland/Baltimore County

We report on the application of poled electro-optic (EO) polymer films as terahertz (THz) emitters and sensors. Appropriately engineered EO polymers have very high EO coefficients that purely originate from the extended μ-electron systems, suggesting their promising role in efficient and broadband generation and detection of pulsed THz radiation via optical rectification (OR) and EO sampling, respectively. We successfully made and poled high-quality polymer films (~75 μm thick) consisting of 40% Lemke/60% APC (LAPC). These films exhibited EO coefficient r33 between 30 and 40 pm/V at 830-nm-wavelength, higher than any inorganic EO crystals currently used for the THz generation and detection. Using a Ti:sapphire regenerative laser pulse amplifier operated at 800-nm-wavelength and a LAPC emitter-sensor pair, we generated and detected transient THz waves with ~12-THz gap-free bandwidth. For THz time-domain-spectroscopy (THz-TDS), the continuous broadband THz spectrum of our EO polymer emitter-sensor pair has advantages over EO crystals, where resonance absorptions always occur in the THz regime. To guide our selection of EO polymers with suitable linear and nonlinear, optical and THz properties, we developed a model to simulate the spectra from EO-polymer-based THz systems and compared the simulation results with our experimental results. We also report our investigation on an in-plane poling technique that points towards more efficient EO polymer sensors. Finally we present the employment of the gap-free, wideband response of an LAPC sensor to characterize phonon absorption bands in the organic crystal DAST.

6472-15, Session 3

Ion-irradiated In0.53Ga0.47As based photoconductive antennas excited at 1.55 μm for THz emission and detection

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The generation of coherent terahertz radiation from photoconductive antenna has attracted considerable interest since it is a way to reach the intermediate terahertz frequency range. The best terahertz performance is achieved by photoconductive antenna excited by ~0.8μm optical pulses and made from low-temperature-grown GaAs material, because this material associates both subpicosecond carrier lifetime and high resistivity. The use of a lower-bandgap semiconductor, such as InGaAs, allows cheap, compact and turnkey terahertz spectroscopy setups based on erbium fiber (Er:fiber) lasers, which can produce sub-picosecond pulses at a central wavelength λ=1.55 μm.

We present a time-domain terahertz spectroscopy set up based on Er:fiber laser which delivers pulses at 1.55 μm wavelength and that integrates photoconductive antennas made on heavy ion-irradiated In0.53Ga0.47As material as emitter and detector. The power spectra of the electric field extend to 1.5 THz with ~ 40 dB dynamic. To experimentally analyze the influence of the carrier lifetime on the emitted terahertz signal characteristics, we made four In0.53Ga0.47As emitters with carrier lifetimes of >1 ns, 4.2 ps, 0.7 ps and 0.3 ps by varying the Br+ irradiation dose. The emitted temporal waveforms change from unipolar shape to asymmetrically bipolar shape as the carrier lifetime is decreased, resulting in peak spectra shift to higher frequency. These direct consequences of the decrease of the carrier lifetime in the emitter are compared to the predictions of charge transport analytical model.

6472-17, Session 3

Widely tuneable ultra stable 1W two colour THz laser source

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Coherent cw-THz-radiation allows access to new applications in the field of medicine, industrial process control, data communication and security applications. Major advantages of radiation in this spectral range are that it penetrates through e.g. plastics but is strongly reflected by metals and that molecules show distinct and distinguishable spectra so that a selective sensing of single species is possible. However, existing THz-sources are either very bulky and expensive, need cryogenic temperatures or emit only low power radiation. Furthermore the setup is often very complicated and sensitive so that field measurements are not possible.

Generation of THz radiation based on the technology of frequency mixing. Frequency mixing requires laser radiation with a difference frequency in the order of 0.1-2 THz. Due to the small efficiency of frequency mixers, high optical power is required for pumping frequency mixers. Furthermore, the small efficiency requires short optical pulses for avoiding a high heat dissipation of the frequency mixers.

We investigated an ultra stable 1W two colour THz pump source for the generation of a THz beat signal with rapid single mode tuning over several THz. The system consist of a fixed wavelength and a motorized tuneable laser pump sources which are optical amplified within a pulse operation module. One laser is stabilized to an atomic reference while the other is locked to an optical cavity which can be tuned continuously.

This signal is pump source for a state of the art frequency mixer, which is typically realized as LT-GaAs crystal with an antenna design.

6472-19, Session 4

Compact THz spectrometers

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We developed a compact THz spectrometer based on millimeter-wave backward wave oscillators combined with frequency multipliers. The instrument operates in frequency range 0.1 - 1 THz, providing for spectral resolution of 1-10 MHz and dynamic range of at least three orders of magnitude. The system consumes less than 200 W of electrical power and does not require water cooling. Dimensions of the instrument are 70 cm x 40 cm x 35 cm and the weight is less than 40 kg. The size and weight of the system can be further scaled down for applications requiring portability.

Vacuum and solid state electronic THz sources have been competing for decades in terms of size, output power and spectral tunability. Ironically, THz generators based on combination of these two technologies offer the best of both worlds. Specifically, combination of low frequency (<200 GHz) backward wave oscillators (BWOs) with shottky-diode based frequency multipliers enables compact THz sources, which provide for sufficiently high power (>0.01 mW) across a wide range of frequencies (0.1-1 THz).

Advantages of low frequency BWOs include compact size, light weight, lower operating voltages, long operating lifetime and ambient air-cooling. Extending operating range of low frequency BWOs by combining them with frequency multipliers offers a way to extend their operating frequency range without increasing size and weight, reducing lifetime and adding water cooling, enabling compact and portable THz instruments.

6472-20, Session 4

Millimeter-wave imaging system with polymer modulators

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We have designed and fabricated polymer modulators as detectors for millimeter-wave imaging. The advantages of the polymer modulator is that it is low-cost, that it can be fabricated in an array configuration, and that the rf and optical waves have similar indices, resulting in a modulator with an excellent frequency response at 95GHz. The efficiency of the modulator is a parameter that combines the frequency response, the optical insertion loss, and the driving voltage, and the efficiency. We present measurements of the efficiency of a polymer modulator. To optimize this modulator for millimeter-wave imaging, we have developed new polymer materials, and investigated electrode and optical waveguide design. The imaging system will include the optics, which couple to an antenna. The antenna will connect to a Dicke switch, and then to the modulator driving electrode. We show design and analysis for these elements of the imaging system. Then, we find the system noise temperature. Our target is to achieve noise temperatures on the order of 7K when the system is uncooled.

6472-21, Session 4

Signature and signal generation in THz time-domain spectroscopy for trace explosives detection

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In recent years, THz time-domain spectroscopy (TDS) has received great attention as a tool to detect explosives, as traces from land mines or improvised explosive devices (IEDs), or to detect bulk explosives, such as on suicide bombers. The efforts have led to a large database of signatures in this frequency range for many explosive related compounds (ERCs). In a collaboration between RPI and JHU on an ARO Multi-University Research Initiative (MURI) on trace explosives detection, we have assembled a database of THz spectra for more than 18 ERC compounds using different methods (TDS, FTIR). We have also related the measured spectral signatures to molecular and inter-molecular vibrations using numerical calculations using (e.g.) semi-empirical and density functional theory approaches. Most of these spectra, including the ones shown in

literature, have been taken either in transmission, or in reflection from bulk explosives. While this was an important step in demonstrating the feasibility of THz TDS for explosives detection, the goal of the presented research was to investigate the TDS signal generation for more practical applications.

The goal of this research is to demonstrate selectivity of THz spectra from the clutter of background spectra coming from the substrate, soil or sand in most applied cases. The most probable application of THZ TDS for explosives detection (other than searching people for suicide bombers) will be in reflection, typically very small amounts of explosives on a rough surface or within the top soil layer. In the case of a solid reflector, the contributions of refractive index and absorptivity to the observed frequency spectrum are very different. For any realistic application, contributions of the rough surfaces such as scattering, the finite penetration of the THz radiation into the (dielectric) substrate as well as clutter need to be considered. The spectrum in this case will also be a combination of reflection as well as double-pass transmission.

We have investigated THz TDS reflection spectra from sand with different grain sizes as well as from metallic spheres in order to distinguish between the signals reflected from the surfaces compared to the finite penetration into the material. With several marker materials such as lactose and tartaric acid, which have both absorption features in the 1-2 THz range, we have investigated the reflection spectra for different sample arrangements, either distributed in the soil or on the surface, or compared to reflection and transmission spectra of solid materials as well as polyethylene-sample pellets. The same experiments have then be performed using TNT, RDX, and HMX, which all have some characteristic feature in the 1-8 THz frequency range. In addition, molecular absorption coefficients for the absorption features of these compounds have been determined in the 1-8 THz range are derived.

6472-22, Session 4

High-speed LiNbO3 modulator for W-band millimeter-wave detection

C. Huang, C. A. Schuetz, R. Shireen, S. Shi, D. W. Prather, Univ. of Delaware

We report the design, fabrication, and characterization of high-speed LiNbO3 modulator for the millimeter-wave (MMW) detection system at W band covering atmospheric window at 94 GHz. The LiNbO3 modulator is used to convert the collected MMW power into optical frequency, and hence predominantly determines the system sensibility. The high sensibility of detection requires the modulator a broad-band response and a small driving voltage. The ridged traveling-wave structure has been used in the modulator design. The effects of velocity matching, impedance matching, and MMW attenuations in this structure on the device's MMW conversion efficiency are investigated. A numerical model has developed to optimize the device geometric parameters and the fabrication processes. The fabricated modulator achieved the 3-dB optical bandwidth of 67 GHz and the conversion efficiency of ~0.7 W-1 at 94 GHz. The detection pixel based on it has shown a high sensibility with a noise equivalent temperature difference of ~6 K at a refreshing rate of 30 Hz. Further improvements in sensibility are discussed in terms of the modulator design.

6472-23, Session 4

Terahertz imaging of burned tissue

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There are approximately 2.4 million reported burn injuries each year in the United States with 75,000 of these incidents resulting in hospitalization.

Current medical imaging modalities have limited capabilities to assess initial burn damage and monitor healing progress. Some of these limitations can be attributed to modality occlusion from bandages, dried tissue and/or blood and inflammation. Since terahertz radiation can see through textiles and bandages1, previous studies2,3 suggested that terahertz radiation, in a reflectance configuration, could be used for non-invasive analysis of tissue thermal damage and healing status. In this study, we perform an analysis of the terahertz absorption and reflection properties of the tissue constituents comprising a wound area, and provide a feasibility assessment of the capabilities of terahertz imaging to provide a clinical tool for initial burn analysis and healing progress.

6472-24, Session 4

Terahertz micro-spectroscopy using a transient mirror technique

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The value of Terahertz (THz) sensing and imaging tools in a wide range of applications is now becoming widely appreciated: THz waves penetrate a range of non-metallic materials, including human tissue; they can determine the chemical composition of a sample; and they can also be harnessed to detect the presence of possibly dangerous or illegal items secreted within materials. It is well known that the characteristic energy of THz frequency probes corresponds to important excitations in semiconductor materials, and that they are the ideal tool for probing semiconductor nano-systems which have characteristic energy levels in the milli-electron volt region. Furthermore, in biology and medicine, it is known that THz waves have the potential to determine the presence of tumours and that THz radiation may interact with cell membranes and other structures. However, the usefulness of THz tools is severely limited by the magnitude of the wavelength, and so near-field techniques are essential for developments in microscopy.

In this contribution, we re-visit a technique first used at near infrared wavelengths and then deployed at THz frequency by Zhang and co-workers a few years ago. In this method, a small area transient mirror is created on a semiconductor material. An experimental sample, placed on the wafer, is irradiated with THz radiation and the response of the material is selected using the small mirror. In an alternative arrangement, a transmission geometry can be used which is more favourable for use with fragile biological samples.

We shall discuss the limits of achievable resolution and describe, for the first time, micro-spectroscopy of simple materials of bio-chemical interest.

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6473-01, Session 1

New possibility of MOVPE-growth in GaN and InN: polarization in GaN and nitrogen-incorporation in InN

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In the application of nitride semiconductors for electronic and optical devices, spontaneous and piezoelectric polarizations have been discussed recently. On the contrary, in light emitting devices, polarization is expected to be absent. This paper describes GaN with different characteristics from usual GaN grown by MOVPE.

Usually, GaN epitaxially grown by MOVPE has Ga-polarity. N-polar GaN is said to show a rough surface. For the MBE growth, GaN usually shows N-polar and has a smooth surface, but p-type GaN has not been obtained yet. We precisely investigated the mechanism in MOVPE growth. As a result, N-polar GaN with a surface as smooth as Ga-polar one was obtained and the density of threading dislocations was in order of 1018/cm2. p-type doping was also possible. This N-polar is very suitable for the growth of InN, which has the high equilibrium-vapor-pressure of nitrogen, because N polarity has the advantage in the capture of nitrogen.

To suppress the polarization effect, GaN growth on A-plane and R-plane sapphire substrates have been attempted. A-plane sapphire has crystallographically symmetry different from GaN. R-plane sapphire has large lattice-mismatch from GaN. We have explored many kinds of substrates suitable for GaN growth since 1987. In 1990, we found out M-plane sapphire which is lattice-mismatched to GaN by less than 3%. In 2001, single-phase GaN was grown on sapphire tilted 15 degrees from an M-plane. GaN with inclination of c-axis to the nominal axis of a substrate by 32 degree was grown. This number is much attractive to suppress the polarization effect in light emitting devices.

6473-02, Session 1

Two-step epitaxial lateral overgrowth of (112-0) a-plane GaN by MOCVD

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We report on growth and characterization of epitaxial lateral overgrown (ELO) (112-0) a-plane GaN by metalorganic chemical vapor deposition. The ELO samples were grown using a SiO_2 striped mask pattern consisting of 4 μm open windows and 20 μm or 10 μm SiO_2 stripes. Different growth rates in Ga- and N-wings along with the wing tilt create a major obstacle for achieving a fully coalesced flat surface in ELO-GaN. To address this problem we have employed a two-step growth method that would provide a high aspect ratio of height to width in the first step followed by enhanced lateral growth in the second step by controlling the growth temperature. Depending on the growth conditions, lateral growth rate of the wings with Ga-polarity were from 2 to 5 times larger than that of the N-polarity wings. We investigated the effects of growth parameters on wing tilt, which was observed to be ~ 0.25° from the Kikuchi lines using Large Angle Convergent Beam Electron Diffraction and accompanied by some twist (0.09°) between two opposite wings. TEM results showed that the threading dislocation density in the resulting fully coalesced overgrown GaN was reduced from 4.2Å~10^10 cm-2 in the window area to 1.0Å~10^8 cm-2 in the wing area, and that the wing areas contained relatively high density of basal stacking faults, 1.2Å~10^4 cm-1. The recombination of carriers/excitons localized at stacking faults was evident in far-field near bandedge photoluminescence (PL) measured at 10 K. Moreover, AFM measurements revealed two orders of magnitude higher density of surface pits in window than in wing regions, which could be decorating dislocation termination on surface.

Time-resolved PL measurements for the a-plane ELO-GaN samples revealed biexponential decays. The recombination times were significantly increased (t_1=80 ps and t_2=250 ps) compared to the regular a-plane epitaxial layers (<45 ps), and ratio of the slow decaying component magnitude to the fast decaying one was more than 1.5, showing considerable reduction of nonradiative centers by lateral overgrowth. In addition, room temperature near-field optical microscopy studies revealed the improved optical quality in the wing regions of the overgrown GaN. As revealed from far-field PL, the band edge luminescence at room temperature was more than two orders of magnitude weaker than the yellow luminescence. Therefore, the overall spectrally integrated near field PL was collected, and its intensity was noticeably stronger in the wing areas with both Ga and N polarity. The much weaker emission at the windows and meeting fronts of the two opposite wings was consistent with the observations of high density of dislocations at the windows and new defects originating at the meeting boundaries from TEM.

6473-03, Session 1

Low dislocation density GaN grown by MOCVD with SiNx nano-network

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GaN epitaxial layers grown on SiC and sapphire, due to very limited availability of native substrates, suffer from high density of line and point defects. To address this problem, new growth methods using in situ or ex situ nano-network masks as dislocation filters have been introduced recently. In this work, we report on metalorganic chemical vapor deposition (MOCVD) of GaN layers on 2-inch sapphire substrates using in situ SiNx nano-networks intended for defect reduction. SiNx interlayers with different deposition times were employed after 1 õÌm GaN growth on sapphire, which was followed by 4.5 õÌm GaN overgrowth for a fully coalesced surface. With increasing SiNx coverage, full width at hall maximum (FWHM) values of (002) and (102) X-Ray diffraction (XRD) peaks monotonously decreased from 252 arcsec to 217 arcsec and 405 arcsec to 211 arcsec, respectively for a 5.5 õÌm thick film. Similarly, transmission electron microscopy (TEM) revealed reduction in dislocations and screw and edge type dislocation densities as low as ~ 4.4¡Á10e7 cm-2 and 1.7¡Á10e7 cm-2 were achieved. The application of SiNx nanonetwork also increased the radiative recombination lifetimes measured by time-resolved photoluminescence to 2.5 ns from less than 0.5 ns in control GaN. Finally, Ni/Au Schottky diodes were fabricated on the overgrown GaN layers and the diode performance was found to depend critically on SiNx coverage consistent with TEM, XRD and TRPL results. A 1.13eV barrier height was achieved when SiNx layer was used compared to 0.78 eV without any SiNx nano-network. Furthermore, the breakdown voltage improved from 76 V to 250 V with SiNx nano-network.

6473-04, Session 2

Enhanced luminescence from AlxGa1-xN/AlyGa1-yN quantum wells grown by gas source molecular beam epitaxy with ammonia

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We report the structural, morphological, and optical properties of AlxGa1-xN/AlyGa1-yN quantum well (QW) structures using transmission electron microscopy (TEM), atomic force microscopy (AFM), and room temperature cathodoluminescence (CL) and time-resolved photoluminescence (TRPL), respectively. All structures were grown by gas source molecular beam epitaxy with ammonia on sapphire (0001) substrates. Growth began with nitridation of sapphire, followed by a 150 nm thick AlN buffer layer. Next, a 70 nm thick undoped buffer-barrier layer of AlxGa1-xN, 0.5<x<0.6, was grown. This thickness was sufficient to reach a 2D growth mode as confirmed by streaky reflection high energy electron diffraction (RHEED) patterns. The growth continued with a QW structure consisting of five pairs of AlyGa1-yN, 0.3<y<0.45, wells (nominally 2nm thick) and AlxGa1-xN barriers (nominally 5 nm thick). All the structures were completed with a 10 nm thick cap layer of AlN. We observed a significant improvement in the CL and PL efficiencies of QW structures when the 3D growth mode, as confirmed by spotty RHEED patters, is induced by reduced flux of ammonia in the growth of wells. Note that for all ammonia fluxes used for well growth the RHEED pattern of the barrier layer recovers and shows 2D growth by the time the next well is grown. We will discuss the plan-view and cross-section TEM results. TRPL data were taken at four different excitation powers. We will discuss the observed decrease in the decay time as the excitation power is increased. The ~ 330 ps average PL decay time was measured in the samples with highest luminescence intensity at ~ 290 nm, which is typical of GaN with defect density in the low 10e8 cm-2.

6473-05, Session 2

Narrow-width photoluminescence spectra of InGaN quantum wells grown on GaN (0001) substrates with misorientation toward [1-100] direction

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We have demonstrated narrow-width photoluminescence spectra, with full width at half maximum (FWHM) below 60 meV, of InGaN quantum wells when grown on GaN (0001) substrates with a misorientation angle between 0.2 and 0.3 degree toward [1-100] direction.

GaN-based lasers have attracted much attention in regards to epitaxial growth and device applications. In previous work, it was found that the surface morphology of GaN-based layers was improved when grown on GaN (0001) substrates with misorientation toward [1-100] direction, rather than when grown on GaN (0001) substrates with misorientation toward [11-20] direction, using atomic force microscopy (AFM) and x-ray diffraction.1) In this paper, micro-photoluminescence (micro-PL) was applied to investigate the optical properties of such small regions of AFM observation and find the optimum misorientation angle toward [1-100] direction.

InGaN quantum wells were grown on some GaN (0001) substrates with a misorientation angle from 0.0 to 0.4 degree toward [1-100] direction. AFM images of these samples show the steps were clearly observed on the surface of the InGaN quantum wells. Moreover, the steps were observed periodically when grown on GaN substrates with a misorientation angle over 0.1 degree, while the period of steps was shorter as the misorientation angle was larger.

Micro-PL was done at room temperature with the diameter of the laser spot size being approximately 2 micrometer. The FWHM of PL spectra was below 60 meV when InGaN quantum wells were grown on GaN substrates with a misorientation angle between 0.2 and 0.3 degree. This result is consistent with AFM observation.

1) K. Tachibana, H. Nago, and S. Nunoue, phys. stat. sol. (c) 3, 1819 (2006).

6473-06, Session 2

AFM and C-AFM studies of ELO GaN films

A. A. Baski, V. P. Kasliwal, X. Ni, J. C. Moore, J. Ortiz, H. Morkoc, Virginia Commonwealth Univ.

We have used the techniques of atomic force microscopy (AFM) and conductive AFM (C-AFM) to study the morphology and conduction properties of a-plane GaN films grown via epitaxial lateral overgrowth (ELO). Two GaN samples were prepared using metal organic chemical vapor deposition (MOCVD) with different final V/III ratios. A GaN layer was grown on r-plane sapphire (1.5 um, 1050°C), and then a 100-nm thick SiO2 mask was deposited and patterned with 4 um windows oriented along the [101bar0] direction. The ELO film was subsequently grown in two stages at 1000 and 1050°C, where the NH3 flow rate during the second stage was either 560 or 3000 sccm. In AFM images, the coalesced ELO films show undulations, where the window regions appear as depressions with a higher defect density than surrounding areas. In one sample the meeting fronts on the wings between the Ga- and N-face c-plane fronts are visible as ridges, and indicate that the Ga-face front grows ~3 times faster than the N-face front. For C-AFM measurements, a Ti-Pt coated AFM tip was brought into contact with the GaN surface to form a microscopic Schottky contact while the sample had an ohmic Ti/Al/Ti/Au contact. At reverse bias below 12 V, most areas on the samples show very low uniform conduction (2 pA) in the window regions and undetectable conduction along the wings. At higher reverse bias above 20 V, however, the sample grown with a lower second stage NH3 flow rate shows localized defect sites inside the window regions with higher leakage (10 pA). Under forward bias conditions, both samples exhibited low conduction in localized regions within the windows (2-10 pA). This C-AFM study confirms that ELO-grown GaN samples show enhanced reverse-bias leakage inside the window regions where a higher defect density is present.

6473-07, Session 2

Magneto-transport properties of MOVPE-grown AlxGa1-xN/AlN/GaN heterostructures with high-mobility two-dimensional electron gas

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Because a two-dimensional-electron-gas (2DEG) in the AlGaN/GaN material system is currently used in high power field effect transistors, the transport properties of such structures are of interest. In this vein, temperature-dependent magneto-transport measurements have been carried out in AlxGa1-xN/AlN/GaN heterostructures. Carrier transport properties of the samples have been analyzed with the quantitative mobility spectrum analysis (QMSA) technique. Several AlxGa1-xN/AlN/GaN samples with different Al-compositions were grown by metal-organic vapor phase epitaxy (MOVPE). At low temperatures, the observation of single-period Shubnikov de-Haas oscillations confirmed the existence of a high-quality 2DEG at the GaN/AlN hetero-interface. Magneto-resistance and Hall measurements were carried out in the temperature range of 1.6-200 K and magnetic field range of 0-6.6 T. QMSA was successfully used to extract and delineate the concentrations and mobilities associated with the high-mobility 2DEG and the relatively-low-mobility bulk electrons in the heterostructure for the temperature range investigated.

6473-08, Session 2

Investigation of current voltage characteristics of n-GaN/i-AlxGa1-xN/n-GaN structures

X. Ni, J. Xie, Y. Fu, H. Morkoc, Virginia Commonwealth Univ.; P. P. Ruden, Univ. of Minnesota; K. Son, Jet Propulsion Lab.

Although standard GaN device structures used for FETs, light emitters, and detectors have been investigated reasonably extensively, the device structures relying on the particulars of current transport over barriers in this material system have not received as much attention, to a large extend due to the insufficient quality of the layers. Unless special measures are taken, the defects present in the barrier material induce current conduction paths that preclude any possibility of observing the fundamental

current conduction mechanisms. To overcome this impediment, high quality GaN layers, followed by the vertical single barrier heterostructures, have been grown on sapphire substrates using epitaxial lateral epitaxy in a metal organic chemical vapor deposition system with the aid of an in-situ deposited SiNx nanonet. Structural and optical properties of the films indicate their superior nature. With these templates in hand, GaN/i-AlxGa1-xN/n-GaN structures with varying barrier width and height have been prepared and tested for their IV characteristics. The rectification observed is consistent with the barrier design. Because the band bending is affected by polarization charge, which is dependent on pressure, current vs. voltage measurements under pressure have also been recorded. In this presentation, the details of the measurements and analyses, as well as the pertinent aspects of growth related issues will be discussed.

6473-09, Session 3

Wide bandgap semiconductor ultraviolet photodetectors: a short review of devices and applications

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Ultraviolet detectors are of a great interest to a wide range of industrial, military, environmental and even biological applications. This presentation will review some of the most relevant recent developments in the field of wide bandgap semiconductor UV detectors and their applications. A special focus will be given on III-nitride based devices, which more and more clearly represent to date one of the most promising and flexible technical solutions for UV detection.

6473-10, Session 3

Spontaneous polarizations, electrical properties, and phononic properties of GaN nanostructures and systems

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Spontaneous polarizations of GaN nanostructures and quantum dots are calculated for different surface terminations. The conductivities of GaN nanowires are modeled. Novel system architectures for non-charge-transfer-based devices will be discussed in terms of chemically self-assembled ensembles of GaN quantum dots with molecular linking elements. Dimensionally-confined phonons GaN-based nanostructures will be discussed.

6473-11, Session 3

Three-dimensional gallium nitride photonic crystals as nonlinear optical materials

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Impregnation of three-dimensional (3D) photonic crystals of synthetic silica opals by semiconductor, metal or dielectric functional materials opens new functionalities of photonic crystals including modification of photonic band structure by external impacts. The dielectric function periodicity imposed by initial opal matrix is utilized for the control of the optical field propagation inside such composite photonic crystals. Nonlinear-optical effects in opal photonic crystals are accompanied with linear and nonlinear light diffraction on the 3D fcc lattice of silica microspheres of submicron diameter. In this paper, realization of enhancement of second-harmonic generation (SHG) in 3D photonic crystals utilizing nonlinear diffraction is demonstrated. The second-harmonic (SH) intensity is increased significantly if the fundamental wavelength is close to the Bragg reflection condition.

The samples are composed from close-packed silicon oxide spheres with diameter of 250 to 300 nm in each sample forming an ordered fcc opal matrix. The opal voids are filled by noncentrosymmetric gallium nitride with filling factor close to unit by the thermal chemical vapor deposition. The photonic band gap (PBG) is obtained for light reflected from the (111) face and localized in the spectral region from 800 to 950 nm for different samples.

The SHG enhancement is attributed to combination of linear diffraction of the fundamental radiation from the (111) opal layers and nonlinear diffraction utilizing the 3D periodicity of the quadratic susceptibility of gallium nitride nanocrystals in opal voids. Spectral position of the maximal SHG achieves at the fundamental wavelength in the vicinity of the long-wavelength-edge of the PBG, where group velocity of the fundamental radiation takes the minimum. Small value of group velocity is equivalent to the enhancement of the photonic mode density in this spectral region and the SH intensity is increased significantly at the PBG edge.

6473-12, Session 4

High power light emitting diodes: the application to LCD back-light units

J. J. Jung, LG Electronics Inc. (South Korea)

Recently, significant progress in semiconductor-based solid state light emitting technologies has realized by commercially available high-power white LEDs with luminous efficiency of over 50 lm/W. This ,in parallel, resulted in vigorous activities to replace cold cathode fluorescent lamps with high power LEDs as white back-light sources in liquid crystal display(LCD) applications. However, there are still many challenges to be overcome in the chip levels of LEDs for the application to LCD back-light units (BLU). In this presentation, I will present our recent research results on photonic crystal LEDs, vertical-type LEDs using laser lift-off method, and a novel wafer-level packaging method in efforts to increase the efficiencies of heat dissipation and light extraction of LEDs.

The light extraction efficiency in GaN-based LED is limited mainly due to the large difference in the refractive index between GaN and surrounding air. Consequently, photonic crystals (PC) can improve LED output power. In this work, the PC LEDs exhibited significant improvements in output power. The maximum enhancement of 25 % was obtained from the PC LED with a lattice constant of 1200 nm at a current of 20 mA.

Vertical type GaN-based LEDs have advantages of uniform current spreading and efficient heat dissipation when employing metal supporter, whereas lateral type GaN-based LEDs give rise to local current crowding. Advanced fabrication processes of vertical type GaN-based LEDs and the improved performance of vertical LED will be addressed.

Furthermore, a novel silicon wafer level packaging (WLP) method for large size LCD back-light units and general lighting will be presented as a new way of high power LED packaging. Our WLP method utilizes the concept of silicon optical bench (SiOB) which can exploit a great deal of benefits from Si technology.

6473-13, Session 4

Reliability of high power GaN vertical light emitting diodes on metal substrate for solid state lighting application

C. A. Tran, SemiLEDs Corp.

In this paper we discuss the reliability of High Power GaN based Vertical Light Emitting Diodes on Metal Substrate (VLEDMS)[1] for Solid State Lighting Application. With very high power (over 100 lumens/watt) achieved in mass production, the next important step is reliability study of the devices under different operation conditions. The robustness of the chips depends strongly on LED epitaxial quality, diffusion of the metal into the p-GaN through the mirror and heat transfer from the active layer into the heat sink. We show that for the same input power, the junction tempera-

ture of the VLEDMS is always lower with respect to that of conventional LED or flip-chip LED. An excellent reliability can maintain for the chip size up to 60x60 mil, making high wattage package simple. With an optimized LED structure and optimized package, the VLEDMS brightness decay at a current density twice higher than the one used for conventional LED is extrapolated less than 20% after 50,000 hrs. This data shows that VLEDMS reliability for solid state lighting application can surpass the conventional light source like incandescent and fluorescent lamps.

[1] T. Doan, C. Chu, C. Cheng, W. Liu, J. Chu, J. Yeh, H. Cheng, F. Fan and C. Tran, "Vertical GaN based light emitting diode on metal alloy substrate for solid state lighting application", Proceedings of SPIE 6134, 61340G-1 (2006).

6473-14, Session 4

Transparent conducting oxide electrodes for GaN-based light-emitting diodes

T. Seong, Korea Univ. (South Korea)

High-brightness GaN-based LEDs are significantly important for their application in solid-state lighting, which requires the achievement of high light extraction in LEDs. To realize solid-state lighting, the light output power of LEDs should be considerably improved. One of the main reasons that white LEDs yield low light output is associated with difficulty in obtaining reliable p-type ohmic electrodes. Semi-transparent electrodes for commercial GaN-based LEDs experience several problems, such as the absorption of a significant amount of light emitted from LEDs and the low refractive index of the electrodes. Thus, the development of p-type ohmic electrodes that have low contact resistivity, high light transmittance, and high refractive index (n″ 2) is essential to increase of external quantum efficiency. In this work, to improve light extraction efficiency, we have investigated different types of transparent conducting oxide (TCO) electrodes, such as doped indium oxides and zinc oxides. It is shown that the TCO electrodes become ohmic with specific contact resistances of ~10-4 Ωcm2 and give transmittance higher than 90% at 405 nm when annealed at 530 - 630 °C. Near-UV LEDs(405 nm) fabricated with these oxide p-type contact layers give a forward-bias voltage of 3.2 - 3.4 V at 20 mA. The output power (at 20 mA) of LEDs with TCO contacts is enhanced 50 -78% as compared with that of LEDs with Ni/Au contacts. The results show that the TCO electrodes could be of technological importance for the fabrication of high-brightness near-UV LEDs.

6473-15, Session 5

Simulation of defects and defect microstructure evolution in GaN-based alloys

M. Ganchenkova, R. M. Nieminen, Helsinki Univ. of Technology (Finland)

GaN-based materials are promising wide band-gap semiconductor for micro- and optoelectronic applications. Many of their properties and unusual features are ascribed to specific defect microstructure of these materials. To be able to predict the physical properties of GaN-based samples after non-equilibrium processing (annealing, mechanical loading, etc.) one needs to realize both the energetics of various defect types and the features of defect kinetic behavior (migration and clustering). Here we discuss the results of electronic structure calculations of various defects in GaN and its triple alloys with In and Al, as well as multiscale modelling of microstructure evolution during high-temperature annealing of GaN and GaInN. In particular, nitrogen vacancies, shown recently to be the dominant defect type in GaN, will be considered in detail. We show a sufficiently high mobility of nitrogen vacancies in n-type GaN at annealing temperature that together with noticeable binding energies between nitrogen vacancies and other point defects (Ga vacancies and impurities) creates favourable conditions for vacancy clustering.

6473-16, Session 5

Summary of deep level defect characteristics in GaN and AlGaN

D. K. Johnstone, SEMETROL

Deep levels in GaN and related materials are a fundamental concern due to their impact on the performance of a broad range of devices. This presentation is a summary of the characterization both from the author's work and from other publications, primarily with deep level transient spectroscopy (DLTS). The state of knowledge of point defects in GaN and AlGaN will be presented. A plot of the emission energy versus capture cross section concisely summarizes the work that has been done for both materials, but also points out unexpected trends. For defects that are expected to be common to samples grown by the same method, the summary plot should show relatively circular groupings of defect characteristics. However, the groupings tend to be linear, where the capture cross section decreases with emission energy. The range of variation in defect characteristics are identified, and reasons for the variations are explained, based on the characterization methods and on material properties. The implication is that there are fewer defect types in GaN and AlGaN than the range of reported trap characteristics suggest.

6473-17, Session 5

Interplay of Ga vacancies, C impurities and yellow luminescence in GaN

F. Tuomisto, F. Reurings, Helsinki Univ. of Technology (Finland); M. Reshchikov, Virginia Commonwealth Univ.; D. C. Look, Wright State Univ.

Both carbon impurities and Ga vacancies have been observed to be related to the broad band yellow luminescence (YL)peaking at around 2.2 eV in GaN. In this work we investigate the relation of these two defects to the YL in six MOCVD-grown GaN samples with different carbon concentrations and electrical and optical characteristics [1]. We use positron annihilation spectroscopy to determine the Ga vacancy concentrations in the samples. Our preliminary results indicate that the Ga vacancy concentrations are of the same order of magnitude as the C impurity concentrations. Interestingly, the results show that the Ga vacancy concentration anticorrelates with that of the C impurities in semi-insulating (SI) GaN samples, but is constant irrespective of the C concentration in the slightly n-type conductive samples. The intensity of the yellow luminescence correlates with the C concentration in the SI GaN samples, while it correlates with the Ga vacancy concentration in the slightly n-type samples. This suggests that the identity of the defect responsible for the YL in GaN depends on the position of the Fermi level. Further positron measurements are underway in order to determine the charge states of the Ga vacancies and the C impurities.

[1] M. A. Reshchikov, R. H. Patillo, and K. C. Travis, Mater. Res. Soc. Symp. Proc. Vol. 892, FF23-12.1 (2006).

6473-19, Session 6

Quantum 1/f noise in GaN FETs, HFETs, MODFETs, and their oscillators' phase noise

P. H. Handel, A. M. Hall, Univ. of Missouri/St. Louis; H. Morkoc, Virginia Commonwealth Univ.

GaN-based FETs, HFETs and MODFETs are ideally suited for use in high-power amplifiers and oscillators, due to their large band gap and high operating voltages. According to the quantum 1/f theory, the larger effective mass implied for the carriers also leads to lower fundamental 1/f noise and to lower resulting phase noise close to the carrier frequency. We have therefore studied the quantum 1/f noise sources in the channel and in the gate insulation. For the channel, a combination of conventional and coherent Quantum 1/f Effect (Q1/fE), with the conventional Q1/fE likely to dominate in the sub-threshold part of the channel toward the drain. It

turns out that the quantum 1/f parameter "s" that determines the fraction of the two forms of Q1/fE, is no longer increasing proportionally to the width of the device w, when the latter exceeds the length of the channel. A logarithmic dependence on w is obtained instead. Conventional Q1/fE applies for the gate insulation, with contributions of the much larger piezoelectric Q1/fE in spontaneously polarized AlGaN, if gate leaking is present. The noise figure is calculated, including all contributions. Finally, the minimal expected oscillator phase noise is calculated from the Q1/fE in the dissipative elements, even for perfectly linear amplifiers, by multiplication with the inverse fourth power of the quality factor, as was first done by us for quartz in 1979.

6473-20, Session 6

Accumulation of hot phonons in GaN and related structures

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Interaction of hot electrons with longitudinal optical (LO) phonons is the dominant energy dissipation mechanism in GaN heterostructure channels subjected to high electric fields. Accumulation of non-equilibrium LO phonons (termed hot phonons) introduces additional friction for drifting electrons and limits frequency of operation of high electron mobility transistors (HEMTs).

Hot-phonon accumulation depends on hot-phonon lifetime. The most direct technique for measuring the lifetime is time-resolved pump-probe Raman scattering: intensity of anti-Stokes line is proportional to the LO-phonon number, the time-dependent intensity after the pump yields the lifetime. However, this technique for hot-phonon lifetime measurement has never been applied to a GaN heterostructure channel with a high-density two-dimensional electron gas. An alternative technique is based on fluctuations and dissipation. It has yielded experimental results on equivalent hot-phonon temperature and hot-phonon lifetime in AlGaN/GaN, AlGaN/AlN/GaN, AlGaN/GaN/AlN/GaN and other channels. At a high electron density, the lifetime is found essentially shorter and the temperature is lower as compared with the values measured at a low electron density. The dependence of lifetime on electron density will be discussed in terms of plasmon-assisted disintegration of LO-phonon-like quasiparticles formed in a high-density electron gas after emission of LO phonons by high-energy electrons. The results will be compared with Raman hot-phonon lifetime measurements carried out for bulk GaN samples.

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6473-21, Session 6

Subpicosecond time-resolved Raman studies of LO phonons in GaN

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A large non-equilibrium phonon population created in a semiconductor under the relaxation of carriers after excitation by an intense laser pulse, in particular with the application of an electric field, not only causes a decrease of energy loss rate of the electronic system (the so-called "hot-phonon effects") but also reduces the electron drift velocity. These have been demonstrated and well understood in a variety of semiconductors such as GaAs and Si. However, for some not so well established semiconductors, a case in point being GaN, the effects of the presence of a large non-equilibrium phonon population are less well understood, and sometimes the results are even contrary to our general belief.

The accumulation of a large non-equilibrium phonon population is a result of efficient electron-longitudinal optical (LO) phonon coupling and a relatively long phonon lifetime. In this presentation, we shall demonstrate a novel experimental technique - time-resolved Raman spectroscopy to interrogate the electron-LO phonon scattering rate and LO phonon population relaxation time in GaN. Our experimental results not only shed light on the possible decay channel of zone-center LO phonon in GaN but also resolve some controversy over the LO phonon lifetime in the literature.

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6473-22, Session 7

InGaN/GaN nanocolumn LEDs emitting from blue to red

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GaN nanocolumns are one-dimensional self-organized nanocrystals, grown keeping the axial direction to be c-axis. The average column diameter are from tens to hundreds nanometers and the column density was ~1E10cm^2. Self-assembling of GaN nanocolumns were first demonstrated in 1996 [1]-[2], and recently applied to the fabrication of InGaN/GaN nanocolumn LEDs [3].

Blue to red emission InGaN/GaN nanocolumn LEDs were prepared on n-type (111) Si substrates by RF-MBE. After the growth of n-type GaN nanocolumns, InGaN/GaN multiple quantum wells were integrated into the GaN nanocolumns. The lateral growth was enhanced in p-GaN cladding layers to make continuous films on the top surface. Finally p-type semi-transparent circular electrodes of 500 mm in diameter were prepared on the surface.

The LEDs were evaluated under the room temperature continuous wave operation. The emission wavelength was controlled from blue to red by changing the growth conditions of the InGaN active layer. Multiple color and nearly homogeneous emission were observed for different LED wafers. Amazingly the emission spectral tails in some multicolor samples spread from blue-green (~ 400 nm) to infrared (~ 800 nm). The emission area of 500 mm in diameter included various InGaN nanocolumns with different character. So as to clarify the nature of nanocolumn, the emission spectrum observation was performed for the micro emission area of 3 mm in diameter. As an example the green emission point of 520 nm was evaluated. No blue shift of the emission wavelength under increased current injection was observed. What's interesting is that red, green and blue emission points were frequently mixed in the same emission area. These suggest that the nanocolumn technology has a chance to open the way for the white semiconductor lighting.

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6473-23, Session 7

Nitride-based LEDs with p-AlInGaN surface layers prepared at various temperatures

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We have prepared bulk p-AlInGaN layers and light emitting diodes (LEDs) with p-AlInGaN surface layers by metalorganic chemical vapor deposition (MOCVD). It was found that surfaces of the LEDs with p-AlInGaN layers were rough with high density of hexagonal pits. It was also found

that pit width and pit density depend on the growth temperature of the p-AlInGaN layer. Furthermore, it was found that we can achieve 62% enhancement in output intensity from the LED with 820oC p-AlInGaN cap layer without increasing the LED operation voltage.

6473-24, Session 7

AlGaN based deep ultraviolet light emitting diodes with reflection layer

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We report on the effect of reflection layer on electrical and optical characteristics of AlGaN-based multiple-quantum well deep ultraviolet (DUV) light-emitting diodes (LEDs). A relatively thick layer (~ 250 nm) of Al-metal was deposited on the p-contact by e-beam evaporator at 2 10-6 mtorr nominal chamber pressure. It is shown that the Al reflection layer on p-contact significantly increases light extraction from an AlGaN-based DUV LED as compared to a reference LED employing a conventional Ni/Au p-contact. However, due to the high resistivity of the deposited Al-metal as a reflection layer, an increase in the forward voltage was observed. The rapid thermal annealing of the deposited layer in ambient as well as water vapors environment was also performed. The present results suggest that, for efficient DUV LEDs, the deposited reflection layer should have an optimal thickness of > 200 nm.

6473-25, Session 7

Prestrained InGaN/GaN quantum-well structures for fabricating orange-red light-emitting diodes

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We demonstrate the spectral red-shift of the quantum wells (QWs) designated for green emission into the orange range in a light-emitting diode by adding a violet-emitting QW at the bottom in metal-organic chemical vapor deposition. An electroluminescence red-shift of 53 nm was obtained. The cathodoluminescence spectra indicated that the long-wavelength QWs close to the violet one were strongly influenced by this added QW and mainly emitted the orange photons. Those near the top were less affected. This influence is supposed to originate from the prestrained effect in the barrier layer right above the violet QW. Such a prestrained effect is expected to be more effective when the underlying QW is well-shaped and the hetero-junction strain is strong, like the case of the violet QW. This effect is weak between the high-indium QWs, in which the formation of indium-rich clusters releases the strain. The operations of an orange and a red light-emitting diodes (LED), which are fabricated with the pre-strained InGaN/GaN QW epi-structure, are demonstrated. With the pre-strained growth, the orange-red LEDs can be fabricated for elongating the emission wavelength by more than 100 nm. The electrical properties of the orange LED are similar to those of the green one, which is fabricated based on the epi-structure without the pre-strain condition.

6473-26, Session 8

InGaN laser diode in blue and green wavelength

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In this paper, we discuss AlInGaN-based LDs in blue and green wavelength region for the application of laser projectors.

LDs were grown by metal organic chemical vapor deposition on sapphire or GaN substrates. The quantum well layers were composed of one or two pairs of InxGa1-xN well and InyGa1-yN barrier. The wavelengths of blue LDs were between 445 and 450nm. The fabricated LDs have been stably operated at cw-110mW in single transverse mode, which has been first achieved in the world. Estimated lifetime of blue LDs was over several thousand hours for APC condition at room temperature.

Indium-rich InGaN quantum wells were grown to fabricate green LDs. When the higher carrier density was injected into the quantum wells in the lasing condition, the strong blue shift phenomena were observed, which is closely related with piezoelectric effect and In composition fluctuation due to high In content in QWs. The longest lasing wavelength has been obtained about 485nm, so far. More experimental work is underway to push the wavelength toward green region in the near future.

6473-27, Session 8

Long lifetime CW InGaN laser diodes grown by molecular beam epitaxy

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The growth and fabrication of 405 nm InGaN laser diodes by molecular beam epitaxy (MBE) has made rapid progress over the last three years. In 2004, the authors reported the first MBE-grown nitride laser diodes. In mid-2005 the authors followed up this success with the demonstration of room-temperature continuous-wave (cw) operation. This was achieved by significantly reducing the threshold current density to 5.6 kAcm-2. Growing on free-standing GaN substrates also yielded significant processing and thermal management improvements. The lifetime of these first MBE-grown was lasers was up to 3 minutes, limited by power dissipation. In particular, the threshold voltage was relatively high at 8.6 V. In this paper we report on the progress we have made in reducing operating voltage and power dissipation. Considerable reductions in both have enabled a significant increase in laser lifetime, now several hours at room-temperature. We will report on the cw characteristics of these long lifetime lasers. Lifetime versus power dissipation data shows that our MBE-grown lasers follow the same trend as lasers grown by metalorganic chemical vapor deposition (MOCVD). This suggests a considerable further increase in lifetime will be achievable by a further reduction in power dissipation. With the lifetime being extended to several hours, it is now becoming important to understand the failure and degradation mechanisms of these devices to aid further progress towards matching the long lifetimes of lasers grown by MOCVD. We will report on work to understand the microscopic nature of degradation of InGaN lasers grown by MBE.

6473-28, Session 8

Degradation studies of an InGaN/GaN heterostructure laser diode using a Kelvin force microscope

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GaN-based laser diodes (LDs) are promising light sources e.g. for high-density digital video recording systems or laser-TV. Such applications require long device lifetimes and thus an understanding of possible degradation mechanisms. Degradation strongly affects the P/I- or the I/V-characteristics of the device but for a precise understanding of the underlying mechanism, a detailed knowledge of the voltage drop across the heterostructure would be of interest. For this task an experimental technique is needed, which combines a high spatial resolution with the ability to extract the voltage drop across heterojunction quantitatively. An appropriate technique is Kelvin Force Microscopy, which has already been used for studying e. g. the electrical potential distribution in operating LEDs [1] or LDs [2] or the voltage distribution in high power laser diodes [3].

In the present study the contact potential difference between a tip and an InGaN laser test structure was measured across the heterojunction as a function of applied bias voltage. The quantitative voltage drop was obtained due subtracting the zero bias result. At low bias (U < 2 V) the majority of the applied voltage drops within the active regime. Comparing fresh laser test structures with artificially degraded test devices, a change of the surface potential distribution of the structure is obtained. Our zero bias data clearly demonstrate a local variation of the contact potential difference across the p-n heterojunction.

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6473-29, Session 9

Are the localized impurity/defect states responsible for electrical and optical properties

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It is well known that localized donor states play an important role in determination a variety of physical properties of GaN and AlGaN. In spite of very intensive research an efficient InGaN-based light emitting device with wavelength above 550 nm has not yet been demonstrated. There are two potential obstacles for achieving this goal. Firstly, a localized donor state (LDS) introducing a level in the band gap of InGaN has been proposed [1]. Accordingly, the involvement of this state in the radiative recombination by means of an electron transition between LDS and Valence Band is responsible for light emission. Secondly, In-segregation phenomena, which are more pronounced in alloys with higher amount of In/Ga ratio, makes the active region of the emitter very inhomogeneous. This results in very broad emission bands and can introduce high concentrations of nonradiative recombination centers. In this work, we studied In-rich InxGa1-xN (x>0.5) alloys, aiming at verification of the possible involvement of the localized states in the microscopic mechanism of light emission and in the electronic transport in n-InGaN. Applying photoluminescence and hydrostatic pressure techniques we demonstrate that in the studied alloys the radiative recombination is related to band-to-band transition without involvement of the postulated localized donor state [1]. Suggestions about contributions of the localized donor level to optical properties of In-rich InGaN led us to perform electrical transport studies of InN and In-rich InGaN. Presence of the localized state (in concentration »2¸4´1017 cm-3) resonant with the conduction band was demonstrated in InN samples with low electron concentrations. However, this state is not active in light emission mechanism. InGaN samples studied here do not show a contribution of this state to the electron transport and light emission. We demonstrate a crucial role of In-segregation phenomena in determination light emission and electron transport phenomena in InGaN alloys.

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6473-30, Session 9

Defect studies in HVPE-GaN by positron annihilation spectroscopy

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Several hundreds of microns thick high-purity GaN layers can be grown by hydride vapor phase epitaxy (HVPE). This enables the study of the basic properties of vacancy defects in GaN by positron annihilation spectroscopy. Here we will give an overview on the results obtained on vacancies (both isolated and paired with impurites) in HVPE GaN, emphasizing the most recent research.

We have studied the behavior of vacancy defects in both hetero- and homoepitaxial c-plane HVPE GaN. The results have been obtained by investigating both the in-grown and irradiation-induced defects, combining positron lifetime and Doppler broadening experiments with electrical and optical data. We have studied also the effect of thermal annealings on these defects, up to temperatures as high as 1700 K. In addition, we have performed preliminary experiments on the behavior of vacancy defects in a-plane HVPE GaN.

Based on our results, we show that the Ga vacancies are the dominant intrinsic acceptors in GaN. In O-doped material they form negative defects complexes by pairing with the oxygen impurities. These in-grown Ga vacancy - oxygen pairs can be dissociated by high pressure and high temperature annealings. From the annealing experiments on both as-grown and irradiated materials we deduce the binding and migration energies of the elementary vacancies and their complexes with impurities. Finally, the Ga vacancy distribution can be correlated with O impurity and extended defect distributions in both c- and a-plane GaN.

6473-31, Session 9

Lanthanide impurity level location in GaN, AlN, and ZnO

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There is a wealth of information and knowledge on lanthanide spectroscopy in wide band gap (6-10 eV) inorganic, mostly fluoride and oxide, compounds. Recently models were developed by us to determine the location of lanthanide energy levels relative to the valence and conduction band of the host lattice using spectroscopic data [1]. The precise location appears crucial to the opto-electron properties of these types of compounds. In this work these new models are applied to understand and predict optical and electronic properties of the lanthanides in the III-V semiconductor GaN and AlN and in the II-VI compound ZnO. The location of the 4f ground state energy of each divalent and trivalent lanthanide ion relative to the valence and conduction bands in GaN, AlN, and ZnO are presented. We will demonstrate that the quantum efficiency and thermal quenching behavior of luminescence from lanthanides like Pr3+, Eu3+, Tb3+, and Yb3+ depends on the precise location of the lanthanide levels. Level location also controls charge carrier trapping properties. Some lanthanides act as electron acceptor others as electron donor whereas again others may act as iso-electronic impurities. The presented models and level schemes predict what behavior one may expect from a specific lanthanide ion in a specific compound.

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6473-32, Session 9

Multiscale simulation of ordering processes in GaInN and GaAlN

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The III-V semiconductors with nitrogen as the fifth-group element have unique properties that make them very attractive for short-wavelength light emitters and high-power/high-temperature electronics applications. In order to provide the adequate performance of electronic devices, these materials must have reliable electronic properties. It is well known, however, that the electronic properties of multicomponent semiconductors are very sensitive to the uniformity of their chemical composition. The inhomogeneities can affect device performance via changes of the band gap energy and localized variations of polarization field.

There exists experimental evidence that III-V alloys are often unstable against phase separation, spatial fluctuations in the second component concentration, or partial ordering. Compositional inhomogeneity (clustering or phase separation) has been experimentally observed, in particular, in InGaN. The microscopic reasons for ordering in InGaN and the ordered structure patterns have been already extensively studied in the literature. Unfortunately, the majority of the theoretical investigations are based on analytical models, which makes the reliability of such predictions uncertain.

In this work we study the minor component ordering in wurtzite Ga1-xInxN and Ga1-xAlxN alloys by the multiscale approach that combines the accurate total-energy density functional calculations and lattice kinetic Monte-Carlo simulation. According to our results In in GaN forms [0001] aligned pairs or chains and, at higher In concentrations, zigzag chains in c-direction, while Al forms a random alloy with the matrix material. The increase of In concentration above 25-30% is shown to lead to the phase separation and formation of InN regions. The effect of the minor component (In,Al) ordering pattern on the band gap of the ternary Ga(In,Al)N alloy is also discussed.

6473-33, Session 10

AlGaN/GaN field-plate FETs for microwave power applications

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This paper describes the performance of AlGaN/GaN Field-Plate FETs for microwave power applications. Recessed-gate FETs with a single field-modulating plate (FP) and an advanced dual FP are developed for high-voltage microwave power operation. The developed single FP-FETs exhibited a 230-W CW output power at 2 GHz and a 100-W CW output power at 5 GHz. The developed dual FP-FET provides higher gain, increased linearity and stability since the second FP effectively reduces feedback capacitance. Under a 2.15-GHz W-CDMA modulation scheme, the dual-FP-FET achieved a-state-of-the-art combination of 160-W output power and a 17.5 dB linear gain.

6473-34, Session 10

Insulator engineering in GaN-based MIS HFETs for higher device performance

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GaN-based metal-insulator-semiconductor (MIS) heterostructure field-effect transistors (HFETs), or GaN-based insulated-gate HFETs, have recently attracted a considerable attention, since they have been shown to effectively reduce the large gate leakage current, which is generally observed in conventional GaN-based HFETs. For proving high potentiality of GaN-based MIS HFETs and pursing higher device performance, we addressed fundamental issues on insulators in MIS HFETs in addition to their device fabrication.

We fabricated AlGaN/GaN MIS HFETs using Al2O3/Si3N4 bilayer gate insulators that exhibited excellent DC and RF characteristics together with the reduced gate leakage current (Ig). The Al2O3/ Si3N4 bilayer gate insulator was to simultaneously utilize (i) the high-quality interface between Si3N4 and AlGaN, and (ii) the high resistivity and high dielectric constant of Al2O3. The Ig was less than 10-4 A/mm even at a gate voltage of +3 V. In a device with a gate length of 0.1 um, the drain current was 1.2 A/mm, and the cut-off frequency (fT) and maximum oscillation frequency (fmax) were 70 and 90 GHz, respectively. :

Insulators are used for the surface passivation in general, other than for the insulated-gate, to prevent so-called current collapse effect. Hence, we systematically examined the deposition effect of insulators on the electrical properties for Si- and Al-based insulators (Si3N4, SiO2, AlN, and Al2O3), and theoretically analyzed the observed increase in the 2DEG density (Ns) for each insulator in terms of the potential profile. One result is that Al2O3 was most effective to increase Ns. The band engineering including insulators is indispensable for interpreting and designing the device performance, because, through the potential profile change, the essential device parameters are altered such as the source resistance, the channel resistance under the insulated-gate, and its threshold voltage.

6473-35, Session 10

Thermal analysis of AlGaN/GaN HFETs using electro-thermal simulation and micro-raman spectroscopy

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GaN based HFETs (Hetero-junction Field Effect Transistors) have been targeted for high power, high frequency, and high temperature electronic devices because of high breakdown voltage, high saturation velocity, and high thermal conductivity. To improve the performance of AlGaN/GaN HFETs, thermal management is still a major issue of concern since the increase of an operation temperature causes deterioration of both performance and reliability of devices. Therefore, analysis of thermal distribution in devices is important to examine intrinsic device performance. In this work, we study on thermal distribution in the AlGaN/GaN HFET devices using electro-thermal simulation, and compare the simulation results with experimental ones measured by micro-Raman spectroscopy.

Thermal and electric distributions in AlGaN/GaN HFETs on sapphire and SiC substrates were calculated using the ISE-TCAD software simulator. We compared the 2-dimensional cross-sectional distributions in devices on sapphire and SiC substrates. The results suggested that the HFET on sapphire showed much higher temperature in whole device area than that on SiC. The region with the maximum temperature appeared at the gate edge side between the gate and drain contacts, which seems to correspond to high electric field region at low drain voltages.

We discussed thermal and electric localizations in devices on SiC substrate at high drain voltages. The maximum temperature region shifted from the gate edge side toward the drain contact at high drain voltages.

We also measured plan-view thermal distribution in HFET devices using micro-Raman spectroscopy. Both devices on sapphire and SiC substrates showed the maximum temperature at gate edge side between the gate and drain contacts, which is good agreement with the simulation results.

This work was carried out in collaboration with High-Power, High-Frequency Gallium Nitride Device Project of NEDO.

6473-36, Session 10

Epitaxial growth and characterization of AlGaN/GaN HEMT devices on SiC substrates for RF applications

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GaN / Al1-xGaxN-based hetero-structures have demonstrated versatility in RF electronic applications which is practically unmatched by any other material system. There are many device structures under consideration for RF and Power amplifiers. These devices are being developed for both commercial and military applications. The applications include 2-10 GHz band and higher frequency applications.

In this paper, we will discuss HEMT device design and growth of GaN/AlGaN layers on semi-insulating SiC substrates by MBE and MOCVD. Both of the growth techniques have shown high quality GaN /AlGaN Epitaxial layers. MBE is an extremely versatile technique for growing GaN/AlGaN semiconductor compounds and multi-layer structures. GaN/AlGaN epitaxial layers were grown using effusion cells to deposit elemental Ga, Al, and In for thin film growth and Si and Mg for n-type and p-type doping. MBE growth was carried out using RF Plasma Assisted MBE Technique. This approach has demonstrated very uniform epitaxial layers with high mobility. Key to high quality HEMT structures is the ability to grow AlN Buffer layers. Details of the electrical and optical characteristics of the layers will be presented.

Similarly, MOCVD reactor used for the Epitaxial layers uses a close-coupled showerhead reactor operating at low pressure. The HEMT structures by MOCVD were grown on 2-inch semi-insulating SiC substrates. In all cases, the growth temperature and growth rate were monitored in-situ by a Lay Tec Epi tool mounted on the reactor optical view port. The results for reflectance measured as a function of growth time, including the AlN nucle-

ation layer, GaN buffer, GaN channel, and AlGaN barrier layers will be presented.

Several of the HEMT wafers grown by these two growth techniques were characterized in detail using AFM measurements of the surface roughness, and non-destructive characterization via contact less sheet resistance mapping, optical reflectance, and high-resolution X-ray diffraction. To characterize the electric properties of the HEMT samples, the room temperature sheet carrier density, ns, and Hall mobility, ∝H, of the two-dimensional electron gas (2DEG) were measured by van der Pauw technique.

The sheet carrier density for samples grown on HEMT wafers was about 1.6 1013 (cm-2) and the room temperature electron mobility values of >1300 (cm2/V.s) have been measured. Several of the wafers were fabricated in to devices, and the results on these devices will be presented.

6473-37, Session 11

GaN optoelectronics on Si

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To achieve the next long awaited goal for GaN based optoelectronics, namely to intrude into the general illumination market, the price per lumen has to be further reduced significantly. Besides increasing the efficiency of LED devices, growth and processing cost need to be further reduced.

One promising way is the growth on large diameter Si substrates. For FET devices commercialisation of GaN-on-Si has already been achieved. For LEDs the situation is still different without bright LEDs in the range of several mW being presented yet. By using large diameter Si substrates growth and processing costs can be reduced, the latter because of the much softer material and suitability to process devices at low cost in standard processing equipment used in Si technology. But such LED layers suffer from limited efficiency mostly because of the nontransparent substrate resulting in a poor efficiency and sometimes cracking. Several groups have already demonstrated that GaN on Si can be grown by MOVPE on 100 mm and 150 mm diameter substrates. We have already presented LED layers grown on 150 mm Si substrates and demonstrated that growth is easier than on large diameter sapphire.

After an overview of the current status of GaN on Si I will address the main problems that have to be solved, show the chances in comparison to the growth on large diameter sapphire substrates, and present latest results of LED devices grown on 150 mm Si substrates.

6473-38, Session 11

GaN light-emitting diodes integrated with monolithic sidewall deflectors for enhanced surface emission

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Inside a GaN light emitting diode (LED) structure grown on a sapphire substrate, a sizable portion of photons generated are trapped and/or guided laterally, limiting the light extraction out of device. As a method of enhancing the extraction efficiency of GaN LEDs, we integrated sidewall deflectors onto the edges of an otherwise conventional LED structure by using a fully monolithic process. A thick photoresist is patterned first and then reflown at an elevated temperature. The reconfigured photoresist pattern is then used as sacrificial masks for dry etch. The angle of the etched GaN sidewalls is determined by the shape of the reflown photoresist as well as the etch ratio between phtoresist and GaN.

To facilitate device characterizations, the LED structure was optically excited using a 325 nm He-Cd laser. The modified LED device with angled sidewalls exhibited emission intensity enhanced by a factor greater than three compared with a reference device. Near-field emission pattern of the modified LED structure showed not only the broad surface emission across the entire device area but also a brighter halo pattern along the device circumference. Electrically injected LED devices with the angled sidewall deflectors have been also fabricated, and their performance characteristics will be also presented.

6473-39, Session 11

Studies of InGaN heterostructures and LEDs

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Due to the progress of AIIIBV based LEDs the idea of the replacement bulbs (incandescent lamps) and luminescent lamps by Light-Emitting Diodes (LED) is very closely for the realization [1, 2]

InGaN Light-Emitting Diodes (LED) and heterostructures were investigated. The results of studies , for example electroluminescence spectrum from the InGaN heterostructures corresponds closely with the results of simulation. We simulated blue and green InGaN LEDs and it was made depending on In concentration and voltage. Also simulation correlates with the results of LED's degradation which were investigated approximately during 9000 hours.

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6473-40, Session 11

Study of interaction between GaN and excimer laser

R. Chen, C. Liu, National Central Univ. (Taiwan)

For the fabrication of thin GaN LED structure, the laser lift-off process is the key process. Therefore, the detail mechanism of the interaction between excimer laser and GaN layer is an important issue to be studied. In this work, excimer laser (248 nm) was used to shine on the different types of GaN, such as, un-dope GaN, n-GaN, and P-GaN. We found that the GaN would absorb the laser energy and decompose into Ga metal droplets and N2 gas. The decomposed depth was found to increase with the laser energy densities. Also, an on-set laser energy to initiate GaN decomposition was found to be about 300 mJ/cm2. In this talk, the detail mechanism of GaN decomposition by excimer laser will be presented. Also, the effect of doping types in GaN on the interaction with laser will be discussed as well.

6473-56, Poster Session

Point defect reduction in GaN layers grown with the aid of SiNx nanonet by metalorganic chemical vapor deposition

S. A. Chevtchenko, J. Xie, Y. Fu, X. Ni, H. Morkoc, Virginia Commonwealth Univ.; C. W. Litton, Air Force Research Lab. - retired

Obtaining of high optical and electrical quality GaN layers is of particular interest for device applications. Degradation of these properties is a result of extended and point defects and their propagation into the upper portions of the layers. Among the methods developed to prevent defect propagation are in situ or ex situ patterned templates and or use of porous dielectrics. GaN layers analyzed in this study were grown by metalorganic chemical vapor deposition (MOCVD) employing single and

double SiNx nanonetwork with benchmark samples grown with SiO2 striped mask or conventional epitaxial lateral overgrowth technique (ELO) and standard GaN wafers. Steady state photoluminescence excited with He-Cd laser (325 nm) was measured at low temperature to characterize optical quality of the layers. Deep traps were identified by deep-level transient spectroscopy (DLTS) and compared with GaN layer grown on standard MOCVD template and standard ELO template. All samples have similar structure with thin ~ 0.5 μm Si doped GaN top layer with carrier concentration in mid-10e16 cm-3, which is where the deep levels were probed by DLTS. Preliminary results demonstrated that the dominant trap for all samples appeared at ~325 K in DLTS spectra measured in the temperature range from 80 K to 400 K. The energy of the trap is in the range from 0.55 eV to 0.58 eV and capture cross-section in low-10e15 cm2. The reduction of trap along with improvement of optical quality was observed for GaN layers grown employing SiNx nanonetwork. Sample structure details, comparison of the results obtained by PL and DLTS and their consistency as well as discussion of defects affecting optical properties and carrier traps will be discussed.

6473-60, Poster Session

COD level enhanced single-mode blue-violet laser diodes with selective current injection

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GaN based blue-violet laser diode at the wavelength around 405 nm have a great attraction to a light source of the next generation optical storage enable to achieve an extra-large data capacity in the disc system.

For satisfying this requirement, reliable single transverse-mode and high-power operation characteristics in LDs are of the essence. Generally, narrow stripe type LDs are adapted to suppress the high order mode, which accompany with high optical power density. It gives rise to catastrophic optical damage (COD) at the mirror facet.

To improve the maximum output power of LD, simply introducing the current blocking near to the mirror facet is most effective to avoid the early COD generation. For this purpose, in general, ion implantation and selective metal deposition of p-contact layers are adapted on III-V high power laser diode due to the current injection spreading. In the AlInGaN material, however the p-side hall mobility is slow comparing to other III-V materials. Therefore we don't need any additional ion implantation process for the purpose of current blocking.

We employ p-metal contact photo-mask pattern with selectively removed around the facet. In this patterning, current injection near to the facet is forbidden, which reduces thermal heating at the LD facet and consequently leads to much enhanced COD level. By the suppression of current injection at the window region, we achieved the enhancement of COD level of up to 29.5% and maximum output power of as high as 420 mW under continuous wave operation condition.

6473-62, Poster Session

AlGaN/GaN MODFET regrown by rf-MBE on MOCVD templates

J. Xie, Virginia Commonwealth Univ.

AlGaN/GaN devices are typically grown on foreign substrates such as SiC and sapphire due to lack of commercial bulk GaN. Metalorganic vapor deposition (MOCVD) is the widely used method for growth of GaN templates for these structures because the growth temperature during molecular beam epitaxy (MBE) is low, dislocation motion is therefore hindered leading to high dislocation density, particularly pure edge type, when grown directly on foreign substrates. On the other hand, low background doping, sharp interface and well-controlled growth rate allow MBE to grow high performance MODFET structures on MOCVD GaN templates. However, the regrowth interface in this case has been reported to act as a parallel channel unless Zn-doped GaN templates were used. In this presentation we report interfacial control of the regrowth interface of GaN/AlGaN MODFETs by rf-assisted MBE on GaN templates prepared by MOCVD. We have found that the defective parallel channel at regrowth interface could be effectively eliminated by a proper growth procedure and cleaning using KOH combined with high temperature (800ϒC) thermal annealing in vacuum. Reflection high energy electron diffraction (RHEED) was used to monitor the interface quality during initial growth stages. Electrical and structural properties at the regrowth interface were analyzed by capacitance-voltage (CV) measurements and transmission electron microscopy (TEM). Al0.3Ga0.7N/GaN MODFET structures grown under the optimized conditions exhibited a maximum transconductance of 230 mA/mm for 1ôlm gate length.

1 M. J. Manfra, N. G. Weimann, J. W. P. Hsu, L. N. Pfeiffer, and K. W. West , S. Syed and H. L. Stormer, W. Pan, D. V. Lang, S. N. G. Chu, G. Kowach, and A. M. Sergent, J. Caissie, K. M. Molvar, L. J. Mahoney, and R. J. Molnar, J. Appl. Phys. v92 p338

6473-63, Poster Session

AlGaN/GaN MOS transistors using crystalline ZrO2 as gate dielectric

X. Gu, N. Izyumskaya, V. Avrutin, J. Xie, H. Morkoc, Virginia Commonwealth Univ.; C. W. Litton, Air Force Research Lab. - retired

Insertion of a gate dielectric in an otherwise standard AlGaN/GaN heterostructure field-effect-transistor (HFET) reduces the gate leakage, allows for the rf gate voltage to be swung substantially in the forward direction and, if left in the gap between the gate-drain and gate-source regions, the effect of surface states. ZrO2 has a high dielectric constant (>20) and wide energy band (5.8eV), enabling one to reduce the leakage current while maintaining the gate control of the interface charge in scaled devices. Moreover, in the trend of integration between ferroelectric materials and semiconductors such as GaN, suitable bridge layers are required to provide a platform for high-quality oxides growth on GaN. In this vein, crystalline, especially single crystalline ZrO2 suitable in such application, since it can serve as both the bridge layer and the gate dielectric material.

We report the growth of crystalline ZrO2 and its use in an AlGaN/GaN FET. The ZrO2 was prepared by MBE on MBE/MOCVD prepared HFET structure using Zr-t butoxide and H2O2 as Zr and O sources, respectively. The effects of growth temperature and II/VI ratio on the crystal structure of ZrO2 were studied. The XRD indicates that (111)-oriented ZrO2 was deposited with decent rocking curve values. The HFETs with Zr2O showed increased the saturation-current density and pinch-off voltage as well as near symmetrical gate-drain IV behavior. The effect of crystalline quality of ZrO2 on the FET performance is discussed.

6473-64, Poster Session

Dislocation reduction in GaN layers grown on nanoscale columnar SiC substrates by metalorganic vapor phase epitaxy

Y. Fu, Ü. Özgür, J. Xie, S. A. Chevtchenko, X. Ni, N. Biyikli, H. Morkoc, Virginia Commonwealth Univ.; Y. Ke, R. P. Devaty, W. J. Choyke, Univ. of Pittsburgh; C. K. Inoki, T. Kuan, SUNY/Univ. at Albany; J. V. Foreman, H. O. Everitt, Duke Univ.

Dislocation reduction in GaN grown on semi-organized nanoscale columnar 6H-SiC by metalorganic vapor phase epitaxy (MOVPE) is reported. These columnar structures have average pore diameters of 15~25 nm and roughly 55 nm between pore centers. These pores go through the entire thickness of SiC substrates. GaN layers were grown on these columnar SiC substrates with and without GaN nucleation layers (grown between 800 °C and 900 °C). Transmission electron microscopy (TEM) revealed half dislocation loops within the 100 nm GaN thickness due to nano-scale lateral overgrowth of GaN on columnar SiC, and the threading dislocation (TD) density is estimated to be 5Å~10^8 cm-2. Most of

the observed dislocations extending through the overgrown GaN are found to originate from the damaged regions of columnar SiC surface, and these TDs cannot be annihilated by formation of half dislocation loops. To reduce surface damages on columnar SiC, plasma oxidization and subsequent oxide removal of columnar SiC have been employed. GaN grown on the surface-improved columnar SiC shows smooth surface morphology with reduced density of pits and trenches. Further reduction of TD density in GaN overlayers resulted from improved columnar SiC surface is expected, and the samples are being characterized by TEM. The radiative recombination lifetime data are consistent with reduced defect density.

6473-65, Poster Session

Polarity control and growth of GaN and AlN grown on carbon-face SiC by metalorganic vapor phase epitaxy

Y. Fu, J. Xie, S. A. Chevtchenko, N. Biyikli, X. Ni, Ü. Özgür, H. Morkoc, Virginia Commonwealth Univ.; Y. Ke, R. P. Devaty, W. J. Choyke, Univ. of Pittsburgh; C. K. Inoki, T. Kuan, SUNY/Univ. at Albany

The polarity control of GaN and AlN grown on carbon-face (000-1) SiC (C-SiC) by metalorganic vapor phase epitaxy (MOVPE) are studied. N-polarity layers are obtained on C-SiC when grown with a high V/III ratio (>1000) or a pre-growth NH3 treated C-SiC, plausibly C-Ga (C-Al) bonds being more energy favorable than C-N bonds when growth initiates on bare C-SiC surface. However, the Ga-polarity GaN can be grown on C-SiC by a pre-flow of TMAl into growth chamber. And the Al-polarity AlN can be grown on C-SiC using a very low V/III ratio (~7) and without the TMAl pre-flow. We suggest that this polarity conversion might be due to deposition of several Al adlayers on bare C-SiC surface from TMAl pre-flow or very low V/III ratio. In the subsequent growth process, N adatoms bond to the Al layer in first sequence and this results in a stable Al- (or Ga-) terminated surface. However, a pre-flow of TMGa on C-SiC alone cannot convert the polarity of AlN and GaN layers possibly because that the high mobility of Ga adatoms would make it unlikely to form stable Ga adlayers. We also observed that density of the hexagonal pyramids which typically appear on N-polarity (000-1) GaN surface and was confirmed to be Ga-polarity domains, is much reduced on N-polarity GaN grown on off-axis C-SiC compared with N-polarity GaN grown on on-axis C-SiC. We suggest the suppression of Ga-polarity domains is due to enhanced GaN nucleation on off-axis C-SiC.

6473-66, Poster Session

Highly reflectivity ultraviolet distributed Bragg reflectors based on AlGaN/AlGaN multilayer

R. Shimada, J. Xie, H. Morkoc, Virginia Commonwealth Univ.

Nitride-based on distributed Bragg reflectors (DBRs) have the highly potentials to be used for ultraviolet (UV) devices such as vertical cavity surface emitting lasers (VCSELs) and resonant-microcavities. The fabrication of high quality UV DBRs is a key issue in the development of these kinds of UV devices.

We report AlGaN/AlGaN DBRs for UV region grown on sapphire substrate by molecular beam epitaxy (MBE). The DBRs consist of 41nm-thick Al0.5Ga0.5N and 38nm-thick Al0.15Ga0.85N in each pairs which are quarter-wavelength stacking, designed for peak reflectivity at around 380nm at room temperature. To achieve crack-free growth, Al0.3Ga0.7N 200nm-thick layer was used for buffer layer. No evidence of cracks was observed by optical microscopy and cross sectional scanning electron microscopy (SEM) imaging.

The reflectivity spectra were measured at room temperature at near normal incidence using a deuterium lamp source. The spectra are calibrated by UV-enhanced Al mirror. The reflectivity spectra for 26.5 pairs Al0.5Ga0.5N/ Al0.15Ga0.85N DBRs shows high reflectivity more than 90% and stop band width around 20nm. The calculation by means of transfer matrix method shows a good agreement with experimental results.

Of special interests, in conjunction with DBRs and emitting region in the wide band gap semiconductor microcavities such as GaN and ZnO based on microcavities, is the achievement of cavity polariton which is the coupled mode between exciton and photon modes. Moreover, the exploitation of cavity polariton could be expected in the course of the development of extremely low-threshold optoelectronics devices.

6473-41, Session 12

TM-mode lasing and anisotropic polarization property of AlGaN multiple quantum well lasers in deep-ultraviolet spectral region

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We report on our experimental discovery of a transverse-magnetic-field (TM)-mode polarization of lasing and spontaneous edge emissions (anisotropic polarization emissions) above and below the lasing threshold from the AlGaN MQW laser at 240.8 nm. The deep ultraviolet MQW emitted very weak or no surface emission (anisotropic polarization emission) below the threshold. On the other hand, the AlGaN multiple-quantum-well laser at 355.1 nm operated in the transverse-electric-field (TE) mode above the threshold, and homogeneous high-intensity spontaneous surface emission and both TE- and TM-mode edge emissions (isotropic emissions) were observed from c-plane AlxGa1-xN with x=0-0.41 (280-365 nm)below the threshold.

However, strong surface emission was detected from m-plane AlxGa1-xN single layer with x=0-0.76 (240-365 nm) which were grown on a (1-100) plane 6H-SiC substrate. These results indicate that crystal-field splitoff hole valence band plays an important role in (E//c) polarization and isotropic emissions from AlxGa1-xN with x larger than 0.5.

6473-42, Session 12

Comparison of optical properties of the InGaN/GaN/AlGaN laser structures grown by MOVPE and MBE

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Although the production of nitride based optoelectronic devices still relies on Metalorganic Vapor Phase Epitaxy as a main growth method, Molecular Beam Epitaxy (MBE) attracts growing attention of the research community. This is because of its ability of growing the structures characterized by low level of contamination and atomically flat and sharp interfaces. In our study we focused on the optical gain measurements, carried out on laser structures grown by both techniques with the desired emission wavelengths ranging from 380nm to 480nm.

All structures, with the exception of MBE grown 480 nm diode, were previously used for the construction of current injection lasers operating in CW regime.

To estimate the gain values we use the variable stripe length method technique. The power of pumping beam covers a range from 30 kW/cm2 to 2 MW/cm2 which corresponds to gain values changing from transparency to 300 cm-1, assuring high excitation conditions present in a real device. To get a detailed insight into the physics of the laser structures we thoroughly analyze not only the gain curves but also focus on the differential gain parameters (90-150 cm-1), saturation lengths (150-350 μm), activation energies for nonradiative recombination (20-50 meV), widths of the gain curves which give information on recombination processes, growth quality of the structures, inhomogenous broadening due to band profile fluctuations. The research we performed reveals the high potential of MBE growth technique which is manifested by superior properties of the latter structures with respect to the differential gain and threshold for stimulated emission.

6473-43, Session 12

Progress in etched facet technology for GaN and blue lasers

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We report recent progress in chemically assisted ion beam etching (CAIBE) of GaN/AlGaN materials leading to improved performance of 405nm blue lasers fabricated with etched mirrors. Using a proprietary Etched Facet Technology (EFT) designed for GaN, we have fabricated ridge lasers in conventional GaN/sapphire material. Typical 3um ridge lasers with 600um cavity lengths exhibit threshold currents of 150mA with high yield and cross wafer uniformity. This represents a factor of five reduction in threshold current over previous results. Additional processing (such as FIB) was not required to improve the mirror verticality and smoothness as in previous work. Continuing improvements in laser performance are anticipated with further optimization of facet smoothness, laser design, and improved epitaxial material. We are also investigating the benefits of shorter cavity lasers, made feasible by etching, to realize improvements in laser reliability and yield. The yield advantage is based on the concept that shorter cavity devices will intercept fewer defects per device. Combined with EFT advantages like low cost wafer-scale testing and monolithic integration, this is a promising approach for next generation blue lasers for optical storage applications.

6473-44, Session 12

High quality UV AlGaN/AlGaN distributed Bragg reflectors and microcavities

O. Mitrofanov, S. Schmult, M. Manfra, T. Siegrist, N. Weimann, A. M. Sergent, Lucent Technologies/Bell Labs.; R. Molnar, MIT Lincoln Lab.

High quality distributed Bragg reflectors (DBR) and microcavities (MC) are essential for the development of UV GaN-based monolithic vertical cavity surface emitting lasers and other optical devices. However, the growth of DBRs and MCs remains a fundamental challenge in the nitride systems. The difficulty lies in maintaining the structural integrity of a relatively thick structure that contains materials with a large lattice constant mismatch and different thermal expansion coefficients. We demonstrate that high-reflectivity crack-free AlGaN/AlGaN DBRs and monolithic MCs can be grown by molecular beam epitaxy on thick c-axis GaN templates. The elastic strain energy in the epilayer is minimized by compensating the compressive and tensile stress in each quarter-wave pair. It allows growth of high quality DBRs. Structural characterization of the samples shows that the epilayers are coherently strained without introduction of cracks. A 25 period DBR mirror provides a 26 nm wide stop band, which can be centered at the wavelegth of GaN quantum well exciton (~350 nm) with the maximum reflectivity higher than 99%. The high-reflectivity DBRs can be used to form a monolithic AlGaN/AlGaN MC. We will present optical characteristics of MCs containing GaN quantum wells (QW) and discuss the MC design considerations for studies of the strong coupling regime.

6473-45, Session 13

Extended defects in GaN from an atomistic modelling point of view

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Wide band gap semiconductors play an important role in today's electronics and optoelectronics, with nitrides being among the most prominent wide gap materials used.

However, still today many issues regarding extended defects - in particular dislocations - are not fully understood yet. Hence in this contribution extended defects in GaN will be discussed from an atomistic modelling point of view with an emphasis on dislocations.

After a brief introduction to the theories and methods applied, the specific problems of modelling extended defect structures are explained.

In the second part, case studies in GaN will be presented, including models for basal plane and threading dislocations. Discussion will include the dislocations' medium range strain fields, their atomistic core structures and the corresponding electronic structures.

6473-46, Session 13

Structural characterization of III-nitrides using electron microscopy

D. J. Smith, L. Zhou, M. R. McCartney, Arizona State Univ.

Electron microscopy provides a wide range of techniques for structural characterization of III-nitrides. 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 combinations 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 III-nitride heterostructures and nanostructures. InAlN/GaN heterostructures showed lateral phase separation that caused development of vertical 'honeycomb cell' structures [1]. The effectiveness of porous TiN nanonetworks on the reduction of GaN threading dislocations was established [2]. Indium compositional fluctuations caused local electric field inhomogeneities that seemed to be more pronounced near the onset of InGaN layer growth, suggesting strain relaxation as a strong contributing factor [3]. Relaxed InN QDs were invariably associated with threading dislocations in the underlying GaN buffer layer, and the interfacial misfit was accommodated by periodic dislocation arrays [4].

We are pleased to acknowledge ongoing collaborations with Hadis Morkoç (Virginia Commonwealth), Ted Moustakas (Boston University) and David Storm (Naval Research Laboratory) and their colleagues.

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6473-48, Session 14

Characterization of transient behaviors of AlGaN/GaN HEMTs

T. Mizutani, Nagoya Univ. (Japan)

Transient behaviors of AlGaN/GaN HEMTs have been studied using drain current DLTS. The surface-state-related positive peaks have been observed in the DLTS signal. The positive peaks were suppressed by the Si3N4 surface passivation. The current DLTS technique is especially effective in studying the transient behavior of the normally off HEMTs, where the carriers in the active layer are depleted in the normal bias condition resulting in a difficulty in using capacitance DLTS. Low-frequency noise and frequency dispersion of the conductance have also been studied at various bias temperatures. The obtained activation energies were compared with the results of the DLTS. The slow transient with a time constant more than seconds has been studied using bias stress and Kevin probe force microscopy. It has been clarified that the electrons injected from the gate and captured by the surface states play a dominant role in the current collapse.

6473-49, Session 14

Charge trapping on defects in AlGaN/GaN field effect transistors

O. Mitrofanov, M. Manfra, Lucent Technologies

Charge trapping on defects is common in field effect transistors (FET). Carriers trapped in the structure locally deplete the channel and limit the source-drain current at high operating frequencies. In this talk we discuss dynamics of the trapped charge in AlGaN/GaN FETs. Analysis of electron capture and emission processes helps identifying trapping mechanisms and the origin of the trapping centers. In AlGaN/GaN systems, strong electric field plays an important role in the electron trapping processes. Our discussion will focus on analysis of the field-assisted charge trapping and emission and identification of location and parameters of the trapping centers.

6473-50, Session 14

Analytical model, simulation and parameter extraction of AlGaN/GaN HEMT for microwave circuit applications

H. F. Huq, The Univ. of Tennessee

Abstract: In this paper an improved temperature model for AlGaN/GaN high electron mobility transistor (HEMT) is presented. The two-dimensional Gaussian Standing Wave (GSW) equation is used to include the dependence of electron drift velocity on the longitudinal electric field. The effects of channel conductance in the saturation region and the parasitic resistance due to the undoped GaN buffer layer have been included. The effect of both spontaneous and piezoelectric polarization induced charges at the AlGaN/GaN heterointerface has been incorporated. The proposed model is used to determine the output current-voltage characteristics and small-signal microwave parameters of HEMTs. The investigated temperature range is from 100 K-600 K. The small signal microwave parameters have been evaluated to determine the unity current gain cut-off frequency (fT). High fT (10-70 GHz) values and high current levels (650 mA/mm) are achieved for a 1∝m AlGaN/GaN HEMTs. The calculated critical parameters and the simulation results suggest that the performance of the proposed device degrades at elevated temperatures.

6473-51, Session 14

1/f noise in the dark current of GaN QWIPs

P. H. Handel, A. M. Hall, Univ. of Missouri/St. Louis

The dark current of Quantum Well Inter-subband Photodetectors is affected by 1/f noise that limits the detectivity. This paper applies for the first time conventional quantum 1/f noise expressions to calculate the expected level of 1/f noise in QWIPs and applies the resulting engineering formulas to the case of GaN/AlGaN QWIPs. Both the collisionless and collision-dominated cases are considered. The elementary process causing the dark current is the transfer of an electron from one well to the neighboring well. This happens under the influence of the applied electric field, and has in general both thermally activated and tunneling components. The larger the applied electric field, the larger is the squared velocity change of the carriers, and the larger is the obtained conventional quantum 1/f effect. The detectivity of the devices is calculated on this basis.

6473-52, Session 15

Light extraction analysis for GaN-based LEDs

T. Lee, K. Kao, T. Chung, C. Sun, National Central Univ. (Taiwan)

In the paper, we will present analysis of light extraction of GaN-based LEDs with surface texture and/or pattern substrate. Besides, current spreading is also considered in the simulation.

6473-53, Session 15

Electroluminescence in nitride light-emitting-diodes

T. Suski, Institiute of High Pressure Physics (Poland); S. Grzanka, TopGaN Ltd. (Poland); G. Franssen, G. Targowski, Institiute of High Pressure Physics (Poland); R. Czernecki, TopGaN Ltd. (Poland); P. Perlin, Institiute of High Pressure Physics (Poland); M. Leszczynski, TopGaN Ltd. (Poland)

In spite of considerable progress in terms of output power and lifetime, much basic optical and electrical properties of nitride light-emitting heterostructures are at present poorly understood. Particularly, the low-temperature characteristics of nitride light emitting diode (LED) structures have not been investigated thoroughly. In this region of operation, essential problems related to the reduced thermal energy of carriers might be expected, such as insufficient ionization of Mg acceptors in the p-type and inadequate hole injection into the active region. Furthermore, some reports suggest the negative influence of localization effects in InGaN-based active layers on radiative recombination processes at low temperatures. Presence of internal electric field results in reduction of electroluminescence efficiency also.

In this work, we present a study of the light emission properties of a set of nitride LEDs with varying device parameters (e.g., wavelength of emitted light between 380 and 430 nm). We measured photoluminescence (PL), electroluminescence (EL) and current-voltage (I-V) characteristics in the temperature range 10-300 K and for pressures up to 2 GPa. The drastic influence of the lowering of temperature on the EL of a typical LED is displayed in Fig. 1. At around 250 K, the EL intensity shows a sharp collapse of more than two orders of magnitude. At the same time, the PL intensity shows regularly activated behavior.

Possible causes for the collapse of the EL intensity are examined. The regular behavior of the PL intensity indicates, in contrast with statements in exidting reports, that the obstruction of radiative recombination at low temperatures is not the cause of the observed EL collapse. In order to identify the source of the EL collapse, LED structures with different active regions and electron blocking layers were investigated. Furthermore, the low-temperature carrier transport properties of the p-type GaN were examined. Our results suggest the impediment of the carrier supply from the p-type to the active layers to be the most likely cause of low-temperature EL breakdown in nitride LED structures. Moreover, we do not confirm a suggestion about the carrier localization contribution to the studied effects. Pressure dependence of electroluminescence energy shows clearly a lack of built-in electric field in our diodes.

6473-54, Session 15

Photoreflectance, electroreflectance and photoluminescence excitation spectroscopic system for characterization of InGaN/GaN multi-quantum well light-emitting diodes

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We present a converged spectroscopic system design which can be used for photoreflectance (PR) and electroreflectance (ER) spectroscopy and photoluminescence excitation (PLE) spectroscopy. The design of the system setup is described in detail. Test measurements of a series of InGaN/GaN multi-quantum wells (MQW) with various Indium compositions and quantum well (QW) thicknesses are carried out by using this system design. The measured PR, ER and PLE spectra are affected significantly by the indium compositions and the QW thicknesses. Photoluminescence (PL) and electro-luminescence (EL) spectroscopic measurements are also performed on the same system. In addition, time-resolved photoluminescence (TR-PL) are also taken for comparison. All of the measured data demonstrate the performance of the system. ER peaks which are related with formation of indium-rich clusters are observed. As the reverse DC bias voltage is increased, ER transition peak related to InGaN QW is gradually shifted to higher energy. The blue-shifting features show different behaviors in different QW thicknesses.

6473-55, Session 15

Confocal scanning electroluminescence spectro-microscope for multidimensional light-emitting property analysis

S. Hong, G. Onushkin, J. Park, B. Kim, D. Lee, A. Fomin, K. Ko, J. W. Kim, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea)

We report new type of micro-EL instrument and its applications for light emitting devices. Our new micro-EL, so-called confocal scanning electroluminescence sprctro-microscope (CSESM) has not only fast image acquisition time but also high image resolution. The newly developed CSESM is combined with confocal laser scanning photoluminescence micsoscope, i.e. micro-PL. Therefore, micro-EL distribution can be directly matched with micro-PL and mechanical chip structure of LED. It is fruitful for providing a fast and non-destructive method to analyze the homogeneity of LEDs in its completely proceeded form. Using this apparatus, we study local intensity and wavelength distribution of electroluminescence for InGaN/GaN blue LED chip. Our results represent that local fluctuations of electroluminescence intensity and wavelength position are closely connected with the fluctuation of local current density, i.e. current spreading features on LED chips.

Conference 6474: Zinc Oxide Materials and Devices II

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6474-01, Session 1

New developments in ZnO materials and devices

D. C. Look, Wright State Univ.

In this talk, we review some interesting advances in ZnO materials and devices occurring in the last year. In the materials area, the hydrothermal growth method has advanced to a commercial stage following the successful growth of 2-inch- and even 3-inch-diameter boules. Hydrothermal ZnO displays significantly different optical and electrical properties than those found in crystals grown by the more familiar vapor-phase and melt processes, which are themselves steadily improving in quality. In the area of thin films, many more researchers have now produced p-type ZnO, primarily by incorporating group-V elements during growth. However, implantation, mainly with N+ ions, is also becoming popular, and N-implanted p-n homojunctions have been created. Although group-V elements lead the way in creating p-type ZnO, at least two group-I elements, Li and Na, has been theoretically predicted to be shallow acceptors, and indeed, a few workers have now made p-type ZnO with Li, evidently by successfully suppressing concomitant donor formation. Measurements of acceptor activation energies in p-type ZnO, although problematic, are encouraging, with values as low as 100 - 150 meV having been reported.

Defect studies have made great strides in 2006. For example, new density-functional theoretical results predict that both Zn and O interstitials should diffuse easily at room temperature, suggesting that isolated interstitials should be rare. Thus, any ZnI-related donors are likely to be complexes, such as ZnI-NO. Interestingly, the same considerations should hold for H, so that that the commonly observed H-related donors are also probably complexes. Electron paramagnetic resonance studies have confirmed the instability of ZnI at room temperature, but also the stability of the vacancies, VZn and VO. In the characterization of large defects, holography in a transmission electron microscope has been used to show that threading edge dislocations in n-type ZnO are negatively charged, as has earlier been observed for GaN.

Commercial applications of ZnO include white lighting to replace tungsten bulbs, and colored lighting for displays. Some of the latest ZnO-based light-emitting diodes (LEDs) are designed around multi-quantum-well structures involving either MgZnO or BeZnO. Typical emission wavelengths vary from 385 - 390 nm at room temperature, and powers and efficiencies are improving steadily. Also, nanowire, even single-nanowire, LEDs have been fabricated, and offer interesting possibilities on the small scale. Another application area is transparent thin-film transistors (TTFTs) for active-matrix LCD displays. ZnO TTFTs have improved greatly in the last year, and completely outshine the present workhorse, amorphous Si. High-frequency, high-power MgZnO/ZnO field-effect transistors have also become a possibility following the recent demonstration of an excellent two-dimensional electron gas, with high carrier concentration and high mobility.

Thus, ZnO materials and devices have both advanced strongly in the last year. Details will be discussed.

6474-02, Session 1

Analysis of localization dynamics of excitons in ZnO-related quantum wells by Monte-Carlo simulation

T. Makino, Univ. of Hyogo (Japan)

The dynamics of photocreated excitons in ZnO-based quantum wells (QW) was studied by comparing the experimental photoluminescence (PL) data with the results of Monte Carlo simulations of the exciton hopping. The temperature-dependent PL linewidth was found to be in a reasonable agreement with the model of exciton hopping, with an additional inhomogeneous broadening (Gamma) accounted for. The simulation analysis revealed fluctuations of the band potential to be 20 meV with an additional inhomogeneous broadening of Gamma=29 meV, and a crossover from a non-thermalized to thermalized exciton energy distribution at about 100 K. In addition, a Bose-Einstein distribution like temperature dependence of the exciton energy in the wells was extracted using the data on the PL peak position [J. Appl. Phys. 99 (6) p. 066108, (2006).].

6474-03, Session 1

Theory of doping and defects in ZnO

S. B. Zhang, National Renewable Energy Lab.

In this talk, I will review some of the recent development in first-principles theory of doping in zinc oxide. For p-type ZnO, potential impurities include group V, group IA, group IB elements, and others. Density functional theory (DFT) calculations show that among group V dopants, only nitrogen, whose solubility can be increased by using metastable but existing molecular sources, can produce relatively shallow acceptor level of several hundred meV. All others, due to their large size mismatch to oxygen, produce too deep levels to be of practical use. However, these large impurities can form antisites and subsequently complex with zinc vacancies to effectively produce shallow acceptor levels. DFT calculations for group IA impurities suggest significantly shallower acceptor levels. However, the inability of the current approach to correctly include the Jahn-Teller (J-T) effect at the impurity site casts serious doubt on these results. Possible correction to overcome this shortcoming will be discussed. For group IB impurities, recent DFT calculations also suggested shallow levels, but the lack of J-T effect can also be a problem here. For n-type ZnO, for quite some time hydrogen has been perceived as the only possible unintentional n-type dopant. However, recent experiment and theory showed that by forming complex with nitrogen during post growth cooling, interstitial Zn can at least play an as important role as H. Finally, I will discuss oxygen vacancy in the context of green band luminescence and photopersistent conductivity. Work supported by the U.S. DOE/BES and EERE under contract No. DE-AC36-99GO10337.

6474-04, Session 2

Metalorganic vapour phase epitaxy of ZnO: towards p-type conductivity

A. Krost, Otto-von-Guericke-Univ. Magdeburg (Germany)

Although there are many reports in the literature on p-type ZnO, the achievement of high quality epitaxial p-type ZnO still remains the most important issue for electronic and optoelectronic applications. So far, no reliable and reproducible process has been reported. Nitrogen is considered to be one of the most promising candidates to achieve p-type conductivity of zinc oxide. However, up to now doping experiments suffer from a non-controlled incorporation of the nitrogen atoms within the ZnO crystal during growth as well as an absence of suitable post-growth procedures to activate the wanted nitrogen acceptors.

We present first results of a novel approach towards p-type ZnO: the simultaneous doping with nitrogen and arsenic. The samples were grown by metalorganic vapor phase epitaxy in a two step growth process on GaN/sapphire templates. After the growth of a ~300 nm thick ZnO layer grown at 450°C using DMZn and tert-butanol a high temperature ZnO layer was grown at 850°-900°C using DMZn and N2O. For doping experiments the high temperature layer was doped with arsenic using AsH3 and nitrogen using unsymmetrical-dimethylhydrazine. All samples were investigated by XRD in regard of their crystalline quality and lattice parameters.

The electrical properties of these layers were characterized by conven-

tional C-V-analysis with a mercury probe. Remarkably, the C-V-curves of some samples revealed signals which are typical for p-type layers, whereas the rest of this sample set including undoped reference samples was n-type (<1016 cm-3) without an unambiguous relation to the doping parameters. To clarify this, we performed a systematic study with atomic force microscopy (AFM) in conjunction with scanning capacitance and scanning surface potential microscopy (SCM, SSPM). In contrast to C-V-analysis, these techniques allow the electrical characterization on a submicron scale and a correlation to topographical features. Here we found, that in most of the co-doped samples there is no uniform conductivity type. The SCM profiles suggest that the layers exhibit coexisting n- and p-type regions which are evidently related to the surface morphology. Furthermore, we correlate local optical properties as obtained by spatially resolved cathodoluminescence and photoluminescence to these morphological features. Domain boundaries have been identified as preferential sites for the incorporation of impurities. Local p-type conductivity has been achieved by simultaneous doping with Arsenic and Nitrogen during MOVPE growth.

6474-05, Session 2

Toward reliable p-type ZnO expitaxial films and devices

J. Liu, F. Xiu, L. J. Mandalapu, Z. Yang, Univ. of California/ Riverside

ZnO is an emerging semiconductor material that has potential applications in optoelectronics. One difficulty that hinders the fast development of this material toward commercialization is related to non-reliable p-type doping. Although many researchers worldwide have demonstrated p-type conductivity in their ZnO films and fabricated pn-junction devices that both emit and absorb lights in UV and visible region, more effort is needed to make p-type films reliable and their devices highly efficient. In this talk, we report our effort on p-type ZnO epitaxial films based on plasma-assisted molecular beam epitaxy (MBE). Results on the doping effect from Group-V elements, namely N, P, As, Sb, and Bi are shown. We compare their p-type conductivity making abilities and discuss the doping mechanisms. In particular, LEDs and photodetectors based on Sb-doped ZnO p-type films are presented.

6474-06, Session 2

ZnO epilayers doped with nitrogen and phosphorus

M. Pan, J. Nause, Cermet, Inc.

Zinc oxide with a band gap of 3.37eV and a free exciton binding energy of 60meV at room temperature has been considered as a strong candidate material for optoelectronic devices, such as blue/UV solid sate emitters and detectors. Development of high efficiency, homojuntion device, however, has been limited by the lack of reliable p-type ZnO which is necessary to produce p-n junction. It has been believed that the most promising dopants for p-type ZnO are the group V elements, including nitrogen, phosphorus, arsenic, antimony, and bismuth. Among group V elements, nitrogen has an ionic radius similar to oxygen, therefore, should allow for easy substitution. It has been predicted by theoretical calculation that N has small ionization energy 0.4eV, which leads N function as shallow acceptor in ZnO. Recently it was also reported that p-type ZnO has been achieved with phosphorus, arsenic and antimony as dopants by sputtering and molecular beam epitaxy (MBE). In this work, we report epigrowth of ZnO doped with nitrogen and phosphorus and comparison of the optical and electrical properties of these thin films. Metal organic chemical vapor deposition (MOCVD) was used to perform epigrowth. Nitrogen and phosphorus were in-situ doped into the ZnO films during growth, respectively. As-grown films were characterized for crystal structure, optical property and electrical property. Details will be presented at the conference.

6474-07, Session 2

Characterization of Ag-doped p-type ZnO films

G. H. Kim, B. D. Ahn, H. W. Chang, D. L. Kim, S. Y. Lee, Yonsei Univ. (South Korea)

ZnO:Ag films have been fabricated on a (0001) Al2O3 substrate, using Ag-doped ZnO target by pulsed laser deposition. The effect of (0002) peak shift on the structural property of those films have been systematically characterized to investigate the substitution of Ag^{+} for Zn^{+}. Narrow deposition temperature for Ag-doped *p*-type ZnO films has been obtained in the range of 200-250°C with the hole concentration of $4.9\xi10^{16}$-$6.0\xi10^{17}cm^{-3}$. A neutral acceptor bound exciton has been clearly observed by photoluminescence emitted at 3.317 eV in Ag-doped *p*-type ZnO thin films.

6474-08, Session 2

Study of N doping of ZnO thin films

D. Rogers, Univ. de Technologie de Troyes (France); F. H. Teherani, Nanovation SARL (France)

No abstract available

6474-09, Session 3

Surface and interface engineering in ZnO epitaxy

T. Yao, T. Minegishi, S. H. Park, J. S. Park, I. H. Im, T. Hanada, K. Fuji, M. W. Cho, Tohoku Univ. (Japan)

Surface and interface engineering plays a crucial in growing high-quality epitaxial layers in heteroepitaxy, in which dissimilar materials are used for substrates. Since the surface finish of ZnO wafers is still inferior compared with those semiconductors whose surface treatments are well established, there is some room for surface and interface engineering to play a role in growing high-quality ZnO layers. This presentation will focus on surface and interface engineering in ZnO epitaxy.

6474-10, Session 3

Expanding thermal plasma-deposited ZnO films: material properties and film growth studies

M. C. M. Van De Sanden, Technische Univ. Eindhoven (Netherlands)

The extensive research on ZnO films focuses on the application of this versatile transparant conductive oxide in applications ranging from photovoltaics to organic light emitting diodes. Many deposition techniques have been explored with varying success. In this talk we will discuss a remote-Plasma Enhanced Chemical Vapour Deposition technique, the Expanding Thermal Plasma (ETP) technique, which uses mixtures of diethyl zinc and oxygen as the primary feed gases to deposit ZnO from an argon-fed ETP system. The ETP technique has been succesfully applied previously for high rate deposition of silicon oxide, hydrogenated amorphous carbon, silicon and nitride.

An overview of the work performed at the Eindhoven University of Technology in recent years will be given. We will discuss the succesful implementation of highly conductive natively textured ZnO films in amorphous silicon solar cells and which have a similar efficiency as solar cells with Asahi fluorine doped tinoxide front contacts. In addition we will discuss the doping of ZnO by means of nitrogen and aluminum. The doped ZnO layers are deposited using an Ar-fed ETP system in which oxygen, diethylzinc, nitrogen gas (for N doping) and trimethylaluminum (for Al doping, respectively), are admixed downstream in the expanding beam. Apart from studies of the bulk material properties and implementation in devices, in-situ growth studies of surface morphology are presented.

A particularity of the ETP technique is that typical downstream ion energies in this remote plasma are <2 eV, therefore energetic ion bombard-

ment does not contribute/assist the film growth. We use in-situ spectroscopic ellipsometry to monitor the refractive index, thickness and roughness development during the film growth. Atomic force microscopy, Hall and X-ray diffraction measurements are used to determine the morphological, electronic and structural properties of the films, respectively. During nitrogen doping, infrared spectroscopy and mass spectrometry measurements point towards the incorporation of nitrogen as -C≅ N which is segregated to the grain boundaries. Hall and XRD measurements indicate that CN behaves as impurity and not as dopant. By means of Al doping we can obtain conductive films (5*10-4 Ωcm) with native roughness of ~45 nm for 1 ∝m thickness, suitable for solar cell applications. The film conductivity, however, shows a strong inhomogeneous depth profile, which could affect the suitability of this material for applications requiring thinner (< 200 nm) films, i.e. diodes and thin film transistors. To manipulate the growth process, the (doped) ZnO film growth is investigated by studying the overall effect of the substrate temperature, working pressure, and ion bombardment (as delivered by an external RF bias).

6474-11, Session 3

Polarization Management in p-type CdZnO/ZnO and MgZnO/ZnO

A. V. Osinsky, SVT Associates, Inc.

No abstract available

6474-12, Session 3

Current-transport properties of isotype n-ZnO/n-GaN heterostructures

Y. I. Alivov, Virginia Commonwealth Univ.; C. W. Litton, Air Force Research Lab. -retired; H. Morkoc, Virginia Commonwealth Univ.

ZnO is a very perspective material for many applications due to its some physical properties as large exciton binding energy (60 meV) ZnO/GaN type heterojunctions are most promising because GaN and his alloys with Al are most promising materials for fabrication ZnO based heterojunctions because of appropriate physical properties of these pairs. And a number of reports has been done on the research of such type of heterostructures, however, mostly focusing on anysotype of n-ZnO/p-(Al)GaN or p-ZnO/n-GaN heterostructures and their electroluminescence properties. Isotype n-ZnO/n-GaN type heterostructures are also of interest because of many reasons, in particular, 1) isotype heterostructures sometimes have also very strong diode-like rectifying behavior; 2) such heterostructures are part of the p-GaN/n-ZnO/n-GaN double heterostructures; 3) highly conductive ZnO has been found to be a good ohmic contacts to GaN. Therefore, understanding of the properties n-ZnO/n-GaN heterojunctions is very important.

In this work n-ZnO/n-GaN heterostructures were fabricated by radio-frequency sputtering deposition of ZnO films with 3x10-5 cm thickness on n-type GaN grown by metal-organic chemical vapor deposition. 2.5x10-2 cm diameter size mesa structures were fabricated using conventional photolithography. As ohmic contacts to ZnO and GaN were used Au/Al (300/300 □) and Au/Al (300/300 □). And then the electrical properties of the n-ZnO/n-GaN mesa structures were studied by employing room temperature (I-V), temperature dependent current-voltage (I-V-T), capacitance-voltage (C-V), electron-beam induced current (EBIC) measurements.

6474-13, Session 4

Homoepitaxy of ZnO: from the substrate to epitaxial films

B. K. Meyer, N. Volbers, S. Lautenschläger, C. Neumann, J. Sann, Justus-Liebig-Univ. Giessen (Germany); J. Bläsing, A. Kritschl, A. Krost, F. Bertram, J. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

In order to allow controlled p-type doping in ZnO it is absolutely necessary to control and understand the role of point and extended defects in the epitaxial films. This starts with the choice of the substrate. We report on the homoepitaxial growth of ZnO thin films by chemical vapor deposition techniques. The preparation of the ZnO substrates after mechanical polishing employed a high temperature annealing step which produced atomically flat surfaces and removed all of the surface and subsurface damage. Two dimensional epitaxial growth was achieved without an additional buffer layer. The crystallographic properties of the substrate - (0002) rocking halfwidth of 25 arcsec - were transferred to the films, which showed no twist and tilt. Surprisingly, the c-axis lattice constant of the films changes from the interface towards the surface as shown by X-ray diffraction and cathodoluminescence experiments (compressive strain). One of the reasons might be the pile up of the lithium concentration at the interface as demonstrated by secondary ion mass spectroscopy. We demonstrate the influence of the II/VI ratio, pressure and substrate temperature on the morphological, electrical and optical properties of the films. The films can be doped or alloyed by evaporation of the solid sources (Li, Mg).

6474-14, Session 4

P-type nitrogen- and phosphorus-doped ZnO thin films grown by pulsed laser deposition on sapphire substrates

J. Mosnier, B. P. Doggett, E. McGlynn, M. O. Henry, Dublin City Univ. (Ireland)

Nitrogen- and phosphorus-doped ZnO thin films were grown by pulsed laser deposition using an electron cyclotron resonance (ECR) nitrogen plasma ion source or a ZnO:P2O5 doped target, as the dopant source, respectively. The crystalline, optical and electrical properties of the doped ZnO thin films were measured using X-ray diffraction, photoluminescence and Hall effect apparatus, respectively.

The N-doped samples were grown on sapphire substrates coated prior with ZnO buffer layers. The X-ray diffraction analyses indicated some deterioration of the ZnO thin film crystalline quality upon nitrogen incorporation. Temperature-dependent Van der Pauw measurements showed consistent p-type behavior over the measured temperature range of 200-450 K, with typical room temperature acceptor concentrations and mobilities of 5 x 1015 cm-3 and 5.61 cm2/V-s, respectively. The low-temperature photoluminescence spectra consisted of a broad emission band centered around 3.2 eV. This emission is characterized by the absence of the green deep-defect band and the presence of a band around 3.32 eV. Surface XPS studies confirmed the incorporation of nitrogen in the samples.

The ZnO:P layers (with phosphorus concentrations of between 0.01 and 1 wt %) were grown on pure ZnO buffer layers. The samples typically showed weak n-type conduction in the dark, with a resistivity of 70 Ω.cm, a Hall mobility of μn ~ 0.5 cm2V-1s-1 and a carrier concentration of n ~ 3 x 1017 cm-3 at room temperature. After exposure to an incandescent light source, the samples underwent a change in conduction from n- to p-type, with an increase in mobility and decrease in concentration for temperatures below 300K. Electrical measurements showed noticeable differences when carried out in air or in vacuum. These results are discussed in terms of both the presence of surface conducting channels [1] and the influence of photoconductive effects [2].

[1] O. Schmidt, P. Kiesel, C. Van de Walle, N. Johnson, J. Nause, G. Dohler, Jpn. J. Appl. Phys. 44 (2005) 7271

[2] B. Claflin, D.C. Look, S.J. Park, G. Cantwell, J. Cryst. Growth 287 (2006) 16

6474-15, Session 4

Formation of 2D electron gas and enhancement of electron mobility by Zn polar ZnMgO/ZnO heterostructures

H. Tampo, H. Shibata, K. Matsubara, A. Yamada, P. Fons, S. Niki, National Institute of Advanced Industrial Science and

Technology (Japan); M. Yamagata, H. Kanie, Tokyo Univ. of Science (Japan)

A two-dimensional electron gas (2DEG) was observed in Zn polar ZnMgO/ZnO (ZnMgO on ZnO) heterostructures grown by radical source molecular beam epitaxy. Reflection high energy electron diffraction patterns taken during the growth of the ZnMgO layer remained streaky; x-ray diffraction measurements showed no evidence of phase separation for up 44 % Mg composition. These results shows that the high quality ZnMgO layers up to 44 % Mg composition were obtained without phase separation. The electron mobility of the ZnMgO/ZnO heterostructures dramatically increased with increasing Mg composition and the electron mobility (∝~250 cm2/Vs) at RT reached a value more than twice that of an undoped ZnO layer (∝~100 cm2/Vs) due to the 2DEG formation. The carrier concentration in turn reached values as high as ~1 1013 cm-2 and remained nearly constant regardless of Mg composition. Strong confinement of electrons at the ZnMgO/ZnO interface was confirmed by C-V measurements with a concentration of over 4 1019 cm-3. Temperature-dependent Hall measurements of ZnMgO/ZnO heterostructures also exhibited properties associated with well defined heterostructures. The Hall mobility increased monotonically with decreasing temperature, reaching a value of 2750 cm2/Vs at 4 K. Zn polar “ZnMgO on ZnO” structures are easy to adapt to a top-gate device. These results open new possibilities for high electron mobility transistors (HEMTs) based upon ZnO based materials.

6474-17, Session 4

Thin films of ZnO and related compounds grown by pulsed-laser deposition for optoelectronic applications

E. Millon, Univ. d’Orléans (France); J. Perriere, Univ. Paris VI (France); C. M. Boulmer-Leborgne, Univ. d’Orléans (France)

ZnO is a wide and direct band-gap material (3.37 eV at room temperature) with a quite high exciton binding energy (60 meV) making this compound very suitable for UV photodetector applications as well for UV and blue light emitting devices. As an electronic conductor, ZnO may be used as transparent and conducting electrodes for flat panel displays and solar cells. ZnO doped with various atoms can also lead to new or enhanced functional properties. For example, doping with group III elements (Al, Ga, In) or Si and H allows to decrease its resistivity to below 10-4 cm, while keeping the high optical transparency of the intrinsic host ZnO material. In addition, rare-earth doped ZnO thin films have been studied for potential applications in optics and optoelectronics such as visible or infrared emitting devices, planar optical waveguide amplifiers. Ferromagnetic semiconductors can be obtained by doping ZnO with transition metal atoms (Mn, Co, Ni...) that could be used as spin injectors in spintronics.

These new and exciting properties of pure and doped ZnO requested the use of thin films or multilayer structures with a perfect control of the crystalline quality and the stoichiometry. As a result, ZnO thin film growth by pulsed-laser deposition (PLD) with or without any dopants or alloyed atoms has been intensively studied, as a function of the growth conditions. In this presentation, we will first review the general features of ZnO thin films grown by PLD, in order to prepare dense, stoichiometric and crystalline ZnO layers. The most recent interesting applications of such films will be also presented. The specific features of ZnO epitaxial films will be then reported and discussed with a special emphasis on the structural defects in relation to the physical properties. Finally the formation and the properties of nanocrystalline films obtained under “high pressure” atmospheres or by the use of ultrashort laser pulses will be considered.

6474-18, Session 4

Advances in nonpolar ZnO homoepitaxy: 1D surface nanostructure and electron transport

H. Matsui, H. Tabata, Osaka Univ. (Japan)

The development of epitaxial growth technique towards the fabrication of nanostructures provides advantages to nanoscale engineering and has yielded many impressive results. ZnO possesses attractive characteristics that include optical, electric and magnetic properties. This material can be utilized to delineate new phenomena through investigation of surface nanostructures and quantum heterostructures. Homoepitaxy in ZnO can generate specific growth directions in the absence of lattice mismatch at the interface between the film and substrate. Rapid successions of reports have appeared in the past year concerning the layer growth of nonpolar ZnO. Nonpolar planes are anticipated to yield large in-plane anisotropy in electrical and optical characterizations. In nonpolar (10-10) growth using laser-MBE, we found that novel in situ growth techniques allowed for the fabrication of dense arrays of conductive one-dimensional nanostripes with high degree of lateral periodicity. Highly anisotropic surface morphologies markedly influenced electron transport of ZnO single layers and Mg0.12Zn0.88O/ZnO multi-quantum wells (MQWs) with conductivity parallel to the nanostripe arrays by more than one order of magnitude larger than that observed perpendicular to the nanostripe arrays.

In this presentation, we focus on investigations concerning the growth dynamics of ZnO (10-10) homoepitaxy and large anisotropy of electron transport including nonpolar growth of ZnO (11-20) homoepitaxy. These arrays are expected to yield higher functionality reflected by selective guidance of electron transport, for future device concepts including surface nanostructure-modified field-effect transistors.

Ref. Appl. Phys. Lett. 89 (2006) 091909., J. Appl. Phys. 99 (2006) 124307.

J. Appl. Phys. 99 (2006) 024902., Appl. Phys. Lett., 87 (2005) 143109.

6474-68, Session 4

Microscopic luminescence properties of ZnO and ZnO based heterostructures

J. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

The II-VI-semiconductor ZnO has recently re-emerged into the center of international attention. It is a very promising material for optoelectronic devices, because of its wide direct bandgap (Eg = 3.361 eV at room temperature) and its high exciton binding energy (60 meV), which makes the exciton stable at room temperature. Having the strongest excitonic effect in all common semiconductors ZnO is a potential candidate for generating a polariton laser due to the strong light matter interaction with its exciton polariton. ZnO is radiation hard, thus electronic devices may operate in satellites circling in low earth orbits. ZnO is a solar blind material and many applications such as transparent front electrodes in solar cells make use of this fact. Although known for many years, there is still a lack of information on its microstructure and in particular its microscopic electronic and optical properties. We present highly spatially resolved luminescence investigations directly correlating the optical characteristics to the nano-scale morphology. The strong impact of local internal fields (Franz-Keldysh-Effect) is directly evidenced. Expected for hetero-interfaces due to the strong spontaneous and piezoelectric polarization fields, this is also found at ZnO-ZnO-homo-interfaces and even in ZnO single crystals at domain boundaries. In epitaxially grown ZnO films, a direct correlation between defects and morphology and specific spectral features is found. The bound exciton luminescence I8 directly images the dislocation network and its spectral position maps the lateral strain profile. A selective incorporation of those impurities associated with I0 and I1 at the micro-domain boundaries is evidenced.

The situation further complicates when adding ternary alloys such as MgZnO or CdZnO, needed for heterostructures and Quantum Wells. A mixture of ZnO and CdO (Eg = 2.2 eV) is interesting for the optical properties. The ternary ZnCdO-alloy allows an expansion to narrower bandgap, i.e. into the visible spectral range. However, an additional problem for the epitaxial growth of the alloy arises from the fact that ZnO crystallizes in the wurtzite phase while CdO forms a rock-salt structure. A one-by-one correlation of local stoicheometry and micro-morphology as well as its impact on the relaxation and recombination kinetics is presented. Alloying ZnO with MgO (Eg = 7.8 eV) further expands the optical properties into the UV and far UV. Furthermore MgZnO/ZnO heterostructures or multilayers are essential for fabricating Bragg mirrors for laser and micro cavity application. A nano-scale characterization of MgZnO/ZnO/MgZnO quantum wells is presented and the impact of potential fluctuations in the

MgZnO-barriers on the kinetics of carrier transfer and capture into the quantum well is investigated in spatial-time-resolved experiments.

6474-19, Session 5

Inductively coupled plasma etching of ZnO

K. J. Nordheden, The Univ. of Kansas

The etching characteristics of ZnO epitaxial layers in an Oxford Plasmalab ICP system are investigated. Etch rates are studied as a function of gas composition, pressure, ICP coil power and rf power. Surface profilometry and scanning electron microscopy are used to characterize etch rates and surface morphologies. Recent results from other laboratories are also discussed.

6474-20, Session 5

Dry etching of ZnO towards the development of ZnO homostructure LEDs

K. Minder, Northwestern Univ.; F. H. Teherani, D. Rogers, Nanovation SARL (France); C. Bayram, R. P. McClintock, P. Kung, M. Razeghi, Northwestern Univ.

Although ZnO has recently gained much interest as an alternative to the III-Nitride material system, the development of ZnO based optoelectonic devices is still in its infancy. Significant material breakthroughs in p-type doping of ZnO thin films and improvements in crystal growth techniques have recently been achieved, making the development of optoelectonic devices possible. ZnO is known to be an efficient UV-emitting material (~380 nm) at room temperature, optical UV lasing of ZnO has been achieved, and hybrid p-GaN / n-ZnO LEDs have been demonstrated.

In this paper, processing techniques are explored towards the achievement of a homo-junction ZnO LED. First, a survey of current ZnO processing methods is presented, followed by the results of our processing research. Specifically, we have examined dry etching through an n-ZnO layer to expose and make contact to a p-ZnO layer.

6474-21, Session 5

Ion-beam processing of ZnO

S. O. Kucheyev, Lawrence Livermore National Lab.; V. A. Coleman, C. Jagadish, The Australian National Univ. (Australia); J. Zou, The Univ. of Queensland (Australia); J. Williams, H. H. Tan, The Australian National Univ. (Australia)

Excellent fundamental material properties as well as recent significant success in the growth of high-quality single crystals make ZnO an ideal candidate for a range of (opto)electronic device applications. However, at present, there are significant challenges for processing ZnO. Ion implantation can be used for various processing steps in the fabrication of ZnO-based devices. In this presentation, we give an overview of our recent experimental research covering several aspects of ion-beam processing of ZnO. In particular, we discuss (i) the formation, evolution, and thermal stability of implantation-produced structural disorder, (ii) the nonequilibrium crystalline-to-amorphous phase transition, and (iii) effects of radiation damage on electrical and optical properties. We also demonstrate that an understanding of the above fundamental ion-beam-defect processes is crucial for a successful application of ion beams for doing, electrical isolation, and quantum well intermixing of ZnO-based devices.

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6474-22, Session 5

Schottky barrier and ohmic contact control by subsurface processing

L. J. Brillson, The Ohio State Univ.

Rectifying and ohmic contacts are fundamental to realizing ZnO device applications, yet their control has proved challenging. Until now, Schottky barrier (SB) studies have not taken a comprehensive approach to isolating effects due to surface contamination, lattice defects, impurity dopants, and interface chemical reactions. We have used a combination of plasma processing, low energy depth-resolved cathodoluminescence spectroscopy (DRCLS) at 10 K in an ultrahigh vacuum scanning electron microscope, and macroscopic diode measurements to characterize and control SB and ohmic contact formation at a wide variety of metals on ZnO crystal surfaces. Prior to metallization, DRCLS revealed orders-of-magnitude difference in native bulk defect densities for crystals grown by different techniques, and these defect densities varied substantially between the crystals' bulk and surface. For all crystals, surfaces treated with remote plasmas created clean, ordered surfaces and reduced defect emissions in the surface region. Micro-DRCLS taken through the metal diodes revealed defect transitions that change dramatically with process steps and metal. These transitions are associated with native point defects predicted theoretically and identified experimentally and which can increase by orders of magnitude at the surface. This near-interface defect accumulation depends on the ZnO-metal chemical interaction and crystal quality. These metal-induced defects impact device performance. Oxygen and hydrogen plasma treatments strongly affect which defects form with subsequent metallization, change contacts from Schottky to ohmic and vice versa, and improve contact idealities. These results demonstrate that remote plasmas can provide clean, stable surfaces and interfaces with improved device performance.

6474-23, Session 6

Review of current issues in ZnO LED

S. Park, Gwangju Institute of Science and Technology (South Korea)

No abstract available

6474-24, Session 6

Realization of p-type P-doped ZnO and homojunction diodes

H. Gong, National Univ. of Singapore (Singapore)

We have demonstrated the success in the growth and control of the conductivity type (n or p) of ZnO doped with phosphorous (P). The success of p-type P-doped ZnO is confirmed by Hall Effect measurements, Seebeck measurements, and the realization of p-n homojunctions. The room temperature carrier concentration, mobility and resistivity of the as-deposited p-type P-doped ZnO are 2.8 Å~ 1017 cm-3, 0.341 cm2 / V s and 65.4 Ω cm, respectively. The room temperature carrier concentration, mobility and resistivity of the as-deposited n-type P-doped ZnO on quartz are 8.5 Å~ 1019 cm-3, 6.1cm2 / V s, and 0.012 Ω cm, respectively. We could understand why we have p- and n-type P-doped ZnO at different growth conditions. The undoped ZnO films show insulating properties. The measurement of the P-doped ZnO p-n homojunction shows a typical p-n junction I-V curve with a turn-on voltage of 3.4 V. Experimental characterizations and theoretical calculations have been performed to understand the structural, electronic and light emission properties.

6474-25, Session 6

Surface plasmon mediated emission from metal/ZnO: an example for the fabrication of high brightness top-emitting light emitting diodes

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As metal electrode is invariably used as a medium for carrier injection, surface plasmons (SPs) arising from metal/semiconductor interface could evolve as an effective means to increase the light emission efficiency of light emitting diodes (LEDs). In fact, recent results have indicated that 17- and 15-fold of emission enhancement can be realized in InGaN quantum wells [1] and ZnO films [2] by means of SPs. However, the emission enhancement so far is observed from the backward direction in which light is emitted through the substrate. The backward geometry works well if a transparent substrate is used. For the implementation on opaque substrate such as silicon or the fabrication of top-emitting LEDs, only the forward emission is useful. Therefore, it is worthwhile to realize the SP mediated forward emission. Here, we report our progress in realizing high brightness top-emitting LED based on SP mediated emission. Through theoretical calculations, we find that it is possible to maximize the SP energy transfer from metal/ZnO interface to metal/air surface by carefully adjusting the optical properties and geometry of metal and ZnO and thereby realize a situation where forward emission is stronger than backward emission. In addition, together with the strong SP mediated emission from ZnO, we eventually observe more than an order of magnitude emission enhancement from metal/ZnO heterostructure with good Ohmic behavior. We believe this cross coupling of SP occurring in ZnO can serve as an example to open up a new route for fabricating top-emitting LEDs.

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6474-27, Session 7

Photonic properties of ZnO epilayers

A. Hoffmann, Technische Univ. Berlin (Germany)

No abstract available

6474-28, Session 7

Ultrafast spectroscopy in ZnO

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The readily available homoepitaxial substrate for ZnO combined with radiation hardness and high exciton binding energy (~ 60 meV) has resulted in significant research efforts towards the development of this material system for wide bandgap optoelectronic applications. The continued advances in growth have resulted in ZnO films with relatively low defect densities. Unfortunately, device developments have been hindered by the difficulties in realizing high quality p-type ZnO. Moreover, to date, the carrier dynamics (recombination and transport) in ZnO based materials is not well understood. The study of the basic optical properties of these materials by steady state and transient optical techniques such as photoluminescence (PL) and time-resolved photoluminescence (TRPL) is needed. Here, a survey of our ultrafast TRPL on MBE grown ZnO thin films will be presented. The PL lifetimes of the near band edge emission ranging from our streak-camera resolving limit (~ 20 ps) to a few hundred picoseconds. First, we will provide a comparative study of the PL lifetime and PL intensity as a function of material quality, injected carrier density and mobility. Next, we will present the effects of annealing on the carrier dynamics of ZnO. In addition, we will discuss the mechanism of carrier trapping, as well as an interesting U-shape temperature dependence of the PL lifetime. Finally, the temperature and power dependence of the TRPL of a novel ZnCdO thin film will be presented.

6474-29, Session 7

Studies of PLD-made thin ZnO layers by x-ray scattering methods: beyond the too restrictive ZnO(00.2) FWHM figure-of-merit

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Some X-ray scattering methods (X-ray reflectometry and Diffractometry) applied to the study of PLD-made thin ZnO layers deposited onto Al2O3(00.1) substrates are presented with a particular focus, for practical purposes, on the description of fast, accurate and robust techniques. We show that the simple well-known measure of the ZnO (00.2) full-width at half maximum is far from sufficient to conclude about the structure of such layers even as a figure of merit. The use of X-ray scattering metrology as a routinely working non-destructive testing method, particularly by using procedures simplifying the data-evaluation, is emphasized. Process of deconvolution in any detailed study of peak diffraction broadening is usually carried out either by the Fourier technique or by the variance method but in many applications a fast measure of peak diffraction breadths (called Integral-Breath methods) is adequate for practical purposes. In particular, the broadening of the (00.l) reflections in both the and Rocking-curves modes is used to determine the crystallite size (i.e. coherent domain sizes of diffraction) in both the growth direction and parallel to the film surface.

The thickness determination of the ZnO layers can be performed using either the Kiessig fringes from X-ray reflectometry profiles or Laue fringes appearing around the ZnO(00.2) diffraction peaks. However, the definitions of thicknesses are different between both XRR and HRXRD since, in XRR, thicknesses are defined as distances between interfaces, whereas in HRXRD, thicknesses are defined as coherence lengths of crystalline planes. The complementary of both methods is reported.

6474-30, Session 8

A comparative study of free standing zinc oxide substrates

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The ZnBeMgCdO alloy system has many desirable semiconductor properties such as: high exciton binding energies; the ability to achieve direct-bandgaps in the green-UV portion of the spectrum with a small change in lattice constants; high radiation resistance; high saturation velocity; relatively high mobility, especially for an oxide; low growth temperatures; and fast etch rates. ZnO-based devices should also have cost advantages over other compound semiconductor material systems due to the relative abundance of zinc and the lower processing temperatures required for high quality films. Commercial availability of low-defect single crystal ZnO substrates will allow researchers to fully investigate the viability of growing low-defect active layers in the ZnBeMgCdO alloy system. The large pressure (> 50 atm) necessary to prevent ZnO from decomposing prevents growth by molten techniques at or near atmospheric pressures. Therefore, other techniques (i.e. vapor, high-pressure skull melting, hydrothermal) are being developed to provide a cost effective method to grow large-area ZnO single crystals which can be processed into large diameter wafers.

This talk will begin with a history of ZnO bulk growth with emphasis on recent progress in producing large diameter material. Subsequently, the initial results of a study to evaluate commercial ZnO substrates will be presented. Optical, structural, and chemical evaluation of 1 cm2 C-plane ZnO substrates purchased from different vendors was conducted. The study found there is a wide variability in the properties of material evaluated. Initial structural evaluation by Synchrotron White Beam X-ray Topography (SWBXT) and High Resolution X-ray Diffraction (HRXD) revealed that material analyzed could range from high-perfection with low dislocation density and a small number of macro-defects, to material that was composed of large sub-grains. Low temperature photoluminescence revealed that PL intensity was not directly proportional to long range crystal perfection. The talk will conclude with discussion of efforts to obtain semi-insulating and conducting low-defect substrates in addition to substrates with non-polar surfaces, the next logical step in advancing ZnO substrate technology. The research conducted by the Air Force Research Lab was partially supported by the Air Force Office of Scientific Research. The topography experiments were carried out at the Stony Brook Synchrotron Topography Facility at the National Sychrotron Light Source, Brookhaven National Laboratory supported by the Department of Energy.

6474-31, Session 8

The state of the art of ZnO bulk crystal growth

T. Fukuda, Tohoku Univ. (Japan) and Fukuda Crystal Lab. (Japan); D. Ehrentraut, Fukuda Crystal Lab. (Japan); Y. Mikawa, Tohoku Univ. (Japan)

Zinc oxide (ZnO) crystals can be grown by vapor phase transport, hydrothermal solution growth, and high pressure melt growth. Three inch size single crystal has been demonstrated by hydrothermal growth. We will emphasis on the hydrothermal technology of large size ZnO crystal. Material characteristics are discussed and compared to ZnO from vapor phase and melt growth. A route to obtain high-quality, single-crystalline ZnO films with mechanically untouched surfaces is employed to screen doping in ZnO grown under the conditions of thermodynamic equilibrium. Future trends in ZnO crystal growth technology will be discussed.

6474-32, Session 8

Vacancy defect distributions in bulk ZnO crystals

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We have used positron annihilation spectroscopy to study vacancy defects in ZnO single crystals grown by various methods from both commercial and academic sources. The combination of positron lifetime and Doppler broadening techniques with theoretical calculations provides the means to deduce both the identities and the concentrations of the vacancies. The annihilation characteristics of the Zn and O vacancies have been determined by studying electron-irradiated ZnO grown by the seeded vapor phase technique [1, 2]. The different growth techniques studied were: the hydrothermal growth method (Tokyo Denpa, Scientific Production Company), the seeded vapor phase technique (Eagle Picher, Zn-Technology), growth from melt (Cermet), both conventional and contactless chemical vapor transport (Polish Academy of Sciences), and physical vapor transport (University of Valencia). Our results show that Zn vacancies or Zn vacancy related defects are present in as-grown ZnO, irrespective of the growth method. The Zn vacancies act as dominant acceptor-type centers in the materials grown by the seeded vapor phase, melt and contactless chemical vapor transport techniques, while they belong to neutral defect complexes in the ZnO samples grown by the hydrothermal conventional chemical vapor transport and physical vapor transport methods. Their concentrations are in the low 1015 cm-3 range in the samples grown by the seeded vapor phase technique and from melt, and in the low 1016 cm-3 range in the other samples. Neutral oxygen vacancies, with concentrations in the low 1017 cm-3 range, are observed in the ZnO crystals grown by the conventional chemical vapor transport and hydrothermal methods. Interestingly, the vacancy distributions in the samples grown by the physical vapor transport, conventional chemical vapor transport and hydrothermal methods are similar.

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6474-33, Session 8

UV-modulated one-dimensional ZnO/SiO2 photonic-crystal resonator for visible lights

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The one-dimensional photonic-crystal (ZnO/SiO2)6/ZnO/(SiO2/ZnO)6 resonator is fabricated and characterized. By selecting suitable thicknesses for the ZnO and SiO2 layers, the resonant mode of the resonator locates at visible light. Furthermore, due to the absorption of ultra-violet (UV) light by the ZnO layers, the refractive index of ZnO layers is changed temporally. This fact led to a temporary shifting of the forbidden band and the resonant mode of the resonator under UV irradiation. These results point to the possibility of developing a UV sensor by using the one-dimensional photonic-crystal (ZnO/SiO2)6/ZnO/(SiO2/ZnO)6 resonator.

6474-34, Session 9

Surface acoustic wave (SAW) devices

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Starting with an introduction to surface acoustic waves, their generation and detection using interdigital transducers (IDTs) on piezoelectric materials (e.g. LiNbO3 and ZnO) will be reviewed. Then the application of surface acoustic waves in electronic devices will be presented. Moreover, recent studies, using the technique of attaching the material of investigation onto the sound path of the acoustic delay line between the IDTs discussed.

6474-35, Session 9

Analysis of the observed longitudinal guided mode surface acoustic waves in ZnO thin films grown by pulsed laser deposition

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ZnO is well-known as a piezoelectric thin film material for surface acoustic (SAW) devices. In this paper, we report the observation and the study of the SAW longitudinal guided (LG) mode in the ZnO thin film. The experimental study was conducted using a technique based on Brillouin Light Scattering (BLS).

The theoretical study has concluded that the acousto-optic interaction in the layer was the relevant main interaction scattering mechanism between Electromagnetic (EM) wave light and acousto-optic phonons.

LG modes are promising for the development of novel, high-speed SAW devices operating in the GHz-band.

6474-36, Session 9

Growth and characterization of doped ZnO films

A. K. Pradhan, Norfolk State Univ.

The increasing demand for transparent conducting oxides and p-n junction based-short wavelength light emitting diodes has created a lot of research interest. Two important characteristics, such as direct wide band gap (3.37 eV) and large exciton binding energy (60 meV), make ZnO a promising material for above applications. However, the importance of p-type doping in ZnO remains a clue to realize potential applications as UV light emitters, transparent high-power electronics, piezoelectric transducers, chemical and gas sensors. We report here the synthesis of epitaxial doped and undoped ZnO films by the pulsed-laser deposition technique using various novel conditions. The dopants are As, Ga, Al and N. The films show excellent crystalline quality with atomically smooth surface morphology. The electrical resistivity was found to be close to 1.5 –10-4 ohm-cm and transmittance >85% with both Ga and Al doping. The p-ZnO: (N,Al)/n-ZnO:Al homojunctions fabricated on sapphire substrates combining with the intrinsic ZnO buffer layer show acceptable p-n diode characteristics. Doping with As shows several distinct transitions in their electrical resistivity and strong aging effects. On the other hand, doping with Mn in ZnO reduces the grain size and shows ferromagnetic properties at room temperature for a particular synthesis condition.

A substantial enhancement of diagonal Piezo-optic effect (up to 3.7*10-13 m2/N at =633 nm) was demonstrated in Er doped ZnO films under photoinduced treatment due to creation of additional dipole moments at the interface of the film and the substrate. This effect is enhanced with the increasing film thickness. The observed phenomenon may be used for optically operated piezooptic and acoustoptic modulators. The detailed results will be discussed.

6474-37, Session 9

Ga:ZnO based transparent conducting oxides and devices

V. M. Bhosle, J. Narayan, North Carolina State Univ.

We report on the synthesis and processing, and structure - property correlations in gallium doped ZnO films grown on (0001) sapphire and glass substrates by pulsed laser deposition. Films with varying microstructure were grown on amorphous glass by changing the pulsed laser deposition parameters, namely temperature and oxygen partial pressure. The results corresponding to these films were compared with those from epitaxial single crystal films grown on (0001) sapphire. It is shown that resistivities and transmittance comparable to epitaxial Zn0.95Ga0.05O films (π=1.4x10-4Ω-cm, %T>80) can be achieved in the nanocrystalline films (π=1.8x10-4Ω-cm, %T>80) deposited on glass by carefully controlling the deposition parameters. We have investigated and modeled the conduction mechanisms (carrier generation and carrier transport) in the novel Ga:ZnO films through detailed structural characterization, chemical analysis, and electrical and optical property measurements. The device applications based on these highly conducting and transparent films as electrodes will also be discussed. Our preliminary results have demonstrated that power conversion efficiencies comparable to indium tin oxide (ITO) based organic photovoltaic devices can be achieved using ZnGaO films as the anode.

6474-38, Session 9

Scaling and parasitic effects in ZnO transparent thin film transistors

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Recent development of transparent TFTs (TTFTs) using large bandgap (Eg>3eV) semiconductors (e.g. ZnO and related metal oxides) is of particular interest for active-matrix displays since they could render a nearly 100% aperture ratio or even fully transparent displays. To meet the requirements for high-resolution display applications, we investigated the scaling and parasitic properties of miniaturized ZnO TTFTs. Inverted staggered type ZnO TTFTs with varied channel lengths (2 to 50 um) and channel widths (20 to 200 um) were fabricated using the RF-sputtered ZnO active layer, the ITO source/drain/gate electrodes, and gate insulators consisting of Al2O3 and HfO2. These ZnO TTFTs operated in the n-type enhancement mode, and exhibited hard saturation in long-channel devices (> 5 um). Mobilities larger than 8 cm2/Vs and on/off ratios up to 10E7 were achieved. The transmission was more than 80% in the whole visible range. The device characteristics were rather immune to ambient illumination, which implies an advantage of needing no black matrices or light-shielding structure in active-matrix applications.

These ZnO TTFTs retain well-behaved transistor characteristics down to channel length of ~5 um, rendering possible high-resolution applications. Apparent short channel effects (e.g., lowering of threshold voltages, degradation of subthreshold slope with the decrease of the channel length and the increase of drain voltage, and loss of hard saturation, etc.), however, were observed when the channel length was reduced below 5 um. These short channel effects can be explained by the charge sharing or drain-induced barrier lowering. Parasitic series resistance and channel resistance were also extracted using devices of various dimensions. The parasitic series resistance Rp*W was typically on the order of 100 ~ 1000 ohm-cm, depending on the gate voltages. Parasitic series resistances have substantial influences on device performances when the channel length is reduced and the gate voltage is increased. The implications of these results on requirements of TTFT contacts will also be discussed.

6474-39, Session 9

The characteristics of transparent metal-ZnO contacts and ZnO-based photodiodes

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Low resistivity and high transparent ITO, RuOx (1≥x≥2) and TiW ohmic contacts to ZnO film was achieved by RF sputter system and annealing treatment. The transmittance of 450°C-annealing ITO, 650°C-annealing Ru and 200°C-annealing TiW were measured to be 94, 68 and 61%, with wavelength of 400 nm, respectively. Moreover, the specific contact resistance of 450°C-annealing ITO, 650°C-annealing Ru and 200°C-annealing TiW on ZnO films was estimated to be 2.15 10-4, 2.72 10-4 and 2.56 10-4 Ω-cm2 by circular transmission line model (CTLM) method, respectively. In the study of ZnO-based photodiodes, high quality and vertical well-aligned ZnO nanowires were selectively grown on ZnO:Ga/glass templates by vapor-liquid-solid method. Ultraviolet (UV) photodetectors using these vertical ZnO nanowires were also fabricated by spin-on-glass technology. With 2 V applied bias, it was found that dark current density of the fabricated device was only 3.8  10-9 A/cm2. It was also found that UV-to-visible rejection ratio and quantum efficiency of the fabricated ZnO nanowire photodetectors were more than 1000 and 12.6%, respectively.

6474-40, Session 10

Nanodevices and electric nanogenerators based on ZnO nanobelts and nanowires

Z. L. Wang, Georgia Institute of Technology

One-dimensional (1D) nanostructures (nanowires, nanobelts and nanorods) are the forefront nanomateirals for nanotechnology. Oxide nanostructures have been synthesized for a wide range of semiconducting oxides [1] that are potential building blocks for constructing numerous nanodevices. Field effect transistors [2], ultra-sensitive nano-size gas sensors [3], nanoresonators and nanocantilevers [4] have been fabricated using nanobelts. Among all of the oxide nanostructures we have investigated, ZnO is very unusual. The two important characteristics of the wurtzite structured ZnO are the non-central symmetry and the polar surfaces. The polar surfaces give raise a few interesting growth features, such as the formations of nanosprings [5], nanorings [6], nanobows [7] and nanohelices [8]. These nanostructure are semiconductive and piezoelectric and have potential applications as nano-scale sensors, traducers, and actuators.

This presentation will be focus on the synthesis, characterization, biocompatibility and potential applications of these novel nanostructures as biosensors and electric generators for self-powering nano- and bio-technology [9, 10]. I will demonstrate a technology that has the potential of converting mechanical movement energy (such as body movement,

muscle stretching, blood pressure), vibration energy (such as acoustic/ ultrasonic wave), and hydraulic energy (such as flow of body fluid, blood flow, contraction of blood vessel) into electric energy that may be sufficient for self-powering nanodevices and nanosystems. The nano-generator discovered by us could be the foundation for exploring new self-powering technology for in-situ, real-time and implantable biosensing, biomedical monitoring and biodetection.

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6474-41, Session 10

ZnO based nanostructures for optoelectronics

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ZnO based semiconductor devices are potentially interesting for optoelectronics in the UV, invisible electronics, and magnetoelectronics. An additional aspect of ZnO is the possibility to fabricate ZnO nanopillars by self-organisation, with a high degree of c-axis orientation. Due to the small footprint of ZnO nanopillars on the substrate, virtually any substrate can be used. Defect densities are small, which is due to the high aspect ratio of 100 and above, which can be achieved for these nanopillar systems. Such structures can even be grown on plastic substrates, when a wet chemical growth method is used. A substantial advantage of ZnO based nanopillars is the fact that surface oxidation obviously does not play a role, unlike in other material systems like GaAs.

The goal of our work related with ZnO nanopillars is to gain control on the nanopillar characteristics, and still leaving the self-organisation mechanism untouched. This relates to control on size, position, composition, and doping.

We report on the fabrication of ZnO nanopillars, leading to well aligned, c-axis oriented nanopillar systems, with typical diameters between 50 nm and 500 nm. ZnMgO-ZnO quantum well structures have been embedded into these nanopillars, with quantum well widths between 1 nm and 4 nm. For that, an optimised MBE based process using RHEED oscillation techniques has been used. Detailed TEM investigations indicate that there are no extended defects in the nanopillar, as expected for such high aspect ratios, since the footprint is small. Optical and electrical characterisation of nanopillar ensembles as well as single nanopillars will be reported.

6474-42, Session 10

Zinc oxide nanocrystals for optical chemical sensing

C. Baratto, E. Comini, G. Faglia, M. Ferroni, G. Sberveglieri, Univ. degli Studi di Brescia (Italy)

ZnO performances for conductometric chemical sensing have been known for forty years, even if ZnO is a metal oxide yet much more resistive and less sensitive than other like SnO2. Indeed recent breakthroughs in preparation technology, as high quality single crystals by PLD and quasi one-dimensional structures by evaporation condensation and MOCVD, have given new impulse for developing devices based on ZnO not only for optoelectronics but also for chemical sensing. Due to their peculiar characteristics and size effects, these materials often show some novel physical properties, like an environmental dependent excitonic and visible PL, which are different from those of the bulk and are of great interest both for fundamental studies and for potential nanodevice applications.

An overview of the most recent results obtained in the field of chemical sensing with ZnO will be presented, focusing mainly on PL quenching selectively produced by gaseous NO2 traces on nanowires. ZnO nanowires were prepared according to the recently proposed evaporation-condensation (EC) process, by Vapour-Phase (VP) and Vapour-Liquid-Phase (VPS) growth mechanism. A few possible explanations of physical origin of the effect in terms of dynamic or static quenching will be given and the performance of preliminary prototypes will be discussed.

6474-43, Session 10

Integration of multifunctional ZnO and its nanostructures for novel devices

Y. Lu, J. Zhong, J. Zhu, H. Chen, G. Saraf, Y. Chen, Z. Zhang, Rutgers Univ.; J. J. Song, C. K. Choi, ZN Technology, Inc.

There has been increasing interest in ZnO-based materials, nanostructures, and devices. Semiconductor ZnO has a direct energy bandgap (Eg » 3.3 eV at room temperature). It can be alloyed with CdO and MgO to form the ternaries of CdxZn1-xO and MgxZn1-xO, extending the direct energy band gap from 2.8eV to 4.0eV. Through proper doping, ZnO can be made transparent and conductive, piezoelectric, or ferromagnetic. Furthermore, ZnO based single crystal nanostructures can be grown at relatively low temperature. It is possible to use ZnO based multilayers and nanostructures to design and construct completely new integrated devices.

We have grown epitaxial ZnO and MgxZn1-xO films on r-plane sapphire substrates using MOCVD. The ZnO based semiconductor and piezoelectric multilayer structures have been used to demonstrate various new devices, such as monolithically integrated tunable surface acoustic wave (SAW) filters and wireless SAW UV detectors. The MOCVD technology has also been developed to grow multifunctional ZnO nanotips on various substrates. The single crystal and well aligned ZnO nanotips are integrated with piezoelectric substrates to form nano-ZnO SAW and bulk acoustic wave (BAW) sensors. These highly sensitive and portable sensors have biochemical and biological applications. The heterojunction blue light LED composed of n-type ZnO nanotips and p-type GaN is fabricated. Enhanced light extraction efficiency is also demonstrated by integrating ZnO nanotips on top of a GaN LED. The results show promising potential applications of ZnO nanotips for UV/blue optoelectronics.

6474-44, Session 11

Morphological control of ZnO nanostructures on silicon substrates

R. T. Rajendra Kumar, J. Grabowska, J. Mosnier, M. O. Henry, E. McGlynn, Dublin City Univ. (Ireland)

We report on ZnO nanostructure growth on silicon substrates using vapour phase transport, which is a topical research area with many potential applications. The mechanisms reported in the literature often use a variety of substrate preparations (e.g. gold thin film deposition), diverse (and different) source material and substrate temperatures, and the growth is often attributed to a variety of mechanisms including vapour-liquid-solid (VLS), self-catalysed VLS and vapour-solid (VS) deposition. Our experience is that while reproducible growth is achieved in any one group, the replication of reported conditions by another group can often lead to different nanostructures.

We have examined the growth of ZnO nanostructures and have demonstrated reproducible growth over a variety of temperatures. We identify different nanostructure growth modes which we believe are associated with Zn VS deposition and subsequent oxidation at low temperatures,

VLS growth via gold catalyst at intermediate temperatures and ZnO VS deposition at higher temperatures, though there is considerable temperature overlap in these mechanisms. We have extended our study in an attempt to independently control supersaturation levels of source materials and to understand the effects of these parameters on growth and also to independently examine both carbothermal reduction and evaporation of ZnO source powders.

6474-46, Session 11

Optical characteristics of ZnO nanowires synthesized by nanoparticle-assisted deposition and their application to sensors

T. Okada, J. Suehiro, Kyushu Univ. (Japan)

ZnO nanowires have been synthesized by the nanoparticle-assisted deposition technique and the ultraviolet stimulated emission characteristics of single nanowire under optical pumping were investigated. The highly sensitive ultraviolet photo-detectors were successfully fabricated by trapping these nanowires between electrodes using the dielectrophoresis technique.

6474-47, Session 11

Patterned growth of ZnO nanorod by solution chemical method

S. Yi, S. Choi, J. Jang, S. Go, J. Kim, W. Jung, Kookmin Univ. (South Korea)

ZnO has a wide band-gap energy of 3.37 eV and a large exciton binding energy of 60 meV. ZnO has substantial interest for practical application such as ultraviolet/blue emission devices, piezoelectric devices, acousto-optical devices, and chemical sensors. Recently, the application prospect of ZnO nanostructure largely relies on the ability to control their location, alignment and packing density. To control the location of ZnO nanorod, photolithography technique was applied in the present study. Aligned ZnO nanorod arrays were fabricated using solution chemical method at normal atmospheric pressure without any metal catalyst.

Aligned ZnO nanorod arrays were grown using a simple route. A simple way to create patterned ZnO seed array is to use negative photoresist for ZnO seed coating. Various substrates were used in the present worke. The UV exposures were performed though mask patterned various shape. The ZnO seed precursor was prepared by sol-gel reaction. A NaOH solution in methanol (0.03M) was added slowly to a solution of 0.01M zinc acetate dihydrate (Zn(CH3COOH)2•2H2O) in methanol at 60ϒX and stirred for 2 hours. The solution was spin coated on patterned substrate, and the photoresist layer was stripped. Lastly, the substrate coated with ZnO seed was submerged in 0.025M zinc nitrate hexahydrate (Zn(NO3)2•6H2O) and 0.025M diethylentriamine aqueous solution stirring at 90ϒX for 1 hours to grow aligned ZnO nanorod. Then the ZnO nanorods were grown from the patternd ZnO seed. The grown ZnO nanorods on substrate were washed with deionized water and dryed.

The structure of ZnO nanorod was characterized by FE-SEM, XRD, TEM. The optical property of ZnO nanorod was measured by PL.

6474-48, Session 11

Carrier relaxation and stimulated emission in ZnO nanorods grown by catalyst-assisted vapor transport on various substrates

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ZnO-based nanostructures, including nanorods, nanobelts, etc., have attracted a great deal of attention primarily due to their prospective applications in light-emitting devices. In this study, ZnO nanorods were grown by catalyst-assisted vapor phase transport on different substrates: Si, c-sapphire, GaN, and bulk ZnO. A mixture of powdered bulk ZnO and C powder was used as a material source and placed in the high temperature zone of a horizontal furnace. The substrates were located downstream of a Ar carrier gas in a lower temperature zone, and the growth temperature was 600-650 °C. The morphology of the prepared structures was studied by scanning electron microscopy and atomic force microscopy (AFM). Different morphologies were obtained for structures grown on different substrates. Localized conduction behavior was examined using conductive AFM via indium ohmic contacts.

Steady-state photoluminescence (PL) recorded both at 15 and 300 K from the prepared nanorod structures showed very intense emission that was comparable to emission from bulk ZnO. PL spectra were correlated with various types of morphologies obtained on different substrates. Near field optical microscopy was employed to identify emission from individual nanorods. Time-resolved and excitation-intensity dependent PL were measured to investigate carrier dynamics and natural cavity formation, respectively. Time-resolved Raman and micro-Raman spectroscopy were used to study transient carrier transport and phonon modes in the ZnO nanorods. The crystal structure of the ZnO nanorods was characterized by transmission electron microscopy. Characteristics of the ZnO nanostructures grown on different substrates are correlated to their microstructure and peculiarities of growth mechanisms.

6474-49, Session 12

Electron mediated ferromagnetism in epitaxial co-doped ZnO

S. A. Chambers, Pacific Northwest National Lab.

Continued progress in spintronics requires the advent of ferromagnetic semiconductors in which magnetically aligned dopant spins couple to the band structure of the host lattice, resulting in spin polarization of free carriers, at and above room temperature. The 2000 prediction by Dietl et al. of Curie points above room temperature in Mn-doped ZnO, and the subsequent 2001 observation of RT ferromagnetism in Co-doped TiO2 anatase by Matsumoto et al. have resulted in significant efforts aimed at discovering and understanding new candidate diluted magnetic oxide and nitride semiconductors. However, these materials are deceptively complex, and careful materials science is essential to avoid drawing false conclusions about them. Our approach is to combine optimized epitaxial growth, detailed materials characterization, transport and magnetic measurements, and theory to elucidate defensible structure-function relationships. In this talk, I will present our recent efforts on one of the more promising materials, Co-doped ZnO. We have grown Co:ZnO by metal organic chemical vapor deposition and pulsed laser deposition on r- and c-plane sapphire substrates. We find that as grown, Co:ZnO is insulating and paramagnetic. However, upon making the material n-type by injection of interstitial Zn, it becomes n-type and ferromagnetic at and above room temperature. Moreover, there is a direct kinetic correlation between the concentration of interstitial Zn and both the conductivity and room-temperature saturation magnetization. These results reveal a cause-and-effect relationship between shallow donor electrons and room temperature ferromagnetism. However, many mysteries remain, such as the anomalously low moment per Co, and these will be discussed as well.

6474-50, Session 12

Spin injecting devices based on ZnO

S. Ramachandran, J. T. Prater, J. Narayan, North Carolina State Univ.

The field of spintronics envisages revolutionizing the way information is stored and processed, by utilizing the spin degree of freedom of the charge carrier in addition to its charge. Prime requirements to this end are developing materials called as diluted magnetic semiconductors which are ferromagnetic at room temperature and also which can inject spin polarized electrons into semiconductors. In this talk we will address the develop-

ment of such material systems and devices based solely on ZnO which exhibit interesting properties in terms of magnetization and magnetoresistance behavior. Such devices, if harnessed fully can enhance the efficiency and functionality of microelectronic devices.

6474-51, Session 12

Transition metal-doped ZnO: a comparaison of opical, magnetic, and structural behaviour of bulk and thin films

I. T. Ferguson, Georgia Institute of Technology

No abstract available

6474-52, Session 12

Physical properties modulation of magnetic and non-magnetic ZnO thin films by field effect

E. Bellingeri, I. Pallecchi, L. Pellegrino, A. Caviglia, G. Canu, A. Gerbi, A. S. Siri, D. Marre, Univ. degli Studi di Genova (Italy)

The integration of ZnO based high mobility transparent semiconductors with perovskites that exhibit a wide spectrum of physical properties (superconductivity, ferroelectricity, ferromagnetism, etc.) may lead to a wide variety of new electronic/optoelectronic devices; recently we reported about the realization of epitaxial ZnO/SrTiO3 heterostuctures and about their application in the fabrication of field effect transistors transparent at visible wavelength. As further development in this field, here we present results about the deposition of high crystalline quality Al or Co doped ZnO films grown by pulsed laser deposition on 110 face of strontium titanate single crystals. Field Effect (FE) experiment, allowing to change the carrier concentration of the film by more then 4 order of magnitude (from 1015 to 1020 e-/cm3, estimated by Hall effect measurements under FE), were employed to deeply investigate transport mechanisms. In particular we observed a crossover of low temperature magnetoresistance from a negative behaviour in accumulation state to a positive one in depletion state. The measure of the activation energy as a function of the Gate potential allowed us to get information on the density of states.

6474-53, Session 12

Spontaneous polarization in ferroelectric wurtzite (ZnO) perovskite (BaTiO3) heterostructures: theory, experiments and further prospects

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Spontaneous polarization in oxide semiconductor materials constitutes a very attractive but yet little known property with potential for many attractive applications. While materials with permanent and switchable magnetization and their coupling phenomena are under intensive investigation, little attention was paid so far to phenomena associated with the spontaneous lattice charge in piezoelectric material such as the wurtzite structure ZnO and related compounds. When brought into contact with ferroelectric oxides, interface charge coupling occurs with new controllable parameters. In pulsed-laser-deposition fabricated heterostructures of ZnO and BaTiO3 thin films - which turn out as excellent example system - we observe P-V, I-V and C-V junction-like behaviour with strong asymmetric hysteresis properties. We present a dynamic interface charge model which we developed accounting for interface-charge induced depletion zones within the ZnO layer, and which successfully describes the observed inferace-induced polarization switching for our investigated structures. We propose ZnO-based electronic device structures involving interface-charge coupling with ferroelectric materials, and discuss further prospects involving magnetic ferroic or antiferroic order for fabrication of systems were coupling between spontaneous magnetic and dielectric polarization may be driven towards magnetoelectric material properties in oxide semiconductors.

6474-56, Poster Session

Surface modification of ZnO nanostructures for use in gas sensing

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The recent synthesis of a wide range of ZnO nanoscale structures (wires, belts, rings, cages, tetrapods) has attracted much interest as a possible leverage for creating novel applications, one of the promising applications being gas sensing. High sensitivities for gas sensors made of ZnO nanostructures have already been reported. In a previous report, we described the fabrication of a three-dimensional network of ZnO tetrapods forming a porous layer with high sensitivity to ethanol. The high sensitivity was attributed to the high surface to volume ratio of the network of tetrapods. However the physico-chemical properties of the nanostructure surface were not fully characterized, so that the contribution of these properties to the improvement in gas sensitivity remains for the most part unknown. Further, to our best knowledge, there has been no attempt to modify the physico-chemical properties of the nanostructure surface so as to improve the gas sensing properties of nanostructured materials.

In this report, we examined the effects of surface treatments such as wet etching in weak acids and physical etching by plasma on gas exposure responses of ZnO nano-structured materials. The changes in the nanostructures morphology upon surface treatments were characterized by UHV-STM and the changes in the surface chemical state were analyzed by CL and XPS. An increase in defect density upon chemical etching was evidenced by a large increase in the intensity of the green below-band-gap emission relatively to the near-band-gap peak of the CL data. Further, the density of defects as estimated by the CL green emission intensity could be controlled by adjusting acid concentration. The effects of defect density generated by the surface treatments on the gas sensing properties of ZnO nano-structured materials are reported.

6474-57, Poster Session

Fabrication of well-aligned ZnO nanorods by hydrothermal process using GaN epitaxial layer

J. Jang, S. Yi, S. Choi, J. Kim, W. Jung, Kookmin Univ. (South Korea)

Zinc oxide (ZnO) is very important I-ς semiconductor with direct band-gap of 3.37eV and a large exciton binding energy of 60 meV. It is suitable for short-wavelength optoelectronic application, piezoelectric sensor, and semiconductor electrode. In recent years, much effort has been focused on controlling the size and lower index of inorganic nanostructure, because these physical properties are changed excellently from these for bulk structure.

One dimensional (1-D) ZnO nanorod structure of hexagonal shape was fabricated on epitaxial GaN layer by hydro-thermal method. The growth of GaN epitaxial layer was carried out in a two-flow horizontal MOCVD reactor maintained at a pressure of 200 torr. Firstly, a 25nm thick GaN buffer layer was grown at 520ϒX. Then 2~3∝μ thick GaN epilayer was deposited at 1070ϒX. Trimethylgallium (TMG) and NH3 were used as Ga and N source, and H2 gas was used as carrier gas. After the deposition of GaN epilayer thin-film, single crystalline ZnO nanorod was fabricated in aqueous solution. XRD and FE-SEM results showed ZnO nanorod arrays were oriented highly along the (002) plane. The ZnO nanorod was analyzed to have good quality crystallization by FE-TEM. The SAED pattern has shown that ZnO nanorod was grown in direction along the (002)-plane.

Photoluminescence (PL) has shown that the GaN-ZnO ohmic contact structure has shown ultra-violet lasing action at room temperature. Narrow and strong ultra-violet peak was observed in comparison with PL

result from epitaxial GaN layers. The analysis results have proved that aqueous solution growth method developed in the present work can be a good application for optical electronic device.

6474-59, Poster Session

Transition metal-doped ZnO: a comparison of optical, magnetic, and structural behavior of bulk and thin films

M. H. Kane, W. E. Fenwick, Georgia Institute of Technology; R. Varatharajan, Cermet, Inc.; M. Strassburg, Georgia Institute of Technology; W. Nemeth, Cermet, Inc.; D. Keeble, Univ. of Dundee (United Kingdom); H. El-Mkami, G. M. Smith, Univ. of St. Andrews (United Kingdom); J. Nause, Cermet, Inc.; C. J. Summers, I. T. Ferguson, Georgia Institute of Technology

Following theoretical predictions of room temperature (RT) ferromagnetism in transition-metal (TM)-doped zinc oxide, extensive experimental studies have attempted to produce ferromagnetic behavior in Zn1 xMnxO and Zn1 xCoxO. The nature of ferromagnetism remains unclear in all cases, and crystalline defects may play a significant role. This work reports on the optical and magnetic properties of Co- and Mn-doped ZnO grown by a modified melt-growth technique and metalorganic chemical vapor deposition, and the effects of annealing and co-doping on magnetic behavior. Good crystalline quality was confirmed by X-ray diffraction (XRD), which revealed that the as-grown crystals are pure single crystals with no second phases. Mn doping up to 5% results in an increase in c-axis lattice parameter (5.207 Å to 5.211 Å), and in X-ray linewidths (78 arcsec to 252 arcsec). Structural properties were also investigated with Raman spectroscopy. The standard Raman active modes were visible in the Raman spectra, suggesting good crystalline quality. An additional Raman mode observed at 522cm-1 has been attributed to Mn incorporation in the crystal, though the dominant feature with transition metal doping is the activation of 'silent' Raman modes within the wurtzite lattice due to a loss of translational symmetry with Mn-doping. Similar Raman results are seen for Co-doped ZnO. Optical transmission shows distinct absorption spectra related to the color of the Zn1 xTMxO sample resulting from interatomic transitions within the divalent transition metal ion in a tetrahedral crystal field. Electronic paramagnetic resonance strudies confirm the divalent nature of the substitutional transition metal atoms. Magnetization measurements reveal a paramagnetic behavior at all temperatures for both Mn- and Co-doped ZnO with the dominant exchange mechanism in both the Mn- and Co-doped ZnO single crystals as antiferromagnetic (AFM) superexchange. The results will be compared with temperature-dependent optical and magneto-optical spectroscopies, in order to examine binding energies of the dopants and defect centers and to investigate the incorporation and possible formation of spin-split electronic states leading to ferromagnetic behavior. The influence of annealing and codoping in both bulk and thin film samples within the framework of relevant current theories of ferromagnetism will also be discussed.

6474-60, Poster Session

Fabrication and characterization of zinc oxide based rib waveguide

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In this work we investigate the possibility to use Zinc Oxide thin films, deposited by RF magnetron sputtering from, for the realization of waveguides working at 1550 nm.

Structural properties of sputtered Zinc Oxide (ZnO) thin films were studied by means of X-ray diffraction (XRD) measurements, while optical properties were investigated by spectrophotometry and spectroscopic ellipsometry (SE). In particular, ellipsometric measurements have allowed to determine the dispersion law of the ZnO complex refractive index ñ = n - jk through the multilayer modeling using Tauc-Lorentz (TL) dispersion model.

We have found a preferential c-axis growth of ZnO films, with slightly variable deposition rates from 2.6 to 3.8 Å/s. Conversely, the refractive index exhibits, from UV to near IR, a considerable and almost linear variation when the oxygen flux value in the deposition chamber varies from 0 to 10 sccm.

In order to realize a waveguide structure, a 3-∝m-thick ZnO film was deposited onto silicon single crystal substrates, where a 0.5-∝m-thick thermal SiO2 buffer layer was previously realized as lower cladding.

Dry and wet chemical etch processes have been investigated to achieve controllable etching rate and step etching profile with the aim to realize a rib structure. The etched surfaces were inspected using scanning electron microscopy (SEM) and optical microscopy.

Moreover, we carried out the design and the analysis of a ZnO rib waveguide structure using the Beam Propagation Method (BPM) and we studied the possibility to use the ZnO piezoelectric effect to realize a waveguide integrated amplitude modulator.

6474-63, Poster Session

Influence of annealing in oxygen ambient on crystal properties of rf-sputtered PZT layers on ZnO substrates

Y. I. Alivov, F. Agra, B. Xiao, S. A. Chevtchenko, Virginia Commonwealth Univ.; C. W. Litton, Air Force Research Lab.; H. Morkoc, Virginia Commonwealth Univ.

Lead zirconium titanium PbZr1-xTixO3 (PZT) is an ABO3 family perovskite which is considered as one of the promising material for production nonvolatile random access memory devices because of its low crystal growth temperature around 600 C that is compatible with the silicon technology and its high value of remanent polarization and dielectric constant. However, it suffers from fatigue -i.e.degradation of hysteresis curve with time which prevents its utility. The fatigue is believed to result from oxygen deficiency near the electrode-PZT interface. One of the approaches is to use oxide bridge layers between PZT and the platinum electrodes with some success in reducing the oxygen non-stoichiometry using different perovskite materials as, for example, SrRuO3, LaNiO3, LaAlO3. ZnO appears to be a better choice for this purpose since it has several advantages over perovskite bridges: first, it is much simpler to grow and growth temperature is low; second, it can be highly doped with donors to get high conductivity to be used as the second electrode. Despite these advantages, there have been only a few reports on PZT growth on ZnO. From this point of view, studies of PZT growth on ZnO are warranted. In the present work we grew PZT films of composition x=0.48 on ZnO layers by rf-sputtering and investigated their crystal properties as a function of growth parameters (substrate temperature, ambient pressure, O2/Ar ratio) and postgrowth annealing. The crystal quality was characterized using X-ray diffraction (XRD), atomic force microscopy (AFM), electron dispersive spectroscopy (EDS), and photoluminescence (PL) methods.

The studies revealed that most critical factor influencing the properties of the rf-sputtered PZT films is the postgrowth annealing in oxygen ambient. The growth parameters have very little effect on PZT quality, and the XRD data of all as-grown PZT layers prior to annealing are similar and dominated by the pyroelectric phase (101) peak. After annealing in oxygen atmosphere pyroelectric phase almost fully disappeared, and the perovskite phase peaks (111) dramatically increased. This transformation depends also little on annealing temperature which was varied in the range 550-700 C indicating that only the oxygen pressure was responsible for PZT crystal quality improvement. AFM, EDS, PL studies also support to some extent these conclusions. The details of the abovementioned investigation will be discussed.

6474-64, Poster Session

Electrical characteristics of n-ZnO/n-6H-SiC heterostructures grown by rf-sputtering

Y. I. Alivov, B. Xiao, Q. Fan, Virginia Commonwealth Univ.; D. K. Johnstone, SEMETROL; C. W. Litton, Air Force Research Lab.; H. Morkoc, Virginia Commonwealth Univ.

Zinc oxide (ZnO) is under consideration for a variety of optical device owing to its large exciton binding energy (60 meV), relative ease of bulk material growth, and the possibility of growing highly conductive transparent layers. Because high quality, reproducible p-type ZnO layers are not yet available, p-n junctions are fabricated that take advantage of heteroepitaxy. Heteroepitaxial structures are also of interest on their own merits because of advantages provided by the resulting valence and conduction band offsets. One of the vital criteria in heteroepitaxial based devices is to match the lattice parameters, and from this point of view GaN and its alloys with aluminum (Al) have been considered as one of the best candidates for such device fabrication by many authors. Another good candidate for ZnO based heterostructure based devices is SiC, which matches the wurzite crystal structure, and has a relatively small lattice mismatch of about 4% with ZnO. To better understand heterostructure device performance, knowledge of the band offset between materials forming the heterostructure is necessary. In this report we have studied current transport properties, defect structure of the n-ZnO/n-6H-SiC isotype heterostructures and measured the conduction band offset of this materials system by using a variety of methods, namely temperature dependent current-voltage characteristics (I-V-T), photocapacitance (PC), and deep level transient spectroscopy (DLTS) measurements.

The n-ZnO/n-SiC heterostructure samples were fabricated by growing of 3.0x10-5 cm thick undoped ZnO film by RF sputtering on 3.0x10-2 cm commercial n-type 6H-SiC substrates. ZnO layers were deposited directly on 6H-SiC substrates at 750 °C by RF magnetron sputtering in an Ar+O2 ambient atmosphere with subsequent postgrowth annealing at 950 °C for 1 hour to improve film crystal quality. The 2.5 10-2 cm diameter mesa structures were fabricated by conventional photolithography method. The ohmic contacts to n-ZnO and n-SiC were formed by depositing Au/Al (300/300 □) and Au/Ti/Ni (300/300/300 □) metal layers, respectively, with subsequent rapid temperature annealing at 800 C for 2 min. The I-V-T and DLTS measurements were performed in the temperature range of 80-700 K. The photocapacitance spectroscopy was taken at 80 K, using a xenon lamp passed through a monochromator.

Strong dependence of transport properties of n-ZnO/n-6H-SiC heterostructures on temperature and applied voltage was observed. Conduction band offset of n-ZnO/n-6H-SiC heterostructures measured by I-V-T, PC, and DLTS measurements showed close values equal to 1.25 eV, 1.1 eV, and 1.22 eV, respectively.

6474-65, Poster Session

An overview of ZnO research activity in Hong Kong

H. C. Ong, The Chinese Univ. of Hong Kong (Hong Kong China)

ZnO and related materials has become one of the major research areas in Hong Kong. Much of the attention has been paid to the nanotechnology. To date, 10% of the total nanotechnology research is devoted to the growth, characterization and device fabrication of ZnO. In this talk, I will give an overview of the recent ZnO research activity in Hong Kong and our collaborations with the China counterpart.

6474-66, Poster Session

ZnO thin film growth on various substrates

F. H. Teherani, D. Rogers, Nanovation SARL (France)

No abstract available

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6475-01, Session 1

Characterization of a quality-factor tunable integrated silicon microtoroidal resonators

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Microresonators are basic building blocks for compact photonic integrated circuits (PICs). The performance of the microresonators depends on their intrinsic and loaded quality factors (Q). Most of the integrated microresonators reported to date have fixed loaded Q due to fixed coupling. Previously, we have reported the first silicon microdisk resonator with integrated tunable coupler. Here we demonstrate a single crystalline silicon microtoroidal resonator with MEMS-actuated tunable optical coupler for the first time. The microtoroid provides tighter confinement of the optical mode and eliminates multiple radial modes observed in microdisks.

The device is realized on a two-layer silicon-on-insulator (SOI) structure. The fabricated resonator has a ring radius of 19.5 μm and a toroidal radius of 200 nm. The waveguide dimensions are 0.7μm x 0.26μm. At zero bias, the initial gap spacing between the resonator and the waveguide is 1μm, and the coupling is negligible. When increasing bias, the suspended waveguide in the top SOI layer is pulled down electrostatically towards the microtoroid in the lower SOI layer, increasing the coupling. At an actuation voltage of 64.8 V, the extinction ratio at a resonant wavelength (1548.18 nm) reaches 10.2 dB. The device can be operated in all three coupling regimes: under-coupling, critical coupling, and over-coupling. We have also developed a comprehensive model based on time-domain coupling theory. The experimental and theoretical results agree very well. The loaded Q is extracted by fitting the experimental curve with the model. The loaded Q is continuously tunable from 110,000 to 5,400. This device has potential applications in variable bandwidth filters, reconfigurable add-drop multiplexers, and optical sensors.

6475-02, Session 1

Micro-photonic cylindrical waveguide based protein biosensor

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In this paper we experimentally demonstrate the fabrication and operation of a rapidly prototyped optical cylindrical micro waveguide based biosensor. This device works on the principle of variation to the light intensity and path of coupled input light due to the binding of protein biomolecules onto the micro waveguide surface as a method of physical transduction. The variation to the coupled light intensity and path is dependant on the nature of the bio-molecule and the density of the biomolecules. This technique has been used to identify protein biomarkers for inflammation and thrombosis namely Myeloperoxidase (MPO) and C-reactive protein (CRP). The detection limit that has been demonstrated is pg/ml. The detection speed in is in the order of seconds from the time of injection of the bio-molecule. The optical signature that is obtained to identify a protein bio-molecule is entirely dependant on the nature of adsorption of the bio-molecule on to the cylindrical cavity surfaces. This in turn is dependant on the protein conformation and the surface charge of the bio-molecules. Hence a specific protein bio-molecule generates a unique optical identifier based on the nature of binding/adsorption to the cavity surface. This physical phenomenon is exploited to identify individual proteins. This technique is a demonstration of detection of nano-scale protein bio-molecules using optical biosensor technique with unprecedented sensitivity.

6475-03, Session 1

Optical waveguide biosensor based on 2D diffractive elements obtained by nano-imprint lithography

S. Grego, RTI International; Y. Cao, The Univ. of North Carolina at Charlotte; C. A. Bower, B. R. Stoner, RTI International; T. J. Suleski, The Univ. of North Carolina at Charlotte

Optical waveguide-based devices that rely on a grating-coupler to detect changes of upper cladding refractive index can be used as biosensors upon a suitable surface functionalization. This biosensor methodology offers the advantage of sensitivity based on evanescent wave interactions on a compact area (~ 1 x 1 mm2) while not requiring cumbersome fiber-optic “pigtailing” for laser coupling into a single-mode waveguide. This work focuses on the effects of custom-designed, two-dimensional grating structures on the sensitivity of silicon oxynitride waveguides. Theoretical calculations suggest that suitably designed diffractive structures with optimum pitch in two orthogonal directions can increase the sensitivity of devices when compared to a conventional one-dimensional grating under the same conditions. The use of theoretically optimized grating patterns to increase sensitivity and device functionality enables a more compact, potentially portable biosensor system as compared to conventional systems already available.

A set of diffractive structures designed for both visible and near infrared lasers was analyzed; the grating patterns were defined by deep UV stepper lithography on silicon substrates. The silicon wafers were dry-etched to provide molds for thermal nano-imprint lithography. The imprinting was performed with a high-precision die-bonder with independent temperature control of the top and bottom vacuum chucks. The experimental evaluation of the optical waveguide devices integrated with two-dimensional gratings was performed on a custom-made apparatus and compared to a conventional device structure.

6475-04, Session 1

Demonstration of a liquid core optical ring resonator sensor coupled with an ARROW waveguide array

I. M. White, H. Oveys, Univ. of Missouri/Columbia; T. L. Smith, J. Zhang, 3M Co.; X. Fan, Univ. of Missouri/Columbia

The liquid core optical ring resonator (LCORR) sensor is a newly developed capillary-based ring resonator that integrates microfluidics with photonic sensing technology. The circular cross-section of the capillary forms a ring resonator that supports whispering gallery modes (WGM), the WGM evanescent field is exposed to the capillary core and detects the aqueous samples conducted by the capillary using a label-free protocol. The high-Q of the WGM allows for repetitive light-analyte interaction, resulting in excellent sensitivity. Recently a detection limit of the LCORR on the order of 10-6 refractive index units was reported.

In this work, we have further integrated the LCORR with an anti-resonant reflective optical waveguide (ARROW) array for multiplexed sensor development. The ARROW, with an array of 8 waveguides separated by 250 microns each, consists of a core and a lower reflective double-layer with alternating high and low refractive index, and thus has a significant evanescent field above the waveguide. The WGM is excited at each LCORR/ARROW junction simultaneously when the LCORR is brought into contact with the ARROW array. We experimentally investigated the optimal waveguide geometry for WGM excitation using a range of waveguide heights from 2 to 5 microns. An intrinsic Q-factor of 10^7 and near-critical coupling are observed. Furthermore, the sensing capability of this LCORR/ARROW system is also investigated.

The LCORR/ARROW system is not only essential for assembling a robust, practical, and densely multiplexed sensor array, but also enables on-capillary flow analysis that has broad applications in capillary electrophoresis, chromatography, and lab-on-a-chip development.

6475-05, Session 1

Direct detecting thin polymer and organic adlayers using a local evanescent-field array coupled waveguide sensor

G. Yuan, M. D. Stephens, D. S. Dandy, K. L. Lear, Colorado State Univ.

A novel local, evanescent-field, array coupled (LEAC) photonic waveguide biosensor is being developed to provide simultaneous, reagentless immunobiosensing of multiple pathogens or other protein based species

for point-of-care clinical diagnostics, food safety, environmental monitoring, and biosecurity applications. In a complete sensor, a buried, evanescently coupled detector array is implemented into the lower cladding regions of the waveguide, where each detector element is placed opposite a region of a specific antibody type. Local changes in the evanescent field, which indicate the presence of adsorbed species on the upper surface of the waveguide, can be sensed by detector array elements.

Here, we present the development and characterization of LEAC waveguide sensors employing buried detector arrays. Numerical simulations are performed to understand and optimize the operation of the buried detector arrays. Larger core-to-detector separations yield higher fractional signals. LEAC sensors

with electronic readout circuits are being fabricated in a commercial 0.35-micrometer CMOS technology. The metal-semiconductor-metal (MSM) photodetectors exploit a two-layer metal contact technique, providing both high photo responsivity and low optical interference with the guided optical field. In the initial applications, the effect of different polymers and organic molecules bound to the surface of the

waveguide on the detected optical signal will be analyzed with these sensors. In addition, the predicted response to the refractive index changes based on numerical modeling will be compared with the measured detector response. Detailed results will be presented at the conference.

6475-06, Session 2

Glass integrated optics: state of the art and position towards other technologies

J. Broquin, École Nationale Supérieure d'Electronique et de Radioélectricité de Grenoble (France)

Since the beginning of the eighties, a huge effort has been made on the development of integrated optics technologies as different as Lithium-Niobate, Silica on Silicon, III-V alloys, Polymers and Glass to focus on the most popular ones. In this paper, we propose to review the advances made by the glass ion-exchange technology on several areas of integrated optics such as passive and active devices, physical and biological sensors or optical microsystems. For every item of this review, we will try to put the emphasis on the key features provided by ion-exchange in order to compare them with the ones of competing technologies. The article will be concluded by a presentation of some possible evolutions of the ion-exchange technology like 3D devices or heterogeneous integration.

6475-07, Session 2

Chalcogenide waveguide for IR optical range

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Due to remarkable properties of the chalcogenide glasses - large infrared spectral range of transparency (10-20∝m), low phonon energy, photosensitivity, high linear and non-linear refractive index - amorphous chalcogenide films should play a motivating role in the development of integrated planar optical circuits and their components. In this presentation, we discuss the general properties of the selected chalcogenide glass systems and the two complementary techniques used to obtain high-quality films. Amorphous films were prepared by RF magnetron sputtering (RF-MS) and pulsed laser deposition (PLD) using in order to obtain appropriate films in different chalcogenide systems from sulfide to telluride, pure and rare earth doped in the range of nanometer to several microns in thickness. To optimize deposition conditions of films of glass, we report the study of their compositional, morphological and structural characteristics. Some optical properties of prepared chalcogenide films and the propagation modes by means of the m-lines prism-coupling anfd near field configuration were investigated. The photo-luminescence of rare-earth doped Ge-Ga-Sb-S(Se) films were clearly observed in the p-IR spectral domain and their decay lifetime studies will be presented. The methods of obtention of chanel waveguide for RF-MS and PLD will be describded.

6475-08, Session 2

Channel waveguides fabrication in Er3+-doped tellurite glass by ion beam irradiation

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Tellurite glasses are known to be highly promising materials for broadening the amplification bandwidth of Er3+-doped waveguide amplifiers (EDWAs), as they have large stimulated emission cross sections and broad emission bandwidth around the 1.55 micron wavelength. Furthermore, they exhibit a wide transmission range, the lowest vibrational energy among oxide glass formers, and good non linear properties. Nevertheless fabrication of channel waveguides in tellurite glasses appears to be a challenging task and so far it has been reported only in a few papers.

Here we report on the development of a method based on high-energy ion beam irradiation to create active waveguides in a tungsten-tellurite glass doped with Er2O3. A mask with long and narrow windows was obtained as follows. Double side polished silicon slices have been glued to each other with a proper spacer to ensure a gap of about 30 mm, then polished in cross-section to a thickness of about 100 micron. The waveguide stripes have been realized by 1.5 MeV N+ implantation in the glass sample through the mask with doses of 0.5, 1.0, 2.0 and 4.0 x 10^16 ions/cm2 using a 5 MeV Van de Graaff accelerator. Multimode light propagation has indeed been observed in these channels, confirming the effectiveness of this technique.

6475-09, Session 2

Three-dimensional integration of passive functions on glass by means of selectively buried waveguides and multiple ion-exchanges

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Ion-exchange on glass has been successfully used for more than twenty years to realize integrated optics devices such as wavelength multiplexers, splitters, optical amplifiers, lasers or sensors. One of the major issue is today to integrated more functions on a single chip which is usually realized be reducing the dimensions of the waveguides. Nonetheless this reduction is intrinsically limited by the maximum index variation achiev-

able. For this reason, we propose and demonstrate in this article the realization of 3D structures where waveguides are integrated vertically instead of horizontally. Based on the selective burial of ion-exchanged waveguides and the cascading of multiple ion-exchanges , the realization of "vertical" asymetric and symetric Y-junctions have been investigated theoritically and assessed experimentally. Indeed, 3mm length pump-signal wavelength duplexers with crosstalks lower than -30dB have been observed.

6475-10, Session 3

A reconfigurable self-collimation-based photonic crystal switch in silicon

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We present a reconfigurable, compact, low loss, optical switch in silicon. The device utilizes the self-collimation properties of photonic crystal structures and provides a technique for efficiently switching an optical wave guided through a pre-engineered dispersion-based photonic crystal self-guiding structure. The "loss tangent" of dielectric material in the switching region can be modified by external inputs to control the direction of propagation of the self-collimated signal thereby redirecting the light to attain switching. Based on the geometrical orientation and position of the applied electric field, optical waves can be completely redirected (switched), or partially routed towards any arbitrary direction on a Manhattan grid or network. We have found that the induced loss does not significantly attenuate the waves switched in any direction. The structure presented can be generalized to an arbitrary N by M interconnected switching network or fabric, where the switching topology can be dynamically modulated by the application of external fields. To attain switching, the free-carrier absorption loss of Si is controlled by carrier injection from forward-biased PN junction. Active switching was experimentally demonstrated for optical telecommunication wavelengths 1.3 and 1.5 microns.

6475-11, Session 3

Distributed subwavelength grating demultiplexer in SOI

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Two technologies have been actively pursued for integrated wavelength division multiplexing (WDM) systems: the etched diffraction grating multiplexer (EDG) and the phase array waveguide (AWG). Although their overall size is larger and spectral finesse smaller, AWGs are widely used. The principal fabrication challenges for EDGs include the requirement for excellent deeply etched sidewall flatness and verticality, necessary to ensure a low reflection loss by the diffraction grating walls. We propose a novel approach to the problem of high-reflectivity sidewalls for this type of structure in the form of a shallow-etched, distributed diffraction grating. A distributed reflector replaces the deeply etched grating wall. In addition to high reflectivity, the distributed grating has the advantage that the diffractive and reflective effects are decoupled and can be individually tailored, producing a customized reflection/diffraction spectrum. The design approach, using multilayer grating theory and Rigorous Coupled Wave Analysis (RCWA), is discussed. Finite-Difference Time-Domain (FDTD) modeling confirms the RCWA results and predict up to 79% efficiency for the echelle structure over a 60nm wavelength range. Device fabrication using electron beam lithography and electron-cyclotron resonance etching is presented. Device characterization and optical measurements are also presented.

6475-12, Session 3

Waveform generators based on parallel anti-symmetric waveguide Bragg gratings

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The use of arbitrary waveforms in optical communication and processing systems can produce multiple advantages. For example in optical code division multiplexing security and cardinality can be improved. In long haul communications the use of well designed waveforms may be used to reduce detrimental effects due to non-linearities such a ghost pulses. There are several approaches to generate optically arbitrary waveforms. Those approaches mainly operate in the spectral domain modulating the amplitude or phase. Here we propose a different approach which utilizes two Parallel Anti-Symmetric Waveguide Bragg Gratings.

We recently demonstrated Anti-symmetric Waveguide Bragg Gratings (AWBG) in applications such as Optical Add Drop Multiplexers, Encoders/Decoders and Interleaved Sampled Bragg Gratings.

We will demonstrate that with two parallel AWBG sign and amplitude of the signal can be controlled using a very compact and integratable device. Several Parallel AWBGs can be placed in a small area of an optical chip. Since they are passive devices a switching element is required to change the signal profile.

The devices will be fabricated by LightSmyth Technologies, Inc using silica on silicon technologies.

6475-13, Session 3

Narrowband Bragg reflectors in Ti:LiNbO3 optical waveguides and applications

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Bragg grating reflectors etched in amorphous silicon overlay films have been integrated with Ti:LiNbO3 optical waveguides to obtain a narrow (0.05 nm) reflectance spectrum with > 20 dB dip in the transmittance spectrum. These results were realized at a wavelength of 1542.7 nm for TE polarization on an x-cut, y-propagating substrate with gratings etched to a depth of ~ 93 nm in a 105 nm-thick silicon film over a length of 12.5 mm. The reflectance in the channel waveguides is found to be strongly dependent on the depth of the etched grating. The effect of the Bragg waveguide loss factor on the transmittance and reflectance spectra is investigated using a model for contradirectional coupling that includes an attenuation coefficient. Values for coupling constants k and amplitude attenuation constants a of samples etched for different time durations to control the grating depths are obtained from the model through the use of the depth of dips in the transmittance spectra and the spectral widths of the reflectance peaks. It is concluded that the corrugated Si overlay film increases the insertion loss by ~2.7 dB, and the loss is not significantly affected by grating depth. Applications of such integrated gratings have been demonstrated in the fabrication of distributed feedback type and Fabry-Perot type electrooptic intensity modulators, for low switching voltage and high extinction needs.

6475-14, Session 3

The quarter-wave Bragg reflection waveguide: analytical solutions and properties

B. R. West, McGill Univ. (Canada); A. Helmy, Univ. of Toronto (Canada)

The Bragg reflection waveguide (BRW), or one-dimensional photonic crystal waveguide, has recently been proposed for a wide spectrum of applications ranging from particle acceleration to nonlinear frequency conversion. In this work, we conduct a thorough analytical investigation of the quarter-wave BRW, in which the transverse wavevector has a phase thickness of pi/2 in each layer of the resonant cladding. For this case, an analytical solution to the mode dispersion equation is derived, and it is shown

that the quarter-wave BRW is polarization degenerate, although the TE and TM mode profiles differ significantly as the external Brewster angle condition in the cladding is approached. Analytical expressions for waveguide properties such as the modal normalization constants, propagation loss, and overlap factors between the mode and each waveguide layer are derived. Finally, a perturbation theory is developed to calculate dispersion and tuning curves for the waveguide.

6475-15, Session 4

Self-focusing in high-power optical fibers

G. R. Hadley, A. V. Smith, Sandia National Labs.

Recently the use of “vortex” beams of high azimuthal mode number has been proposed as a way of increasing the maximum peak power throughput of optical fibers beyond the few MW allowed for Gaussian beams by self-focusing. We report a numerical investigation of these and other schemes using a beam propagation approach that includes a Kerr-type nonlinearity.

6475-16, Session 4

Goal oriented adaptive finite element method for precise simulations of optical components

L. W. Zschiedrich, S. Burger, F. Schmidt, Zuse Institute Berlin (Germany)

Adaptive finite elements are the method of choice for the precise simulations of optical components. A prominent example is the computation of propagating modes of optical waveguides and fibers. Any adaptive method is based on an error estimation of the quantity of interest (goal, e.g. propagation constant or field distribution). The error estimator steers the adaptive refinement. The mesh hierachy and convergence depend strongly on the goal. For example in the computation of leaky modes one is interested in the longitudinal attenuation. So error estimator should be based on the imaginary part of the propagation constant which is typically orders of magnitudes smaller than the real part. We demonstrate that a goal orientated error estimator captures the damping factor very efficiently.

6475-17, Session 4

Design issues with MMI based photonic switches and routers

L. W. Cahill, La Trobe Univ. (Australia)

There is a demand for reliable photonic switches and routers, of moderate order, that can be integrated easily into photonic integrated circuits. One device type that has shown some promise in such applications is the integrated multimode interference (MMI) structure. For some time, low order MMI devices have been fabricated and used to provide coupling, splitting, combining, switching and WDM routing functions.

One of the disadvantages of using low order devices in switching and splitting applications (such as 2x2 switches) is that if a switch or splitter of larger dimension is required, then it is necessary to use an array of the smaller dimension switches or splitters. The architecture of such switches typically involve a large number of crossovers of the linking waveguides. Moreover, such switches usually have poor power balance and therefore may require the inclusion of dummy switches to restore the power balance. The use of MMI couplers in a generalized Mach-Zehnder configuration has offered the promise of integrated switches having good power balance without needing external crossovers. Similarly, low order MMI splitters have a significant fabrication, real estate and performance advantage over Y junctions.

However the successful fabrication of moderate and high order MMI devices offer significant challenges. As the order of the switch or splitter is increased it becomes progressively more difficult to achieve satisfactory performance in practice. The performance of simple WDM routers based on the MMI structure similarly tends not to live up to expectations.

This paper examines the design criteria and design primitives that are commonly used to carry out the design of MMI photonic circuits and highlights their shortcomings.

6475-18, Session 4

Light exctraction from OLEDs: the waveguide perspective

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Organic light emitting diodes (OLED) are deemed to be valuable future light sources for displays and general illumination. In the last decade remarkable progress was made concerning materials, lifetime, and production techniques of OLEDs. One of the remaining challenges is the increase of the light extraction efficiency. Due to the internal structure of the device the light emitted by electron-hole recombinations within the electroluminescent layer may be transferred to several channels: to slab guided modes, to substrate guided modes, and, to some limited extent only, to air propagating modes, directly.

In order to get some physical insight where and why photons may be trapped in the slab waveguide geometry, a modal analysis is a good starting point. In configurations where metallic materials are used, the transversal magnetic light is prone to be annihilated by coupling to surface-plasmon polaritons which may have propagation length of a few microns only. The high index of refraction of the emitting material and an indium-tin-oxide electrode, eventually, contributes to light confinement within guided modes for both polarisations. In order to evaluate what parts of the dipol-like emission are transferred to what channel, both the Finite-Difference-Time-Domain-Method and an analysis based on a Green-functions approach can be used. The latter method is a quite fast tool, which is well suited for an optimisation of the layered structure.

From the OLED perspective, light trapped into guided modes is lost unless it is recycled to air propagating modes. This can be achieved by e.g. statistical scattering centers and deterministic grating structures. Thus, the grating design in order to increase the outcouplimg efficiency of OLEDs is similar to the design of free-space grating couplers for waveguide applications. Several strategies aiming at the increase of the light exctraction efficiency of OLEDs will be discussed in detail.

6475-19, Session 4

Theoretical analysis of active ring microresonator filter

H. Chen, Yangtze Univ. (China)

Optical filters are one of the key components in dense wavelength division multiplexed systems for wavelength filter, multiplexing, and switching. Common optical filters are Fiber Bragg gratings, arrayed waveguide gratings, and cascaded Mach-Zehnder filters. They are excellent devices for filtering purposes but their complexity or dimensions strongly increase for applications in high-density wavelength division multiplexed systems. In advanced systems, filters based on coupled resonators are more attractive due to their dimension, integrability, optical performance, and flexibility.

This paper addresses on the theoretical analysis of a novel active ring microresonator filter, which is fabricated on Er-Yb co-doped phosphate glass. The filter characteristics of the proposed filter is analyzed by transfer matrix method, some universal relations for coupling of optical power between microresonator and dielectric waveguides and pump power are presented. The analytical expressions of filter bandwidth, free spectral range, finesse, and notch depth are derived. Numerical results demonstrate that the change of pump power do not alter the resonance performance of ring micro- resonator filter, the improvement of which will have important effect on output characteristics of filter: reducing the filter bandwidth and increasing the finesse of the resonator filter.

6475-20, Session 4

Automatic design and optimisation of Si nanophotonics devices using finite element frequency domain solvers

T. P. Felici, D. F. G. Gallagher, Photon Design (United Kingdom)

A numerical optimization technique coupled with a finite element frequency domain solver was applied to a variety of Si nanowire photonic devices, including micro-resonator filters, 90º bends and splitters, in an attempt to improve transmissions or matching to predefined criteria. The optimisation procedures are iterative in nature, in that they approach the optimal solution by exploring a sequence of carefully selected points in the parameter space. For any optimisation procedure to be effective, a good optimiser needs to be coupled with an efficient solver capable of modeling correctly all device configurations allowed by the parameter space. In the case of electromagnetic problems, it is particularly important that the divergence free condition is obeyed. The solver used here satisfies this condition and therefore greatly reduces the chances of the optimiser finding artificial optimal solutions with incorrect field distributions.

Another problem facing EM optimisation problems is the random small errors caused as the Finite Element grid changes with changing device configurations. The optimisation technique used must therefore prove to be sufficiently robust to be insensitive to these small random errors.

We present a deterministic global optimisation method, which systematically subdivides the parameter space to split more quickly in regions most likely to contain an optimum. Since the entire parameter space is eventually explored, this optimisation technique is not only guaranteed to (eventually) find the globally optimal solution, but can also show other interesting local optima. The method works well even in the presence of the random errors typically occurring in this class of problems.

6475-21, Session 5

Closed-loop design of a semiconductor laser

J. V. Moloney, J. Hader, The Univ. of Arizona and Nonlinear Control Strategies; M. Fallahi, L. Fan, The Univ. of Arizona; S. W. Koch, Philipps-Univ. Marburg (Germany)

We demonstrate, for the first time, a complete closed-loop semiconductor heterostructure design, wafer growth verification and end device input-output characteristic determination for a 1.3 micron InGaPAs quantum-well device without employing adjustable fit parameters. Each step in the process is verified experimentally. Critical microscopically computed inputs include optical gain and refractive index spectra and, radiative (spontaneous) and non-radiative (Auger) recombination rates. Cutback experiments on cleaved semiconductor lasers uniquely determine intrinsic and extrinsic cavity losses, thereby leaving no free adjustable parameters to be determined. We emphasize that the approach outlined here is applicable to a broad class of semiconductor material systems, enabling the laser designer to explore different material constituents and structural modifications with the goal of targeting a specific wavelength or performance criterion of the end laser device. This predictive capability provides the capability to fast-track to a chosen device without costly and time consuming multiple growth and packaging cycles.

6475-22, Session 5

Integrated optoelectronics in an optical fiber

J. V. Badding, The Pennsylvania State Univ.; P. J. A. Sazio, A. Amezcua Correa, Univ. of Southampton (United Kingdom); T. J. Scheidemantel, The Pennsylvania State Univ.; C. E. Finlayson, Univ. of Southampton (United Kingdom); N. F. Baril, D. Won, B. R. Jackson, V. Gopalan, The Pennsylvania State Univ.

Via a microfluidic chemical deposition technique, we have fabricated tubes, solid nanowires, and co-axial heterojunctions composed of metals, single-crystal semiconductors, and polycrystalline elemental or compound semiconductors within the empty spaces of microstructured optical fibers. These structures combine the flexible light guiding capabilities of an optical fiber with the electronic and optical functionalities of semiconductors. Our approach provides an elegant and powerful method to spatially organize materials at dimensions down to the nanoscale and allow for co-operative photonic and electronic processes between them. New types of devices that integrate multiple functions not previously possible in a fiber geometry may now become possible.

6475-23, Session 5

Photonic components for 100GBE

M. Schell, Heinrich-Hertz-Institut für Nachrichtentechnik Berlin GmbH (Germany)

100 GB Ethernet is the coming standard for high bit rate data communication. Key in realizing cost efficient transmitters and receivers is the right balance between electrical and optical complexity. We will discuss various approaches from direct modulation to higher order phase shift keying, with a close look on the technical status of the components, their maturity, and the current and future cost potential.

6475-24, Session 5

A new physical approach to understanding bend loss in optical fibers

J. D. Love, C. J. Durniak, A. N. Ankiewicz, The Australian National Univ. (Australia)

Transmission losses due to the bending of single-mode optical fibres and waveguides has traditionally been explained and quantified in terms of two key mechanisms: (i) a transition loss that occurs because of the abrupt change in radius between the straight and bent parts of the fibre or waveguide, and (ii) a continuous loss associated with free-space radiation from the length of fibre of constant bend radius. Over the years this description has been further refined to account for the fundamental mode field shift on bent fibres and waveguides, and the minimisation of bend loss has been addressed through a number of sophisticated designs for the fibre and waveguide refractive index profiles, as well as offsets for the straight and bent waveguide lengths.

A new physical description that simultaneously incorporates both transition and bend loss is based on the coupling of optical power between the fundamental mode and a sequence of cladding modes along the bent fibre due to curvature change. A set of coupled mode equations is derived that quantifies the coupling of power between these modes in terms of the rate of change of curvature along the bend.

It will be shown through simulations that bend loss can be almost reduced to zero for an arbitrary minimum bend radius by (i) controlling the maximum rate of change of curvature along the bend and (ii) using a suitably low-index fibre coating to inhibit cladding mode absorption.

6475-25, Session 6

Design of mid-infrared photodetectors enhanced by surface plasmons on grating structures

Z. Yu, G. Veronis, M. L. Brongersma, S. Fan, Stanford Univ.

Mid-Infrared photodetectors and imaging systems operating in the vicinity of 10 microns wavelength are important in applications ranging from night vision to astronomy research. To suppress noise caused by thermal fluctuation, usually these detection systems have to be cooled, which greatly increases the cost and limits the portability. To improve signal/noise ratio, it is desirable to reduce the active detector volume from which the noise arises without affecting the absorbed light power.

In this paper, we computationally explore the use of surface plasmons in these systems to improve the signal/noise ratio. The proposed structure consists of a metallic slit, surrounded by a linear grating structure. The entire structure is placed on top of an insulating oxide. The slit is filled

with absorptive semiconductor material, and has a width that is far smaller than the operating wavelength. The metal regions serve both as electrical contacts, and as a concentrator that funnels light into the deep-subwavelength slit.

To maximize the concentration effects, we combine two distinct mechanisms that relate to the presence of the slit and the grating structure. The slit forms a Fabry-Perot resonator, and light absorption in the slit is resonantly enhanced. The grating, on the other hand, enhances the light absorption in the slit, by converting incident electromagnetic waves into surface plasmons on the metal surface that can be funneled into the slit. With a careful choice of the geometric parameters of the structure, these two mechanisms can be made to occur at the same wavelength. Using this scheme, we design and optimize a photodetector operating at a wavelength of 9.8 microns with a roughly 250 times enhancement in the absorption per unit of volume of semiconductor material compared to conventional photodetectors operating at the same wavelength.

6475-26, Session 6

SPR waveguide sensor based on combined sensing of modal, phase, and amplitude changes

R. Levy, S. Ruschin, Tel-Aviv Univ. (Israel)

The Surface Plasmon Resonance effect is known to produce both amplitude, attenuation, and phase changes in the propagating SPR wave. When a metallic SPR layer is combined with an underlying dielectric waveguide film, enhanced sensitivity can be achieved due to the interaction between the surface plasmon and waveguide modes [1]. A diversity of sensing schemes has been proposed using either of these two effects. In a recent publication we demonstrated that enhanced sensitivity and flexibility can be achieved when combining the two effects in a Mach-Zehnder configuration with variable splitting ratio [2].

In this presentation we shall describe a new scheme of enhanced sensitivity based on combined sensing of modal changes including amplitude, phase, and shape. The scheme is extremely simple, consisting of a single SPR-waveguide structure supporting two modes acting as sensor section. The two modes are made to interfere by an abrupt discontinuity of the sensing waveguide into a thinner single-mode output waveguide. The geometrical parameters of the entire scheme are chosen as to produce almost total cancellation of the field propagating into the output waveguide. This delicate balance is very sensitive to small changes in the waveguide's environment. Calculated values show sensitivities of an order of magnitude higher compared to previously reported SPR sensors [1]. Additional sensitivity and extended working range can be gained by allowing external control of the differential phase between the propagating modes.

[1] J. Ctyroky, J.Homola, et al. Sensors and Actuaturs B 54 (1999) 66-73.

[2] R. Levy, A. Peled and S. Ruschin, Sensors and Actuators B, In Press, (2006)

6475-27, Session 6

Compact couplers between dielectric and plasmonic slot waveguides

G. Veronis, S. L. Fan, Stanford Univ.

Plasmonic waveguides have shown the potential to guide subwavelength optical modes, the so called surface plasmon polaritons, at metal-dielectric interfaces. In particular, a metal-dielectric-metal (MDM) structure supports a subwavelength propagating mode at a wavelength range extending from DC to visible. Thus, such a waveguide could be potentially important in providing an interface between conventional optics and subwavelength electronic and optoelectronic devices. In MDM plasmonic waveguides the propagation length of the fundamental mode is limited by material loss in the metal and is on the order of tens of microns at frequencies around the optical communication wavelength of 1.55 microns. Thus, conventional dielectric waveguides must be used to carry the optical signal over longer distances. The propagation length in such waveguides is primarily limited by fabrication related disorders and is orders of magnitude larger than the one of MDM plasmonic waveguides. Couplers between MDM and dielectric waveguides will therefore be essential components for optical interconnects.

In this paper, we investigate the properties of couplers between high-index contrast dielectric waveguides and MDM subwavelength plasmonic waveguides. We show that a coupler created by simply placing a dielectric waveguide terminated flat at the exit end of a plasmonic waveguide can be designed to have a transmission efficiency of 68% at the optical communication wavelength. We also show that the transmission efficiency of the couplers can be further increased to 93% by using optimized compact nonadiabatic tapers. In both cases the transmission response is broadband. Finally, we investigate the properties of a Fabry-Perot structure in which light is coupled in and out of a plasmonic waveguide sandwiched between dielectric waveguides.

6475-28, Session 6

Long range plasmonic waveguide devices with Au and PFCB polymer: design and fabrication

J. Guo, R. Adato, R. Gollapalli, J. Jiang, M. Davenport, The Univ. of Alabama in Huntsville; Q. H. Liu, Duke Univ.

Surface plasmon waves in optical frequencies can be supported along the boundary between two optical materials with opposite signs of the dielectric constants, such as a dielectric and a metal. But surface plasmon waves attenuate rapidly in propagation due to the Ohmic loss in the metal materials. In order to reduce the loss in metals, bulk metals need to be reduced to nanometer scale thin metal sheets or metal strips. Since each interface of the metal sheets or strips support one surface mode, both interfaces have to be symmetrical in order to make two surface waves propagating with the same propagation constant. Because it is difficult to grow thick (greater than 10 micron) dielectric layers such as silicon oxide or silicon nitride on metals, we choose to use perfluorocyclobutyl (PFCB) polymer as the dielectric layers. PFCB is optically transparent in the visible and near infrared wavelength range and also chemically and mechanically stable in a large temperature range.

We use photolithographically patterned thin Au strips embedded in PFCB as the plasmon waveguides, and investigate the propagation loss of waveguides of various designs. We will show our simulation and fabrication results of various plasmonic waveguide devices, such as couplers, splitters, and resonators.

6475-29, Session 6

Long-range surface plasmon waveguides and devices in lithium niobate

P. Berini, Univ. of Ottawa (Canada) and Spectalis Corp. (Canada); G. A. Mattiussi, Epocal, Inc. (Canada); N. Lahoud, R. Charbonneau, Spectalis Corp. (Canada)

Lithium niobate is a well-understood material and its use in electro-optic and non-linear integrated optics is well-established. The use of this material within the context of plasmonics is rather unexplored yet the potential for interesting applications exists owing to the peculiarities of the surface plasmon field and to the presence of metallic features. Of particular interest is the use of long-range surface plasmons supported by a thin metal film of finite width surrounded by lithium niobate. The finite width of the metal film provides 2-D confinement allowing integrated optics architectures to be adapted. The metal is centered in the optical path so it can also be used to apply electric fields to the material with good overlap. Furthermore, long-range surface plasmons can propagate over appreciable lengths (cm's) allowing useful non-linear and electro-optic interactions to be accumulated. Various structures will be discussed including straight and curved waveguides, Bragg gratings and electro-optic elements. The fabrication of such structures (a thin narrow metal film embedded in lithium niobate) will also be addressed and preliminary experimental results presented.

6475-31, Session 7

Digital holographic microscopy for nanometric quality control of micro-optical components

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Digital Holographic Microscopy (DHM) is an imaging modality reconstructing numerically the wavefront from a single digitalized hologram. Quantitative data are derived simultaneously from the amplitude and phase of the complex reconstructed wavefront diffracted by the object and it is used to determine the refractive index and/or shape of specimens with accuracy in the nanometer range along the optical axis, and a lateral resolution below the micron. Compared to phase shifting interferometry, standard in micro-optics quality control, DHM offers similar performances in resolution, accuracy, repeatability and field of view, and has in addition three main advantages: DHM is faster, as the wavefront is obtained from a single hologram (capture time of a few microseconds), while at least three acquisitions are required with phase shifting techniques, resulting in a low sensitivity to external perturbations (vibrations and ambient light); the accuracy of the apparatus is not limited by moving parts accuracy, as DHM is exempt of it; the numerical procedures of DHM for automatic wavefront corrections enables a simplification of the optical design and makes it a versatile tool to obtain a wide range of information such as surface topography, phase function, aberrations, ROC, lens height and surface roughness. The theoretical basis of this feature will be exposed and illustrated by examples. DHM can be used without adaptations to investigate a wide variety of micro-optical component, including cylindrical, square and strong aspheric lenses, cornercubes or diffractive elements. DHM ease of use, flexibility, rapidity and accuracy let envisage great perspectives in systematic micro-optical components investigation.

6475-32, Session 7

Fabrication of 400GHz spacing 1.62 nm bandwidth flat-top arrayed waveguide gratings (AWGs)

M. Maweidong, Accelink Technologies Co., Ltd. (China); W. Li II, Huazhong Univ. of Science and Technology (China)

A 400GHz spacing AWG with a ultrahigh bandwidth (1.62 nm @1dB) has been fabricated by PECVD process. The average insertion loss, ripple, uniformity, PDL and total crosstalk of AWG device is 5.6, 0.52, 0.97, 0.22 and 33 dB, respectively. It is a key for making athermal DWDM devices based on Interleaver and AWG cascading method.

6475-34, Session 7

Two-photon absorption for the realization of optical waveguides on printed circuit boards

G. Langer, M. Riester, Austria Technologie und Systemtechnik AG (Austria)

The integration of optical interconnections in printed circuit boards (PCBs) is an emerging field for optical communication that has grown rapidly in the past 10 years. PCB level connections were identified early in the development to be of critical importance to control the cost associated with a system. So, although a number of concepts and demonstrators are available at present, the key issue still is to identify a technical concept, which allows for the realization of optical interconnections that are compatible to existing PWB manufacturing processes. Above all, the material in which the optical interconnections are embedded has to withstand increased temperatures and lamination pressures as well as various wet chemistry processes.

AT&S uses two-photon absorption (TPA) laser structuring to realize optical circuits in a special polymer layer. A near infrared laser is applied working in the femto-second regime. The high photon density that can be reached in the laser's focus results in a modification of the properties of the optical polymer, which is usually photosensitive in the ultraviolet regime only. Here an increase of the refractive index of the optical polymer is attained. The technology allows a modification within the volume resulting in 3D-microstructures inside the polymer layer. Laser power, focus and propagation speed are the parameters to tune the properties of the waveguides embedded within the polymer layer. In addition to the capability of 3D structuring, TPA allows one step fabrication, which reduces costs and production time compared to etching procedures or conventional UV lithography processes. Moreover, this technique allows varying the waveguides cross section geometry and diameter by simply varying size and form of the structuring laser focus.

Whereas the realization of optical waveguides is not challenging anymore the coupling of waveguides with opto-/electronic components is rather delicate. We show a path towards generating optical waveguide coupling structures that allow rapid and cost effective coupling of active and passive optical components to the waveguides.

6475-35, Session 7

Micro ring cavity resonator incorporating total internal reflection mirrors

D. Kim, W. Choi, Y. Choi, Chung-Ang Univ. (South Korea); J. C. Yi, Hong Ik Univ. (South Korea); Y. Chung, Kwangwoon Univ. (South Korea); N. Dagli, Univ. of California/Santa Barbara

Compact photonic integrated circuits have been a very active research area ever since the inception of integrated optics for the application of the wavelength division multiplexing networks. One of the main size limitations to regular integrated optics based circuits is the weak optical confinement. This makes it very difficult to change the direction of optical waveguides in a very short distance with low loss. To resolve this difficulty total internal reflection (TIR) mirrors are used. Such mirrors can be combined with regular optical waveguides and can reduce the size of PIC drastically. Very compact micro ring resonators can be formed by combining TIR mirrors with regular waveguide. In this case, coupling in and out of such a compact resonator is achieved using the deeply etched 2x2 multimode interference (MMI) coupler. The biggest premise of these devices is their very small size compared to other wavelength selective devices. Large numbers of resonators can be integrated on a chip, to increase functionality. We investigate the properties of the MMI coupled micro ring cavity resonator with the TIR mirrors and the semiconductor optical amplifier. The length and width of an MMI are 142 μm and 10 μm, respectively. The free spectral range of the resonator is approximately 1.698 nm near 1571 nm and the extinction ratio is about 16.5 dB. The full-width at half-maximum is about 0.22, and finesse and Q factor are more than 7 and 7000 respectively. These devices might be useful as optical switching and add-drop filters in a photonic integrated circuit or as small and fast resonator devices.

6475-36, Session 8

Nanophotonic integrated lasers

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The unique optical properties of photonic crystals allow a dense and simple integration of optical functionality on a small footprint. We have investigated the integration of tunable photonic crystal (PhC) lasers with a wavelength monitor. The tunable lasers are based on two coupled PhC waveguides with slightly different length. PhC mirrors are placed at the end, joint and front of the two waveguides. Tuning is achieved by a variation of the injection currents in the two segments. The wavelength monitor, which is placed behind the rear mirror of the laser, consists of a multimode PhC waveguide. Mode coupling between the fundamental mode

and a higher order mode results in dips in the waveguide transmission (mini-stopband). Two photodiodes are integrated with the wavelength monitor. The diode at the exit of the waveguide monitors the power in the fundamental mode, the second photodiode is placed lateral to the waveguide and monitors the power in the higher order mode. Any deviation from the target wavelength results in a change of the ratio of the two photocurrents, whereas a change of the laser power will results in a proportional change of the two currents. The lasers have high sidemode suppression ratios between 30 and 45 dB and output powers above 25 mW. The tuning range of the devices is around 20 nm. The photocurrents of the integrated diodes show a clear dependence on the laser wavelength, in good agreement with simulations of the wavelength monitor transmission.

6475-37, Session 8

Superprism phenomena in low index 3D polymer photonic crystal

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The superprism effect in low index polymer photonic crystal is investigated. The woodpile structures were fabricated using a layer-by-layer method. It was found that there is no complete photonic bandgap (PBG) in the low index 3D photonic crystal structures. However it shows extremely sensitivity to the wavelength and angle of the incident light due to the strong anisotropy of photonic band structures. It shows the potential of these low index polymer photonic crystals to be utilized for wavelength-division-multiplexing (WDM) and beam steering application.

6475-38, Session 8

Silicon-based low-loss photonic crystal waveguides

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Photonic crystals (PhCs) are bandgap materials for light, i.e., PhCs are semiconductors for photons. The concept of PhCs was introduced in 1987 by Sajeev John and Eli Yablonovitch, respectively. In PhCs the photonic band structure (PhBS) replaces the dispersion relation of photons in a homogenous dielectric medium. The PhBS results from scattering and interference of light at periodically alternating domains of material with different dielectric constants.

Silicon is the dominating material in today's microelectronics, especially in modern telecommunications, and therefore a lot of experience in microstructuring of silicon exists. Its high dielectric constant makes it a promising candidate for PhC fabrication. Furthermore, the possibility of integrating electronics and optics on one chip is of great advantage for silicon-based PhC devices.

To meet demands on optical telecommunications and data processing of the next few decades, it is necessary to develop optical devices on very small scale. This requires high-index materials like silicon.

We present ridge waveguides and PhC waveguides etched in a new high-index-contrast material made of a thin silicon slab embedded in two silica layers. Hence fully symmetrical structures can be realized and two important conditions for low-loss guiding of light in PhC waveguides can be matched: The symmetry avoids polarization mixing and the high index contrast leads to strong confinement of light, so the PhC waveguides allow theoretically lossless guiding of light because of operating completely below the lightcone. This opens the door for tayloring dispersion properties or slow down the light using PhC waveguides.

6475-39, Session 8

Photonic crystal slab reflectors for compact passive and active optical devices

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One- and two-dimensional photonic crystal (PhC) slabs have many applications in integrated optics. For wave-guided modes whose dispersion characteristics happen to lie above the light line, coupling with the radiated modes is made possible. The wave-guided "state" of the related photons is transitory, thus the photonic structure can operate in both wave-guided and free space regimes. This new approach, named 2.5D microphotonics, constitutes a major extension of planar technology through exploitation of the third ('vertical') dimension [1].

For photonic integration, by using this concept, broadband and compact photonic crystal slab reflectors can be designed. They exploit the ability of high index contrast PhC to slow down waveguided photons, which allows a very good control over the lateral escape losses, resulting in a very efficient extraction of photons in the radiated mode [2].

The introduction of these reflectors in MOEMS (Micro Opto Electro Mechanical) devices shows great promises in terms of widening of the spectrum of (electromechanically actuable) optical functions, achievable with further enhanced compactness structures.

The purpose of our work is to design and fabricate PhC-MOEMS devices, based on the association of such InP-PhC slab reflectors with vertical structuration of InP/air gap-based multilayers.

First results have been obtained on a highly selective tunable polarized Perot-Fabry filter, combining a bottom InP/air Bragg mirror and a top PhC reflector [3]. A PCSEL (Photonic Crystal Surface Emitting Laser), based on the same structure and including a gain medium, is under process. We have also considered the association of several PhC slabs (monolithical and heterogeneous integration) to obtain enhanced performances (selectivity, compactness, polarization control ...).

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6475-40, Session 8

Nanofluidic tuning of photonic crystal circuits

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By integrating soft-lithography-based nanofluidics with silicon nanophotonics, we demonstrate dynamic, liquid-based addressing and high delta n/n (~0.1) refractive index modulation of individual features within photonic structures at subwavelength length scales. We show ultracompact tunable spectral filtering through nanofluidic targeting of a single row of holes within a planar photonic crystal. We accomplished this with an optofluidic integration architecture comprising a nanophotonic layer, a nanofluidic delivery structure, and a microfluidic control engine. Variants of this technique could enable dynamic reconfiguration of photonic circuits, selective introduction of optical nonlinearities, or delivery of single molecules into resonant cavities for biodetection.

6475-41, Session 9

Hybrid organic-silicon electro-optic materials and devices

D. C. Abeysinghe, R. L. Nelson, Air Force Research Lab.; J. W. Haus, B. Birchfield, Univ. of Dayton

The electro-optic response of silicon-organic composite materials consisting of electro-optic polymers and silicon are modeled and fabricated in an attempt to greatly increase the electro-optic response as well as to achieve opto-electronic integration. Devices are fabricated using a combination of e-beam lithography and dry etching techniques. We will show how these devices could be served as optical sources, electro-optic modulators or optical switches.

6475-42, Session 9

Nonlinear electro-optic composite materials

B. Birchfield, Univ. of Dayton

Electro-optic modulators are critical components in the procurement of optical communications. Current modulation schemes, such as the Mach-Zehnder, are used in order to obtain desired optical communication demands. Such modulation devices are often several centimeters in length and a lot or research has been done on reducing this size and making a modulation technique as compact as possible. Recent findings in nonlinear optical materials have created a way to reduce these dimensions. A nonlinear optical composite material is proposed by incorporating the electrodes into an electro-optic (EO) polymer layer. This composite material has optical properties that are different to that of the bulk constituents. With effective medium theory (EMT), comparisons can be made between the bulk material and composite properties. Finally, the incorporation of this composite material will also be discussed in the use of a practical device.

6475-43, Session 9

Active Maxwell Garnett polymers

R. L. Nelson, Air Force Research Lab.

Maxwell Garnett composites have existed for quite some time but only recently have the nonlinear optical properties been investigated. Most the work has been with metals but there has been some activity with dielectrics. Here we present the results of a fabrication of an all-dielectric Maxwell Garnett electro-optic composite material fabricated with an electro-optic polymer host material. Theoretical advantages for uses in integrated photonics include an enhanced nonlinear response as well as refractive index tailorability.

6475-44, Session 9

Tailored nanoaggregates from functionalized organic molecules

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Self-assembly to mutually aligned nanofibers from symmetrically functionalized p-quaterphenylenes on a muscovite mica substrate has been demonstrated recently [1]. The typical width and height of the fibers is in the nanometer scale, but their length can reach several hundred micrometers, depending on the growth conditions. That way the fibers bridge the gap between microscopic and macroscopic dimensions and are an important step forward towards integrated nanoscopic optoelectronics. They proof that it is possible to generate ordered organic nanoaggregates in a bottom up fashion from functionalized molecular building blocks. The symmetrically functionalized p-quaterphenylenes emit intense, polarized blue light after unpolarized UV-excitation, the mostly single-crystalline fibers act as waveguides. Upon implementing electron push-pull functional groups like chlor and methoxy groups to the molecular building block new properties of the nanoaggregates have been generated: the nanofibers exhibit increased non-linear optical properties, acting, e.g., as frequency doublers after excitation with NIR femtosecond laser pulses [2]. Depending on the growth conditions the chloro-methoxy-p-quaterphenylene forms either paralell nanofibers or nano-branches on a muscovite mica substrate, adding another degree of freedom for the design of, e.g., resonator structures.

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6475-45, Session 9

Microfabrication of integrated atomic vapor cells

D. B. Conkey, R. L. Brenning, A. R. Hawkins, Brigham Young Univ.; W. Yang, B. Wu, H. Schmidt, Univ. of California/Santa Cruz

The integration of hollow anti-resonant reflecting optical waveguides (ARROWs) with vapor cells on silicon chips provides a compact platform for a number of optical applications. These include the study of quantum coherence effects such as electromagnetically induced transparency and single-photon nonlinearities as well as frequency stabilization standards. The use of hollow waveguides allows for light propagation in low index (vapor) media with compact mode areas. ARROWs make particularly attractive waveguides for this purpose because they can be interfaced with solid core waveguides, microfabricated on a planar substrate, and are effectively single mode (higher order modes are suppressed). ARROW fabrication utilizes an acid-removed sacrificial core surrounded by alternating plasma deposited dielectric layers, which act as Fabry-Perot reflectors. We have constructed a demonstration platform consisting of solid and hollow core waveguides integrated with rubidium vapor cells. Rubidium was used because it is of particular interest for studying quantum coherence effects. Liquefied rubidium was transferred from a bulk supply into a septum-sealed, on-chip glass vapor cell in an anaerobic atmosphere glovebox. The presence of rubidium vapor within the hollow waveguide platform was confirmed through optical absorption measurements. Coherence dephasing in the small dimensions of the ARROW (an important effect in quantum coherence studies) can be addressed in our platform by adding a buffer gas and adding passivation coatings to the ARROW walls. Buffer gas is added through the re-sealable septum on the vapor cell and monolayer coatings are attached in a liquid phase directly after waveguide fabrication.

6475-46, Poster Session

Improvement of the signal-to-noise ratio in a glass-based guided-wave optical microphone

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Our group is developing a guided-wave optical microphone that can be used in a high magnetic field, such as MRI (Magnetic Resonance Imaging). The optical microphone has a square diaphragm as a pressure-sensitive structure and a straight single-mode waveguide on the diaphragm. Previously, the minimum detectable sound pressure level of a fabricated glass-based guided-wave optical microphone was estimated to be 140 dB-SPL or higher. Since the optical microphone must be able to detect normal speech ranging from 55 to 65 dB-SPL, the signal-to-noise ratio of the guided-wave optical microphone must be improved by a factor greater than 10,000 by increasing sensitivity and reducing noise. Also, sensitivity of the microphone and resonance frequency of the diaphragm are dependent on the area and thickness of the diaphragm. In this study, in order to increase sensitivity, the diaphragm area was enlarged from 16

mmX16 mm in the previous study to 20 mmX20 mm. The diaphragm thickness remained 0.15 mm, same as previously reported. According to theoretical calculations, phase sensitivity and resonance frequency were 2.5 mrad/Pa and 3.4 kHz, respectively. Sensitivity was theoretically expected to be twice as high as that in the previous study. To reduce noise, a bandpass filter with passband from 300 Hz to 3 kHz was used. After fabrication of the optical microphone, sound pressure, ranging from 100 to 122 dB-SPL and with a frequency of 1 kHz, was applied to the microphone. The measured output of the optical microphone was almost proportional to the sound pressure, and the minimum detectable sound pressure level of the microphone was experimentally evaluated to be 100 dB-SPL.

6475-47, Poster Session

Silicon p-i-n optica waveguide modulators fabricated on the silicon and silicon-on-insulator (SOI) substrates

R. W. Chuang, M. T. Hsu, National Cheng Kung Univ. (Taiwan)

A silicon p-i-n diode-based Mach-Zehnder waveguide modulator was fabricated using the spin-on-dopants to pattern the respective p and n regions. Unlike the conventional ion implantation method which is normally used to define the p and n doping region, the utilization of the spin-on-dopants (SODs) offers a cost-effective alternative to speed up the doping process while not compromising the device performance. Heavily-doped p+ and n+ regions with a surface concentration of 1E19 cm-3 were diffused and driven into the 1E15 cm-3 p- substrate to a diffusion depth of ~1-micron. The boron and phosphorous spin-on dopants were used as p+ and n+ doping sources, respectively. The diffusion processes were carried out in nitrogen ambient at 900-1000 degree Centigrade for an hour. The dopant concentration and the corresponding diffusion depth were determined based on the Spreading Resistance Probe (SRP) technique. Furthermore, the doping difference between the heavily doped and p- regions provides a refractive index difference (delta n) of ~0.0469 as a function of injected free carriers in silicon via a Kramers-Kronig transform. This lateral p+-p-n+ (p-i-n) region along with 5000 Å PECVD-grown SiO2 layer, which has a lower refractive index value compared to silicon, forms a functional waveguide modulator.The operation of the modulator was demonstrated by employing 1.5-micron continuous-wave (cw) InGaAsP-based laser diode as a light source, and a germanium (Ge) photodiode as a detector. The laser beam was coupled into the waveguide modulator in normal direction, and both input and output ends of the modulator were polished in order to increase the coupling efficiency. The efficiency of the modulator depends critically on the core width and driving current. The resultant intensity modulation index so determined was approximately 20%

6475-48, Poster Session

Broadband, low ripple 860nm GaAs/AlGaAs quantum well superluminescent diode

C. E. Dimas, R. A. Merola, C. T. Vishton, H. S. Djie, B. Ooi, Lehigh Univ.

High performance superluminescent diodes (SLDs) are key components for high resolution biomedical imaging systems using optical coherent tomography (OCT). Since water and the ocular fundus absorption is minimal at near infrared wavelengths about 850 nm, SLDs in this regime are particularly attractive for ophthalmology applications such as human retinal OCT . We report the fabrication of broadband, low ripple SLDs on GaAs/AlGaAs double quantum well (QW) structure grown on GaAs substrate. The device consists of 4 μm wide index guided ridge waveguide emitter sections and a 50 μm wide broad area slab photon absorber section. The ridge waveguide configuration at the emitter section is adopted to provide highly efficient coupling to the single mode optical fiber. The function of the absorber is to prevent optical feedback oscillation, hence, suppress lasing action under high current injection. To further enable high current injection and reduce the spectral ripple, antireflective coating is applied on the emitter facet. The device gives a Gaussian-like spectrum with a bandwidth as large as 65 nm at a peak wavelength of 860nm. The corresponding power exceeds 1.5 mW, and the spectral modulation is 0.3 dB. Measurements are taken under continuous wave and room temperature operation at an injection current of 200 mA. This performance corresponds to a low coherence length of 5 μm, which would enable competitive axial resolution in the ophthalmic imaging wavelength regime.

6475-49, Poster Session

Image quality improved 1X8 multi-mode interference coupler

A. X. Wang, R. T. Chen, The Univ. of Texas/Austin

Multimode Interference (MMI) couplers are widely used in many photonic integrated circuits (PICs), such as power splitters, optical switches, phased array demultiplexiers and so on. Based on self-image principles, these MMI couplers offer important advantages such as compact size, low cross talk and imbalance. Some theoretical works have been carried out to improve the image quality through a high index contrast in the multimode section.

Low index-contrast materials, for example, silica and polymer MMI devices, have gained distinguished popularity in the past decades due to their low insertion loss and polarization insensitivity. The square cross-section buried channel access waveguide provides a good profile matching to the fundamental mode of an optical fiber as well. To improve the image quality, an attractive approach with the introduction of deeply etched air trenches at the boundary of multimode section was proposed.

We apply the proposed design to the case of a 1X8 MMI coupler. Using the 3-dimentional semi-vector beam propagation method (3-D SVBMP), we compare the performance for the devices with and without air trenches. The optimized MMI couplers fabricated on ZPU12 serial polymers demonstrate an improved image quality in terms of loss, imbalance, and contrast ratio, compared with conventional MMI coupler on the same chip, as the simulation predicts.

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6476-01, Session 1

Waveguides and devices in silicon photonics

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Silicon Photonics is experiencing a significant increase in interest due to emerging applications and several high profile successes in device and technology development. One of the most prominent trends in silicon photonics recently has been a trend towards miniaturising waveguides. The shrinking of the device dimensions provides advantages in terms of cost and packing density, modulation bandwidth, improved performance in resonant structures, and an increase in optical power density within the devices. In this paper we analyse several silicon photonics devices based on both small rib and strip waveguides. We have previously reported on issues related to single mode propagation and polarisation independence of silicon waveguides, and produced design rules for such small waveguides that are reviewed heret. Subsequently a design of a multi-GHz modulator based on depletion of carriers that can achieve the same phase shift for both TE and TM polarisations (polarisation independence) is presented. Means of increasing filters' free spectral range and the quality factor, whilst achieving polarisation independence, is also discussed. A novel switch in SOI technology that is based on total internal reflection is also discussed. It comprises a SiO2 carrier restrictive boundary to create a precise reflection interface and improve carrier injection efficiency over previously reported devices. Finally, we report a novel fabrication technique for silicon photonic circuits and devices.

6476-02, Session 1

Hybrid integration platform based on silica-on-silicon planar lightwave circuit

W. Lin, J. C. K. Sun, K. M. Schmidt, ANDevices, Inc.

This talk reviews the development of hybrid integration of opto-electronic active devices on Silica-on-Silicon Planar Lightwave Circuit (PLC) platform. A hybrid integrated transmitter with 4 wavelengths on silica PLC bench is presented.

6476-03, Session 1

Interaction of metal-oxide functionality on optical chips

R. M. Osgood, Jr., R. M. Roth, D. Djukic, Columbia Univ.

Metal-oxide materials offer an important number of useful functionalities for hybrid integrated photonic chips, including optical scanning, frequency conversion, modulation, etc. This talk will describe an approach to realizing high-performance metal-oxide thin films and for demonstrating their utility for high-performance devices.

6476-04, Session 1

ROADM architectures and technologies for agile optical networks

L. A. Eldada, DuPont Photonics Technologies

We describe the various needs for reconfigurable optical add/drop switching in agile optical networks. For each network need, we present the different ROADM subsystem architecture options with their pros and cons, and describe the optoelectronic technologies supporting each architecture.

6476-05, Session 2

Silicon microspheres for ingrated photonics

A. Serpengüzel, Koç Univ. (Turkey)

Electrophotonic integrated circuits (EPICs), or alternatively, optoelectronic integrated circuit (OEICs) are the natural evolution of the microelectronic integrated circuit (IC) with the addition of photonic capabilities. Traditionally, the IC industry has been based on group IV silicon, whereas the photonics industry on group III-V semiconductors. However, silicon based active and passive photonic microdevices have been making strands in "siliconizing" photonics. Silicon microspheres with their high quality factor morphology dependent resonances (MDRs), or whispering gallery modes (WGMs), are ideal candidates for passive optical channel dropping, and active modulation in the near-infrared communication bands. In our experiments, we are using silicon microspheres with a refractive index of 3.5 and a radius of 500 micrometer operating at wavelengths of1300 and 1475 nm. The observed MDRs have quality factors of 100000, which are limited by the sensitivity of the experimental setup. These optical resonances provide the necessary narrow linewidths, that are needed for high resolution channel dropping and modulation applications. In addition to channel dropping and modulation in the near infrared, we are investigating the channel dropping and modulation properties of this system in the mid infrared experimentally and numerically. The silicon microsphere and silica optical fiber (or potentially silicon on oxide (SOI) waveguide) system shows promise as a versatile building block for silicon based integrated photonics.

6476-06, Session 2

Microring and microdisk resonator integrated circuits on a silicon chip

A. W. Poon, L. Zhou, H. Chen, C. Li, J. Y. Lee, Hong Kong Univ. of Science and Technology (Hong Kong China)

Silicon microring and microdisk resonators that can be electrically switched using embedded electronics and fabricated by CMOS-compatible processing promise compact devices with exciting functionality for optoelectronics integrated circuits. Here we examine three microresonator integrated circuits, each utilize carrier concentration changes for microresonator resonance wavelength tuning.

(i) External-feedback microring resonator switches - a microring resonator is input and output-coupled to a single U-bend waveguide acting as an external feedback. The feedback relative phase is tuned using a forward-biased lateral p-i-n diode across the waveguide. We show a resonance wavelength tuning span exceeding that of directly tuning the microring refractive index.

(ii) Optical-pulse generators using a microring resonator with asymmetrically integrated p-i-n diodes - a microring notch filter is integrated with two cross-connected oppositely biased lateral p-i-n diodes of the same length at two sides of the microring. Under an NRZ electrical signal with the same forward and reverse bias voltages, the resonance wavelength is equally blueshifted at both the high and low signal levels, whereas the resonance wavelength is redshifted to near the passive microring resonance wavelength at the signal equilibrium level. Thus, for an input-coupled continuous-wave light beam at the blueshifted resonance wavelength, such modulated resonance wavelength generates an optical-pulse train following the electrical signal transition edges.

(iii) Metal-oxide-semiconductor (MOS) capacitors embedded microdisk modulators - a microdisk resonator is electrically tuned using a selectively integrated ring-shaped MOS capacitor in accumulation mode. One design employs a microdisk with two notches that enable input and output waveguides butt coupling to the microdisk resonator modes, without the constraint on evanescent coupling.

6476-07, Session 2

Slow light photonic crystal waveguides and their use for confinement control

H. Benisty, L. Martinelli, C. Cambournac, Institut d'optique/LCFIO, CNRS (France); A. David, Univ. of California/Santa Barbara; O. Khayam, Institut d'optique/LCFIO, CNRS (France); C. Weisbuch, Univ. of California/Santa Barbara and Institut d'optique/LCFIO, CNRS (France)

Since the successful realisation of low loss photonic crystal waveguides and very high Q nanocavities, both successes have been seen as due to better technology and better but separate designs. However, there are intrinsic relations between the tightness of confinement and the low group velocity. The modal aspects can be analytically continued from one aspect to the other, for example. We will emphasize the possible consequences that can be drawn from this continuity. We will aim at presenting a set of possible functionalities along two lines: firstly, in monomode waveguides such as "W1" and akin ones, this results in very shallow high Q modes and thus a "photonic conductivity" that can be modulated through modest voltage swings in electrooptic devices. Secondly, in multimode waveguides, low group velocity at ministopbands can be exploited to de-confine light. Demultiplexing CWDM devices with appreciably good characteristics can be made out of this property. Results from the european FUNFOX project in this area will be discussed.

6476-08, Session 3

Photonic device concepts based on photonically engineered nanostructures

G. Bona, IBM Almaden Research Ctr.

At IBM Research we are exploring several promising photonic device candidates for switching and lasing all based on engineered nanostructures.

Hybrid combinations of organic materials with high Kerr-nonlinearities and resonant, planar photonic nanostructures are promising candidates for fast switching elements. Two-dimensional grating structures with active organic laser materials are showing good performance as optically pumped lasers.

This presentation will give an overview of some approaches such as using planar circular-grating resonators to obtain fast switches. The planar design enables controlled in and output coupling as well as integration with other optical functions. Design optimization is performed with full 3D finite differential time domain numerical simulations. The all-optical switching performance is compared to that of Fabry-Perot micro-cavities. These micro-cavities with organic materials sandwiched between dielectric mirrors are also used to determine the nonlinear coefficients of promising materials using an ultrafast pump and probe setup we spectrally resolve the nonlinear transmission of pulses. The analysis is performed for various organic materials. In the same setup switching behavior can eventually be demonstrated with appropriate materials.

6476-09, Session 3

Nanophotonics for information systems

Y. Fainman, Univ. of California/San Diego

The field of nanophotonics is finding myriad applications in information technology, health care, lighting, sensing and national security. Experts predict that nanolithography will reach a resolution of 16 nm by 2020, and that both top-down and bottom-up integration methods will become feasible, enabling reliable, scalable, power-efficient and cost-effective methods for the miniaturization of future systems. Over the past decade, significant progress has been made in the engineering of inhomogeneous composite materials (e.g., dielectrics, semiconductors, metals, organic, quantum dots) and nanophotonic devices with unique optical properties such as polarization and spectral dispersion, negative refraction, nonlinear polarization and quantum effects. Numerous applications, however, rely on our ability to create adaptive and reconfigurable optical devices as well as interfacing with biological and biochemical processes. These applications led to establishing a new research area that we call optofluidics, where fluids are used to create adaptive optical elements, control them, as well as establish interfaces with biochemical systems. We will present our recent research results on nanophotonics and optofluidics, as well as on their integration into sub-systems.

6476-10, Session 3

Optical integrated circuits and networks on micro/nano-scale

E. Lee, Inha Univ. (South Korea)

This paper presents an overview on the theory, design, fabrication, and integration of micro/nano-scale optical networks (O-MNN) that we attempt to realize on what we call "optical printed circuit boards" (O-PCBs) and "VLSI photonic integrated circuit chips"(VLSI-PICs). It is an extension of the macro-scale optical networks down to the range of micro/nano-scale. It also intends to compliment the limitations of the electrical networks and circuits composed of electrical PCBs and VLSI electrical circuits (VLSI-ICs) by way of processing optical signals through optical networks by way of optical printed circuit boards (O-PCBs) and VLSI photonic integrated circuit chips (VLSI-PICs). The new optical systems consist of 2-dimensional planar arrays of optical wires, circuits, and networks of micro/nano-scale to perform the functions of sensing, storing, transporting, processing, switching, routing, and distributing optical signals on flat modular boards or chips. The paper discusses scientific and engineering issues, including design issues for the miniaturization and integration of the micro/nano-photonic systems. The paper also discusses issues and challenges relating to their applications for telecommunication network systems, computer network systems, transportation systems, and bio/sensor systems.

6476-11, Session 4

Semiconductor integrated multi-spectral photo receiver for WDM networks

B. Gilman, M-Borg, Inc.

Semiconductor Integrated Multi-Spectral Photorecever (SIMP) for WDM Networks uses novel physical and design principles of building semiconductor based integrated optoelectronic components, capable of effective multi-wavelength optical signal modulation, demultiplexing, photo detecting and amplifying, all in a single chip format. Above principles include new types of electrical and optical control of semiconductor layer properties allowing for semiconductor integrated patterns to perform different operating functions in the different parts of the structure. The needs for compact, efficient, easy-to-fabricate, reliable components for optical signal modulation and wavelength demultiplexing are widely recognized in both WDM Networks and Computer Chip Interconnection areas.

Proposed methods of semiconductor waveguide transparency control by means of doping and/or electrically enhanced optical excitation represent a non-conventional advanced approach to the design and fabrication of optical modulators and wavelength discriminating components. Due to their efficient optical modulation and demultiplexing capabilities combined with the well established semiconductor integrated fabrication procedures the proposed principles are expected to make a substantial impact on optoelectronic and fiber optic communication components as well as computer chip interconnection markets. Design alternatives can be used to produce integrated components for multiple applications such as wavelength demultiplexers (dmux), tunable photo detectors (TPD) for WDM Networks, fast Parallel Chip Interconnections (PCI) and others.

6476-12, Session 4

Analysis of extraordinary self-images with weak-guiding multimode interference structure for wavelength MUX/DeMUX

J. K. Hong, S. Lee, J. Jung, J. Kim, Hanyang Univ. (South Korea)

This paper would like to analyze the principal causes for the extraordinary self-imaging (Ex_SI) phenomenon which is not mentioned in the multi-mode interference (MMI) theory. Moreover, to more conveniently apply this Ex_SI phenomenon to optical devices, the analytical formula and the graphical method will be suggested.

Guided-modes in a multimode waveguide (MMW) have different effective widths from each other. Because the effective widths of the guided-modes are related to the phases of them, the guided-modes' interference pattern could be different from the information of the MMI theory. This paper analyzes the phase mismatch and discuss about the principal reason of the Ex_SI phenomenon. For the numerical analysis of the Ex_SI phenomenon, the mode propagation analysis is applied. Also, this paper expresses the analytical formula of the guided-modes' phase mismatch with more accurate analytical formula of the effective width of the fundamental mode. In addition, the graphical solution will be suggested to easily apply the Ex_SI phenomenon to optical devices.

The existence of the Ex_SI is also proved experimentally with the silica-based MMI couplers. For the accurate experimental results, the output intensities of the MMI couplers which have different MMW lengths are measured using the fiber-coupling method.

The Ex_SI phenomenon could form a 0-dB self-image at about 4-times shorter distance than the well-known self-imaging phenomenon. From this point, it would be expected that the Ex_SI phenomenon can be effectively applied to some kinds of optical devices which are splitting/combining the optical signals with different physical properties such as wavelengths and polarizations.

6476-13, Session 4

Integrated Sagnac loop mirror circuit for fiber Raman laser

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Broadband reflection mirror is an important optical device to make a wide resonance bandwidth of the multi-wavelength fiber Raman laser cavity including fiber Bragg grating mirrors. Though a chirped fiber Bragg grating has been used for broadband reflection mirror device, it still requires more improvements in the control of reflection wavelength bandwidth and reflection ratio, which are key design parameters of broadband reflection mirror. In this research, we propose an integrated mirror circuit based on polarization-maintaining fiber Sagnac loop interferometer to utilize for tunable resonance cavity of Raman laser. It is available to control both resonance bandwidth by varying the length of polarization-maintaining fiber and reflection ratio by tuning the polarization state of Sagnac loop. Broad resonance bandwidth of 40 nm could be obtained from Sagnac mirror with the 0.14 m length of polarization-maintaining fiber.

6476-14, Session 4

A high-dynamic range transimpedance amplifier with compression

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A transimpedance amplifier (TIA) with nominal 130 MHz bandwidth, maximum 22 kOhms gain, 114 dB dynamic range at the input, 18 nA rms equivalent input noise current, and very high input current (~20 mA) overdrive capability is described. To improve a dynamic range at the input of TIA, a compression of the high input current was implemented. Proposed TIA has therefore two regions of operation: a linear region, when the input current is small, and a compression region, when the input current is high and would normally cause the saturation of the TIA. An input/output transfer characteristic of the TIA exhibits monotonicity till approx. 10 mA of the photocurrent at the input. Above this current at the input, the transfer characteristic of TIA starts to slightly fall down, but circuit still handles the input current pulses properly. Using the compression technique we could achieve low rms equivalent input noise current as well as very high input current overdrive capability of the TIA. The circuit is optimized for an external large-area photodiode. Therefore, the parasitic capacitance of the photodiode used at the input is quite high (~2 pF). The presented high-dynamic range TIA circuit represents the input stage of a complete hybrid optical receiver with integrated differential 50 Ohms output driver. The circuit is realized in 0.35 um SiGe BiCMOS technology and the chip area of the complete receiver is approx. 1.24 mm^2.

6476-15, Session 4

Linear trans-impedance amplifier with functional active loads for analog optical communication systems

D. Kim, H. Kang, I. Jung, Y. Choi, Chung-Ang Univ. (South Korea)

We developed a CMOS-based trans-impedance amplifier (TIA) circuits for analog optical communication systems. Our TIA structure is based on common-source configuration and a novel functional active load (FAL). Proposed FAL structure is composed the two PMOS that have the symmetric structure. In those schemes, transfer curve of TIA can be tuned by the gate voltage of FAL in the way to improve linearity. In analog optical transceiver, TIA employing the FAL can suppress the nonlinearity originated from various sources. Because the nonlinearity deteriorate analog communication systems, enhancement of linearity is crucial to improve the analog transceiver performances.

In this work, we have designed and fabricated the TIA with FAL in a 0.35 μm CMOS technology. The linearity and gain of TIA are controlled by the variation of transfer curve with the change of the FAL bias voltage. Especially, our proposed scheme shows 10 dBc suppression of the 3rd order inter-modulation distortion.

6476-16, Session 5

Free-space quantum key distribution at GHz repetition rates

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While quantum key distribution (QKD) can practically produce of cryptographic key, the performance of any QKD system is critically limited by the signal-to-noise ratio (SNR) on the single-photon channel, and is often limited to key rates that are too low for continuous one-time-pad encryption. We will present our efforts to increase the key production rate by increasing the repetition rate of the quantum channel to 1.25 GHz and beyond by the adaptation of telecommunications clock-recovery techniques, as well our efforts in reducing the SNR on a free-space single-photon channel both by reducing the temporal gating well below the duration of a single clock cycle, and by operating in the H-alpha Fraunhofer window. These techniques take advantage of high-efficiency silicon single-photon avalanche photodiodes with <50ps timing resolution and are expected to enable operation at a repetition rate of 2.5 GHz.

6476-17, Session 5

Progress toward quantum communications networks: opportunities and challenges

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Technologies, Inc.; R. J. Hughes, D. Rosenberg, G. Peterson, K. P. McCabe, J. E. Nordholt, K. Tyagi, P. A. Hiskett, N. Dallmann, Los Alamos National Lab.

Encrypting communications is rapidly becoming an important area of research for securing networks worldwide. Today's key distribution methods, however, depend on algorithmic complexity and the assumed computational capabilities of a potential eavesdropper. The difficulty of predicting future progress in mathematics and advances in computing ultimately limit the lifetime of current key distribution practices. Quantum key distribution (QKD) offers a potential solution for securing optical networks of the future. The security assurances of QKD have their foundation in the fundamental laws of physics. QKD is accomplished by encoding information in the quantum states of individual photons, transmitting photons over a quantum channel, and performing a protocol for distilling a shared secret key.

Although many experimental demonstrations of QKD have been reported, several practical aspects need to be addressed before widespread deployment is possible. These challenges include scaling QKD to more than two communicating parties, carrying the quantum channel over existing network infrastructures, and integrating devices such as single photon sources, interferometers, and detectors into reliable, low-loss optoelectronic subsystems.

In this paper, we report on recent experiments investigating the applicability of quantum communications to existing optical networks. We present experimental measurements of impairments and noise backgrounds that may impact quantum channels when multiplexed onto fibers carrying DWDM traffic, and describe the options for selecting wavelengths for quantum channels on networks. Finally we review recent progress made in integrating the components and subsystems required for QKD and their potential application more broadly to the emerging field of quantum communications.

6476-18, Session 5

Quantum dot devices for single photon quantum systems

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Improved single photon sources and single photon detectors are quantum enabling technologies that will allow rapid advancement of quantum key distribution systems and the pursuit of linear optical quantum computing. Our group is pursuing on-demand single photon sources based on single InGaAs quantum dots (QDs) in microcavities. We have demonstrated about a 20X improvement in performance as compared to an attenuated laser source, and we have also demonstrated single photon operation up to temperatures as high as 120 K.

We are also pursuing a new type of single photon detector, the quantum dot, optically-gated field effect transistor (QDOGFET). This device has demonstrated single photon sensitivity with an extremely low dark count rate. The device is conceptually very simple: an inverted high electron mobility transistor (HEMT) structure with a layer of self-assembled QDs between the gate and the channel is grown using molecular beam epitaxy. The QDs act as an optically-addressable floating gate. The device is engineered so that the electron-hole pair created by an absorbed photon is split by the internal electric field. The photogenerated hole is captured by the QD and remains trapped there until the device is reset. Photoconductive gain enables a single absorbed photon to generate a signal that is larger than the noise of this device. In addition to measuring single photons, this device may be able to be used as a photon number resolving detector, in which the number of photons in a pulse can be determined.

6476-19, Session 6

Onboard optical interconnect technologies for 10 Gbps and beyond

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A number of optical interconnect solutions for high speed boards have been demonstrated in the recent years. We demonstrated prototypes with fully integrated passive components on backplanes for board-to-board optical interconnect systems operating at data rates up to 12 Gbps. Optical interconnects may become a viable alternative to electrical boards at high speeds. Current developments in electrical boards indicate that 10-15 Gbps could potentially be achieved with electrical wiring. At higher speeds, fully electrical boards can become technically and/or financially challenging. Unfortunately, the existing onboard optical solutions do not support these data rates per channel either. We will discuss optical interconnect architectures and technologies required to speed up optical boards.

6476-20, Session 6

Low-cost micro-optics for PCB level photonic interconnects

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We present different low-cost micro-optical modules for photonic interconnects at the printed circuit board-, multi-chip-module-, and at the inter- and intra-chip level.

6476-21, Session 6

Fabrication of a 10Gbps/ch flexible optical-printed circuit board (FO-PCB)

H. Lee, S. An, S. Lee, B. O, E. Lee, Inha Univ. (South Korea)

We report on the fabrication of a flexible optical interconnection module that has been incorporated as a part of an optical printed circuit board (O-PCB). Optical waveguide arrays are fabricated by UV embossing technique on the flexible polyethylen terephthalate (PET) substrate. An optical waveguide arrays including vertical light coupling reflectors and alignment keys are fabricated by embossing technique using a silicon mold. The silicon mold has a waveguide array structure, vertical light coupling reflectors, which have a 45Ῡ-slope shape at the ends of the waveguide, and alignment keys for optoelectronic and electrical devices. The silicon mold is fabricated by two steps (1) dry etching to form rectangular waveguide arrays and (2) wet etching to form 45Ῡ-reflectors. Silicon mold is used to form waveguide arrays including reflectors, and alignment keys on flexible substrate concurrently in one step embossing process. UV curable polymers are used as waveguide materials including core and cladding layer. Electrical lines connecting optoelectronic devices and driver ICs are patterned on the cladding layer and a couple of VCSEL and PD are mounted on the cladding layer. We calculated optical losses of flexible waveguide array with various curvatures and we describe performances of the FO-PCB module. And we tested the transmission performance of each waveguide channel up to 10Gbps data stream. Flexible electrical lines are replaced with high-speed optical interconnection between chips over four waveguide channels up to 10Gbps on each.

6476-22, Session 7

Nanophotonic devices and systems to enable optical interconnects

D. V. Plant, McGill Univ. (Canada)

Recent advances in nanophotonics have prompted researchers to envision highly integrated systems involving a mix of optoelectronics and electronics to achieve enormous connectivity on a single substrate. The confluence of new architectures and technologies opens up new optical interconnect paradigms. We will review recent systems and technology results.

6476-23, Session 7

Toward convergence in optoelectronic integration, packaging, and interconnects

L. A. Eldada, DuPont Photonics Technologies

We describe opportunities for convergence in optoelectronic integration, packaging, and interconnects. Convergence to shared technologies and solutions across markets is key in order for the optoelectronics industry to achieve economies of scale and thrive. We present a barrier analysis, a roadmap, and an action plan developed by an industry consortium at MIT.

6476-44, Session 7

Application of two-photon 3D lithography for the fabrication of embedded ORMOCER(r) waveguides

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The idea of applying the two-photon 3D lithography (2P-3DL) to an industrial printed wiring board (PWB) fabrication process is quite pioneering. Taking advantage of the unique rapid prototyping properties of 2P-3DL, which are its particularly inherent true 3D capability and its high flexibility, this lithographic method can be adapted and optimized regarding the direct laser-writing of integrated optical interconnects with tens of microns in diameter. This will push the method forward towards industrial fabrication of next generation PWBs with integrated optical layers, and put it on the leading edge of printed circuit board technology.

In this context, the concept of a direct laser-written embedded waveguide is based on the local increase of the refractive index of the exposed material, which is triggered by two-photon absorption at the laser focus. The laser induced refractive index difference forms the core of the waveguide, whereas the unexposed surrounding material forms the cladding. Thus, only one optical material is required to form the waveguide using true 3D lithographic process, which significantly simplifies processes. The material is subject to stringent requirements concerning the PWB production process: beside its high refractive index change, a low optical loss of the fabricated optical interconnect is required. The integration of the waveguide into the volume of the material also requires thick films up to 500 μm on the PWB substrate, and the material has to withstand the complete PWB fabrication process, where the board is chemically treated and exposed to high temperatures as well as high pressure during the lamination processes.

For this application, an inorganic-organic hybrid polymer (ORMOCER(r)) film is applied, cast onto a PWB substrate, and the two- photon 3D lithography system parameters and optics are tuned such that waveguides with a diameter of approx. 30 μm can be inscribed. The board is equipped with laser- and photodiodes, which are totally covered by the thick ORMOCER(r) film. The integration of the waveguide in such a preconfigured board requires precise 3D registration of the sample prior to the waveguide writing in order to align the waveguide relative to the optoelectronic components. By means of the 3D registration, the waveguide alignment is an inherent part of the fabrication process. The 3D capabilities of the 2P-3DL permit not only the fabrication of single embedded waveguides with a simple geometry, but also more complex waveguide structure (e.g. bundles) with largely arbitrary waveguide configurations.

In this paper, we present the development and realization of the two-photon 3D lithography for the fabrication of integrated optical interconnects on PWBs. The ultimate goal of this approach is the large scale fabrication of leading-edge PWBs with an integrated optical layer for additional functionality. The functioning of the fabricated and embedded waveguides is demonstrated by measurements of the essential parameters of such an optoelectronic system (photocurrent, optical loss, throughput, etc).

6476-25, Session 8

Type II InAs/GaSb superlattice focal plane arrays for high performance third generation infrared imaging and free space communications

M. Razeghi, A. D. Hood, Northwestern Univ.

High performance infrared imaging technology has been in high demand for meeting the stringent requirements of many applications in the area of defense and in the civilian space. High operating temperature, small temperature resolution, and extended wavelength ranges are among the defining attributes for third generation infrared imaging sensors. Recent advances the quantum mechanical modeling, material growth, and device processing of type II InAs/GaSb superlattice materials have resulted in the demonstration of an emerging and promising infrared technology positioned to meet and even surpass the current state of the art technology. Optimization and precise control of the material quality and device structure have resulted in the realization of high performance infrared sensors operating from 3 to beyond 20 ?m. Furthermore, processing improvements, such as effective sidewall passivation, have resulted in the demonstration of focal plane arrays in the mid and long wavelength infrared with noise equivalent temperature differences of well under 100 mK. Room temperature operation of a mid wavelength focal plane array has also been demonstrated.

Free-space optical communications has recently been touted as a solution to the “last mile” bottleneck of high speed data networks providing highly secure, short to long range, and high bandwidth connections. However, commercial near infrared systems experience atmospheric scattering losses and scintillation effects which can adversely affect a link’s uptime. By moving the operating wavelength into the mid or long wavelength infrared enhanced link uptimes and increased range can be achieved due to less susceptibility atmospheric affects. The combination of room temperature, continuous wave, high power quantum cascade lasers and high operating temperature type II superlattice photodetectors offers the benefits of mid and long wavelength infrared systems as well as practical operating conditions.

6476-26, Session 8

Ultra-compact monolithically integrated photonic switches in InP

D. A. Yanson, J. H. Marsh, Intense Photonics Ltd. (United Kingdom)

Optical switching has been a major area of interest since the advent of optical communication systems. Recently, much attention has been paid to semiconductor optical amplifier (SOA) switches, since they offer large extinction ratios and also have the ability to amplify the signal to offset the insertion losses. Particularly attractive are monolithic implementations of the switch, with the SOA gates and passive interconnects integrated on one chip. Besides having a reduced form factor, cost and power requirements, the chip offers nanosecond switching times and is suitable for use in optical packet switching networks.

We will report the realization of monolithic, fully integrated switches operating at wavelengths around 1550 nm. Indium Phosphide is an attractive integration platform, as light emitters, modulators, amplifiers and detectors can be integrated monolithically to generate, process and detect optical signals. Two key technologies have been developed to enable high-density photonic integration in InP: quantum well intermixing and total internal reflection mirrors and splitters. The former can reduce opti-

cal loss in passive waveguides and interconnects, while the latter can shorten their length and minimize the chip footprint. The demonstration and optimization of these technologies will be presented, followed by a description of the switch design and fabrication.

Monolithic switch devices with 1x2, 2x2 and 4x4 port counts have been successfully realized. The devices are extremely compact incorporating up to 24 SOAs on a 3.5 sq.mm footprint. Preliminary assessment of 1x2 switches indicates device operation as expected. Characterization of 2x2 and 4x4 devices is ongoing and the test results will be presented at the Conference.

6476-27, Session 8

Q-modulated semiconductor laser

J. He, Zhejiang Univ. (China)

Novel structures and mechanisms for high-speed modulation of semiconductor lasers are proposed and analyzed. The modulator consists of an anti-resonant Fabry-Perot cavity acting as a rear reflector of the laser. The change of the absorption coefficient in the modulator results in a change in the Q-factor of the laser, and consequently the lasing threshold and output power. Different structures with simulation results are presented, which involve a distributed feedback laser, a Fabry-Perot laser, a distributed Bragg reflector laser, or a wavelength-switchable compound cavity laser. The monolithically integrated Q-modulated laser (QML) has advantages of high speed, high extinction ratio, low wavelength chirp and no insertion loss, and it does not require bandgap engineering of the quantum well material as in conventional electro-absorption modulated laser (EML).

6476-28, Session 8

Postgrowth wavelength engineering of InAs/InAlGaAs/InP quantum-dash-in-well lasers

H. S. Djie, Lehigh Univ.

Modification of bandgap property in quantum-heterostructures using intermixing technique has enabled the integration of active and passive devices on a single semiconductor chip at postgrowth level in a simple and cost-effective way. Following the advance development of the InAs quantum-dashes/dots (QDs) on InP substrate, there has been an increasing interest to spatially modify the QD properties that offers the combined advantages of postgrowth bandgap engineering and the attractive QD device properties at long wavelength emission (1.3-1.6 μm) that is important for the optical telecommunications. In this paper, we demonstrate the emission wavelength tuning of InAs quantum-dashes within InAlGaAs quantum-wells grown on InP substrate, that gives the initial wavelength emission at ~1.6 μm. The impurity-free dielectric cap annealing and the nitrogen ion-implantation induced intermixing techniques have been implemented to spatially control the group-III intermixing in the structure, which produces differential bandgap shift of 80 nm and 112 nm, respectively. Transmission electron microscopy, optical and electrical characterizations have been performed to evaluate the quality of the intermixed QD material and bandgap tuned devices. Compared to the control (non-intermixed) lasers, the light-current characteristics for the 100 nm wavelength shifted QD lasers are not significantly changed suggesting that the quality of the intermixed material is well-preserved. The intermixed lasers exhibit the narrow linewidth as compared to the as-grown due to the improved QD homogeneity. The integrity of the QD material is retained after intermixing suggesting the potential application for the planar integration of multiple active/passive QD-based devices on a single InP chip.

6476-30, Session 9

Reliability of polymer-PLC-based photonic components, modules, and subsystems

L. A. Eldada, DuPont Photonics Technologies

We report on the reliability of state-of-the-art photonic components, modules, and subsystems based on polymer planar lightwave circuits. Tests conducted include Telcordia GR-1209-CORE/GR-1221-CORE qualification of components, Telcordia GR-1312-CORE/GR-63-CORE qualification of modules and subsystems, as well as accelerated aging tests that significantly exceed Telcordia requirements, such as aging at extreme temperature (5000 hours at 225°C), optical power (6000 hours at 1.5 W of 1550 nm light), and electrical power (10000 hours at double the operational power, resulting in 275°C local heating). The types of components, modules, and subsystems that we describe include variable optical attenuator (VOA) arrays, intelligent optical cross-connects (OXC), and fully reconfigurable optical add/drop multiplexers (ROADM).

6476-32, Session 9

Fabrication of 45-degree-ended polymer waveguides by single step embossing technique

S. An, H. Lee, S. Lee, B. O, S. Park, E. Lee, Inha Univ. (South Korea)

We report on the simple single-step fabrication of 45-degree-ended polymer waveguides by way of embossing technique. The merit of this waveguide is that it can allow vertical light coupling at the ends of the waveguide for both multimode and singlemode light waves. The waveguide embossing is done using silicon molds, which are pre-designed and etched to have the waveguide structure with 45℧-slope at each end of the waveguide. The 45℧-slope on the waveguide is to direct the light waves from the horizontal direction to the vertical direction and vice versa. The waveguide structures in the silicon molds are fabricated on (100)-type silicon wafer by dry etching. When the waveguide structures are patterned on the wafer, the end points of the each waveguide are tilted from the base alignment key of the (100) silicon wafer for the 45℧-slope wet etching. The slope of the etched sidewall is formed at 45℧ due to the dependence to the angle of the etch mask directions. Using this mold, UV embossing is performed to form the undercladding structure and 45℧-slope simultaneously. A metal film is deposited on the surface of the 45℧-slope to enhance the coupling efficiency. Then, the core polymer is filled and cured by UV irradiation. The uppercladding polymer is coated and cured to cover the waveguide core. This process is expected to reduce the number of processing steps and the cost.

6476-33, Poster Session

Novel 1x3 wavelength MUX/DeMUX using extraordinary self-imaging phenomenon

J. K. Hong, S. Choi, S. Lee, J. Jung, J. Park, Hanyang Univ. (South Korea)

This paper would like to suggest the novel 1x3 wavelength multiplexer (MUX)/DeMUX based on the multimode interference (MMI) structure. The novel 1x3 wavelength MUX/DeMUX is designed with considering the wavelengths of 1310nm, 1490nm, and 1550nm to apply optical transceiver modules which are one of the important devices to achieve the fiber-to-the-home (FTTH).

The suggested device is fabricated as buried-structure using silica (SiO_2) material with considering the fiber-coupling efficiency, and the index difference of core and clad layers is 0.75%. This 1x3 wavelength MUX/DeMUX is consisted by cascading two MMI couplers, and the general interference effect is applied to both the MMI couplers. Also, each MMI coupler is designed with the characteristics of separating/combining the specific wavelength.

Moreover, the extraordinary self-imaging (Ex_SI) phenomenon which is not expected in the MMI theory is applied to this novel device for compact and effective design. The substance of that phenomenon is presented in detail in another abstract for this conference by this author. Another advantage of the novel 1x3 wavelength MUX/DeMUX is that any other manipulation, such as electro-optic or thermo-optic effect, is not applied, so that the efficiency of fabrication could be improved.

This paper suggests the novel 1x3 wavelength MUX/DeMUX having low-

cost, high-performance, and effective-fabrication characteristics. The expected application field of the suggested optical device is an optical transceiver module for the end-user of optical communication network. Moreover, it shall be expected to design wavelength MUX/DeMUXs having smaller wavelength-space such as coarse wavelength division multiplexers (CWDM) with some other structural manipulations.

6476-34, Poster Session

Novel bio-signal processing technique with hybrid bio-system integrated with optical microcavity ring resonator

I. Jung, D. Kim, W. Choi, D. Kim, Y. Choi, Chung-Ang Univ. (South Korea)

Biosensors are devices that convert biological interactions to measurable quantities such as an electrical or optical signal. This signal contains information about a biological event, for example, presence of a specific biomolecule in a medium of interest. Important requirements that a biosensor should meet are high sensitivity, high detection speed, repeatability, specificity to the biomolecule of interest, and capability of real time detection. Micro-disk and micro-ring resonators have been proposed as sensitive chemical sensors and biosensors because of their high Q factors of resonance. These sensors depend on accurate measurement of the effective index change due to the presence of biomolecules on the surfaces of sensing areas.

We have demonstrated a novel bio-signal processing technique with hybrid bio-system integrated with optical micro-cavity ring resonator. The intensity of the transmitted light through the ring resonator has periodic sensitive region, as varying the wavelength of the incident light into the ring resonator. It is easy for the light of the single wavelength to fall into the insensitive regions because resonance profile is shifted by biomolecules on the surface of sensing areas. Our processing technique is based on using dual wavelength. In this scheme, very high sensitivity can be achieved by comparing the intensity of two incident lights which has channel spacing of the half period of the sensitive region. More detailed experimental results on novel bio-signal processing technique will be presented.

6476-38, Poster Session

Fabrication of polymer AWG demultiplexer using embossing technique

C. Choi, M. W. Lee, J. Sung, B. Kim, J. Yang, E. Lee, B. O, Inha Univ. (South Korea)

We fabricated an arrayed waveguide grating (AWG) demultiplexer for optical fiber communication systems and photonic integrated circuits. We also used an embossing technique to fabricated AWG instead of traditional semiconductor process, such as photolithography and etch. UV curable polymers (ZPU 12-47 and ZPU 12-45) was used as the core and the upper cladding layers. The polydimethylsiloxane (PDMS) mold used for the embossing process is made to a scale of 4 inch wafer. We tried the embossing onto a fused silica glass of wafer scale using the PDMS mold. After UV curing, the PDMS mold was peeled away carefully, and a pattern of AWG demultiplexer was left on the surface of that substrate. The upper cladding layer was coated over the patterned structure. The fabrication of the AWG demultiplexer was completed by a cleaving process. The residual layer produced after an embossing process was adjusted by the volume of polymer droplet. The embossing technique will have the potential for broad applications in fabrication of photonic devices.

6476-39, Poster Session

Preparation of surfactant-mediated nanoporous PMMA film

S. Lee, I. Chin, H. Kim, Inha Univ. (South Korea)

Nanoporous polymeric materials can be very useful as optical materials including optical planar waveguides. In this study, we prepared a porous poly(methyl methacrylate) (PMMA) film by spin-coating of a PMMA solution containing a water-soluble anionic surfactant, sodium dodecylbenzenesulfonate (NaDDBS). The structure of the nanoporous polymer including pore structure was affected by such parameters as the type of porogen and solvent, the molecular weight and its distribution of the polymer. Upon decomposing of NaDDBS, the nanoporous structure was formed, as observed by SEM. As the resulting pore size was much smaller than the wavelength of visible light, the thin polymer films with nanopores were optically homogeneous. The refractive index was found to be controlled by changing the amount of the surfactant. The refractive index decreased with the increase in the volume ration of the pore.

6476-40, Poster Session

Photonic crystal optical group delay device for optical code division multiple access

J. Sung, C. Choi, M. W. Lee, J. Yang, E. Lee, B. O, Inha Univ. (South Korea)

The Optical code-division multiple-access (O-CDMA) technology is potentially well suited for providing very flexible and high-capacity access to the vast networking capacity available in all-optical LANs. In the past two decades, there has been active research on O-CDMA based on a number of different schemes. We propose and demonstrate a photonic crystal optical group delay device, in which two dimensional chirped photonic crystal line defect waveguide induce the temporal optical group delay for time-spreading/wavelength-hopping O-CDMA. The photonic crystal line defect waveguide allows ultrasmall components and low group velocity due to its strong optical confinement by the photonic bandgap. And chirped photonic crystal waveguides, in which some structural parameters are gradually changed so that the photonic band characteristic is smoothly shifted. We discuss an optical delay line composed of hole-size-chirped waveguides in a two dimensional photonic crystal. When a short pulse signal with a wide spectrum comes into this device, a light localization and large delay occurs at different wavelengths and positions. This concept is effective for realizing a pulse waveform synthesizer and an en/decoder for time-spreading/wavelength-hopping O-CDMA. We have confirmed this device is possible in a practical design by Finite difference time domain simulation.

6476-41, Poster Session

Design and characterization of polymer waveguide grating coupler for normal fiber incidence

J. Yang, C. Choi, B. O, S. Lee, E. Lee, Inha Univ. (South Korea)

Optical interconnections are alternative techniques to fulfill the high-speed, high-density and large capacity required for future information network systems. Especially, fiber-to-waveguide interconnections are expected to provide a breakthrough to overcome the origin limitations of traditional electronic information systems, such as an electromagnetic interference and a crosstalk, and also make it possible to realize integration and electro-optical hybrid. In order to accomplish efficient coupling for optical fiber-to-waveguide interconnections, a novel waveguide grating coupler to vertically couple light from a fiber into a polymer waveguide is proposed. This type of coupler makes it easier to obtain a dense integration and is not need of making mirror facets. It works as an out-of-plane coupler to connect a waveguide with high-refractive-index and an optical fiber. For an efficient characterization of the waveguide grating coupler, the numerical tool is developed based on Bloch-wave analysis because it is one of the most attractive techniques to analyze uniform waveguide grating devices. In this work, we have optimized waveguide grating coupler and investigated its characteristics by analyzing coupling length and coupling efficiency.

6476-42, Poster Session

Nano-patterning fabrication by low energy lithography

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Nano-scale patternings for IC device and optical printed circuit board (OPCB) have been fabricated by low energy microcolumn lithography. The compact sized lithography system consists of a microcolumn, two 2-3/4 inch cubic chambers for a sample load-lock chamber and a main chamber. To obtain the large probe current while keeping the low e-beam energy, the appropriate bias voltages were applied to the accelerator and source lens of the microcolumn. Low energy e-beam lithography was carried out by following the sequence of PMMA coating, exposure, and development on silicon or glass substrates. The exposure parameters like the e-beam energy, dose concentration, and thickness of the resist were optimized by measuring the depth of the developed resist. By using these optimized parameters, the lines were patterned on the PMMA and the line width less than 60 nm has been achieved. The details of nano-pattering fabrication based on the low energy microcolumn lithography will be discussed

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6476-43, Poster Session

Fabrication of multilayer porous silicon optical filter

H. Yim, C. Choi, J. Sung, M. W. Lee, E. Lee, B. O, Inha Univ. (South Korea)

We reported on the characterization of porous silicon (PS) free-standing filter. The advantage of PS used as an optical filter can be easily fabricated by alternating current density because the refractive index of PS depended on current density. Porous silicon filter was fabricated by electrochemical anodic etching with p-type silicon wafer of 2 ohm.cm resistivity. The electrolyte was prepared by adding 49% HF into a mixture of water and ethanol. Here, ethanol was used to reduce surface tension. As the pore depth increases, the availability of fluoride ions at the point of reaction decreases. Therefore, the etch rate and optical thickness were decreased with the depth, respectively. We considered the linear-drifts in the porosity and thickness of the PS layer because the optical thickness depended on both the porosity and layer thickness. In our experiment, the layer thickness was only controlled because that thickness was easily varied by the etch time. Considering to the variation of the layer thickness with depth, the decrease of the etch rate with the etch depth can be compensated by increasing the etching time. After the PS growth process, the anodic electro-polishing current was applied to detach the PS structure from the substrate. The detailed characteristics, such as the reflectance and transmission, will be discussed in presentation.

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6477-01, Session 1

Progress in manufactured silicon photonics

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While investment in advanced silicon photonics research has gained popularity, Kotura with significant customer traction, has focused mainly on manufacturable designs and processes. This paper reviews recent gains in engineering developments where mature monolithic and hybrid methods are integrated to form high-performance manufacturable products with proven long-term reliability. Simplified device models that connect electronic and photonic properties are developed and parametric tradeoffs are discussed. Building block structures are described that lead to components and subsystems suitable for lean manufacturing and automation techniques. A strategy for a low-cost interface to single-mode fiber is presented as are photonic circuits for next generation equipment that require rapid power balancing, optical power transient suppression, subcarrier modulation for channel tracking and system health monitoring, transceivers, and ROADM components.

6477-02, Session 1

OLED-on-CMOS integration for optoelectronic sensor applications

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Highly efficient, low-voltage organic light emitting diodes (OLEDs) are well suitable for post-processing integration onto the top metal layer of CMOS devices. This has been proven for OLED microdisplays so far. Moreover, OLED-on-CMOS technology may also be excellently suitable for various optoelectronic sensor applications by combining highly efficienct emitters, use of low cost materials and cost effective manufacturing together with silicon inherent photodetectors and CMOS circuitry.

The use of OLEDs on CMOS substrates requires a top emitting, low-voltage and highly efficient OLED structure. By reducing the operating voltage for the OLED below 5V, the costs for the CMOS process can be reduced, because a process without high-voltage option can be used.

Red, green and blue OLED-stacks with doped charge transport layers were prepared on different dual-metal layer CMOS test substrates without active transistor area. Afterwards, the different devices were measured and compared with respect to their performance (current, luminance, voltage, luminance dependence on viewing angle, optical outcoupling etc.).

Low operating voltages of 3.2V at 100cd/m(c)˜ for the green p-i-n type phosphorescent emitting OLED stack, 4.85V at 100cd/m(c)˜ for the red phosphorescent emitting OLED stack and 4.5V at 100cd/m(c)˜ for the blue fluorescent emitting OLED have been achieved here. Therefore, the green emitting OLED stack is suitable for use in a CMOS process even within a regular 5V process option. However, the operating voltage achieved so far is expected to be reduced when using different top electrode materials.

Integrating such OLEDs on a CMOS-substrate provide a preferable choice for silicon-based optical microsystems targeted towards optoelectronic sensor applications, as there are integrated light barriers, optocouplers, fluorescence sensors, flow sensors or lab-on-chip devices.

6477-03, Session 1

Active silicon components for chip to chip interconnects

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Among the major challenges confronting the current initiatives to incorporate optical interconnect capabilities for chip to chip I/O is to define, develop and implement the necessary components required for a complete pipeline from source to receiver. For next generation integrated circuits, the need for multi-functionality and multi-dimensional integration has resulted in new demands on interface technology to yield massively parallel data and clock lines. At this point, such methods are primarily limited to static reflectors, filters and gratings for interface and optical routing. One of the crucial elements is to develop a high performance and flexible optical network to transform an incoming optical pulse train into a widely distributed set of optical signals whose direction, alignment and power can be independently controlled. This coupling can be achieved using several methods including active (primarily, MEMS-based) beam steering arrays. For chip to chip applications, the overwhelming majority of the recent research and development effort has been focused on source and detector technologies, but less attention has been devoted to flexible, reconfigurable beam steering modalities. A variety of approaches for such beam steering and distribution of both timing and data lines has been examined. This paper will present an overview of active, silicon components under development at the College of Nanoscale Science and Engineering for array-based I/O management with an emphasis on reconfigurable diffractive devices and adjustable, porous silicon-based components which combine optical beam steering, filtering and focusing capabilities. Design details along with initial performance data from prototype components will be presented.

6477-04, Session 2

High-speed, low-voltage optical receivers consisting of Ge-on-SOI photodiodes paired with CMOS ICs

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Silicon-based, monolithically-integrated optical receivers offer the potential of lowering the cost of optical interconnects through simplified packaging and leveraging established Si-manufacturing technology, in addition to enabling new applications such as inter- and intra-chip optical links that will require large-scale receiver arrays. Silicon photodetectors have progressed, and integrated receivers have been demonstrated to operate above 10 Gb/s; however, the poor efficiency of silicon in detecting 850-nm light results in fundamental tradeoffs in performance and/or operating voltage. In contrast, using Ge as the detector material opens the possibility of producing fast, efficient, and low-voltage photodiodes compatible with CMOS processing. We have fabricated planar, interdigitated Ge-on-SOI photodiodes in Ge absorption layers grown directly on SOI wafers. Devices with 10-micron square active areas, biased at -2 V, with an electrode spacing of 0.6 to 0.8 microns, exhibit dark currents less than 10 nA, bandwidths in excess of 23 GHz, and external quantum efficiencies of 52 % (0.35 A/W) at a wavelength of 850 nm. We have built and characterized three different optical receivers using 0.13-micron CMOS ICs: 1) a 15-Gb/s high-gain full receiver (transimpedance amplifier, limiting amplifier, and output driver); 2) a 10-Gb/s, low-power full receiver (powered by a single 1.1-V supply); 3) a 19-Gb/s high-speed receiver front-end (transimpedance amplifier only). These receivers achieve the highest operating speed, highest sensitivity at > 10 Gb/s rates, lowest-voltage single-supply operation, and lowest power consumption for any all-silicon devices reported to-date, and illustrate the performance that can be attained through combining Ge detectors with CMOS analog circuitry.

6477-05, Session 2

Waveguide integrated MIM tunnel junction NIR detectors

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Optical detectors based on an antenna-coupled tunnel junction devices integrated with submicron silicon waveguides are presented. These devices, which we believe to be the first waveguide-integrated metal-insulator tunnel junction detectors, are inherently broadband, and operate throughout the 1500-1650 nm region. The antennas are made as multilayer stacks, and the active devices are Ni-NiO-Ni edge junctions.

The antennas are fabricated using directional deposition through a suspended Ge shadow mask, using a single level of electron-beam lithography. The waveguides are patterned with conventional 248-nm optical lithography and reactive-ion etching, then planarized using shallow-trench isolation technology.

We also present measurements showing conversion efficiencies of 20% or greater (after correction for impedance mismatch), thus demonstrating the previously very low efficiencies (eta <÷1%) reported for antenna-coupled tunnel junction devices are due to poor electromagnetic coupling and poor choices of antenna metal, not to any inherent limitations of the technology. We also present high speed optical detection results for these devices, showing electrical bandwidths of > 20 GHz, limited by the apparatus.

6477-06, Session 2

Germanium on silicon photodetectors for telecom wavelengths

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The main forecast applications of silicon nanophotonics are on-chip optical interconnects and optical telecommunications. However, a number of fundamental challenges has to be addressed before this technology can successfully be used either to solve current microelectronic bottlenecks or to compete with III/V semiconductor components. One of the key components is the high speed silicon-based photodetector, sensitive for telecom wavelengths. One of the promising candidates to detect light ay these wavelength is to use germanium with strong absorption coefficient. Despite large lattice mismatch between Ge and Si, (about 4.2%), previous works have shown that epitaxial growth of high-quality germanium layers on silicon can be achieved using reduced pressure chemical vapor deposition (RP-CVD) or ultra-high-vacuum chemical vapor deposition (UHV-CVD). Due to a tensile strain after the epitaxial growth, a bandgap shrinkage yields absorption edge shift of about 50 nm is obtained in comparison with bulk Ge, thus allowing strong absorption up to the wavelength of 1.55μm, which is beyond the absorption edge of bulk Ge. The measured carrier mobility of holes was found to be ~1300 V.cm-2.s-1.

We report here experimental results of Ge on Si vertical PIN and MSM photodetectors. Different experimental set-ups have been used to determine cut off frequencies at both 1.31 and 1.55 μm wavelengths.

6477-07, Session 2

5GHz front-end for active pixel applications in standard 0.35um CMOS

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With the advanteges of low cost, low power consumption, high reliability and potential for large scale integration, CMOS monolithically integrated active pixel chips have significant application in optical sensing systems. The circuits discussed will have application in our Optical Scanning Acoustic Microscope System(OSAM), which involves a totally non-contact method of acquiring images of the interaction between surface acoustic waves (SAWs) and a solid material to be chracterized[1]. [2]. In this work, a ultra fast optical front-end using improved regulated cascade scheme is developed based on AMS 0.35μm CMOS technology. The proposed receiver consists of an integrated photodiode, a transimpedance amplifier, a mixer, an IF amplifier and an output buffer. By treating the n-well in standard CMOS technology as a screening terminal to block the slow photo-generated bulk carriers[3] and interdigitizing shallow p+ junctions as the active region, the integrated photodiode operates up to several gigaherts with no process modification. With multiinductive- series peaking technique, the improved ReGulated-Cascade(RGC) transimpedance amplifier achieves an experimentally measured -3dB bandwidth of more than 6GHz and a transimedance gain of 52dBohm, which is the fastest reported TIA in CMOS 0.35μm according to authors' knowledge. The 5GHz mixer produces a conversion gain of 13dB which greatly minimized the noise contribution from the IF stage. Followed IF amplifier and output buffer pick up and further amplify the signal for post processing. The whole of the electrical front end of the active pixel demonstrates an equivalent input noise current of 12pA/sqr(Hz), and a total transimpedance gain of 52dBohm while consumes a current of 40mA from 3.3V power supply. The prototype circuit is probe-tested and all the measurements are taken with Anritsu VNA 37397D and spectrum analyser MS2721A.

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6477-08, Session 3

Silicon photonic-wire waveguide devices

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Silicon photonic-wire waveguide is presently regarded as one of the most promising platforms in fabricating novel compact optical devices, because it can confine the optical field to a core area that is more than 100 times smaller than the modal area of a standard single-mode fiber, in addition to the integration leverage from well-developed silicon processing technologies and the monolithic integration of photonic-electronic devices. The devices based on silicon photonic-wire waveguides with a nano-meter-order cross-sectional-size silicon core can have a bending radius of less than several microns, due to the large difference in the refractive index between the silicon core (n = 3.5) and silica cladding materials (n = 1.5) or air (n = 1). Moreover, due to the large thermo-optical coefficient of silicon, devices based on silicon photonic-wire waveguides would be easily controlled through thermo-optic effect and therefore be compact. Thus, we have developed various optical devices with silicon photonic-wire waveguides, which includes a 3-dB direction coupler, a tunable optical add-drop multiplexer, and an ultra-compact 1 x N optical switch. We are presently fabricating a compact packaged module, which includes a 1 x 4 optical switch and the input and output fiber couplers assembly. At the conference, we will report in detail the device structures, the fabrication processes, and the optical characterization results.

6477-09, Session 3

Growth and band-gap modulation of Group IV semiconductor alloy nanowires

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Group IV semiconductor alloy nanowires offer a continuously variable system with a wide range of energy-band gaps and enhanced light emission, and thus hold premises for nano-photonics. Particularly Si and Ge form a continuous series of substitutional solid solutions, Si1-xGex with a fixed crystal structure over the entire compositional range of $0 < x < 1$, leading to various electrical and optical properties. Here we report growth of single-crystalline Si1-xGex nanowires, whose relative composition is controllably tuned over the entire composition range by Au-catalyst assisted chemical vapor syntheses. We also report the shape-controlled growth of Si1-xGex nanowires, exploiting different growth kinetics of precursors. We then present experimental demonstration of the band-gap modulation from near infrared to ultraviolet regions with alloying of Si and Ge, and their spatial confinement at the nanometer scale. Specifically we show with “local nano-probes” that the optical band-edge of individual Si1-xGex nanowires is modulated with alloying, size and shape variation at the nanometer scale. Our finding demonstrates that the energy band-gap of Si1-xGex nanowires can be modulated in a wider energy range that has not been accessed with conventional Si photonics, and suggests implications for group IV semiconductor photonics.

6477-10, Session 3

Tailoring the response and temperature characteristics of multiple serial-coupled resonators in SOI

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Silicon-on-Insulator (SOI) has emerged as promising material choice for various integrated optoelectronic devices. Two issues make SOI attractive for complex optical systems: the cost reduction due to compatibility with CMOS technology and high refractive index contrast between core and cladding, which is an important property for good confinement of light and efficient guiding and coupling in sub-micron waveguides. However, for those devices that are intended to be part of broadband optical networks, for example multiplexers and de-multiplexers, it is essential to demonstrate a high selectivity and a tunable response. Thus, it is crucial to provide wavelength selective elements with the ability to filter input data streams producing a large Free Spectral Range (FSR), a small Full Width at Half Maximum (FWHM), and a high quality factor (Q), all conditions set by communication standards. Thanks to the generic and adaptable operation, ring-resonator-types of filters in SOI are often considered as candidates to meet these demands. Herein two different designs are investigated from both experimental and modelling standpoints in order to tailor the filter transfer function. These are mutually coupled (Vernier) resonators and cascaded resonators based on small SOI photonic wires. Fabricated filters designed to provide a large FSR and a polarisation independent response are analysed and improvements proposed. Issues associated with temperature control of the transfer function have also been addressed.

6477-11, Session 3

Silicon microspheres in photonics

A. Serpengüzel, Koç Univ. (Turkey)

Silicon is the second most abundant material on earth after oxygen and is the material of choice of microelectronics industry. With the current emphasis on electrophotonic integration, silicon based active and passive microdevices are making strands in “siliconizing” photonics. making microspheres coupled to optical fibers are used for passive optical channel dropping, and active modulation in the near-infrared communication wavelenghts of 1300 and 1475 nm. In our experiments, we are using silicon microspheres with a refractive index of 3.5 and a radius of 500 micrometer. The observed morphology dependent resonances have quality factors of 100000, which are limited by the sensitivity of the experimental setup. These optical resonances provide the necessary narrow linewidths, that are needed for high resolution channel dropping and modulation. In addition to channel dropping and modulation in the near infrared, we are ivestigating the channel dropping and modulation properties of this system in the mid infrared experimentally and numerically. The silicon microsphere and silica optical fiber (or potentially silicon on oxide waveguide) system shows promise as a building block for silicon based photonics.

6477-12, Session 4

Polarization-insensitive ring resonators in SOI using cladding stress engineering and MMI couplers

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We review a novel silicon-on-insulator (SOI) ring resonator design for polarization insensitive operation. The polarization dependence in ring resonators mainly stems from a polarization sensitive coupling ratio between the bus waveguide to the ring, and a polarization sensitivity in the ring waveguide phase accumulation. We use a 2x2 multi-mode interference (MMI) coupler to achieve coupling ratios that are polarization insensitive, as well as tolerant to changes in operating wavelength and device dimension fluctuations due to fabrication inaccuracies. Design considerations for MMI suitable in this context are discussed, and examples of MMI couplers with different splitting ratios are described.

Cladding stress induced birefringence is used to correct the ring waveguide modal birefringence to eliminate the difference in round trip phase accumulation between the TE and TM polarized modes, in order to achieve polarization insensitive resonance wavelengths and free-spectral-range (FSR). This approach allow the waveguide geometry to be optimized for conditions such as bend radius and waveguide loss, independent of constraints imposed by waveguide birefringence requirements. We review the characteristics of the stress-induced birefringence in SOI ridge waveguides, and present design methodology for designing polarization insensitive ring resonators. The design parameters are described for polarization independent SOI ring resonators with couplers having a 50:50 or 15:85 splitting ratio, and 1.5 micron ridge height and width. As designed, the resonators offer a polarization independent FSR of 0.5 nm for a ring radius of 200 micron, and a quality factor Q as high as 55,000. Devices with a range of cross-sectional dimensions and bend radii were fabricated at the Canadian Photonics Fabrication Center, and experimental results will be presented.

6477-15, Session 4

A novel fabrication technique for silicon photonics

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In this paper we report a novel fabrication technique for silicon photonic circuits and devices. The technique is sufficiently flexible to enable waveguides and devices to be developed for telecommunications wavelengths or indeed other wavelength ranges due to the inherently high resolution of the fabrication tools. Therefore the technique is suitable for a wide range of applications. In the paper we discuss the outline fabrication process, and discuss how it compares to conventional processing. We compare ease of fabrication, as well as the quality of the devices produced in preliminary experimental fabrication results. We also discuss

preliminary optical results from fabricated waveguide devices, as measured by conventional means. In these preliminary results we discuss fundamental properties of the waveguides such as loss and modal characteristics, as it is these fundamental characteristics that will determine the viability of the technique. Issues such as the origins of the loss are discussed in general terms, as resulting fabrication characteristics such as waveguide surface roughness (and hence loss), or waveguide profile and dimensions may be traded off against cost of production for some applications. We also propose further work that will help to establish the potential of the technique for future applications in both high and low volume manufacturing environments.

6477-16, Session 5

SOI waveguide based planar reflective grating demultiplexer for FTTH

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Recent deployments of fiber-to-the-home (FTTH) represent the fastest growing sector of the telecommunication industry. The emergence of the silicon-on-insulator (SOI) photonics presents an opportunity to exploit the wide availability of silicon foundries and high-quality low-cost substrates for addressing the FTTH market. We have now demonstrated that a monolithically integrated FTTH demultiplexer can be built using the SOI platform. The SOI filter comprises a monolithically integrated planar reflective grating and a multi-stage Mach-Zehnder interferometer that were fabricated using a CMOS-compatible SOI process with the core thickness of 3.0 μm and optically insulating layer of silica with a thickness of 0.375 μm. The Mach-Zehnder interferometer was used to coarsely separate the 1310 nm channel from 1490 and 1550 nm channels. Subsequently, a planar reflective grating was used to demultiplex the 1490 and 1550 nm channels. The manufactured device showed the 1-dB bandwidth of 110 nm for the 1310 nm channel. For the 1490 nm and 1550 nm channels, the 1-dB bandwidth was measured to be 30 nm. The adjacent channel isolation between the 1490 nm and 1550 nm channels was better than 32 dB. The optical isolation between the 1310 nm and 1490 and 1550 nm channels was better than 45 dB. Applications of the planar reflective gratings in the FTTH networks are discussed.

6477-17, Session 5

Broadband silicon-on-insulator (SOI) polarization splitters and filters

W. N. Ye, National Research Council Canada (Canada) and Carleton Univ. (Canada); D. Xu, S. Janz, P. Waldron, National Research Council Canada (Canada); N. G. Tar, Carleton Univ. (Canada)

Waveguide birefringence always exists, except for cases where the two orthogonally polarized modes are degenerate. Birefringence is in general undesirable as it causes an unwanted polarization dependent wavelength shift and phase shift in all interferometric devices such as spectrometers, Mach-Zehnder interferometers (MZI), and ring resonators. The birefringence due to the waveguide core geometry in high-index-contrast material systems such as silicon-on-insulator (SOI) can significantly increase with decreasing core dimensions. One solution is to separate the two orthogonally polarized TE and TM components of the optical signal and process them individually. Waveguide polarization splitters and filters are the key elements in this approach. In fact, polarization splitting and filtering are the fundamental operations in optical signal processing and monitoring, with applications ranging from polarization mode dispersion compensation, polarimetric sensors, to network monitoring. In this work, novel passive polarization splitters and filters in the SOI platform with a geometrically balanced Mach-Zehnder interferometer configuration are fabricated and demonstrated experimentally. Polarization splitting and filtering functions are achieved by modifying the birefringence in one arm of the interferometer using a stressed cladding film. Only one single post-fabrication step is required for depositing a stressed cladding film on top of the silicon ridge waveguides. A broadband performance of the polarization splitters was observed with an extinction ratio of larger than 10 dB in each of the output ports for the entire C-Band from 1530nm to 1565nm.

6477-18, Session 5

Effective medium based on two-dimensional photonic crystals for index-confinement waveguide application

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Index-confinement waveguides are feasible to integrate with optical fibers due to the characteristic of good mode matching via a proper design. One of the drawbacks of such waveguides is that developing high-efficiency waveguide bends with the relative small radius of curvature is difficult. The microprism with a refractive index different from that of waveguide is utilized to compensate the optical path difference of the bend structure. Unfortunately, the microprism requires complex fabrication procedures to monolithically integrate with the waveguide bend.

In this paper, an effective microprism based on a two-dimensional PhC with a periodic lattice of air-holes is proposed. Those air-holes are used to modulate the reflective index of microprism by altering the lattice arrangement. Since air-holes can be fabricated directly on the material of waveguide core, the proposed PhC microprism with an effective index is a potential approach to facilitate fabrication procedures of sharp waveguide bends.

This PhC microprism at the operating wavelength is designed out of bandgap. To avoid the complicate dispersion characteristics, the operating condition is closed to low-frequency region, which the microprism can be regarded as a homogeneous and isotropic one.

In order to demonstrate the feasibility of proposed microprism for low-index-contrast waveguides, an example of bent waveguide with the eigenmode compatible to the SMF is adopted to design the effective microprism. The simulation transmission efficiency as high as 92% for the proposed structure with the bending angle of 12.96 degree and the bending radius of 89.09um is achieved. The fabrication process is currently developed.

6477-19, Session 5

Efficient and compact silicon-on-insulator rib waveguide 90 degree bends and splitters

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Silicon-on-insulator (SOI) is very promising material for high-index integrated photonic chips because of its compatibility with complementary metal oxide semiconductor (CMOS) technologies. One challenge in integrating many photonic devices on a single chip is to realize compact waveguide bends and splitters, particularly for rib waveguide geometries. In this presentation, we report compact and low loss SOI rib waveguide 90o bends and splitters with SU8-filled trenches based on total internal reflection (TIR). We use the finite difference time domain (FDTD) method to numerically calculate bend and splitter efficiencies. The maximum bend efficiency is 98.0%. The splitter efficiency is 49.0% for transmission and 48.9% for reflection with an 80 nm wide SU8-filled trench. Electron beam lithography (EBL) is used to accurately position the trench interface relative to the waveguides and to pattern the 80 nm wide trench. Inductively coupled plasma reactive ion etching (ICP RIE) is used to achieve a vertical sidewall. For fabricated bends the measured bend loss is 0.32±0.02 dB/bend (92.9% bend efficiency) for TE polarization at a wavelength of 1.55 μm, which is the lowest SOI rib waveguide 90o bend loss reported in literature [Opt. Express 14, 6020 (2006)]. The initial measured splitter efficiency is 54.6% for transmission and 29.2% for reflection. We are currently working to optimize the splitter fabrication and measurement.

6477-20, Session 5

Scattering loss measurement of SOI waveguides using 5X17 integrated optical star coupler

K. P. Yap, Carleton Univ. (Canada) and National Research Council Canada (Canada); S. Janz, A. Delâge, B. Lamontagne, J. Lapointe, P. Chow-Chong, E. Post, National Research Council Canada (Canada); B. A. Syrett, Carleton Univ. (Canada)

We have devised a novel technique to measure the scattering loss of SOI waveguides due to sidewall roughness. Our test structure is an integrated 5x17 star coupler which consists of two arrays of SOI ridge waveguides connected by a free-space slab waveguide region. Input waveguides in the array are identical while output waveguides have different widths. The star geometry was designed to project a Fraunhofer radiation pattern at the slab-output waveguides array interface. Thus, the power of radiation entering the slab is split into the output waveguides array with the intensity envelop of a Gaussian distribution. To investigate the width effect on roughness-induced scattering loss, we fix the width of all odd output waveguides at a nominal value, but vary the width of even waveguides. We then fit a Gaussian profile to the measured output intensities of the equal width odd waveguides. The loss due to extra scattering from the reduction in width of any even waveguide can be easily determined by calculating the intensity ratio of the measured output intensity of that particular waveguide to the expected intensity from the Gaussian fit. Consequently, the scattering loss-waveguide width relation of this SOI sample can be established from a single measurement. This simple method provides an efficient way of monitoring and optimizing process parameters that affect sidewall roughness. We have verified this method by comparing the results from multiple measurements of straight SOI waveguides of different widths on the same chip.

6477-21, Session 6

A 40Gb silicon photonics transceiver

C. Gunn, Luxtera Inc.

As part of the DARPA EPIC program, Luxtera has developed a 40Gb transceiver based on silicon photonics technology. Receive and transmit functionality is integrated into a single CMOS die, which also includes key circuitry such as the modulator drivers and the transimpedance amplifiers. The transceiver employees 4 wavelengths at a 200GHz spacing and modulates each at 10Gbps. All four wavelengths are multiplexed and transmitted down a single mode fiber. This talk will give an overview of the on-chip system architecture for both transmit and receive, as well as discuss the results of the building blocks for the WDM system, including modulator performance, optical filtering, receive sensitivity, and link performance. The building blocks used for the 4Gb transceiver will culminate in a single-chip 100Gb transceiver by the end of the EPIC program.

6477-22, Session 6

Integrated optical components in silicon for high speed analog-to-digital conversion

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ADC performance at high sampling rates is fundamentally limited by the timing jitter of the electronic clocking circuits, typically a quarter of a picosecond or higher. The goal of this program is to leverage the low (femtosecond) jitter properties of mode-locked lasers to develop an electronic-photonic integrated circuit (EPIC) that facilitates high speed ADC beyond the bottleneck set by electronic jitter.

A number of integrated optical components are necessary for this application, including detectors, filter banks, and modulators. Ge photodiodes were fabricated on silicon substrates with ~40 mA/cm2 reverse leakage currents at 300K and -1.0 Volt bias. These diodes have greater than 0.5 A/W responsivity, and a 34 dB SFDR for a 2-GHz noise bandwidth and 3 dB drop-off frequencies in the GHz range.

Filter banks were fabricated using ring resonator structures in both silicon-on-insulator (SOI) and silicon nitride. An 8 channel, second order filter bank was fabricated in silicon nitride. This device had an average channel spacing of 159 GHz, a drop loss of 1.5±0.5 dB and a crosstalk of less than -30 dB. SOI filters achieved quality factors (Q's) of 8,000-20,000, with losses as low as 1 dB. A five channel filter bank was fabricated with a maximum relative error in wavelength between channels of 1.5 nm.

Optical modulators, based on silicon p-n diodes, were fabricated in small SOI waveguides. The devices demonstrated extremely low $V\pi L$ of 0.02 Vcm and 1 mW operation at frequencies up to 100 MHz. At 10 GHz, the devices achieved a modulation depth of 25% with an rf input power of only 200 mW.

6477-23, Session 6

Advances in fully CMOS integrated photonic devices

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The complete integration of photonic devices into a CMOS process flow will enable low cost photonic functionality within electronic circuits. BAE Systems, Lucent Technologies, Massachusetts Institute of Technology, Cornell University, and Applied Wave Research are participating in a high payoff research and development program for the Microsystems Technology Office (MTO) of DARPA. The goal of the program is the development of technologies and design tools necessary to fabricate an application specific, electronic-photonic integrated circuit (AS-EPIC). The first phase of the program was dedicated to photonics device designs, CMOS process flow integration, and basic electronic functionality. We will present the latest results on the performance of optical modulators, detectors, high index waveguides, tunable optical filters, and the first EP-integrated channelizer chip.

6477-24, Session 7

Field effect light emitting devices

R. J. Walters, H. A. Atwater, California Institute of Technology

While clear development pathways exist for integrated on-chip waveguides and Si detectors, silicon photonics is badly in need of a suitable light source technology. Quantum dots are attractive material building blocks for this purpose because of their high quantum efficiency and tunable emission properties, but electrical carrier injection across the insulating barriers that isolate the dots poses a significant challenge.

Field Effect Light Emitting Devices (FELEDs) employ a tunneling injection mechanism to form excitons via the sequential injection of one carrier of each sign into each quantum dot in a planar ensemble. These excitons can create light directly by radiative recombination or can non-radiatively transfer energy to excite a secondary emitter. FELEDs can operate at CMOS compatible voltages and show little or no performance degradation over time. Output intensity is fundamentally limited by the density of the quantum dots and the overall radiative rate for photon generation.

We will present new experimental observations and computer simulation results for light output from silicon nanocrystal FELEDs operating in the near IR and devices designed to emit at telecom wavelengths near 1.5 microns. Additionally we will discuss SOI-based "slot" waveguide integrated FELEDs and comment on the potential for electrically pumping silicon nanocrystal sensitized Erbium as a gain medium for a CMOS compatible laser source.

6477-25, Session 7

Spontaneous emission dynamics of Si nanocrystals in microdisk resonators

R. D. Kekatpure, M. L. Brongersma, Stanford Univ.

Nanocrystalline silicon (nc-Si) is being actively investigated as an active medium for on-chip silicon-based light sources. Numerous reports exist on Si-nanocrystal formation and evolution, photoluminescence optimization, and gain in planar nc-Si waveguides. However, detailed studies of continuous-wave and transient photoemission from nc-Si in microcavities are relatively few in number.

We will present results of photoluminescence measurements from Si-nanocrystals embedded in microdisk resonators. The photoluminescence of the silicon-rich oxide (SRO) layer containing Si-nanocrystals is first optimized by scanning through a temperature-concentration matrix. Thereupon, microdisk resonators situated on silicon pedestals, are fabricated by a combination of electron-beam lithography and wet-chemical etching of the SRO and the underlying silicon layers. Continuous-wave photoluminescence measurements show microdisks of very high quality with Q >1,800 at 750 nm wavelength. Our modeling indicates that the Q's of these microdisks are limited by the absorption loss from the nanocrystals layer.

It is well known that local density of optical states (LDOS) in microcavities alters the emission properties of embedded quantum-dots. We use our high quality microdisk resonators to probe the spontaneous emission rate modification for Si-nanocrystals in the visible range. The emission lifetimes are compared against the theoretical Purcell factor values by relating to the Q's and calculated modal volumes. Since the LDOS modifies only the radiative lifetimes, our experiment directly yields values of radiative and non-radiative lifetimes thereby providing the internal emission efficiency. We believe that the study of photoluminescence of Si-nanocrystals in microcavities has dual prominence - study of fundamental photoemission physics and luminescence characterization in realistic laser cavities.

6477-26, Session 7

Integrating luminescent Si nano-crystal films into low loss optical waveguides

J. N. Milgram, J. Wojcik, O. Zalloum, P. Mascher, A. P. Knights, McMaster Univ. (Canada)

In this work Si nano-crystals (Si-nc) embedded in a silica host are used to explore the monolithic integration of an optical source in a silicon compatible waveguide. Whereas the majority of work to date has concentrated on improving emitter efficiency, stabilizing electroluminescence, and achieving stimulated emission, this work explores mechanisms for efficient coupling of the emission into a waveguide. At this point, electroluminescence of the films is unreliable, but photoluminesence at 800 nm is easily achieved and thus provides a frame work with which to study integration. In this work, Si-nc are fabricated by depositing silicon rich silicon oxide films using electron-cyclotron resonance plasma enhanced chemical vapor deposition (ECR-PECVD) followed by high temperature annealing. A waveguide is typically formed using a Si-nc core sandwiched between two silicon dioxide cladding films. This design, while simple and easily fabricated, suffers from a very high propagation loss due to absorption and scattering from the Si-nc core. We explore an improved design where Si-nc emitting regions are monolithically coupled into low-loss silicon oxy-nitride waveguides. The emitting Si-nc region is optically excited from the surface with a pump laser, and the edge emission is examined. We attempt to optimize coupling of the spontaneous emission by tailoring the waveguide geometry and refractive indices of the films.

6477-27, Session 7

Two order increase in the optical emission intensity of CMOS integrated circuit Si LED's (450nm - 750nm)

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We have over some time realized silicon light emitting devices (Si LED's) in a standard 1.2 and 2 micron CMOS technology with a bipolar capability with no changes to the design and processing procedures. The devices operated in the reverse breakdown avalanche mode and emit visible light in the 450 - 750 nm wavelength region at intensities up to 2nWum-2 at operating conditions of 8-20V and 80 uA to 2mA.

In a latest device configuration, a four component device was designed. One device component was placed in strong avalanche light emitting mode. Electrons were injected into the avalanching junction by forward biasing a fourth n+ device component relative to the avalanching component. A high intensity spot appears at the avalanching n+ junction. New peaks appear at 2.2 and 2.8 eV in spectra taken from the emission. The luminescent intensity are about two orders higher than the intensity observed from previous single avalanching light emitting junctions. The emission intensity is also much higher as compared with previous multi-junction devices that operate in full injection with slight avalanche mode.

The developed high intensity device have particular technological significance since the intensity per unit area is a key parameter for future all - silicon optical integrated circuits, some particularly requiring 450nm-750 nm emissions (Wada et al, 2004). The current energy emission levels of about ~10nW /μm2 are at least three orders higher than the low frequency detectability limit of corresponding area silicon CMOS integratable detectors (pW's/ μm2).

The contents of this work forms the topic of an approved USA Patent No 5,994,720.

6477-28, Session 9

Nano-engineered crystalline silicon for enhanced photoluminescence and 1.28um laser action

J. M. Xu, S. G. Cloutier, C. Hsu, P. Kossyrev, E. Rotem, J. M. Shainline, Brown Univ.

Enhanced light emission and laser action have been observed in nanopatterned silicon. Refinement of techniques raised the lasing temperature of the nanopatterned silicon from below 30K to above 80K; enhanced photoluminescence has been demonstrated at room temperature. Undoped, crystalline, electronic-grade silicon-on-insulator wafers have been patterned using a highly-uniform self-assembled anodic aluminum oxide nanopore array as an etch mask for reactive ion etching. The resulting pores etched into the silicon assist in populating G centers, carbon-silicon defect centers 0.17eV below the conduction band minimum. Increased light emission at and around the 1278nm peak results from G center-mediated direct recombination. Nano-patterning contributes to light emission by creating a densely packed array of Emissive Structural Deformation (ESD) zones in the side-wall region of the nanopores. Three main features of the ESD zones contribute to enhanced light emission and lasing. First, the silicon lattice in the ESD zones is strained, resulting in a local narrowing of the band gap which promotes funneling of carriers into the ESD zones where they populate the G centers or recombine via phonon-assisted processes. Second, lattice strain and nano-scale symmetry breaking give rise to phonon localization and phonon selection rule breaking which enhances carrier capture by G centers in the ESD zones. Third, the existence of the nanopore surface causes a local reduction of the dielectric function for carriers in the ESD zones, which increases the binding energies of excitons and vacancy defect-associated states below the band edge, resulting in a further increase in the capture rate of electrons by G centers.

6477-30, Session 9

Towards an electrically pumped silicon laser

T. L. Koch, Lehigh Univ.

Silicon photonics has shown great promise for achieving OEIC's designed to be fabricated in a silicon CMOS electronics foundry, and also the integration of optical functions with standard VLSI circuitry functions on a single silicon chip. Recent developments include foundry-fabricated Mach-Zehnder modulators with speeds as high as 20Gb/s.

The ability to combine optical communications and sensor devices with control, amplification, and signal-processing electronics at very low cost is extremely compelling for markets including telecommunications, biomedical and environmental sensors, and military signal processing. The InP-based or GaAs-based light source in today's silicon photonics is typically coupled onto the chip using surface gratings or a mode transformer to match the high-index-contrast waveguides that optimize performance and density. This still requires hybrid III-V and silicon packaging solutions, and thus one point of view is that silicon photonics essentially represents a shift in the most cost-effective partitioning between the two technologies within a module. Development of a Si-based light source, however, may allow for a complete compact, low-cost, low-power CMOS-compatible single-chip solution.

Approaches to this goal can be grouped into five categories; (1) signal generation using nonlinear optical techniques, (2) hybrid materials solutions using proven III-V gain media, (3) "extrinsic" solutions using electrically-excitable Er ions, nanocrystals, defect structures, or other species introduced into Si, SiO2 or other dielectrics, and (4) "intrinsic" solutions utilizing engineered SiGe structures, and (5) intersubband designs such as quantum-cascade lasers. This talk will review some recent design concepts and experimental results that offer promise towards achieving the electrically-pumped Si laser.

6477-46, Poster Session

Plasmonics and the parallel programming problem

U. Vishkin, I. I. Smolyaninov, C. C. Davis, Univ. of Maryland/ College Park

While many parallel computers have been built, it has generally been too difficult to program them. Now, all computers are effectively becoming parallel machines. Computer vendors are building multi-core computer architectures growing exponentially the number of cores on a single chip. Thus, the parallel programming problem is becoming more critical. The only known solution to the parallel programming problem in the theory of computer science is through a parallel algorithmic theory called PRAM. Unfortunately, some of the PRAM theory assumptions regarding the bandwidth between processors and memories did not properly reflect a parallel computer that could be built in previous decades. Reaching memories, or other processors in a multi-processor organization, required off-chip connections through pins on the boundary of each electric chip. Using the number of transistors that is becoming available on chip, on-chip architectures that adequately support the PRAM are becoming possible. However, the bandwidth of off-chip connections remains insufficient and the latency remains too high. This creates a bottleneck at the boundary of the chip for a PRAM-On-Chip architecture. This also prevents scalability to larger "supercomputing" organizations spanning across many processing chips that can handle massive amounts of data. Instead of connections through pins and wires, power-efficient CMOS-compatible on-chip conversion to plasmonic nanowaveguides is introduced for improved latency and bandwidth. Proper designs for incorporation of our ideas offer exciting avenues to resolving the parallel programming problem. They also offer an alternative way for building faster, more useable and much more compact supercomputers.

6477-47, Poster Session

Guided-mode resonance device constructed with membrane structure: theoretical analysis and experimental demonstration

J. Chang, M. Wu, C. Hsu, Y. Lee, Y. Tsai, H. Lan, Y. Liu, Z. Tu, National Central Univ. (Taiwan)

In this paper, the guide-mode resonance (GMR) devices associated with silicon-based materials are theoretical studied and experimentally demonstrated. The silicon nitride membrane including etched grooves is utilized as the main structure of GMR device to form the simplest optical filter. The rigorous-coupled-wave-analysis (RCWA) and finite-differential-time-domain (FDTD) methods are used to calculate the spectral response and analyze the field distribution in the GMR structure to explain the resonance behaviors of proposed GMR device, respectively. The effects of structural parameters on spectral properties are also analyzed and discussed. Combined with the theories of planar waveguide, diffraction grating and effective medium, versatile spectral properties can be achieved. By incorporating the silicon oxide membrane of lower refractive index as the compensating layer, the spectral response can be effectively modified to more symmetric line shape and better sideband unlike the previously presented GMR filters fabricated on a solid substrate results in immobile spectral characteristics. Since the proposed GMR structure is realized with silicon-based materials, therefore the presented silicon-based GMR device is potential to be integrated with other devices to form a micro/nano optical system for further applications.

6477-49, Poster Session

Lab-on-a-chip platforms based on highly sensitive nanophotonic Si biosensors for single nucleotide DNA testing

J. Sánchez del Rio, Ctr. Nacional de Microelectrónica (Spain); L. G. Carrascosa, Consejo Superior de Investigaciones Científicas (Spain); F. J. Blanco, IKERLAN (Spain); M. Moreno, Ctr. Nacional de Microelectrónica (Spain); J. Berganzo, IKERLAN (Spain); A. Calle, C. Dominguez, L. M. Lechuga, Ctr. Nacional de Microelectrónica (Spain)

Evanescent wave photonic biosensor devices based on standard microelectronics and related micro/nanotechnologies are providing an integrated technological solution for achieving high sensivity arrays of biosensing devices. These evanescent wave sensors show a great potential for sensing biomolecular interactions in real-time without labeling requirements, which have made them quite useful for applications ranging from biomedical, environmental, industrial to genomic and proteomics. But problems of stability, sensitivity and size have prevented the general use of optical biosensors for real field applications.

In order to solve the drawbacks of sensitivity and portability, we work on the development of ultrasensitive and miniaturized photonic silicon sensors able to be integrated in a "lab-on-a-chip" microsystem platform. As sensors we use integrated Mach-Zehnder interferometer based on TIR optical waveguides (Si/SiO2/Si3N4) of micro/nanodimensions.

We have applied this biosensor for DNA testing and for detection single nucleotide polymorphisms from BRCA-1 gene, involved in breast cancer development, without target labeling. The oligonucleotide probe is immobilized by covalent attachment to the sensor surface through silanization procedures. The hybridization was performed for different DNA target concentrations showing a lowest detection limit at 10 pM for a 58mer complementary DNA. Non-complementary oligonucleotides did not shown any significant signal. Additionally, we have detected the hybridization of 100 nM DNA target with two mismatching bases corresponding to a mutation of the BRCA-1 gene.

Following the way of the lab-on-a-chip microsystem, integration with the microfluidics has been achieved by using a novel fabrication method of 3-D embedded microchannels using the polymer SU-8 as structural ma-

terial. In and out-coupling of the light is pursued by embedded grating on the waveguide interferometer structure. The final microsystem will incorporate also specific photodetectors with CMOS electronics for data acquisition and processing.

6477-50, Poster Session

A CMOS-compatible rib waveguide with local oxidation of silicon isolation

L. K. Rowe, N. G. Tarr, Carleton Univ. (Canada); A. P. Knights, M. Elsey, McMaster Univ. (Canada)

A Local Oxidation of Silicon (LOCOS) process is used to define optical rib waveguides in silicon-on-insulator (SOI) substrates. The LOCOS process is identical to that used in many purely microelectronic CMOS technologies. It provides a near-planar surface ideal for the monolithic integration of CMOS electronics and optical devices in silicon. CMOS device wells and optical ribs can be defined in the same lithography step, allowing for a very simple process. Optical mode simulation was used to determine rib geometries suitable for single-mode propagation in the 1550 nm optical telecommunications band. Test devices were then fabricated in Smartcut SOI material with 3.4 um Si film thickness. Growth of a 1 um field oxide by wet oxidation yielded a 0.5 um rib height. As-drawn rib widths ranged from 3 um to 5 um, giving final rib widths ranging from 2 um to 4 um after oxidation. Cut-and-etchback optical testing of 3 um drawn width ribs showed loss to be less than 1 dB/cm at 1555 nm. The low loss is due to the very smooth rib sidewall produced by the oxidation process. Unbalanced Mach-Zehnder interferometers with Y-splitter junctions were also fabricated and tested with input wavelength swept from 1470 to 1580 nm. These devices showed an extinction of 10 dB, demonstrating the ability of the LOCOS rib technique to produce more complex waveguide devices.

6477-51, Poster Session

Fabrication strategies for continuous Raman gain in a silicon waveguide via defect engineering

D. Walters, A. P. Knights, McMaster Univ. (Canada)

The prospect of achieving continuous net gain in a defect engineered silicon rib waveguide is discussed. It is well established that irradiation-induced defects created within the rib region can act as trapping centers and effectively reduce the gain-limiting free carrier lifetime in silicon waveguide based Raman lasers. Specifically, the free carrier lifetime in self-implanted silicon is ~ 1 ps. The potential benefit is however limited by the increased optical absorption due to the implanted defects. By creating heavily damaged regions adjacent to the rib structure, the free carrier lifetime can be sufficiently reduced to allow continuous net Stokes gain. Carrier lifetime and optical losses have been simulated (SILVACO, BeamPROP) as a function of the rib distance from the damaged region. An optimal distance exists that maximizes Raman gain, which is dependent on waveguide geometry. By using defect engineering, an effective, zero-power solution is available to remove free carriers in a silicon rib waveguide and increase net Raman gain. Preliminary measurements of carrier lifetime and the modification of effective refractive index will be presented for a number of device geometries.

6477-31, Session 10

Ge electroabsorption modulators and SiGe technology for optical interconnects

Y. Kuo, National Taiwan Univ. (Taiwan)

Ge/SiGe quantum well electroabsorption modulators grown on silicon through relaxed SiGe buffers had shown strong quantum-confined Stark effect (QCSE), even though Ge is an in-direct band gap semiconductor. The absorption characteristic near the direct band gap edge can be tuned by applying an electric field. QCSE is the most efficient optical modulation mechanism through direct light absorption and promising for reducing the device size and power consumption. The device fabrication here is based on Ge-rich SiGe technology, which is also commonly used for other silicon photonic devices (such as Ge photodetectors on Si or SOI). Here I will discuss our recent progress in Ge QCSE electroabsorption modulators as well as SiGe process integration considerations for optical interconnects.

6477-32, Session 10

Cavity enhanced electro-optic effect in silicon and its applications

C. Chen, B. Miao, D. W. Prather, Univ. of Delaware

Silicon photonics has been of great interest recently due to the increasing commercial demand for bandwidth and the fact that Silicon is a well-understood, plentiful, and inexpensive material and its processing tools are widely available in industry. High speed, reliable, and no-mechanical electrooptic components, such as modulator and switch, are fundamental in the development of Silicon photonics. Unfortunately Silicon exhibits no linear electrooptic (Pockels) effect. The Franz-Keldysh effect and the Kerr effect are very weak in Silicon too. In 1987, Soref and Bennett (R. A. Soref and B. R. Bennett, “Electrooptical effects in Silicon”, IEEE J. Quantum Electron., Vol. QE-23, pp. 123-129, 1987) experimentally studied the electrooptical effects in Silicon and found that a change in refractive index in Silicon due to plasma dispersion could be achieved by injecting/depleting electrons/holes in the intrinsic silicon region by creating a forward or inverse biased p-i-n diode. Since then, this effect has been widely explored in the development of electro-optic components. But this mechanism is still relatively slow since it relies on the charge movement in the device. Nevertheless, A significant breakthrough has been made in this area. A. Liu et al. at Intel demonstrate an all-silicon optical modulator with a modulation bandwidth exceeding 1 GHz by using a metal-oxide-semiconductor (MOS) capacitor structure embedded in a Silicon waveguide to eliminate the slow carrier generation and/or recombination processes common in the accumulation operation of such device. While this work represents an important milestone towards all-Silicon integrated photonic system, the proposed device is large (on the order of millimeters) due to the relatively weak dependence of silicon’s refractive index on the free carrier plasma dispersion effect. The large size is not only power consumptive but also hard to integrate with other components.

To this end, in this effort we propose to combine optical cavity for enhancing the free carrier plasma dispersion effect in Silicon with the MOS capacitor structure for eliminating the slow carrier recombination processes to design high-speed and compact all-silicon optical modulator and/or switch with low insertion loss and high modulation depth (or large extinction ratio for optical switch). In order to minimize the insertion loss and maximize the modulation depth or the extinction ratio for optical switch, it is very important to form propagating wave cavity since only this type of cavities could be designed such that at each point only single wavevector exists. Therefore, efficient in-coupling and out-coupling structures could be designed with desired matching mode. By doing this, very low insertion loss and very high modulation depth or extinction ratio could be achieved. Ring cavity, as adopted in the silicon modulator device proposed by Q. Xu et al at Cornell University, is one example of propagating wave cavities. Recently, A whispering gallery mode (WGM) was demonstrated in a quasi-periodic photonic crystal cavity. This would serve as a propagating wave cavity if being properly excited. In addition, non-channel light guiding and efficient beam bending have been demonstrated in self-collimation photonic crystal. These could be utilized to develop a propagating wave cavity if the self-guided beam is bent in a loop. In this effort, we will investigate these propagating wave cavities in enhancing the free carrier plasma dispersion effect in Silicon for designing highly efficient Silicon electro-optic components.

6477-33, Session 10

High-speed electro-optical silicon modulators based on photonic crystal waveguides

L. Gu, W. Jiang, X. Chen, R. T. Chen, The Univ. of Texas at Austin

Silicon remains the dominant material for microelectronics ever since the invention of the integrated circuit. The driving force behind the development of silicon photonics is the monolithic integration of optics and microelectronics. Silicon-on-insulator (SOI) has been identified as a promising material for integrated optoelectronics. CMOS circuits fabricated on SOI benefit from reduced parasitics and absence of latch-up problem, which enable high-speed and low-power operations. In addition, SOI provides strong optical confinement for the telecommunication wavelengths and holds great potential for realizing guided-wave micro- and nano- photonic devices. Silicon microelectronic devices have undergone numerous generations of feature size reduction. However, there has been little progress made in the miniaturization of the silicon based optical components. Photonic crystal provides a promising platform to build ultra-compact and high-performance photonic devices. It has been previously demonstrated that the light propagation in a photonic crystal waveguide (PCW) can have much slower group velocity than that in the conventional waveguide. The slow-photon effect allows an interaction enhancement between the light wave and the wave-guiding material, which potentially leads to a significant reduction in devise size and power consumption. In this paper, we propose a high-speed SOI electro-optical (EO) Mach-Zehnder interferometers (MZIs) based on PCWs. The optical modulation at 1 GHz has been experimentally demonstrated by a device using an 80 μm long interaction region. Both theoretical simulation and experimental demonstration will be presented at the conference.

6477-35, Session 11

Recent advances in high speed silicon optical modulator

A. Liu, L. Liao, Intel Corp.; D. Rubin, Intel Corp. (Israel); H. D. Nguyen, Intel Corp.; Y. Chetrit, Intel Corp. (Israel); M. J. Paniccia, Intel Corp.

Silicon photonics has currently become a subject of intense interest because it could provide a low-cost solution for optical interconnect and communications. In the past few years there have been many breakthroughs in the field, including fast silicon optical modulator [1, 2] and Raman silicon laser [3] based on Silicon-on-Insulator (SOI) technology. As one of the key components in the photonic integrated circuits, fast silicon optical modulator has been extensively investigated. Data transmission with a bit rate of 10 Gb/s based on a MOS capacitor modulator has been demonstrated [2]. Even higher speed using depletion effect in a pn junction has been predicted [4]. In this talk, we present recent results of a high speed silicon modulator. The device design, fabrication, and characterization are described. Optical testing and high-frequency measurement are discussed. Technical challenges for high-speed high-capacity applications are addressed.

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6477-36, Session 11

Assessment of the effective carrier lifetime in a SOI p-i-n diode Si modulator using the reverse recovery method

D. Zheng, M. Asghari, Kotura, Inc.

Effective carrier lifetime is a critical parameter for the design of Si photonic modulators and Raman lasers. It is desirable to have an electrical method to test this parameter at the wafer level.

In this work, we modified the classical reverse recovery method and applied it to the measurement of effective carrier lifetime in a lateral p-i-n diode SOI ridge waveguide. A forward-biased electrical pulse was applied to the diode in series with a 50 ohm resistor followed by a reverse pulse. The voltage signal across the latter was monitored to gauge the current passing through the diode. There was a period of time, named the storage time ts, immediately after the application of the reverse bias pulse such that the reverse current Ir through the diode was constant. By fixing the duration and the voltage of the forward pulse and varying the reverse bias pulse voltage level, a relationship between the storage time, and the ratio of the forward charging current If and the reverse discharging current Ir could be established. Theoretical analysis showed that ts had a linear dependence on 1+If/Ir, and the slope of the curve gave the effective carrier lifetime.

Several Si modulators of waveguide sizes ranging from 4-12 mms were fabricated. The attenuation performance of the modulators were linked to the effective carrier lifetime.

6477-37, Session 11

Hybrid photonic crystal microcavity switches on SOI

M. Haurylau, J. Zhang, S. P. Anderson, P. M. Fauchet, Univ. of Rochester

We report the development and characterization of 2-D photonic crystal (PC) microcavity devices on silicon on insulator. The transmission of light through a 2-D PC microcavity near resonance can be switched on and off by modulating the refractive index of the PC. Because silicon has poor electro-optical properties, it is advantageous to insert electro-optic materials inside the air holes. In this presentation, we will focus on two classes of such materials, liquid crystals and polymers. The changes in the refractive index of liquid crystals is very large but the response time is slow. In contrast, the response time of polymers is very fast, but the achievable refractive index changes are much smaller.

In this presentation, we report the design, fabrication, and characterization of such hybrid PC microcavity switches. We will demonstrate a method that eliminates electric field screening by the more conducting silicon host.

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6477-38, Session 11

High performance total internal reflection type optical switches in silicon-on-insulator

D. Thomson, B. D. Timotijevic, G. Z. Mashanovich, G. T. Reed, Univ. of Surrey (United Kingdom)

The requirement of a precise and controllable reflection interface in total internal reflection type optical switches is widely acknowledged. When these switches are based upon carrier injection such as those fabricated in silicon-on-insulator the ability to set up a precise reflection interface becomes difficult due to the free diffusion of carriers.

This free diffusion of carriers across the reflection interface creates a refractive index gradient which is likely to cause the input light to be bent into the ‘reflected’ output port a process which is less efficient than reflection from a precise interface in terms of loss due to the absorption by the free carriers.

In our work we propose the use of a thin SiO2 barrier along the reflection interface and around a completely enclosed injection region to stop the free diffusion of carriers and therefore set up a precise reflection interface. The barrier will also improve the injection efficiency since the carriers are being injected into a much smaller volume. This will lead to reduced switching current and faster switching speeds. This paper reports the modelling of the device and predicts the bandwidth performance for one specific switch design.

6477-39, Session 12

Integrated silicon optical sensors based on hollow core waveguide

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Hollow core waveguide have received great attention in the last years due to their versatility.

Many techniques have been proposed in order to realize hollow waveguides like metallic walls or dielectric cladding optical waveguides.

In this work we show that integrated silicon hollow core Antiresonant Reflecting Optical Waveguide (ARROW) can be used as a basic tool for the realization of optical sensors. ARROW waveguides, with hollow core, permit to confine the light in a low refractive index liquid core, by means of two high refractive index cladding layers designed to form a high reflectivity Fabry-Perot antiresonant cavity. This arrangement allows to realize microchannels that can simultaneously act as microfluidic networks and optical waveguides with a strong advantage in the integration and with an increased interaction efficiency between the light and the liquid substance that can be very useful in sensing applications (Fluorescence, absorption spectroscopy, etc). Another ARROW waveguides advantage is the ability to tailor the wavelength response of the device. In fact, the waveguide propagation losses strongly depend on the change of the resonant condition inside the interference cladding.

In this paper we report three sensing applications of hollow core ARROW waveguide. A long path absorbance cell for colorimetric protein assay, a high sensitivity integrated refractometer and a micro flow cytometer for cell/particles analysis.

The proposed devices have been realized in standard silicon technology by using two silicon wafer bonded together. The channels have been realized by etching the silicon wafer, while the two claddings have been deposited on both wafers by PECVD.

6477-40, Session 12

Tailoring the transmission of liquid-core waveguides for wavelength filtering on a chip

U. Hakanson, ETH Zürich (Switzerland); D. Yin, P. Measor, Univ. of California/Santa Cruz; E. J. Lunt, Brigham Young Univ.; V. Sandoghdar, ETH Zürich (Switzerland); A. R. Hawkins, Brigham Young Univ.; H. Schmidt, Univ. of California/Santa Cruz

The combination of integrated optics and microfluidics in planar optofluidic devices carries the potential for novel compact and ultra-sensitive detection in liquid and gaseous media. Single molecule fluorescence detection sensitivity in planar beam geometry was recently demonstrated in liquid-core antiresonant reflecting optical waveguides (ARROWs) fabricated on a silicon chip. A key component of a fully integrated single-molecule sensor is the addition of an optical filtering capability to separate excitation beams from much weaker generated fluorescence or scattering signals. This capability will eventually allow for integration of an on-chip photodetector by eliminating the need for an off-chip filter. It has been theoretically shown that the wavelength-dependent transmission of liquid-core ARROWs can be tailored to efficiently separate excitation and fluorescence.

Here, we present design and characterization of liquid-core ARROW waveguides with integrated filter function. The waveguides consist of a hollow-core surrounded on top and bottom by silicon nitride and oxide multilayers for optical confinement. We designed the bottom layers to produce wavelength-dependent transmission that is optimized for fluorescence resonance energy transfer (FRET) studies with high transmission at 573 and 690nm, and low transmission at 546 and 633nm. These waveguides were fabricated and their wavelength-dependent transmission was characterized using a highly nonlinear photonic crystal fiber to generate a broadband excitation spectrum. The waveguide loss shows pronounced wavelength dependence in good agreement with the design, demonstrating the capability of tailoring the optical properties of liquid-core waveguides to accommodate single molecule sensing on a chip.

6477-41, Session 12

High-speed laser scanning detection of protein binding on the silicon BioCD

D. D. Nolte, Purdue Univ.

The Silicon BioCD has two key attributes that separates this technology from other optical or interferometric biosensor technologies. The first is the intrinsic scalability of surface-normal interferometric detection with capacity for hundreds or thousands of assays per disc because the footprint per measurement can be as small as a square micron. The second is the high-speed laser scanning that moves the detection frequency far off 1/f noise allowing repeatable surface height sensitivity to below 50 picometers. These two simple attributes provide the potential for high-speed label-free multi-analyte assays with future applications in diagnostics, prognostics and drug discovery. In this paper, we discuss the recent progress in the silicon BioCD that consists of patterned protein on thermal oxide on silicon. The thermal oxide provides the condition of interferometric quadrature for stable common-path interferometry of bound protein on the disc surface. We have demonstrated a scaling surface mass sensitivity of 300 femtograms/mm with a concentration detection sensitivity of 1 ng/ml at 32 assays per disc. This performance places the silicon BioCD at or better than the performance of surface plasmon resonance sensors, but with the crucial benefit of scalability that the SPR approaches lack. The scaling relations of the BioCD and extension of current performance onto a “Moores Law” of protein detection will be presented.

6477-42, Session 13

Optical DNA sensing based on resonant porous silicon structures

S. M. Weiss, Vanderbilt Univ.

The development of optical sensors for the ultra-sensitive detection of chemical and biological species is critically important for disease detection, food safety analysis, and biowarfare agent recognition. Sensing on a silicon platform allows simple and inexpensive fabrication techniques, small device size, and suitability for integration with silicon microelectronics. Porous silicon is a promising silicon-based material for label-free biosensing applications because of its high surface-area-to-volume ratio and its versatility as a thin film optical material. Porous silicon, described as a nanostructured matrix of silicon with void spaces, is primarily fabricated by electrochemical etching. A large range of refractive indices, from approximately 1.4 to 2.7, can be obtained by varying the pore size and density. Two-layer porous silicon planar waveguides have been designed and fabricated as highly sensitive platforms for biosensing applications. Guided waves travel in a high refractive index porous silicon layer and are bound by total internal reflection with a low refractive index porous silicon layer below and air above. Biomolecules are infiltrated directly into the porous silicon waveguide, such that the optical energy is confined exactly where the biomolecules are immobilized. Any change of the refractive index of the waveguide, for example due to DNA hybridization in the pores, will alter the way light propagates in the waveguide and will cause a measurable deviation in the angle at which light is coupled into and out of the sensor. Theory suggests that porous silicon waveguide sensors

should perform with a substantial increase in sensitivity over both surface plasmon resonance sensors and other waveguide sensors for which the optical wave is attenuating as it penetrates the biomolecules. Experimental demonstrations of the porous silicon waveguide sensor response to the binding of DNA sequences will be presented.

6477-43, Session 13

Thin silicon waveguides for biological and chemical sensing

A. S. Densmore, D. Xu, P. Waldron, S. Janz, A. Delâge, P. Cheben, J. Lapointe, National Research Council Canada (Canada)

We show that thin silicon-on-insulator (SOI) microphotonic waveguides offer significant advantages over other material platforms for the applications of biological and chemical sensing. The high index contrast inherent to SOI waveguides allow an extremely large yet highly localized electric field to be supported in the evanescent tail of the waveguide mode, ideal for the probing of thin biological layers.

We experimentally demonstrate a new series of evanescent field sensors exploiting this property, using 0.26 micron Å~ 0.45 micron silicon photonic wire waveguides, integrated with microfluidic channels. The performance of various sensing geometries including Mach Zehnder interferometers and high quality factor ring resonators are described for the sensing of both bulk chemical solution concentration and the adsorption of thin biomolecular layers. These devices are shown to provide higher intrinsic sensitivity over comparable sensor designs reported in all lower index contrast planar waveguide systems.

Furthermore, theoretical comparisons of the maximum obtainable sensitivity of devices constructed on various common material platforms are provided, highlighting the advantages of high index contrast for evanescent field sensing. Finally the device design conditions for optimized sensitivity of SOI sensors are examined for the sensing of both bulk solutions and thin adsorbed biomolecular layers.

6477-44, Session 13

Si based waveguide and surface plasmon sensors

P. Debackere, D. Taillaert, S. S. Scheerlinck, K. De Vos, P. Bienstman, R. G. Baets, Univ. Gent (Belgium)

Silicon-on-Insulator (SOI) is a very interesting material system for highly integrated photonic circuits. The high refractive index contrast allows photonic waveguides and waveguide components with submicron dimensions to guide, bend and control light on a very small scale so that various functions can be integrated on a chip. Moreover, SOI offers a flexible platform for integration with surface plasmon based components which in turn allows for even higher levels of miniaturization. Key property of both waveguide types is the mode distribution of the guided modes: a high portion of the light is concentrated outside of the core material, thus making them suitable for sensitive detection of environmental changes.

We illustrate chemical and label-free molecular biosensing with SOI microring resonator components. In these microring resonator sensors, the shift of the resonance wavelength is measured. A ring of radius 4 micron is capable of detecting bulk refractive index changes of 10-5 RIU (Refractive Index Units), approaching the literature stated limit of 10-6 for biomolecular sensing. We describe the integration of surface plasmon waveguides with SOI waveguides and discuss the principle of a highly sensitive and compact surface plasmon interferometric sensor suitable for biosensing. The device is two orders of magnitude smaller than current integrated SPR sensors, and has a highly customizable behaviour. We obtain a theoretical limit of detection of 10-6 RIU for a component of length 10 :m. We address material issues and transduction principles for these types of sensors.

6477-45, Session 13

Optical biosensor based on arrays of waveguided cantilevers

K. E. Zinoviev, J. A. Plaza, C. Domínguez, V. J. Cadarso, L. M. Lechuga, Ctr. Nacional de Microelectrónica (Spain)

Ultra-thin microcantilevers produced by standard silicon technologies possess low spring constants and can be used as high sensitivity transducers for biosensing applications. The cantilever deflection caused by any kind of biochemical reaction occurring on its surface can be detected with subangstrom resolution if an appropriate detection system is employed. This principle has become widely used in biological research since a few years ago. For the readout of the nanomechanical response of the micro beams to bio-specific interactions produced on one side of the cantilevers usually a technique similar to the AFM is employed. The optical read-out method has some disadvantages, such as low degree of integration and difficulties in work with arrays of cantilevers. In the technique presented in this work the cantilever itself is an optical waveguide butt coupled with another one. The device is fabricated as an array of 20 waveguide cantilever channels which allows for higher integration level. The analysis of the capabilities of the device, the problems associated with the design and the fabrication of the device, the choice of the material and the technology for the fabrication of very flat cantilevers have been successfully addressed. The characterisation of the device was done, showing that the resolution of the device is comparable with the one using the optical lever read-out. The complex steps associated with the immobilisation procedure of the optical cantilevers will be discussed. A protective layer deposited on one side of the cantilevers was applied in order to provide a selective immobilisation only on one side of the cantilever sensor. Results of the simulations and experimental data on the optical cantilevers coated with an absorbent material will be presented. The choice of the appropriate thickness of the absorbent material on the cantilever surface allows for acceptable losses, for single mode behaviour and adjustment of the initial displacement of the cantilever.

Conference 6478: Photonics Packaging, Integration, and Interconnects

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6478-01, Session 1

Flexible polymer pillars for optical chip assembly: materials, structures, and characterization

P. A. Kohl, Georgia Institute of Technology; A. L. Glebov, Fujitsu Labs. of America; E. Elce, Promerus LLC; D. Bhusari, M. Bakir, J. D. Meindl, Georgia Institute of Technology; M. G. Lee, Fujitsu Labs. of America

The materials and processing for chip-to-chip optical interconnects have been developed with compensation for the lateral displacement of assembled components. The lateral displacement is necessary for compensation of thermal and mechanical displacement. Without compensation, the displacement can result in optical signal losses that can critically deteriorate the bit-error-rate of the digital system. We demonstrate the use of flexible, optical, polymer pillars (150 μm height and 50 μm diameter). The lateral displacement tolerance doubles from about 15 to 30 μm for a given loss budget of 1 dB. The pillars were used to form an air-free light path between the chip and the substrate. The pillars were fabricated from Avatrel 2090P photodefinable polymer. The mechanical and optical properties leading to the low optical loss and mechanical compliance will be presented.

6478-02, Session 2

Optoelectronic packaging for 16-channel optical backplane with VHOEs

J. Choi, H. Bi, R. T. Chen, The Univ. of Texas/Austin

16-channels optical backplane using thin film volume holographic gratings is demonstrated for a high-performance computing system. The optical backplane contains TO-46-CAN packaged VCSELs and photodiodes as an optical transmitter and receiver, respectively. Packaging issues including crosstalk and alignment tolerance are studied to fabricate 4 X 8 optical packaging plate for VCSELs and Photodiodes alignment.

Volume holographic grating films are fabricated on a glass substrate to redirect I/O signal beams. Using VHOE(volume holographic optical elements), all 16-channels fan-out beam intensities are in the uniform range of 90 W ~ 150 W. Experimentally measured minimum equalized fan-out power is ~ 5dB higher than the minimum power requirement of this system.

This paper successfully demonstrates 1.6 Gbps of data transmission (100Mbps per single channel) through optical backplane system using volume holographic gratings.

6478-03, Session 2

Low cost optical interconnects

E. J. Palen, PalenSolutions

Optical interconnects to couple light from single mode fiber to waveguides and photonic elements have remained expensive due to tight alignment tolerances, materials choices, fabrication methods and assembly processing techniques. Methods that have been used to lower the cost of optical interconnects will be reviewed and compared to current and future market application demands. Design approaches, fabrication methodologies, and assembly processing techniques for optical interconnects to meet future lower cost market application demands will be shared.

6478-04, Session 3

Thermal considerations in high power semiconductor lasers and semiconductor optical amplifiers

M. Dagenais, S. H. Cho, S. S. Saini, X. Liu, Univ. of Maryland/ College Park

No abstract available

6478-05, Session 3

High-power, slab-coupled optical waveguide laser array packaging for beam combining

L. J. Missaggia, R. K. Huang, B. Chann, C. T. Harris, J. P. Donnelly, A. Sanchez-Rubio, G. W. Turner, MIT Lincoln Lab.

Slab coupled optical waveguide laser (SCOWL) linear arrays are ideal sources for beam combining of array elements using techniques such as wavelength beam combining (WBC) and possibly coherent beam combining (CBC). SCOWL array elements have very high brightness, low divergence and nearly diffraction limited output beams. 87 W CW has been demonstrated in a 1.2-cm width bar. Also, the relatively long cavity length of SCOWL arrays (typically 3-mm to 1-cm), compared to that of conventional ridge and broad area (BA) laser arrays (typically 2-mm to 3-mm), provides for improved thermal management at high power.

In this presentation, the packaging techniques developed to ensure proper performance of SCOWL arrays will be discussed, with particular emphasis on the application to beam combining. A commercial high performance micro impingement cooler (MIC) was used to provide thermal management for these arrays. Based on performance data for this cooler, a numerical thermal model was constructed and used to model the thermal performance of SCOWL arrays.

In order to promote uniform optical performance of SCOWL array elements, assembly procedures were developed which included fluxless soldering using In and AuSn solder alloys, along with the use of thermal expansion matching materials. These techniques resulted in minimal contraction (~2 μm) and smile (~1 μm) of the laser bar during the packaging process, in order to minimize any detrimental impact on the resultant WBC beam quality.

CBC of SCOWL arrays requires phase control of the array elements. Array packaging providing for individual addressability of the array elements has been developed, allowing for phase control by current adjustment.

6478-06, Session 3

Surface roughening on n-GaN surface and its effect on lighting performance of thin-GaN LED

T. C. Hsu, C. Liu, National Central Univ. (Taiwan)

Texture on n-GaN surface is an important issue to improve the light extraction for GaN-based LEDs. Currently, using photo-enhance chemical etching (PEC) has been proven to be an efficient method to roughen the n-type GaN surface. Regular pyramids would form on the n-GaN surface. We have studied the kinetics of PEC etching on n-GaN layer. The detail results will be reported in this talk. To improve ohmic contact and the current spreading into the roughened n-GaN layer, an ITO (Indium Tin Oxide) is required to deposit on the n-type GaN surface. The correlation between the degree of the roughness on n-GaN surface and lighting performance, contact resistance, light extraction efficiency will be discussed in this talk as well.

6478-07, Session 3

Experimental investigation of optical spectrum deformation of FBG sensors

X. Zhang, J. Max, X. Jiang, L. Yu, H. Kassi, ITF Optical Technologies, Inc. (Canada)

Fiber Bragg grating (FBG) sensors have been used in civil engineering, geotechnology, oil and gas, and other structural monitoring for many year where it has demonstrated many advantages over electrical gauges. One of the common methods of FBG interrogation uses wavelength scanning. Such technology shows severe speed limitations, making it suitable for static, long-term monitoring only. Applications involving impact and vibration monitoring require measurement bandwidth above 1kHz. We have developed and prototyped a high-speed FBG interrogation system with a sampling rate up to 5 kHz. It is found that FBG sensor spectral deformation may affect the performance of the interrogator. Such deformation can be introduced during FBG sensor packaging. Experiments show that in some cases, the spectrum deformation can be related to strain or temperature variations applied to the sensor or other parameters under test. This paper reports on the experimental investigation of the impact of these deformations on the interrogator accuracy. In the unusual case where the spectrum becomes asymmetrical beyond a certain level, the measurement accuracy is affected. Sensors with different optical spectral shapes are tested and analyzed. Based on the results, we formulate a tolerance to deformation taking into account the accuracy of the system.

6478-08, Session 4

Fiber optic interconnect and optoelectronic packaging challenges for future generation avionics

M. W. Beranek, Naval Air Systems Command

No abstract available

6478-09, Session 4

Realization of integrated optical interconnections on printed circuit boards

M. Riester, G. Langer, Austria Technologie und Systemtechnik AG (Austria); G. Leising, Joanneum Research GmbH (Austria)

The development of integrated optical interconnections (IOIs) represents a quantum leap for the functionality of printed circuit boards (PCBs). This new technology will allow highly complex product features and hence, higher product added value. PCBs with optical interconnections will be used where applications call either for very high data streams between components, modules or functional units (e.g. backplanes or multiprocessor boards) or for a space-saving design for interconnection paths (e.g. mobile applications).

We report on a new and innovative concept for the integration of an optical interconnection system in PCBs. This revolutionary concept is highly supporting the worldwide trend towards miniaturization of not only electronic but also optoelectronic systems in PCBs. The alignment of the optoelectronic components to the waveguides is the biggest problem, which has to be solved for the realization of IOIs in PCBs. This is due to the different tolerances allowed for the production of electronic interconnection systems (standard PCB production process) and the production of the optical interconnection system (alignment of the optoelectronic components to the waveguides).

The shown concept offers the possibility to combine two totally different technology areas -PCB manufacturing processes and the production of optical interconnections. In this paper the compatibility of both areas will be demonstrated. Optoelectronic components are attached on FR4-inner layers and are completely embedded within an optical polymer layer. By using a two-photon absorption (TPA) laser structuring method it is possible to realize optical circuits inside the polymer connecting different optoelectronic components. Due to the TPA process the optical material increases its refractive index and optical waveguides can be inscribed in 3 dimensions within the optical layer. Due to this outstanding advantage of this structuring method, the waveguide ends can easily be aligned to the optoelectronic components. The PCB is laminated by means of standard PCB manufacturing processes to achieve a multi layer PCB featuring integrated optical interconnections. The compatibility of the optical material to the PCB production process as well as the performance of first PCB demonstrators featuring IOIs will be discussed.

6478-10, Session 4

Minimising crosstalk in microchannel free-space optical interconnects with the presence of higher order modes

F. F. Tsai, C. O'Brien, A. D. Rakic, The Univ. of Queensland (Australia)

Free-space optical interconnects (FSOI) have been proposed as the solution to address the limitations of electrical interconnects. One of the major factors that determine the maximum channel density and signal-to-noise ratio (SNR) is the optical crosstalk noise within the system. Furthermore, Vertical-Cavity Surface-Emitting Lasers (VCSELs) tend to operate in several transverse modes simultaneously. The presence of higher order transverse modes will cause a significant degradation in SNR in the FSOI channel. We consider two types of optical crosstalk present in FSOI systems: the diffraction-caused crosstalk noise (DCC) and the stray-light crosstalk noise (SLC). While both types of crosstalk are related to the finite aperture of the transmitter and receiver microlenses and depend on the modal structure of the VCSEL beam, they behave very differently with respect to the FSOI design parameters.

In this paper we demonstrate that there exists an optimal focal length of the transmitter microlens array which maximises the SNR by minimising the combined effects of DCC and SLC. To the best of our knowledge this has not been investigated so far. The optical system simulation software (Code V) was used to simulate both the stray-light and diffraction-caused crosstalk. Experimentally measured spectrally-resolved near-field images of VCSEL higher order modes were used as extended sources in our simulation model. The simulation was performed using a combination of exact ray tracing and the beam propagation method. Our results show that shorter focal length needs to be used for higher order modes to obtain optimal SNR in an FSOI system.

6478-11, Session 4

3.2Gbps multi-channel optical backplane bus demonstrator using photopolymer volume gratings

H. Bi, J. Choi, The Univ. of Texas/Austin; W. Jiang, Omega Optics, Inc.; X. Han, Brewer Science, Inc.; R. T. Chen, The Univ. of Texas/Austin

A 3-slot optical backplane bus demonstrator based on glass substrate with large area (3cmx5cm) photopolymer volume gratings (PVG) on top surface is built to allow 16 channels of data to be broadcast from central slot to two daughter slots or uploaded from any daughter slot to central slot. VCSELs and photodetectors packaged in the form of TO-46 can are assembled on top of each PVG and interleaved to reduce the crosstalk to below noise level. By carefully aligning the fabrication system, the incident angle deviation from Bragg condition is reduced to below 0.1 degree to maximize optical power delivery. The orientation and period of hologram fringes are uniform in the active area by collimating recording beams.

3.2Gbps data transmission is successfully demonstrated using the multi-channel system. Three computer mother boards using FPGA are made to verify the data transmission among the slots. Interface boards between the FPGA boards and optical transceivers are designed and fabricated to separate the implementation of digital layer and optical layer. Single chan-

nel transmission with 10Gbps data rate is also tested with above 100uW input power, showing the potential to improve. Alignment tolerance of the optical interconnect system is investigated theoretically and experimentally. By analyzing the diffractive characteristics, the bandwidth limit of the optical layer is determined to be in the order of Terahertz. Design and fabrication issues are discussed for future optical backplane bus to make terahertz bandwidth into reality.

6478-12, Session 5

Three-dimensional microoptic systems integration: advances in fabrication and packaging

J. Jahns, M. Bohling, M. Jarczynski, T. Seiler, Fern Univ./Hagen (Germany)

The use of the third spatial dimension in optical systems is of interest for many applications such as sensing and data communications. Furthermore, the need for small size and low cost requires suitable concepts for integration and packaging. Here, free-space optical integration based on a planarized configuration is described. Recent advances are shown in the fabrication of the elements using grey-scale lithography and micromachining. Systems demonstrations will be presented for the field of optical interconnection.

6478-13, Session 5

Innovative materials tailored for advanced microoptic applications

R. Himmelhuber, micro resist technology GmbH (Germany) and College of Optical Sciences/The Univ. of Arizona; M. Fink, K. Pfeiffer, U. Ostrzinski, A. Klukowska, G. Gruetzner, micro resist technology GmbH (Germany); R. Houbertz, H. Wolter, Fraunhofer-Institut für Silicatforschung (Germany)

The handling of a continuously increasing amount of data leads to a strong need for high-speed short-range connections. Conventional Cu technology between chips on a board is limited. Optical interconnects will dominate the market, since they can overcome the limitations. One of the issues for materials used, e.g., for waveguides embedded in printed circuit boards (PCBs) is the compatibility with standard epoxies used for PCBs during the entire board fabrication process. Materials applied for optical interconnects should be mechanically and optically reliable, and of low costs. From the material production side, the process should be easy to up-scale. Therefore, anticipatory research strategy, and suitable tailoring is asked for.

The handling of light in the UV and visible range often requires the use of specially designed materials. Most polymer materials show an increased yellowing effect upon being exposed to shorter wavelength light. The major influence on the absorption in the UV and visible range of a UV curable material is related to the UV initiator, beside any other chromophores formed mainly during the exposure.

Different material approaches will be presented which fulfill the requirements for highly sophisticated applications in optics / optical packaging technology. Firstly, the adaptation of a UV patternable inorganic-organic hybrid material (ORMOCER(r)), originally developed for waveguide applications in the data and telecom regime, will be discussed with respect to applications in the visible regime. Secondly, an epoxy-based material system for optical chip-to-chip interconnection will be introduced. Spectroscopy and UV-DSC measurements were carried out to investigate the influence of standard photointiators on the optical properties for an ORMOCER(r) system suitable for microoptic applications. The results show that the resulting material properties were significantly improved by exchange of the initiators compared to the originally incorporated one.

6478-14, Session 5

A characterization of UV effects on optical silicones used in opto-electronic devices and new developments in resistant materials

B. Riegler, NuSil Technology LLC

Opto-electronic devices such as LEDs, optical sensors, LCDs and color filters have the need for optically transparent encapsulants or adhesives. Maintaining the highest transmission possible of the encapsulant/adhesive throughout the life of the device is a critical criteria for the device designer. Silicones as encapsulants/adhesives in opto-electronic devices have been used throughout the last decade. The high light flux and associated heat proved too much for the traditional epoxies. Data confirms silicone encapsulants/adhesives provide longer optical transmission life than epoxy encapsulants.

Almost all optical devices have some interaction with UV wavelengths. Manufacturers of blue LEDs with wavelengths near 405nm, and other LEDs that emit wavelengths deeper into the UV (365-399nkm), have concerns about the effects of this radiation on the light transmission of the encapsulant over time. LCD and sensor devices may have UV radiation from the sun to contend with. This paper looks at many different encapsulants/adhesives, silicone, epoxy and acrylate, for their change in optical transmission due to a 680-6800J/cm2 dose of radiation with the following spectral output:34% in the UVA (320-399nm), 17% in the UVB (80-319nm), and 49% concentrated at 405nm and 450nm. All samples were prepped and exposed the same way so that comparisons between the samples would be meaningful. Results show that silicones perform better than acrylates, which perform better than epoxies, and not all silicones perform equally. Data will be provided of the best performing materials and a discussion of future work given the understanding of the chemistry.

6478-15, Session 5

Novel cost effective carbon nanotubes deposition technique using optical tweezer effect

K. Kashiwagi, S. Yamashita, The Univ. of Tokyo (Japan); S. Y. Set, Alnair Labs. Corp. (Japan)

Carbon nanotubes (CNTs) are very attractive in photonics device applications for their saturable absorbtion characteristics, ultra-fast response time, high optical nonlinearity, etc. However, handling the CNTs is one of the problems for device applications. Conventionally, CNTs are sprayed, directly synthesized onto a device, embedded into polymer materials. With these techniques, several processes are complicated, process setups are required and CNTs are not efficiently used.

Thus, easy and cost effective handling technique for CNTs deposition is required for device applications. We propose and demonstrate novel technique to deposit CNTs onto an end facet of an optical fiber. By using optical tweezer effect, we can easily deposit CNTs onto the fiber end facet only around core region with simple setup. By this technique, CNTs are successfully deposited onto end facets of optical fibers and confirmed by raman spectroscopy. By using this fiber, passively mode-locked fiber ring laser was realized.

This technique will allow us to realize low cost CNTs-based photonics devices.

6478-16, Session 6

High speed IC design trends and optoelectronic packaging: a perspective on cost reduction

B. N. Gomatam, B. Mayampurath, Vitesse Semiconductor

No abstract available

6478-17, Session 6

WDM over POF: the inexpensive way to breakthrough the limitation of bandwidth of standard POF communication

U. H. P. Fischer-Hirchert, M. Haupt, Hochschule Harz (Germany)

Standard polymer optical fibers (POF) are used in various fields of applications. As a medium for communication systems, they offer many advantages in comparison with copper or glass. They are applied for communication in the automotive sector. Furthermore POF are used for in-house communication. There POF are established for PC-Data, VoIP and IP-TV, it is the so called “Triple-Play”.

These applications have high demand on bandwidth. Because till now only one wavelength is used to carry information over the fiber, communication is limited in bandwidth by about 2Gbit/s for a POF. Hence new ways have to be developed to breakthrough this limitation. One promising attempt is the use of wavelength division multiplexing (WDM), where information is carried over one single fiber by different wavelengths.

To use this technique, there have to be two technical key-elements added into the communications system: a multiplexer that combines the multi-wavelengths signals into one fiber and a demultiplexer at the end of the network to separate the colored signals.

There are several demultiplexer for glass-fiber networks available, but they are not suited to use them in the mentioned applications in the polymeric transmission window between 400nm and 700nm. Therefore a new demultiplexer with new technology is needed to satisfy the demands.

The design simulation, the set-up and the new hybrid packaging and fabrication technology of the demultiplexer will be shown. It separates the monochromatic parts of light by means of a high dispersive prism and will be produced by injection molding technology, ready for mass-production.

6478-18, Session 6

10Gb/s bi-directional optical sub-assembly module for the application of FTTH network

T. Shih, National Kaohsiung Univ. of Applied Sciences (Taiwan); M. Lin, Y. Chiu, National Sun Yat-Sen Univ. (Taiwan); C. Li, T. Hung, APAC Opto Electronics Inc. (Taiwan); W. Cheng, National Sun Yat-Sen Univ. (Taiwan)

To upgrade the transmitted data rate from gigabit/s to 10Gb/s for the FTTH optical network, a 10Gb/s Bi-directional optical sub-assembly (BOSA) module was designed and fabricated. The transmitter side of this BOSA adopted a proprietary 1310nm TO-56 based low-cost DFB laser diode to emit the up-stream optical signal. The receiver side used a 10Gb/s PIN-TIA TO-Can device to detect the down-stream 1550nm optical signal. A 1310nm/1550nm WDM filter was placed in a metallic housing with 45 degree to deflect the down-stream 1550nm optical signal into the PIN-TIA device and couple the up-stream 1310nm optical signal into the optical fiber. Laser welding technology was used to attached the fiber pigtail and assemble all the components together. The materials and fabrication processes used were designed to be compatible with low-bit-rate devices to lower the manufacturing cost and ease of mass production. A PCB with the transmission lines and a MAX3971 limiting amplifier IC was attached to the leads of PIN-TIA device. The measured receiver eye diagram opened clearly and met the 10GbE standard. Sensitivity is estimated to be higher than -10dBm at 10^-9 BER. The transmitter eye diagram was measured and shown to be good in the 10GbE transmission. To our best knowledge, such a 10Gb/s BOSA module have not been reported before. This 10Gb/s BOSA demonstrated not only the feasibility of 10Gb/s Bi-directional transmission on a single SM fiber for FTTH or PON applications, but also showed the low-cost possibility to ensure the success of next generation 10Gb/s access network.

6478-19, Session 6

Optical coupling to monolithic integrated photonic circuits

E. J. Palen, PalenSolutions

Methods of coupling optical fiber and light sources to monolithic integrated photonic circuits are needed to expand future photonics communications markets. Requirements are low cost, high coupling efficiencies, and scalability to high volume production rates. Key features of the different optical coupling options will be discussed along with implementation examples. Requirements for low cost optical coupling and high volume production scalability will be shared.

6478-20, Session 7

Hybridization of active and passive elements for planar photonic components and interconnects

M. R. T. Pearson, S. Bidnyk, A. Balakrishnan, Enablence Inc. (Canada)

No abstract available

6478-21, Session 7

Integrated silicon photonics: packaging and chip level assembly

M. Asghari, P. Zhou, Kotura, Inc.

No abstract available

6478-22, Session 7

Silicon photonics packaging: characterization of a waveguide grating coupler and modeling of the fiber coupling ratio

C. H. Kopp, J. Fédéli, P. Grosse, S. Poncet, Lab. d’Electronique de Technologie de l’Information (France)

Surface grating couplers are of great interest to couple light from a waveguide to an optical fiber. The main advantage is that such a coupler allows for in and outcoupling without the need for cleaving and polishing facets, which makes wafer-scale testing of photonic circuits possible. In this paper the outcoupled beam of a grating coupler is experimetally charaterized in order to get a cartography of the power distribution over the grating and the propagating properties of the beam. Such a characterization goes beyond usual experimental singlemode fiber coupling giving more detailed informations required to improve the grating coupler design. In a first step, those measurements are introduced into a home-made modeling tool which allows to calculate the singlemode fiber coupling ratio and the positionning tolerances for any kind of fiber from usual SMF28 to high numerical aperture fibers. In a second step, the cartography of the power distribution over the grating will be compared to the modeling results and will be used to improve the grating coupler design in order to get a beam mode closer to the fiber mode. Finally, packaging considerations will be discussed to integrate optical fiber connecting into the IC packaging flowchart.

6478-23, Session 7

Efficient fiber to waveguide coupling structure for optical systems integration using grayscale lithography

T. E. Dillon, J. A. Murakowski, C. Chen, D. W. Prather, Univ. of Delaware

Integrated photonic systems are of great current interest due to their enhanced functionality, bandwidth, and speed of operation as compared to their electrical counterparts. But issues still remain with respect to their packaging and integration with other components; in particular, a simple means for efficient coupling of light into these devices is a challenge. This is due in part to the large mode mismatch between the optical fiber and high index contrast waveguides as well as difficult mechanical alignment. We have developed a unique structure for coupling of signals from fiber to waveguide which addresses these issues. The device essentially consists of a parabolic reflector based on total internal reflection, which couples light from fibers plugged through the backside of the wafer into the plane of the device layer of an SOI platform. The device is simple to fabricate based on HEBS glass grayscale lithography, alignment is non-critical, and the efficiency is high as compared to other methods of optical coupling. We will discuss the design and FDTD simulation of this device, the enabling fabrication processes developed for it, as well as present empirical results on its operation and efficiency.

6478-24, Session 8

Long period gratings for integrated optical power splitters

J. N. McMullin, C. P. Wong, C. J. Haugen, Univ. of Alberta (Canada)

Long period gratings (LPGs) in singlemode fibers have been used in recent years to make optical sensors. The grating-assisted coupling of light from the bound fibre mode to an unbound cladding mode is sensitive to local influences such as temperature and stress. In this paper, we investigate the possibility of using LPGs to modify the behavior of planar multimode interference (MMI) devices by coupling power between selected bound modes of the planar device. In particular, it is shown that by adding a LPG to a MMI 1xN splitter, the splitting ratio can be changed. By making the grating dynamic, a tunable splitter can be realized. Examples are given for 1x2, 1x3 and 1x5 splitters. Possible methods for realizing such devices are discussed.

6478-25, Session 8

Polarimetric imaging cross talk effects from glue separation between FPA and micropolarizer arrays at the MWIR

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We have designed and built a setup that can model a pixel from a focal plane array (FPA) and determine the effect of crosstalk from adjacent gold wiregrid micropolarizer pixels. The FPAs and micropolarizers work at the mid wave infrared (MWIR). The general idea to implementing a snapshot polarization-imaging device is to stack and glue two substrates: micropolarizer array substrate on top of a FPA. We evaluated several array of super-cells of four pixelated polarizers by modeling the near fields behind the devices. Each polarizer in the super-cell is oriented to allow solving three Stokes parameters by themselves or four Stokes parameters in conjunction with a birefringent waveplate. In addition, we fabricated sets of super-cells for determining optimum polarizer-FPA separation. Modeling and empirical data indicate cross talk between the adjacent pixels at several microns after crossing the polarizer plane. Cross talk between adjacent pixels increases uncertainty in the measured polarization states of a scene of interest. Data shows that a micropolarizer pixel in a super-cell the extinction ratio will reduce by 17% when moving the FPA from 0.5 ∝m to 1.0 ∝m away from the polarizer. These changes in extinction ratio are important given that typical glue separation is approximately 10 ∝m.

6478-26, Session 8

Multichannel fiber optical inclination measuring transducer

Y. N. Kulchin, O. B. Vitrik, A. V. Dyshlyuk, Institute for Automation and Control Processes (Russia)

A multichannel fiber optical intensity based sensor for remote inclination measurement has been developed based on light beam displacement caused by a transparent free hanging parallel sided deflector glass plate as it changes its angular position relative to the sensor body. The deflector plate is mounted on a gimbal suspension to avoid interference between orthogonal tilt directions. In order to enable vibration resistant measurement the deflector plate is damped by a transparent viscous liquid. Light intensity drift compensation is achieved through the comparison of two output signals obtained from the two spaced measuring channels integrated in the sensing element. The specifications of the sensor are as follows: threshold sensitivity - 0,010, dynamic range - 25 dB, measuring angle range - ±40. As a result of performance equalization sensor's output signal variation corresponding to 30% input light intensity decrease does not exceed ±4%. Due to the utilization of standard low-loss multimode optical fibers the sensing element can be removed from the light generation and processing units to a distance of up to several kilometers. High sensitivity and stability of the proposed technique allow wide spread application of the sensor in structural health monitoring, machine building, seismology and other areas where precision angular positioning or monitoring is required.

6478-27, Session 8

An all-optical nonlinear threshold gate based on microring resonators

X. Lu, L. Zheng, J. Vaillancourt, Univ. of Massachusetts/Lowell

An all-optical nonlinear threshold gate based on microring resonators were investigated using the transmission matrix formalism. A Kerr nonlinear enhancement factor of exceeding 2.5x103 can be obtained at the ring-coupling coefficient of 0.02. Simulation results show that the nonlinear optical threshold gate has a sharp optical intensity-dependant switching property with a low switching threshold (> 80%) of -10dBm. The optical intensity-dependant switching property preserves for a wide optical signals ranging from c.w. to pulses as short as 10ps. The nonlinear optical threshold is capable of removing side-lobe noises and cross-correction noise whose intensity is below the switching threshold and thus increases the signal to noise ratio.

6478-28, Session 8

Hybrid mutichannel fiber-optic strain gauge

A. D. Lantsov, Far Eastern State Technical Univ. (Russia); O. B. Vitrik, Y. N. Kulchin, Institute for Automation and Control Processes (Russia)

One of the most promising optical fiber sensors (OFS) for distributed strain monitoring is a single-fiber multimode interferometer (SFMI), enabling effective combination of ultimate measuring scheme simplicity with high metrological performance. However the basic problem associated with SFMI deals with the extraction of deformation rating data from the random and inhomogeneous multimode interference speckle pattern distribution. The solution of this problem that can be found in literature, is based on the dependence of correlation coefficient of speckle fields, formed by SFMI, on phase changes of the guided modes of the optical fiber under deformation. However correlation holographic filters and amplitude filters, presented in those works, demand constant rewriting owing to uncontrollable mismatch of a speckle-pattern with the reference image written down on a header at change of an ambient temperature. That prevents the methods from wide spread practical application. Apparently, digital electronic device usage for SFMI speckle-signals registration and processing is capable to solve the problem mentioned above

due to automation of reference images rewriting processes and correlation calculations accuracy increase.

Therefore the purpose of the present work was a development and researching a correlation method of processing single fiber multimode interferometer (SFMI) signals using a charge coupled device and a PC.

In the present work a correlation method of processing single fiber multimode interferometer (SFMI) signals using a charge coupled device is investigated both theoretically and experimentally.

Optimal statistic and geometrical parameters of speckle pattern's registration by CCD, which provide maximum correlation processing accuracy and compensation of CCD-matrix nonlinearity are determined.

It has allowed us to achieve the following specifications of the SFMI-based strain gauge: precision of absolute elongation measurement - up to ± 3 μm, temperature inaccuracy of tensile elongation measurements 7.3*10^-7 1/C in a temperature span from 15 to 60Ỳ Ñ, dynamic range - 80 dB.

The possibility of creation of distributed strain monitoring system based on SFMI has been shown. Maximum number of measurement channels of the monitoring system - 12 (using 320*240 resolution CCD-matrix).

Conference 6479: Quantum Sensing and Nanophotonic Devices IV

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6479-01, Session 1

Recent developments and perspective in spintronics: spin transfer, spintronics with semiconductors, molecular spintronics

A. Fert, UMR CNRS/Thales (France) and Univ. Paris Sud (France)

The lecture will be a presentation of some recent developments in spintronics and a discussion of the perspective in this field. This includes a review of results on spin transfer (current-induced magnetic switching and generation of microwave oscillations), spin injection into a semiconductor, spin transport in a semiconductor between spin-polarized source and drain, spin transport in molecules. The synchronization and phase locking of a collection of STO's (Spin Transfer Oscillators) is an example of important new problem raised by the progress in the generation of microwave oscillations by spin transfer. Finally, the natural evolution of spintronics towards nanospintronics will be illustrated by recent results on single-electron spintronics and on the spin lifetime in nanoparticles.

6479-02, Session 1

Measurement of spin torques

H. Siegmann, Stanford Synchrotron Radiation Lab.

Beam experiments, valid for ballistic injection of spin polarized electrons into a ferromagnet, can actually measure the magnitude and direction of the spin torque T as spin polarized electrons are reflected or transmitted. After the interaction of the electrons with the ferromagnet, the spin polarization vector P changes. From the motion of P one obtains T according to dP/dt = const.T. The experiments [1, 2, 3] show that two types of torques are active, a large precessional torque TP leading to precession about the easy direction of M, and a damping or frictional torque TD driving the spins into or against the easy magnetization direction.

In most of the promising applications using spin injection to switch M, one has diffusive rather than ballistic spin currents. The measurement of P of the diffusive current is not possible so far. But we have recently been able to show, using a typical CPP-spin valve pillar, that one can measure the magnetization of the sensor layer M2 as it depends on location and time using x-ray magnetic circular dichroism (XMCD), with spatial resolution of 30 nm and temporal resolution of 200 ps at present [4]. Owing to Newtons law of opposite and equal reaction, the measurement of M2 is equivalent to the measurement of P. By imaging M2 (x,y,t), where x and y are the coordinates in the plane of the sensor film and t is the time, we are able to observe the detailed magnetic switching process induced by the flow of electrons using advanced pump-probe x-ray microscopy.

It turns out that the switching actually occurs in a new mode, namely by lateral motion of a magnetic vortex across the magnetic film. The vortex structure is favored by the Oerstedt- field produced by the charge current while the spin current induces the lateral motion of the vortex leading to switching as soon as the center of the vortex moves out of the film and the resulting C-state relaxes into the uniform state. The energy barrier of this switching mode is substantially lower compared to uniform rotation over the magnetic anisotropy barrier. Of course, the experiment [4] also clearly shows that we have observed the effect of the torque induced by the Oerstedt field superimposed onto the torque produced by the spin current. To obtain the spin torques without such bias, future experiments must eliminate or compensate the Oerstedt field. This appears to be possible for instance in lateral spin valve structures.

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6479-03, Session 1

Nanoscale spintronic devices

L. W. Molenkamp, Univ. Würzburg (Germany)

This talk will give an overview of recent developments in spintronic device physics, across the range of materials now available to the eperimenter.

One example are resonant tunneling diodes (RTDs) fabricated from paramagnetic II-VI semiconductors that can be operated as a voltage controlled spin-switch. I will demonstrate how these devices act as very efficient spin detectors, and, in tandem, offer the functionanlity of a fully bias controlled spin-valve. A quantum dot version of these RTDs exhibits, unexpectedly, remanent magnetism at zero external fieldm which we interpret as resulting from tunneling through a single magnetic polaron.

In the ferromagnetic semiconductor (Ga,Mn)As, we have a novel magnetoresistance effect, dubbed tunnel anisotropic magnetoresistance (TAMR), which results from the strongly (magneto-)anisotropic density of states in the material, that stems from the large spin-orbit coupling. The effect leads to the observation of a spin valve-like behavior in tunnel structures containg a single ferromagnetic layer and also dominates the spin-valve signal obtained from structures containing two (Ga,Mn)As layers. While the effect usually amounts to severals tens of percent in amplitude, at low temperatures resistance changes of five orders of magnitude. This is caused by the fact that the system undergoes a metal-insulator transition upon reorientation of the magnetization.

Finally, I will briefly address the spintronics one can do in materials that have strong spin orbit coupling. Improved mobilities and improved control of the so coupling strength have led to a number of novel experiments in narrow gap II-VI compounds, including an observation of the Aharonov-Casher effect.

6479-04, Session 2

Band-gap induced electron spin precession upon reflecting from ferromagnetic surfaces

L. Joly, J. K. Ha, M. Alouani, J. Kortus, W. Weber, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

It has been shown that high current densities of polarized electrons can cause magnetization reversal in a ferromagnetic film via transfer of spin-angular momentum. In order to controllably utilize this effect, it is therefore necessary to achieve a better understanding of the spin-induced torques. Recently, we studied the spin-transfer phenomenon by examining the transmitted part of an electron beam incident onto a ferromagnetic film. In order to maximize the spin precession of the reflected electrons, the polarization direction of the incident electron beam has been chosen perpendicular to the magnetization direction of the ferromagnet. While that study was important in itself, it did not address the behavior of the reflected electrons. However, this information is essential to obtain a more complete picture of the spin-transfer process.

Here, we present experimental data on polycrystalline Fe, Co, and Ni films to show how the spin polarization vector of an electron beam changes

upon reflecting from a ferromagnetic surface. The spin polarizations of both the incident and the reflected beam were determined. A strong precessional motion around the magnetization direction has been observed at low kinetic electron energies. This can be quantitatively accounted for by including the effect of a spin-dependent gap in the electronic band structure of the ferromagnet.

6479-05, Session 2

Spin injection and accumulation in mesoscopic metal device structures

M. S. Johnson, Naval Research Lab.

There have been several recent experiments involving spin injection and accumulation in mesoscopic metal samples, using lateral spin valve structures. The results have been interesting from the perspectives of both fundamental physics and applications. The resistance change associated with spin accumulation, ΔR, has been predicted to scale inversely with sample volume and this inverse scaling has been observed over 9 decades. A value of ΔR = 1 Ohm has been reported, at room temperature, in a thin film Al wire structure with transverse dimensions of roughly 100 nm. High values of ΔR have been observed in samples characterized by electrode interface resistances that vary by 6 decades. Results will be discussed within the framework of Johnson-Silsbee theory, and factors that will limit inverse scaling will be identified. Lateral spin valves with dimensions of tens of nm may be competitive for device applications. Structures with ΔR of order 1 Ohm are very competitive with CPP spin valves of comparable dimensions. Prospects for improved performance, the plausibility of a lateral spin valve with output levels of 10 Ohms and output impedance of 50 Ohms, and relevance to hard drive read heads and integrated nonvolatile random access memory applications will be discussed.

6479-06, Session 2

Observation of coupled magnetic vortex structure dynamics by time-resolved magneto-optical Kerr effect microscopy

R. Antos, J. Hamrle, The Institute of Physical and Chemical Research (Japan); H. Masaki, T. Kimura, The Univ. of Tokyo (Japan); J. Shibata, Y. Otani, The Institute of Physical and Chemical Research (Japan)

Increasing interest in the detailed understanding and control of micromagnetic behavior of laterally confined submicron magnetic elements calls for extensive development of monitoring techniques. Among them, time-resolved Kerr microscopy (TRKM) provides a unique possibility to monitor magnetization excitation development in sub-nanosecond scale. We use TRKM to monitor arrays of magneto-statically coupled submicron circular magnetic dots with vortex spin structures. For this purpose we have developed a measurement apparatus consisting of two parts, a magneto-optical (MO) Kerr microscope and system for operating magnetic pulse excitation. The microscope consists of the picosecond pulse laser diode PIL040 (working at 408 nm), an apochromat objective with a long working distance, nearly crossed polarizer and analyzer, beam-splitter, CCD camera, and a set of lenses collimating the light beam to the sample and detector. The measurement can be alternatively performed either in the wide-field mode (providing the direct magnetic image of the sample) or in the scanning mode (detecting the Fourier transform of the beam focused to and reflected by a submicron area of the sample which is then resolved into the magnetization components thus observed in that area). In addition, we apply a compromise between the both wide-field and scanning mode measurements, referred to as the MO Fourier transform (MOFT) method. The MOFT approach measures the Fourier image of the magnetization distribution within the illuminated area which is then inversely transformed into the direct magnetic image. We present experimental results of spin vortex dynamics obtained on pairs and larger arrays of coupled magnetic vortices and a comparison with recent theoretical predictions. Particularly we show the experimental time evolution of magnetization components for various combinations of vortex polarities and chiralities from which such observations can be deduced as the vortex core trajectories or damping rates.

6479-14, Session 3

Magnetic race-track: a novel spintronic storage-semory

S. S. P. Parkin, IBM Almaden Research Ctr.

A proposal for a novel storage-class memory is described in which magnetic domains are used to store information in a “magnetic race-track” [1]. The magnetic race-track shift register storage memory promises a solid state memory with storage capacities and cost rivaling that of magnetic disk drives but with much improved performance and reliability. The magnetic race track is comprised of tall columns of magnetic material arranged perpendicularly to the surface of a silicon wafer. Magnetic domain walls (DWs) are moved up and down the race-track by nanosecond long current pulses using the phenomenon of spin momentum transfer and are detected using magnetic tunnel junction sensing devices. A series of experiments [2-4] which explore the current and field induced motion of DWs along permalloy nanowires will be discussed. The DW structure, whether vortex or transverse, and the DW chirality can be readily detected from its resistance. The current induced depinning of DWs from artificially created pinning sites - notches along the edges of the nanowires- is shown to be surprisingly insensitive to the DW structure [2]. The velocity of domain walls [3], driven by current alone in the absence of magnetic field, is shown to exceed 110m/sec. A number of studies which show the importance of the precessional nature of the DW motion will be presented [4,5].

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6479-15, Session 3

Electron tunneling through a spin-orbit-split barrier

H. M. Drouhin, École Polytechnique (France); G. Fishman, Univ. Paris-Sud II (France)

Spin-dependent tunneling is a major field of interest because applications concern a huge industrial market. Tunnel barriers constitute building blocks for a number of spintronics devices, in particular reading heads, based on tunnel magnetoresistance (TMR). Many years ago, evanescent states in semiconductors have been studied in pioneering works, for instance by Heine, Jones, Chang and others.[1] The rather involved structure of the complex bands was explored. However, when dealing with III-V semiconductors with zinc-blende symmetry, the spin-orbit interaction and the absence of inversion symmetry had never been simultaneously considered. In recent papers, it was shown that, taking both of them into account, leads to drastic modifications of the electronic structure.[2] Concerning the fundamental gap, the evanescent branch associated to an imaginary wave vector, which usually connects the first conduction band to the light hole band, disappears in the directions where the D’yakonov-Perel’ internal effective magnetic field,[3] which is a consequence of the

spin-orbit interaction in the absence of inversion symmetry, is non-zero. Along these directions, the evanescent states correspond to complex wave vectors, having both a real and an imaginary component. Calculating solutions of the Schrödinger equation corresponding to these complex wave vectors is a well-defined mathematical problem, determining how the tunneling channels are altered by this symmetry breaking is a different question, of physical nature. Recently, Perel' and al. addressed this question in the framework of the effective-mass approximation in the case of a [100]-oriented barrier under off-axis incidence.[4] There, it can be shown that a standard tunnel process is restored, in a very subtle way, and large - in the 1 to 10 percent range - spin filter effects are calculated. In the present work, we consider this question under a more general angle, for GaAs-like barriers with an arbitrary orientation. Using symmetry considerations, we demonstrate that, when the complex wave vectors have orthogonal real and imaginary components, almost standard tunnel channels are recovered. On the contrary, when these components are not orthogonal, the situation becomes more complex. An illustration is developed in the model case of an [110] oriented barrier : there, we address a simple case, where the evanescent waves involve complex wave vectors. A striking conclusion is that the up- and down-spin channels can no longer be separated. Standard problems dealing with one-dimensional electron transmission through barriers, are revisited, with non-trivial consequences.

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6479-61, Session 3

Spin injection and detection in GaMnAs-based tunnel junctions: theory and experiments

H. Jaffres, M. Elsen, J. George, R. Mattana, A. Fert, Thales Research & Technology (France); A. Lemaitre, Lab. de Photonique et de Nanostructures (France)

High tunnel magnetoresistance (TMR) have been achieved using the p-type ferromagnetic semiconductor (Ga,Mn)As as electrodes of tunnel junctions [1][2]. It was also reported that a large variation of the tunneling current can be observed depending on the orientation of (Ga,Mn)As magnetization [3]. This tunneling anisotropic magnetoresistance (TAMR) was attributed to the anisotropy of density of states (DOS) within the (Ga,Mn)As fermi surface associated to the anisotropy of the exchange term for spin-orbit coupled states.

In this paper, we will report on both experimental and theoretical TMR and TAMR observations on various types of Ga0.093Mn0.07As-based junctions constituted of different barriers (AlAs, GaAs, InGaAs). A maximum TMR value of 150% is measured at 4K considering an In0.25Ga0.75As barrier. The TAMR reaches a maximum value of 20% with AlAs barriers in between the [001] and [100] magnetization direction (out of plane experiment). In-plane variations reaches 3-4% at maximum. Effects of annealing will be also discussed.

In the framework of the 6x6 transfer matrices approach adapted to the kp theory [4] and using the Landauer formula, we have calculated both, the TMR and the TAMR that are shown to be in good agreement with our experimental data and those of Saito et al. [5]. The TMR was calculated as the relative difference of conductance in between the parallel and the anti-parallel magnetic arrangement when magnetizations of the layers lies in the plane along the [100] direction. The TAMR was calculated as the relative difference of conductance, in the saturation regime, i.e. when the magnetization is respectively aligned along [1 0 0], the easy in-plane magnetization axis, or along [0 0 1], the direction parallel to the tunneling current. The role of key parameters as spin splitting, Fermi level or barrier thickness on both TMR and TAMR will be also discussed.

Finally, confrontation between model and experiments can lead to a rough estimation of the spin splitting and the carrier density of the GaMnAs electrodes.

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6479-07, Session 4

Integration of micro/nano-photonic and quantum devices for circuit board and VLSI photonic application

E. Lee, Inha Univ. (South Korea)

We report on the design, fabrication and integration of micro/nanophotonic and quantum devices for board-scale and chip-scale photonic integration applications. Practical applications we are pursuing include the optical printed circuit board and VLSI photonic integrated circuits. These integrated circuits are designed to perform the functions of transporting, switching, routing and distributing optical signals on flat modular boards or chips in place of electrical circuits and electrical signals. For VLSI micro/nano-photonics we use photonic crystals, plasmonic devices and quantum photonic devices. We examine and discuss the scientific and technological issues concerning the miniaturization, interconnection, and integration of these devices in micron or submicron scale. These include: size effect, proximity effect, energy confinement effect, microcavitiy effect, single photon effect, optical interference effect, high field effect, nonlinear effect, noise effect, quantum optical effect, and chaotic noise effect.

6479-08, Session 4

Quantitative characterization of carrier transport in nanowire photodetectors

L. J. Lauhon, Northwestern Univ.

Despite the frequently cited potential for new high-performance nanoscale devices based on semiconductor nanowires, quantitative measurements of their fundamental transport properties are not abundant. This is due in part to the challenge of adapting standard characterization techniques to very small devices. The identification and development of promising nanowire optoelectronic devices, including emitters, waveguides, and detectors, will be facilitated by the development of techniques to quantify fundamental metrics including carrier mobility, diffusion, and lifetime. We will describe our recent investigations of carrier generation, transport, and collection in semiconductor nanowire photodetectors using near-field[1] and far-field[2] scanning photocurrent microscopy. By measuring the photocurrent as a function of the illumination position in biased devices, we have been able to extract carrier diffusion lengths and explore the sensitivity of charge collection to the state of the nanowire surface. The sensitivity of the photocurrent to internal electric fields also provides a direct means of distinguishing Ohmic and Schottky metal-nanowire contacts.

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6479-09, Session 4

Dual cavity, three-terminal, quantum dot VCSELs emitting near 1300 nm

J. A. Lott, Air Force Institute of Technology

We present design and performance trade-offs for optically coupled-microcavity, vertical cavity surface emitting lasers containing multiple active layer sheets of self-assembled InAs/InGaAs quantum dots. Each of the two microcavity active regions is electrically-biased independently or in concert to enhance the overall power conversion efficiency.

6479-10, Session 5

Free-standing quantum dots for electronic applications

M. Chason, A. Skipor, Motorola, Inc.

Free-Standing Quantum dots (FSQdot), also known as nano-crystals, are semiconductors composed of II-VI, III-V, or IV-VI materials. Ranging in size from 2-10 nanometers in diameter, these FSQdots have size-tunable band gaps. Unlike Qdots produced on semiconductor wafers, FSQdots can be manufactured using scalable colloidal solution chemistry. These FSQdots have high photo-luminescence quantum efficiencies, good thermal and photo-stability, narrow emission line widths (atom-like spectral emission), and are compatible with solution processing.

Solution processable FSQdots can be modified using innovative surface functionalization schemes. Once appropriately functionalized, the FSQdots can be incorporated into printable inks and bound to surfaces. These capabilities unlock a realm of possibilities for producing novel commercial electronic products, from unique surface coatings to new display constructions.

6479-11, Session 5

Micro pore optics from planetary x-ray imager to industrial market

J. Mutz, R. Fairbend, J. Seguy, Photonis S.A.S. (France)

Since many years, Micro Pore optics (MPO) were imagined and designed to focus X-Ray. It was developed to challenge the heavy and large Nickel X-rays mirrors for space mission and intented for X-Ray Lithography. After more than 8 years of development with the European Space Agency (ESA) a reliable manufacturing process has been established able to produce optic reaching the tight requirements of a Wolter type X-ray focussing mirror.

Optimizations in glass drawing technology, on line process control, stacking processes, core glass etching and slumping have been carried out. Those improvements enable Photonis to propose MPO with square channel from 100*100 μm down to 10*10 μm, with high length to channel ratio up to 500, with radial or square-pack stacking in various shape or curvature.

Space program such as BEPI COLOMBO and LOBSTER are foreseen to be first users of this unique technology. Space qualifications are in progress with measurements being carried out at the BESSY (Germany) and Leicester (UK) facilities. Slumping and radial stacking are expected to improve more the first results.

New applications are today in progress such as X-ray source based navigation for autonomous position determination (DARPA program, USA) or XRF analysis. The industrial market is interested in using this product as an X-ray focussing tool or also as X-ray collimator. One of the main advantage of this technology besides its very low mass and compactness is that it is an imaging system.

6479-12, Session 5

Calculations of bandstructures on the lens and pyramid-shaped InAs quantum dot for confirming the photoluminescence and photoresponse

T. Huang, S. Tang, Chung-Shan Institute of Science and Technology (Taiwan); T. Chen, Chung Cheng Institute of Technology (Taiwan); F. Lu, C. Chiang, Chung-Shan Institute of Science and Technology (Taiwan)

Electronic and optical properties of ideal and real quantum dots (QDs) are extensively studied and derived for the recent decade. Strain caused by the differences of the lattice constants of dot and wetting, barrier materials are decisive for both the self-assembly mechanisms and the electro-optical properties. The research is mainly investigated for realizing the strain effects and the optical properties on InAs/GaAs self-assembled QDs embedded in GaAs barrier layer incorporated with the three-dimensional (3D) Schrödinger equation and solved by using finite element method (FEM). From 3D geometrical profiles QDs establishing by the spatially geometric equations, the confined electron and hole bandstructures on altering sized lens and pyramidal shape-like QDs with numerical calculations and strained heterostructure of the finite element approximations have been proposed. Applying the fast FEM models, it is demonstrated that the correspondence of ground, excited eigenstates, the probability of density function (|Ψ|2) of the confined levels in the single InAs QD with different geometrical sizes to obtain the transition energy and coordinated absorption wavelength to be predicted and summarized clearly.

Through calculating the bandstructure for the InAs/GaAs heterostructure with FEM to incorporate optical oscillator strength with corrected to linear absorption spectra, the maximum probability of optical transitions can be achieved for verifying to being the probably absorption intensity at specific wavelengths from photoluminescence and photoresponse measurements for quantum dot infrared photodetector. By fitting the energy differences among the subbands and calculating the optical oscillator strength, the geometrical shape and size of QD can be predicted. And from the atomic force microscopy (AFM) measurement, the dominant sizes of QDs in the really grown wafer remain the consistent with the numerical analyses applied in 3D QD profile that is interpreted using spatially geometric equations.

6479-16, Session 6

Ballistic transport and luminescence from semiconductor nanowires and quantum dots

V. Narayanamurti, Harvard Univ.

No abstract available

6479-17, Session 6

Colloidal quantum dots as optoelectronic elements

Y. Li, M. Dutta, M. A. Stroscio, M. Vasudev, J. Yang, D. Ramadurai, Univ. of Illinois/Chicago

Novel optoelectronic systems based on ensembles of semiconductor are addressed in this paper. A variety of colloidal semiconductor quantum dots and related quantum-wire structures are characterized using absorption and photoluminescence measurements. The electronic properties of these structures are modeled and compared with experiment. The characterization and application of ensembles of colloidal quantum dots with molecular interconnects are considered. The chemically-directed assembly of ensembles of colloidal quantum dots with biomolecular interconnects is demonstrated with quantum dot densities in excess of 10+17 cm-3.

Supported by ARO, and AFOSR.

6479-18, Session 6

Photonic crystal nanowire emitters

E. Towe, L. Chen, Carnegie Mellon Univ.

No abstract available

6479-19, Session 7

Advances in 3rd generation and large format focal plane arrays at Raytheon Visions Systems

R. E. Bornfreund, Raytheon Vision Systems

No abstract available

6479-20, Session 7

Recent progress in HgCdTe detectors and focal plane arrays at DRS

P. Mitra, DRS Infrared Technologies LP

No abstract available

6479-21, Session 7

Layer interdiffusion in HgTe/CdTe superlattice based infrared materials

C. H. Grein, J. W. Garland, H. S. Jung, P. Boieriu, EPIR Technologies, Inc.

HgTe/CdTe superlattices possess a number of desirable properties, especially for very long wavelength infrared detection applications. However, an important question remains open despite previous research efforts, namely the extent of layer interdiffusion caused by post-growth processing. The stability of the superlattices against interdiffusion was tested by annealing them at temperatures ranging from ~125C to ~325C for time periods ranging from 5 minutes to 72 hours and performing FTIR measurements on annealed and unannealed samples. No interdiffusion was observed after 12-hour anneals at temperatures =140C, but interdiffusion was easily observable by FTIR after 12 hours at 180C or 5 minutes at ~275C, although not enough to affect device performance other than by reducing the cutoff wavelength by ~1.4 μm (~10%). We also model the effects of layer interdiffusion using electronic bands structures computed employing a 14 band k.p model.

6479-22, Session 8

Plasmon resonance based in-line fiber optic sensing

M. D. Gerhold, U.S. Army Research Office; A. Dhawan, J. F. Muth, North Carolina State Univ.

Novel fiber optic sensors based on localized surface plasmon resonance and evanescent wave interactions with the environment will be discussed with the focus on new types of sensors that are mechanically robust yet sensitive. A novel in-line sensing structure that consists of graded index fiber lenses and coreless fiber segments fused into a continuous optical fiber structure was fabricated and characterized. These in-line sensors are more robust than conventional tapered fiber optic sensors and have a continuous fiber diameter of 125 ∝m. The optical design of lens elements within the fiber allows the guided wave to be expanded and collected in a controlled manner. The environmental sensing length of 6-35 mm in these in-line sensors is orders of magnitude larger than fiber tip based sensors. Sensing was based on exciting the resonance of localized surface plasmons (LSPs) in metallic nano-particles deposited on the surface and tip of the optical fibers. The effect of particle size and material composition, on the plasmon resonance wavelength, was studied to tailor the plasmon spectra for different sensing applications and interrogation wavelengths and to allow multiplexing of sensors. These fiber-optic sensors are being employed for proximity sensing of chemicals as well as biological molecules.

6479-23, Session 8

Surface plasmon enhanced III-V based THz detectors

A. G. U. Perera, Georgia State Univ.

The THz region is of considerable interest with research on both single element detectors and imagers. Results are reported on heterojunction and homojunction detectors using III-V semiconductor materials. Both Nitride and Antimonide based detectors showed broad response frequencies above 1 THz. Arsenide based detectors have shown a threshold frequency tailorable in the range of 2.3-20 THz. The mechanisms of operation in these detectors will be discussed, and potential advantages and disadvantages of the materials for various frequency ranges will be considered. Among these are the increased control in tailoring the workfunction in antimonides, and increased THz absorption in the nitrides. The usage of surface plasmon effects in surface structures such as gratings to enhance detector response will also be considered. The enhanced frequency for a given grating can be determined from the phase matched condition. For a grating with 3 micron spacing this leads to increased absorption at ~15 microns. Experimental results on the effects of surface plasmons on absorption and reflection will be presented. Designs for improved THz detectors based on these ideas will also be discussed.

This work was supported in part by the US NSF under grant #ECS-0553051.

6479-24, Session 8

Prospects for next generation HgCdTe-based infrared sensors

S. Sivananthan, Univ. of Illinois/Chicago; P. Boieriu, EPIR Technologies, Inc.

The development of HgCdTe grown by molecular beam epitaxy (MBE) for multicolor photovoltaic detector arrays is assessed and compared with other material systems possessing similar detection abilities. Type II InSb/AlGaAs superlattices (SLs) have demonstrated their potential to be superior to HgCdTe alloy-based and QWIP detectors at the single-color diode level. HgCdTe can meet stringent requirements of high sensitivity, high resolution, and multifunction sensor integration while covering the entire infrared spectrum. An alternate approach for detecting wavelengths beyond 17∝m is to use type III HgTe/CdTe SLs. Such SLs can be employed together with HgCdTe alloys in two-color structures or independently, with both colors based on SL material. MBE is the method of choice for multiple layer growth because it produces material of excellent quality and allows composition and doping control at the atomic scale level. We report on the steady progress that has been made towards creating reproducible and portable methods to grow high quality HgCdTe-based MBE materials with uniformity suitable for future generations of sensors and arrays. Addressing material growth issues (such as substrates and buffers layers) is not only relevant to material manufacturability but also allows for improved imaging system operation due to the reduction of residual non-uniformity. Issues related to substrates for HgCdTe (size, quality and availability) are currently preventing the large scale deployment of HgCdTe-based sensors and will also be discussed in this presentation.

6479-25, Session 9

Some tactical considerations for hyperspectral imaging

J. G. Pellegrino, J. G. Zeibel, U.S. Army Night Vision & Electronic Sensors Directorate; R. T. Littleton, Consultant; N. Supola, P. Perconti, U.S. Army Night Vision & Electronic Sensors Directorate; W. J. Gunning III, J. F. DeNatale, Rockwell Scientific Co., LLC

The Night Vision Lab is exploring hyperspectral techniques to improve upon existing imaging systems and to perform target feature selection

and clutter rejection through judicious band choices. In addition to in-house spectrometers for SWIR and MWIR/LWIR, NVL is monitoring DARPA's Adaptive Focal Plane Array program with Rockwell Scientific. This talk will examine the advantages of hyperspectral in the context of various tactical applications and the advantages of on-chip spectral tuning versus more conventional approaches.

6479-26, Session 9

InGaAs avalanche photodiode arrays for photon counting applications

R. Sudharsanan, J. C. Boisvert, P. A. McDonald, P. Yuan, E. Labios, T. Isshiki, N. H. Karam, Spectrolab, Inc.; F. Yan, C. M. Stahle, P. K. Shu, NASA Goddard Space Flight Ctr.

Precise target identification under low-light level conditions poses a great challenge in many military and commercial applications. LAser Detection And Ranging (LADAR) using eye-safe wavelength operating in the Short wavelength infrared (SWIR) region (1-1.6 μm) is a promising tool for 3D-imaging thus enabling precision target identification. Focal pane arrays (FPAs) are a critical LADAR component and many LADAR missions require photon counting FPAs with low noise and high speed. InGaAs SWIR avalanche photodiode (APD) arrays operating in either linear or Geiger mode offer several advantages such as low noise, high uniformity, large-format and low-cost. At present these detector arrays are in the early stages of development for these applications.

We have designed and demonstrated both linear mode InAlAs/InGaAs APD and Geiger mode InGaAsP/InP APD arrays with array sizes varying from 10x10 to 64x64. InGaAs/InAlAs APDs showed low dark current density of the order of 1 μA/cm2 and gains as high as 100 at 300K. InGaAsP/InP Geiger mode APD arrays showed low dark count less than 5x105 at 300K and breakdown voltage uniformity of >99.5%. We have used analytical models based on material parameters to predict the device performance and optimized the device structures growth conditions to improve the uniformity of detector arrays. In this presentation, the design, development and characteristics of InGaAsP/InP and InAlAs/InGaAs APD detector arrays for the LADAR applications will be presented.

6479-27, Session 9

Type-II "M" structure photodiodes: an alternative material design for mid-wave to long wavelength infrared regimes

B. M. Nguyen, M. Razeghi, Northwestern Univ.

With recent advances in material growth, device processing and imaging, Type II superlattices are considered a viable technological alternative for high performance Long and Very Long Infrared detection. Many Type II system such as binary InAs/GaSb, strain balanced InAs/(InGa)Sb and W-structure are in a competitive course for breaking and passing the record hold by the state-of-the-art HgCdTe technology in this infrared regime. In this paper, we present the initialization of a new Type II structure: a binary InAs/GaSb/AlSb/GaSb superlattice, called M structure, which potentially gathers many of the advantages of pre-existing Type II structures. We pointed out that this structure effectively reduce the dark current by blocking the electron diffusion in the conduction band, and have high quantum efficiency due to the high electron-hole wavefunction overlap. Moreover, the biggest advantage of this new structure is a new bandgap engineering method without the constraint of lattice matching.

6479-28, Session 9

Growth studies on short period superlattices for mid-infrared detection

G. J. Brown, H. J. Haugan, Air Force Research Lab.; F. Szmulowicz, Univ. of Dayton; K. Mahalingam, S. Houston, Air Force Research Lab.

For type-II superlattices with spatially indirect optical transitions across the band gap, short-period superlattices are often employed. The oscillator strength of intraband transitions, from holes states confined in one layer to electron states confined in a neighboring layer, are enhanced by increasing the wave function overlap of these states through reduced superlattice period. However, there are limits to accurately controlling an epitaxially grown semiconductor superlattice structure as the number of monolayers in each layer is decreased. Reducing the epitaxial growth rate aids in the layer thickness control as well as reducing instabilities in the layer compositions during growth. For InAs/GaSb type superlattices, periods of 40Å or less are relevant to mid-infrared detection. Characterization and modeling results for a series of InAs/GaSb superlattices with periods ranging 50Å to 15Å will be presented. These results explore the break point between when thinner is better and when reducing the period no longer optimizes the superlattice optical performance.

6479-29, Session 9

A resonant tunneling CdSe/ZnS core shell quantum dot photodetector for spectral resolution in the visible region

A. Dindar, J. M. Therrien, Univ. of Massachusetts/Lowell

Based on the 3D quantum confinement of electrons in quantum dots and selection rules for optical transitions, we have designed and made a resonant tunneling photodetector, which is sensitive to specific wavelengths in the visible region. Changing the voltage across the device shows some discrete jumps in current. These points correspond to the different energy states inside the quantum dots and thus to different excitation wavelengths. The magnitude of the jump corresponds to the amount of light at that wavelength falling on the detector, allowing the spectral intensity of the incoming light to be determined. We have used monodisperse CdSe/ZnS core-shell quantum dots self assembled onto InP and GaAs substrates with an ITO top contact. The photoexcited states within the dots are read out via resonant tunneling at various biases on the device. When the bias aligns valence state in the dot with the fermi level of the semiconductor, conductivity is enhanced if the state is populated with holes from the photoexcitation.

6479-30, Session 10

Demonstration of 640x512 pixels long-wavelength infrared (LWIR) quantum dot infrared photodetector (QDIP) focal plane array

S. D. Gunapala, Jet Propulsion Lab.

We have exploited the artificial atomlike properties of epitaxially self-assembled quantum dots for the development of high operating temperature long wavelength infrared (LWIR) focal plane arrays. Quantum dots are nanometer-scale islands that form spontaneously on a semiconductor substrate due to lattice mismatch. QDIPs are expected to outperform quantum well infrared detectors (QWIPs) and are expected to offer significant advantages over II-VI material based focal plane arrays. QDIPs are fabricated using robust wide bandgap III-V materials which are well suited to the production of highly uniform LWIR arrays. We have used molecular beam epitaxy (MBE) technology to grow multi-layer LWIR quantum dot structures based on the InAs/InGaAs/GaAs material system. JPL is building on its significant QWIP experience and is basically building a Dot-in-the-Well (DWELL) device design by embedding InAs quantum dots in a QWIP structure. This hybrid quantum dot/quantum well device offers additional control in wavelength tuning via control of dot-size and/or quantum well sizes. In addition the quantum wells can trap electrons and aide in ground state refilling.

Recent measurements have shown a 10 times higher photoconductive gain than the typical QWIP device, which indirectly confirms the lower relaxation rate of excited electrons (photon bottleneck) in QDIPs. Subsequent material and device improvements have demonstrated an absorption quantum efficiency (QE) of ~ 3%. Dot-in-the-well (DWELL) QDIPs

were also experimentally shown to absorb both 45o and normally incident light. Thus we have employed a reflection grating structure to further enhance the quantum efficiency. JPL has demonstrated wavelength control by progressively growing material and fabricating devices structures that have continuously increased in LWIR response. The most recent devices exhibit peak responsivity out to 8.1 microns. Peak detectivity of the 8.1 μm devices has reached ~ 1 x 1010 Jones at 77 K. Furthermore, we have fabricated the first long-wavelength 640x512 pixels QDIP focal plane array. This QDIP focal plane array has produced excellent infrared imagery with noise equivalent temperature difference of 40 mK at 60K operating temperature.

In addition, we have managed to increase the quantum efficiency of these devices from 0.1% (according to the data published in literature) to 20% in discrete devices. This is a factor of 200 increase in quantum efficiency. With these excellent results, for the first time QDIP performance has surpassed the QWIP performance. Our goal is to operate these long-wavelength detectors at much higher operating temperature than 77K, which can be passively achieved in space. This will be a huge leap in high performance infrared detectors specifically applicable to space science instruments.

The research described in this abstract was performed by the Jet Propulsion Laboratory, California Institute of Technology.

6479-31, Session 10

Innovative hyperspectral applications of dualband, infrared focal plane array technology

P. D. LeVan, Air Force Research Lab.; J. P. Hartke, U.S. Military Academy; E. L. Dereniak, College of Optical Sciences/The Univ. of Arizona

Dualband infrared focal plane arrays (FPA) were developed originally for multi-spectral imaging applications, where it was recognized that advantages in compactness and band-to-band pixel registration were of significant importance. As the dualband architecture is matured for quantum well and mercury cadmium telluride focal plane arrays, and is easily within the grasp of strained layer superlattice technology, applications other than multi-waveband imaging come to mind. In various hyperspectral applications that employ gratings, the different grating orders can sometimes be paired with the wavebands of the dual- (or multi-) waveband FPA, allowing high efficiency hyperspectral imaging over very broad wavelength regions.

Applications of this nature will be described.

6479-32, Session 10

Uni-traveling-carrier photodiodes for high-speed detection and broadband sensing

H. Ito, Nippon Telegraph and Telephone Corp. (Japan)

A high-speed and high-output photodiode is an important device for both digital and analog applications. For these, the uni-traveling-carrier photodiode (UTC-PD) is a promising solution. In this paper, we describe recent progress in our UTC-PD technologies.

The UTC-PD has a unique mode of operation where only electrons are the active carriers. This is the key to achieving high-speed and high saturation-output-current simultaneously. To date, a record 3-dB bandwidth of 310 GHz for PDs operating at 1.55 um and high-power millimeter(mm)-wave generation of over 20 mW at 100 GHz have been achieved.

A primary application of the UTC-PD is as a component of the photoreceiver in optical communications systems. We demonstrated photodetections at up to 160 Gbit/s with a UTC-PD module. The large output voltage provided by the UTC-PD (more than 0.8 V at 100 Gbit/s) can directly drive digital circuits to improve the operation speed of the photoreceiver. Another promising configuration is an avalanche photodiode (APD). We demonstrated a UTC-PD-based APD with a record 3-dB bandwidth of 40 GHz.

Photonic generation of mm- and sub-mm-waves is also promising for signal transmission in active sensing systems, such as spectroscopy and imaging systems, and for local signal supply in detection systems, such as the receivers for radio telescopes and high-frequency spectrum analyzers. We have developed compact rectangular waveguide output UTC-PD modules and have succeeded, for example, in generating a very-high output-power of 17 mW at 120 GHz using an F-band module. We also developed a quasi-optical module with an antenna-integrated UTC-PD and demonstrated a very-broadband signal generation over the frequency range from 200 GHz to 1.5 THz.

6479-33, Session 10

To be announced

E. H. Aifer, Naval Research Lab.

No abstract available

6479-34, Session 11

Mid-infrared active optical antennas and optofluidic lasers

F. Capasso, N. Yu, E. Cubukcu, K. Crozier, L. Diehl, B. G. Lee, M. A. Belkin, P. Berhoozi, M. Loncar, Harvard Univ.

Quantum cascade lasers are rapidly becoming a mature technology in terms of device design and performance levels. However there are still major opportunities in adding new functionalities that can significantly increase their range of applications.

In this talk I will describe two new directions: (1) active optical antennas, i.e. a new generation of mid-infrared light sources capable of creating high intensity subwavelength (~ /20) size spots in the near field for spatially resolved absorption spectroscopy and chemical analysis, (2) optofluidic lasers, based on intracavity microfluidic delivery, for new lab-on-a chip (chemical sensing of fluids and of analytes carried by the latter).

6479-35, Session 11

Thermal properties of mid-infrared and THz Quantum Cascade Lasers

V. Spagnolo, A. Lops, M. S. Vitiello, G. Scamarcio, Univ. degli Studi di Bari (Italy)

Understanding the heat dissipation processes and their interplay with the electrical and optical characteristics are key issues for the realization of quantum cascade lasers (QCLs) with improved thermal management. Heat extraction from QCLs is difficult because of two main reasons: i) the high electrical power at the laser threshold; ii) the large device thermal resistance, mainly due to the anisotropic thermal conductivity of the multilayered active region. To address these topics we developed a band-to-band photoluminescence technique to determine the local lattice temperature in operating QCLs. Using these data as inputs, we validated a two-dimensional anisotropic thermal model and extracted the heat dissipation patterns and the in-plane and the cross-plane active region thermal conductivities in GaInAs/AlInAs mid-IR QCLs.1 In the temperature range 80K-250K, the cross-plane thermal conductivity monotonically increases with temperature and remains one order of magnitude smaller than the thermal conductivities of bulk constituent materials. Comparison between the calculated thermal performance of GaInAs/AlInAs QCLs sharing the same active region structure, but having either a buried or a ridge waveguide, shows that devices with Au contact layers thicker than 4μm have better thermal properties than the buried structures. The same experimental approach has been employed to determine the facet temperature mapping in GaAs/AlGaAs THz QCLs. From the analysis of the experimental data using a Joule-heating model we extracted the active region anisotropic thermal conductivity and determined the influence of the electrical contact configuration on the temperature distribution.

1 A. Lops, V. Spagnolo and G. Scamarcio, J. Appl. Phys., 100(3), August (2006).

6479-36, Session 11

Electronic and thermal properties of mid-IR QCLs

G. Scamarcio, M. S. Vitiello, V. Spagnolo, C. DiFranco, Univ. degli Studi di Bari (Italy); C. J. Pflügl, W. Schrenk, G. Strasser, Technische Univ. Wien (Austria)

The development of quantum cascade lasers (QCLs) is allowing to fabricate high performance devices, already suitable for several applications. A deep insight into the crucial design parameters is being obtained by the systematic investigation of the influence of the injection barrier thickness, electron confinement, and injector doping density in doped quantum cascade structures. We present an experimental comparative analysis of the electronic, thermal and optical characteristics of GaAs/Al0.45Ga0.55As quantum cascade lasers emitting at a wavelenght of 11μm and based on a bound-to-continuum scheme and on a different doping concentration, during device pulsed operation. The results have been obtained by comparing infrared optical and micro-probe photoluminescence measurements. For the latter investigation we employed for the first time an intensified CCD detection system allowing us to determine the time evolution of the lattice and electronic temperatures during and after the current pulses. To study the effects of the doping concentration closely similar structures have been fabricated, differing only for the doping level. In the doping range (1.25*10^17 cm-3 - 5*10^17 cm-3) we found that the threshold current density varies with the doping and that the emission efficiency becomes progressively lower. The doping has also an effect on the maximum working temperature that becomes progressively lower, by reducing the active region mean doping. We will discuss, finally, the influence of the doping concentration on the device electronic temperatures, thermal management and on the electron-lattice energy relaxation rates.

6479-37, Session 12

Emission properties of THz quantum cascade lasers

A. Tredicucci, NEST CNR-INFM (Italy) and Scuola Normale Superiore di Pisa (Italy)

No abstract available

6479-38, Session 12

Dual interband cascade laser based trace gas sensor for studying urban air pollution

G. Wysocki, Y. Bkhirkin, M. Fraser, S. G. So, R. Lewicki, F. K. Tittel, Rice Univ.; R. Q. Yang, Jet Propulsion Lab.

The presence of highly reactive alkenes in the emissions from petrochemical manufacturing results in the rapid formation of ground-level ozone, one of the most pressing environmental problems facing southeastern Texas. Laser based trace gas sensors provide the ability to rapidly and accurately quantify trace gases important to urban air pollution including formaldehyde (H2CO) and ethylene (C2H4).

We will report the development, performance and application to environmental monitoring of a fully automatic spectroscopic gas sensor based on two distributed feedback cw interband cascade lasers (ICL-DFB) operating at liquid nitrogen temperature suitable for in-situ trace gas measurements of H2CO and C2H4. The optical sensor targets the absorption features of H2CO at ~ 2807 cm-1 and C2H4 at ~ 2997 cm-1. Absorption measurements are performed using a 100 meter long astigmatic Herriott multipass absorption cell and thermoelectrically cooled MCT detectors. For H2CO, minimum detectable concentrations of the order of 1 ppbv (~ 1sec) are obtained by applying a wavelength modulation technique. Details will be presented of a recent application of such an ICL based sensor for the quantification of gas-phase ethylene and formaldehyde in a study of ozone formation in the Greater Houston area, which was part of a summer 2006 air quality field campaign (TexAQS 2006).

6479-39, Session 12

Visible submicron semiconductor disk laser

Z. Zhang, L. Yang, K. J. Vahala, A. Scherer, California Institute of Technology

Semiconductor microdisk lasers have been studied for more than 15 years. By shrinking the disk size, large scale integration with low energy consumption and low threshold pump power could be realized. However, due to the high loss of the small size disk, the research still focuses on the size larger than 2um in diameter. Here, we report an ultrasmall visible disk laser lasing at around 670nm fabricated within thin membranes of InGaP/InGaAlP quantum well material. This 645nm-diameter free standing disk laser working at room temperature by free space optical pumping has low excitation threshold of 50uW. The submicron disk lasers exhibit low threshold powers and can be lithographically tuned from 650-690nm. Their cavity volumes of approximately 0.03 cubic microns are well suited for use as spectroscopic sources.

Electron beam lithography patterning within the Zep520 resist followed by an iodine-based inductively coupled plasma reactive ion etching formed the submicron pillars. After removal of the Zep resist, time controlled oxidation of the AlGaAs by water vapor followed by the potassium hydroxide chemical dissolution of the aluminum oxide formed the mushroom shape final structure. The linewidth was measured as 0.4nm at threshold, yielding an effective Q of about 1612. Below threshold at 29uW, the linewidth was measured as 0.9nm. The distinct change of the linewidth and the linearity above the threshold indicates the lasing demonstration. Above 120uW, heating of the laser cavity limited the output power, and the L-L curve saturated. The lasing peak can be tuned by changing the disk thickness or diameter as well as the strain in the quantum wells. Also, the peak can be tuned by changing the environment refractive index.

6479-40, Session 12

High brightness GaSb-based optically pumped semiconductor disk lasers at 2.3 μm

M. Rattunde, N. Schulz, C. Ritzenthaler, C. Manz, K. Köhler, C. Wild, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

Optically pumped semiconductor disk lasers (OPSDL), also known as vertical external cavity surface emitting laser (VECSELs), are capable to emit a high power, nearly diffraction limited output beam with circular symmetry. Due to this unique property, VECSEL are attracting increasing interest within the semiconductor laser community for a wide range of applications. Up to now, research has been focused on the development of high-power VECSELs emitting in the near infrared (wavelength »1 μm). For wavelengths beyond 2 μm, there have been only few reports on VECSELs so far with their output power restricted to the several mW range [1].

In the present work, we have realized VECSEL structures based on the (AlGaIn)(AsSb) material system, emitting at 2.3 μm. A first set of VECSEL structures has been optimised for barrier pumping with a Nd:YAG laser (1064 nm) or a high-power diode laser (980 nm). A maximum output power exceeding 1.5 W in CW operation was achieved at 20°C heatsink temperature, and still over 1 W at +10°C. With the resonator aligned for maximum output power, the measured beam quality parameter M2 was in the range of 2 to 3. Optimising the resonator for maximum beam quality, results in an TEM00 mode operation of the VECSEL with M2 =1.05 and still around 70 % of the maximum output power given above. This is the first realization of a high-power, high-brightness VECSEL in this wavelength range.

Further on, we have developed an in-well pumped VECSEL with the same

emission wavelength of 2.3 μm, optimised for pump absorption in the QWs at 1.95 μm. This way, the quantum deficit between pump photon energy and emitted photon energy can be reduced. First results, using a GaSb-based diode pump laser, will be presented, demonstrating the potential of this approach.

[1] A. Ouvrard et al., IEEE Photon. Technol. Lett. 17, 2020 (2005).

6479-41, Session 12

Interband cascade distributed feedback lasers

J. R. Meyer, C. Kim, M. Kim, C. L. Canedy, W. W. Bewley, J. R. Lindle, I. Vurgaftman, Naval Research Lab.

We have used molecular beam epitaxy to grow 5-10 stage interband cascade lasers with "W" active transitions. Some of the devices achieved pulsed operation at 300 K, and at 78 K the cw output power was as high as 1.1 W and the wallplug efficiency up to 21%. To obtain a spectrally pure output, we fabricated W-ICLs whose narrow index-guided ridges incorporated distributed-feedback (DFB) line gratings. The ridges were formed by chemical etching to a GaSb SCH etch-stop layer, while the first-order DFB grating was etched into a Ge layer that was deposited on top of the ridge. For one device, the stop-band width of 5 nm was consistent with a grating coupling coefficient of Lcav 3. While the side-mode suppression ratio was nominally 20 dB, all of the features above 30 dB appeared to result from the FTIR apodization artifact rather than actual parasitic modes. The measured spectral width of 0.46 Å was instrument limited. For operation at T = 110 K, the output at = 3.419 ∝m remained single mode up to a current density 1.5 times the lasing threshold, where the cw output power was 3 mW. The second mode appearing at higher currents was likely related to a second lateral mode that appeared in the amplified spontaneous emission spectrum just below threshold. The single-mode wavelength could be tuned linearly with either current (0.031 nm/mA) or temperature (0.28 nm/K). In ongoing work, devices are being patterned with larger grating coupling coefficients, in order to make the single-mode emission more robust.

6479-59, Session 12

High performance THz quantum cascade laser with different optical waveguide configurations

M. S. Vitiello, G. Scamarcio, Univ. degli Studi di Bari (Italy); V. Spagnolo, Politecnico di Bari (Italy); J. Alton, Univ. of Cambridge (United Kingdom); S. Barbieri, S. S. Dhillon, C. Sirtori, Univ. Paris VII (France); H. E. Beere, D. A. Ritchie, Univ. of Cambridge (United Kingdom)

The recent demonstration of far infrared GaAs/Al0.15Ga0.85As quantum cascade lasers (QCLs) has increased significantly the interest in the THz frequency range, and a variety of components and applications is fuelling a rapid progress in this previously underdeveloped spectral region. We report on the fabrication of THz QCLs based on different optical waveguide configurations and compare the thermal properties of THz quantum cascade lasers (QCLs) fabricated with metal-metal optical waveguides based on Au/Au or In/Au wafer bonding. The fabrication of devices with adequate thermal and mechanical properties is strictly related with the wariness during the metal bonding. In particular we shall show how the careful choice of the metal sequence used for the reactive bonding may lead to a considerable improvement of the device thermal performance. This information was obtained from the analysis of microprobe band-to-band photoluminescence spectra measured on devices operating in continuous wave (cw). The experimental normalized thermal resistances (RL*), show that the use of Au/Au wafer bonding optimizes the heat dissipation. Finally we compare our results with those obtained on surface-plasmon based THz QCLs, demonstrating that the use of metal-metal wafer bonding can allow cw operation at progressively higher temperatures. Finally, the fabrication of a bound-to-continuum QCLs (2.85 THz) emitting 75 mW peak power at 10K, based on MBE wafers acquired by a commercial provider, will be reported.

6479-60, Session 12

Pentenary GaInAsPSb for mid-infrared light emitting diodes and lasers grown by liquid phase epitaxy

A. Krier, V. M. Smirnov, P. J. Batty, R. Jones, Lancaster Univ. (United Kingdom); V. I. Vasil'ev, G. S. Gagis, V. I. Kuchinskii, A.F. Ioffe Physico-Technical Institute (Russia)

The realisation of practical mid-infrared light-emitting diodes (LEDs) and lasers, which work efficiently at room temperature is hampered by competing non-radiative Auger recombination and intervalence band absorption (IVBA) [1]. Several different methods to overcome these obstacles are being investigated including the creation of quantum cascade lasers based on intersubband transitions [2, 3], and structures using type II quantum wells or superlattices [4]. These approaches have been very successful but are complex, requiring careful epitaxial growth of many ultrathin layers and are unlikely to be inexpensive in practice. In the present work we report on a simpler approach where the innovation is based on engineering suitable structures by making use of the additional degree of freedom allowed by the GaInAsPSb pentenary alloys [5,6]. The presence of the fifth element allows one to control the material electro-physical properties by changing the alloy chemical composition. For a given value of the bandgap (or lattice constant) properties such as the refractive index, spin-orbit valence band splitting (Δso) or thermal expansion coefficient can be independently varied. This is impossible to realise in ternaries or quaternaries and offers a new approach to control optical confinement, carrier leakage, IVBA, and Auger recombination. In this paper the successful epitaxial growth of GaInAsPSb/GaSb p-n and p-i-n structures from the liquid phase and a study of their luminescence properties is presented.

Epitaxial growth of Ga1-xInxAsyPzSb1-y-z single epilayers as well as p-i-n structures in which p-type layers were doped with Zn (p=1 x 1018 cm-3) and n-type layers were doped by Te (n=4.4 x 1017 cm-3) was carried out from antimony-rich melts on GaSb (100) Ge doped p-type substrates. The alloys obtained were of excellent structural quality with mirror like surfaces and abrupt heterointerfaces. The single epitaxial layers exhibit bright photoluminescence with superior thermal quenching behaviour arising from the detuning of the spin-orbit band - band gap resonance. Light emitting diodes based on homojunction p-i-n Ga0.02In0.98As0.84P0.02Sb0.14 structures were fabricated and exhibited electro-luminescence peaking near 4 um at room temperature. A simple analysis shows this to be comprised of mainly radiative recombination at low injection.

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6479-13, Poster Session

Size-dependent quantum dynamical influence of metal nanoparticles on surface plasmon resonance

D. Kang, D. Kim, E. Sim, Yonsei Univ. (South Korea)

We present a description of surface plasmon resonance (SPR) with quantum dynamical simulations based on the path integral method. SPR represents the excitation of surface plasmons, i.e., collective oscillations of conduction electrons in a metal film, usually created by the plane-polarized visible light. In the classical description, the momentum matching between incident photons and surface plasmons allows the energy of the incident photons to be absorbed into exciting surface plasmons and to form evanescent waves on the metallic thin film surface. While SPR has been understood through classical approaches using Maxwell¡¯s equations, extremely small nanoparticles coupled with surface plasmons induces electromagnetic field enhancement often called localized surface plasmon resonance (LSPR) that is classically not well understood. Use of such nanoparticles smaller than a few nanometers in size has made it imperative to consider quantum effects such as quantum size effect and Bohr correspondence principle. We modeled LSPR using quantum states that interact with a dissipative medium according to size-dependent absorption spectra of nanoparticles. Based on the real-time path integral simulations, it is observed that the reflectance of SPR/LSPR depends on variables relevant to the incident light as well as the nanoparticles. The amount of energy absorption and the reflectivity by surface plasmons is discussed by varying the diameter of spherical nanoparticles approximately from 100 nm down to 1 nm.

6479-43, Session 13

Artificial haircells and artificial lateral line

C. Liu, Univ. of Illinois at Urbana-Champaign

Biological sensors are responsible for the survival of humans and animals in complex, unstructured environments. As such, these sensors possess superb combination of sensitivity, robustness, and efficiency of data processing. There are many things to be learned from biological sensory functions, structures, materials, and perception. Advancements in microfabrication and nanofabrication make mimicking such functions and structures feasible today. The Micro and Nano Technology Research Group (MNTR) is developing artificial haircell sensors that mimics the biological haircell or hair-like receptors that are used in wide range of functions including hearing, balancing, touch, vibration- and flow sensing. We are also developing artificial lateral line sensors, consisting of an array of flow-sensing artificial haircell sensors. The artificial lateral line sensor mimics the lateral organ of fish and amphibian animals, which are useful for forming images of water flow and instrumental in controlling underwater movement.

In this talk, we will discuss the design of several generations of haircell sensors, along with the advancement of polymer MEMS technology and sensor-circuit integration. This effort is a global collaboration between biologists and engineers to advance understanding of biology, applying biological findings in engineering practices, and building advanced engineering sensors and sensor-rich systems.

6479-44, Session 13

Purification and optical properties of biofunctionalized carbon nanotubes: implications for multi-analyte sensing

M. C. Hersam, Northwestern Univ.

Using noncovalent biofunctionalization strategies, single-walled carbon nanotubes (SWNTs) show great promise for electrical and optical biosensing. By varying the encapsulating molecule or the surrounding solvent, the optical properties of SWNTs can be controllably tuned within the near-infrared. With femtosecond pulsed pump-probe spectroscopy, detailed information regarding carrier dynamics and stimulated emission can also be discerned [1]. In an effort to achieve greater uniformity in the optical properties of SWNTs, purification by electronic structure is needed. Specifically, the bulk enrichment of SWNTs by diameter has been achieved through ultracentrifugation of DNA-wrapped SWNTs in aqueous density gradients [2]. The enrichment is identified by the visual formation of colored bands of SWNTs in the density range of 1.11-1.17 g/mL. Furthermore, the optical absorbance and fluorescence spectra of the separated SWNTs indicate that SWNTs of decreasing diameter are increasingly more buoyant. This nondestructive and scalable separation approach is expected to impact many SWNT applications that require a monodisperse bandgap.

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6479-45, Session 13

A novel bio-inspired single photon infrared detector

P. Kung, H. Mohseni, O. G. Memis, S. Kong, A. Katsnelson, Northwestern Univ.

We present a novel single photon detector based on carrier focalization and nano-injection, methods that are used in the rod cells. The combination of these techniques provides high quantum efficiency and high internal gain simultaneously. We have developed a detailed three-dimensional model based on finite-element method to simulate the device. InP based devices show a high internal gain, exceeding 1000, at bias values around one volt at room temperature. Experimental results show good agreement with the simulation predictions.

6479-46, Session 14

ZnO and GaN: choices, comparisons, challenges and configurations

D. J. Silversmith, Air Force Office of Scientific Research

Wide band-gap, non-cubic semiconductors, such as ZnO and GaN, represent significant potential as the basis for multifunctional high-performance electronic and optical devices, signal sources, sensors, detectors, amplifiers and circuits. Utilization of these materials has presented challenges in maintaining stoichiometry, dealing with defects, growing suitable heterostructures and alloys, fabrication of strained multiplayer heterostructures, preparing quantum dot and well configurations, doping with electronic and magnetic impurities, and methods of atomic layer growth processes on both native and non-latticed matched substrates. This talk will review the salient concepts and technology in these specialized fields, the suitability of these closely related, but different, materials for optical and electronic applications, and the challenges that must be met to fully exploit the potential utilization of these materials.

6479-47, Session 14

GaN/AlN multiple quantum well structures grown by MBE for 1.5 μm intersubband absorption

T. G. Andersson, T. Aggerstam, P. Holmstrom, P. Janes, X. Y. Liu, S. Lourdudoss, L. Thylén, Chalmers Tekniska Högskola (Sweden) and Kungliga Tekniska Högskolan (Sweden)

Multiple quantum well structures with a few nm thick GaN quantum wells and AlN barriers were grown by molecular beam epitaxy. Both non-intentionally doped and Si-doped structures were grown on sapphire (0001), Si(111) and GaN-templates grown by MOVPE. The layer thicknesses and strain were studied by high resolution X-ray diffraction. Internal electric fields and the energy level positions were calculated self-consistently. Absorption wavelengths, as measured by Fourier transform infrared spectroscopy, from intersubband transitions were observed at ~ 1.5 - 3.5 μm. It is described how parameters, such as the AlN barrier and the GaN well widths, affect the absorption wavelength. The absorption consists of narrow subpeaks, which agree to monolayer fluctuations of the well widths.

6479-48, Session 14

Fabrication and characterization of self-assembled InGaN quantum dots by periodic interrupted growth

S. Choi, J. Jang, S. Yi, J. Kim, W. Jung, Kookmin Univ. (South Korea)

In recent years, the group-III nitrides have attracted much attention due to their potential for the realization of blue and green light emitting diodes (LEDs) and laser diodes (LDs), all of which use Indium-Gallium-Nitride (InGaN) alloy in active regions. The InGaN quantum dot (QD) structure is low dimension confinement structure and has many unique physical properties. Self-assembled quantum dots structure is currently studied for device applications. InGaN quantum dots have recently been used in the active region of laser diodes to improve their performance and expected to improve the temperature stability of devices.

Self-assembled InGaN quantum dots are fabricated in a two-flow horizontal MOCVD reactor maintained at the pressure of 200torr. The precursors were trimethyl-gallium (TMG) and trimethyl-indium (TMIn) and ammonia (NH3) and the carrier gas was N2 and H2. Gallium-Nitride (GaN) nucleation layer was grown at 500℃ with thickness of 25nm. Then 2~3μm thick GaN buffer-layer was deposited at 1050℃. H2 carrier gas was used for both GaN nucleation layer and GaN buffer layer. InGaN quantum dots were growth on GaN buffer layer. Carrier gas changed with N2 instead of H2 in QD growth. InGaN quantum dot was grown at 700℃ with diameter 20~50nm and height 3~6nm. In InGaN quantum dots growth NH3 was supplied in cyclic periodic interrupted mode with the interval of 5sec.

The influence of the number of periodic interrupted NH3 on the structural and optical properties of InGaN quantum dots was investigated by high-resolution X-ray diffraction (HR-XRD), atomic force microscopy (AFM), photoluminescence (PL).

6479-49, Session 14

Progress on new wide bandgap materials BGaN, BAlN, BGaAlN and their potential applications

A. Ougazzaden, S. Gautier, C. Sartel, J. Martin, Georgia Tech Lorraine (France); W. E. Fenwick, Georgia Institute of Technology; N. Maloufi, UMR CNRS (France); F. Jomard, Univ. de Versailles Saint-Quentin-en Yvelines (France)

The development of wide band gap semiconductors extends their applications in optoelectronics devices to the UV domain. Compact lasers and high sensitivity APD detectors in UV range are currently needed for different applications such as, purification, covert communication and real time detection of airborne pathogens. Until now, the full exploitation of these potential materials has been limited by the lack of suitable GaN substrates. Recently, a novel class of materials has been reported based on BGaN and BAlN, potentially reducing the crystal defect densities by orders of magnitude compared to existing wide band gap heterostructures. Characteristics of these new alloys are similar to those of AlGaN materials with the advantage that these can be lattice matched to AlN and SiC substrates. In addition, these materials offer the possibility of using quaternary BAlGaN alloys at UV wavelengths and hence lead to more degrees of freedom in designing sophisticated device structures.

In this paper we will describe the MOVPE growth conditions used to incorporate boron in (Al)GaN. Detailed characterization and analysis of bulk and MQWs structures in terms of structural, optical and electrical properties will be presented. The results of these first structures based on B(Al)GaN will be reported.

6479-50, Session 15

Optimization of nanoscale phenomena in AlGaN for improved UV emitters

M. Wraback, G. A. Garrett, A. V. Sampath, P. H. Shen, Army Research Lab.

Recently we have reported on the development of AlGaN films deposited by plasma assisted molecular beam epitaxy (PA-MBE) that possess enhanced internal quantum efficiency due to the presence of nanometer scale compositional inhomogeneities (NCI-AlGaN) within a wider bandgap matrix that inhibit nonradiative recombination through the large defect densities in these materials. These NCI-AlGaN films exhibit intense room temperature photoluminescence (PL) that is ~ 1000x stronger than, and greater than 250 meV red-shifted with respect to, the normally expected AlGaN band edge emission. In this paper, we discuss optimization of these nanoscale features for improved UV emission in the 270 nm to 340 nm spectral range. In particular, we shall address the role of density of these NCI regions and size (surface/volume ratio) of individual NCI, and the relation of these factors to Stokes shift, luminescence efficiency, defect saturation through carrier concentration in the NCI, and transport through the wider bandgap matrix to these nanoregions.

6479-51, Session 15

Achieving conductive high-Al content AlGaN alloys for deep UV photonics

J. Lin, H. Jiang, Kansas State Univ.

This talk will provide a brief overview on the current status, future perspective, and technical challenges of achieving highly conductive Al-rich AlGaN alloys and pure AlN.Al-rich AlGaN alloys are ideal materials for the development of chip-scale photonic devices such as deep ultraviolet (DUV) emitters and detectors operating at wavelengths down to 200 nm. Active DUV optoelectronic devices require conductive n- and p-type AlGaN alloys with high Al contents. One of the major difficulties in obtaining highly conductive n-type Al-rich AlGaN alloys is due to the effect of compensation of electrons by cation vacancies and their complexes. On achieving p-type materials, besides the large activation energy of the Mg acceptors in Al-rich AlGaN, we believe that compensation of holes by intrinsic defects such as nitrogen vacancies is another cause for the highly resistive nature of Mg-doped Al-rich AlGaN alloys and AlN.

Deep UV photoluminescence and Hall-effect measurements were employed to characterize Si- and Mg-doped Al-rich AlGaN alloys and AlN grown by metal organic chemical vapor deposition. Strong correlations between the optical and electrical properties were identified and utilized for material and conductivity optimization. For Al0.7Ga0.3N, we have achieved a record low room temperature n-type resistivity of 0.007 ?cm by Si doping and confirmed p-type conduction at high temperatures with a p-type resistivity of about 40 ?cm at 800 K with Mg doping. By minimizing the PL emission intensity associated with cation vacancy (VAl) related transitions by varying the growth parameters, we have also achieved the n-type conductivity control at room temperature in pure AlN. Improved conductivity in Mg-doped AlN at elevated temperatures was also observed by suppressing the nitrogen vacancy related emission line. We have successfully incorporated the optimized Al-rich AlGaN and AlN into various devices, including DUV LEDs and detectors.

6479-52, Session 15

III-nitride avalanche photodiodes

K. Minder, R. P. McClintock, C. Bayram, P. Kung, M. Razeghi, Northwestern Univ.

In order for solar and visible blind III-Nitride based photodetectors to effectively compete with the detective performance of photo-multiplier tubes there is a need to develop photodetectors that take advantage of low noise avalanche gain. In this paper we investigate the device processing necessary to support the large applied reverse biases, and prevent pre-

mature breakdown. Through optimization of the processing steps critical to the operation of these devices, including device layout, surface cleaning, and passivation, our APDs survive higher applied power. This, combined with the significant reduction of dark current through improved processing, allows us to reach higher reverse biases and thus observe higher gains. We then present our latest GaN based visible-blind avalanche photodetector results, as well as our AlGaN based avalanche photodetectors (APDs) operating at 280 nm. The devices are designed for back illumination and consist of an AlGaN or GaN active regions grown atop a high quality AlN template layer on sapphire substrate. We investigate various active region designs both through modeling and experimental results to understand the electric field build up in the multiplication region. Finally, future prospects for improving upon the performance of these devices are outlined.

6479-53, Session 15

Techniques for high quality SiO2 films

J. Nguyen, M. Razeghi, Northwestern Univ.

No abstract available

6479-54, Session 16

Super growth: from highly efficient impurity-free CNT synthesis to DWNT forests, CNTsolids and super-capacitors

K. Hata, National Institute of Advanced Industrial Science and Technology (Japan)

This presentation will provide an overview of our recent development of the “Super Growth” CVD. First, the synthesis of highly efficient impurity free SNWT forest will be described. Second, the growth dynamics will be explored with our recent advance in CNT synthesis. Characterizing of the physical and chemical properties of SWNT forests will be given. Various applications of the super-growth CVD, spanning from material and energy storage to flexible transparent CNT films and super-capacitors would be presented. Third, various new forms of carbon nanotube material, such as DWNT forests and CNT solids, made by utilizing the super-growth technique will be demonstrated. Lastly, challenges and future projects that are planed will be summarized.

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6479-55, Session 16

Phase conjugation for space Lidar applications

A. Brignon, S. Richard, J. Huignard, Thales Research & Technology (France); M. P. Georges, J. D. Plesseria, T. Thibert, P. Blanche, Ctr. Spatial de Liege (Belgium); A. I. Gussarov, F. Berghmans, SCK•CEN (Belgium); Y. Lien, ESA/ESTEC (Netherlands)

Pulsed laser sources for space applications (doppler wind lidar) require excellent performances such as single frequency operation and high beam quality. However, thermally induced phase distortions corrupt the beam quality of high-power or high energy solid-state lasers. It has been shown that phase conjugation is a route to dynamically correcting these aberrations. This is why phase-conjugated laser architectures received considerable interest in recent years. In a first design, the phase conjugate mirror corrects the phase distorsions of master-oscillator double-pass power amplifiers. For this purpose, we present a solid-state phase conjugate mirror based on SBS in a fused silica rod. Reliable operation at 100 Hz repetition rate with 200 mJ incident pulse energy is demonstrated. Vacuum/thermal and radiation (protons and gamma rays) tests have been conducted showing that the device is compatible with space environment. Alternatively, self-adaptive laser resonators in which phase conjugation, or more generally, four-wave mixing, is self generated by the intra-cavity field. This last scheme allows to obtain extra highly desirable features such as self Q-switching, and single longitudinal mode operation without injection seeding. By using this scheme, we present a flash lamp self-adaptive laser resonator with intracavity four-wave mixing delivering up to 350 mJ at 100 Hz with a beam quality M2 ~ 2. The laser naturally operates single frequency and it is shown that its frequency can be easily controlled by a very low power cw seeding laser.

6479-56, Session 16

Holographic polarimetry enhanced target recognition and remote sensing

S. M. Shahriar, J. T. Shen, S. Tseng, G. S. Pati, Northwestern Univ.

Recently, we have developed a Holographic Stokes-Meter (HSM) that can be used to generate polarimetric images of objects at a high speed. In this talk, we will describe potential applications of this technology. First, we will describe how such a device can be integrated into a conventional laser radar. Such a device, called the polarimetric ladar, can see through clutters and obscurants such as fog, dust, cloud and vegetation. We will also describe how the HSM can be integrated into a holographic smart-eye that performs rapid automatic target recognition by using a terabyte scale holographic video disc as a database and a photorefractive thin-film as a translation invariant correlator.

Conference 6480: Photonic Crystal Materials and Devices VI

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Part of Proceedings of SPIE Vol. 6480 Photonic Crystal Materials and Devices VI

6480-01, Session 1

Infrared and visible photonic crystal light emitters

A. Scherer, California Institute of Technology

Microfabrication through lithography and etching has enabled the miniaturization of many optical devices over the past 10-20 years, and has led to lasers with ultrasmall (0.01 cubic micron) mode volumes or ultra-low (9fJ) threshold values. The design of such microfabricated lasers can generally be divided into photonic crystal devices and whispering gallery devices. In this presentation, the recent developments in cavity designs, lasing materials and measurements are reviewed and microdisk lasers with ~600nm diameter as well as visible photonic crystal lasers are shown.

6480-02, Session 1

Photonic band gap materials: engineering the fundamental properties of light

S. John, Univ. of Toronto (Canada)

Photonic Band Gap (PBG) materials [1,2] are artificial, periodic, dielectrics that enable engineering of the most fundamental properties of electromagnetic waves. These include the laws of refraction, diffraction, and spontaneous emission of light [3,4]. Unlike traditional semiconductors that rely on the propagation of electrons through an atomic lattice, PBG materials execute their novel functions through selective trapping or "localization of light" [5]. Three dimensional (3D) PBG materials offer a unique opportunity to simultaneously (i) synthesize micron-scale 3D optical circuits that do not suffer from diffractive losses [6] and (ii) engineer the electromagnetic vacuum density of states in this 3D optical micro-chip [7]. This combined capability opens a new frontier in integrated optics as well as the basic science of radiation-matter interactions.

I review recent approaches to micro-fabrication of photonic crystals with a large 3D PBG centered near 1.5 microns. These include direct laser-writing techniques [8], holographic lithography [9], silicon double inversion [10], and a newly invented optical phase mask lithography technique [11].

I describe the use of anomalous refraction in 3D photonic crystal thin films for the efficient trapping and absorption of light from an external source [12]. This has possible applications in photo-voltaics.

I introduce a new type of PBG-Quantum Well Hetero-structure in which excitons (bound electron-hole pairs) can propagate. I demonstrate that in a suitably engineered electromagnetic vacuum, excitons are strongly dressed by coherent radiative emission and re-absorption enabling long range exciton hopping. This occurs when the exciton recombination energy and momentum coincide nearly with a photonic band edge, leading to considerable lowering (~8 meV) of the exciton kinetic energy at the band edge wave-vector. I refer to this as "exciton dressing and capture by a photonic band edge" [13]. In this dressed state, the exciton exhibits a long lifetime and has an effective mass that is many orders of magnitude smaller than in an ordinary electromagnetic vacuum, resulting in anomalously large mobility. This may have important implications for quantum effects such as exciton Bose-Einstein condensation in the PBG-Quantum Well.

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6480-03, Session 1

Three-dimensional visible photonic crystal

S. Lin, Rensselaer Polytechnic Institute

I will describe our experimental realization of a three-dimensional (3D) metallic photonic crystal structure with shortest pitch to date (300 nm) over large area (5 mm x 5 mm) that exhibits characteristics of a 3D complete bandgap extending from near-infrared down to visible wavelength at around 650nm. I will also report, what we believe, the first experimental observation of a non-localized passband mode in the infrared far beyond the metallic waveguide cutoff of the visible 3D photonic crystal mentioned above. Device consequences of the passband mode will also be discussed.

6480-04, Session 2

Photonic crystal LEDs: design rules for in plane photonic crystal structure

C. Weisbuch, Univ. of California/Santa Barbara and LCFIO, CNRS (France); A. David, Univ. of California/Santa Barbara; H. Benisty, LCFIO, CNRS (France)

No abstract available

6480-05, Session 2

Random lasers from chiral photonic crystal films

Y. Huang, Y. Zhou, S. Wu, College of Optics & Photonics/Univ. of Central Florida

Random lasers exhibit fascinating spectral properties of multi-mode laser oscillation within the fluorescence spectrum range of the emission

materials. They are strong contenders for making broadband lasers such as white light lasers, which have many applications in experimental testing of laser materials, identification markers, displays, information technology, and inertial confinement laser fusion. Most of the present random lasers are realized by the scattering mechanism from randomly disordered media. In these disordered media, the light wave undergoes a complicated multiple scattering process. When the scattered light is fed back after the multiple scattering processes and if the gain overcomes the optical losses, then the random laser action would occur. Since the light can be scattered to various directions, the random lasers induced by the scatters barely exhibits a specific propagation orientation and beam shape, which dramatically limits their applications.

In this paper, we have produced random lasers from an ordered medium which is a dye-doped cholesteric polymer film. Different from the random lasers originated from a disordered medium, the random laser from the dye-doped cholesteric polymer film is based on multiple Bragg reflections rather than multiple scattering. Therefore, the laser exhibits a Gaussian-like beam shape and propagates towards a specific orientation which is normal to the cholesteric planar surface. This makes the random lasers from cholesteric polymer films or any other ordered media stand out from those induced in disordered media from both scientific study and practical application viewpoints.

6480-06, Session 2

Fiber coupled photonic crystal bandedge laser

Y. Park, Seoul National Univ. (South Korea); C. Cho, Samsung Electronics Co., Ltd. (South Korea); S. Kim, H. Jeon, Seoul National Univ. (South Korea)

We propose a new fiber coupling scheme for photonic crystal nano-lasers based on a WDM (wavelength division multiplexing) 1*2 coupler. The bare fiber tip of the single port is directly positioned to the sample surface in a close proximity to optically pump the laser and collect photons emitted from the device. The pump laser light at 980 nm is fed into the fiber from the input end of the two-port side while the collected photons at 1550 nm are delivered to a detector through the other. This coupling scheme is especially appropriate for bandedge lasers operating at the Γ-point since the radiation profile is more or less isotropic so that emitted photon capture in the vertical direction can be quite high. In addition, the bandedge laser is structurally homogeneous without any cavity-like structure, requiring neither stringent fiber coupling procedure nor auxiliary optical components

As a proof-of-the-concept, we have configured such a device by employing a photonic crystal bandedge laser, which was generated on a large area by a holographic method. The bandedge laser lases at the threshold optical excitation level comparable to that for the conventional optical pumping scheme using an optical microscope objective lens when the fiber probe tip is brought to the device nearly in physical contact. If the two-dimensional photonic crystal in the bandedge laser structure can be made chirped in its period, a dense-WDM nanolaser source array can be realized by employing a fiber bundle.

6480-07, Session 2

GaAs based InAs quantum dot photonic crystal lasers

Y. Zhang, The Arizona State Univ. and NTT Basic Research Labs. (Japan); T. Tawara, N. Cade, NTT Basic Research Labs. (Japan); D. Ding, The Arizona State Univ.; T. Tanabe, E. Kuramochi, NTT Basic Research Labs. (Japan); S. R. Johnson, The Arizona State Univ.; S. C. Huang, M. Notomi, NTT Basic Research Labs. (Japan)

Quantum-dot (QD) photonic crystal (PhC) lasers have great potential in many applications such as on-chip optical interconnects and chemical sensing. In this talk, we present our latest study of semiconductor lasers comprising a single-defect cavity in a 2D PhC consisting of a hexagonal array of air holes in a GaAs slab containing InAs QDs embedded in an InGaAs well. The samples were grown using molecular beam epitaxy and the air holes were fabricated using inductively coupled plasma etching. Optical characterization of the PhC indicated that it has a very high quality (Q) factor for the confined optical mode. Continuous-wave single-mode operation of many PhC laser devices was demonstrated between 1080-1150 nm at 4.2 K under optical pumping of a 532 nm green laser. The PhC laser output was linearly polarized and its L-L curve showed a very soft turn-on, indicating strong coupling of the spontaneous emission into the lasing mode due to microcavity effects. When the device was pumped with a 100 fs mode-locked Ti:Sapphire laser at a wavelength of 775 nm, single-mode lasing with a spectral linewidth of 0.066 nm was observed up to 367 K (95 °C), which is limited by the experimental setup. Time-resolved measurements using an InGaAs photomultiplier tube revealed that the decay time of various photoluminescence peaks was between 0.70-1.0 ns while the decay time of the PhC laser emissions was 0.12 - 0.20 ns. Further details regarding the Q factor and the lasing characteristics will be presented.

6480-08, Session 3

Polarization stop bands in chiral 3D photonic crystals

M. Thiel, M. Decker, M. Deubel, S. Linden, G. von Freymann, M. Wegener, Univ. Karlsruhe (Germany)

Three-dimensional chiral photonic crystals, e.g. composed of a square lattice of circular spirals, allow for polarization stop bands connected with pronounced circular dichroism. For example, using polymers as constituent material, we have achieved 95% optical transmittance for one circular polarization and 5% transmittance for the other at the same wavelength. We review our corresponding work based on direct laser writing. Furthermore, we show that such structures can be used as compact and scalable “thin-film” optical isolators.

6480-09, Session 3

Plasmonic antireflection surfaces for the mid-infrared

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In a similar manner to the frequency selective surfaces commonly used in the microwave regime, we have designed antireflective surfaces in the mid-infrared (2-5microns). Translation of microwave designs to the infrared is not trivial for several reasons. Properties of applicable IR materials are significantly different than their microwave counterparts. Additionally, the required feature sizes need a completely different fabrication methodology. Our surfaces are metallic, yet have a high-transmission angular and frequency passband. We take advantage of photon-plasmon interaction to maximize transmission through holes in the metal surface. Simulations have been completed using both rigorous coupled wave analysis and method of moments codes. The design process has followed a path that insures that we are able to fabricate the designed structures considering cases of normal and off-angle incidence. We designed our surfaces to be compatible with shapes that we will etch in silicon and then coat in gold: this process allows the greatest flexibility in etching shapes for vias while maintaining a metallic layer for plasmon propagation on the surface. We anticipate over 90% transmission in the infrared passband. Our design methodology would also be applicable to the 8-12micron band.

6480-10, Session 3

An interface-isolator in 2D magneto-optical photonic crystals

Z. Wang, Z. Yu, S. Fan, Stanford Univ.

Photonic bandgaps in periodic structures can strongly enhance

nonreciprocal effects of magneto-optical systems[1]. When magnetic domain walls are present in a unit cell, the degeneracy between the forward and the backward propagation along certain directions is strongly perturbed. With the broken time-reversal symmetry, the band edges of a two-dimensional magneto-optical photonic crystal become asymmetric and allow one-way transmission at an air-photonic-crystal interface.

We consider a 2D PC of air holes in Bismuth Iron Garnet supporting TE modes with an incomplete bandgap between band 1 and 2. In each unit cell, the high-index garnet is partitioned into two magnetic domains with opposite magnetization along out-of-plane directions. The magnetic perturbation tilts the band structure asymmetrically and creates a direction-dependent frequency gap near the band edge. By interfacing the photonic crystal with a reciprocal medium, total internal reflection at band edge frequencies takes place along only one-direction. At the same interface, transmission is allowed along the opposite direction. With the small group velocity near the photonic band edge, the nonreciprocal effects are greatly enhanced by the high-index-contrast periodic structures.

Numerically, we modeled the proposed structure with finite-different time-domain method. Using a realistic material constant, we estimate the isolation bandwidth to be 240GHz at 633nm.

[1] Z. Wang and S. Fan, “Optical circulators in two-dimensional magneto-optical photonic crystals,” Opt. Lett., 30, 1989-91 (2005)

6480-11, Session 3

Transmission enhancement and suppression by subwavelength hole arrays in polaritonic films

P. B. Catrysse, S. Fan, Stanford Univ.

In polaritonic media, a transverse optical phonon and a transverse electromagnetic wave can couple to create a frequency range, the so-called polariton gap, in which the propagation of electromagnetic waves is prohibited. The polariton gap is a bulk property. For silicon carbuide(SiC) it ranges from 10.34 to 12.59 micrometers and it causes a homogeneous thin film to be entirely opaque with zero transmittance and near-perfect reflectance. In this work, we analyze subwavelength structured composite SiC films. We report that they exhibit unanticipated optical properties that are very different from the bulk properties.

We find numerically that a free-standing SiC film (thickness 4 microns, surrounded by air) with a two-dimensional periodic arrangement of subwavelength cylindrical holes (period 10.4 microns, radius 2.8 microns, air inside) features high transmission window with a near-perfect transmission peak, which lies entirely inside the polariton gap. We perform a dispersion analysis of the subwavelength holes and conclude that the near-perfect transmission peak is largely due to the presence of a propagating waveguide mode inside the subwavelength holes.

Furthermore, we discover an unusual region of transmission suppression inside the high transmission window. This suppression cannot be explained by the propagating mode alone. A surface resonance analysis reveals that it is in fact caused by the destructive interference of the propagating waveguide mode inside the subwavelength holes and surface phonon polaritons on the SiC-air interface.

6480-12, Session 4

Miniature infrared gas sensors using photonic crystals

A. Lambrecht, S. Hartwig, Fraunhofer-Institut für Physikalische Messtechnik (Germany); S. L. Schweizer, R. B. Wehrspohn, Univ. Paderborn (Germany)

The sensitivity of an infrared gas sensor depends on the interaction length, i.e. a reduction in cell size generally results in a reduced sensitivity, too. However, low group velocity regions in the bandstructure of photonic crystals should enable the realization of very compact gas sensors.

Using photonic crystals based on macroporous silicon experimental results with CO2 show an increase of the sensitivity in the photonic crystal compared to an empty cell of same dimensions.

For practical applications the results are compared with gas measurements using conventional multireflection cells and hollow fiber setups.

6480-14, Session 4

Design and experimental verification of a novel anisotropic photonic crystal band edge device

Y. Cao, R. Hudgins, T. J. Suleski, M. A. Fiddy, J. Raquet, The Univ. of North Carolina at Charlotte; K. Burbank, M. Graham, P. Sanger, Western Carolina Univ.

We have been studying a novel 1D anisotropic photonic crystal structure which can be designed to have a strong resonant effect, a very low group velocity over a specific bandwidth. The structure requires two anisotropic layers and one isotropic layer per period and was first introduced by Figotin and Vitebskiy. By the careful design of the parameters of the structure, we can find a special band edge point which has fourth order degeneracy, and is called degenerate band edge (D.B.E). It was predicted that in the case of a transmission resonance in the vicinity of the D.B.E, the resonant field intensity increases as N4, where N is the total number of periods, while in the case of a regular band edge, the field intensity is proportional to N2. By making a comparison among different anisotropic materials, we have found that the giant resonant effects in the vicinity of the D.B.E also need a large anisotropy of the materials. However, materials with the required anisotropy at optical wavelengths are difficult to find and so we use equivalent form-birefringence layer to replace the anisotropic layer in our photonic crystal structure design. We have verified our design by using finite-difference time domain simulation first, and then make a real device for use at microwave frequencies using a rapid-prototyping tool. Our measurement results show that using form-birefringence to design this novel device is feasible and can push this novel photonic crystal structure to a lot of potential applications.

6480-16, Session 4

Multilayer antireflection coating for photonic applications: a theoretical analysis

M. Chen, Rensselaer Polytechnic Institute and National Taiwan Univ. (Taiwan); S. Lin, J. Xi, E. F. Schubert, Rensselaer Polytechnic Institute; A. J. Fischer, M. H. Crawford, Sandia National Labs.; H. Chang, National Taiwan Univ. (Taiwan)

We investigated many continuous profiles for anti-reflection (AR) coating for lighting and solar applications. We found out that Gaussian profile performs better than the Quintic, which is believed the best profile for AR coating in literatures [1][2]. We discussed the difference and provided theoretical description between those two profiles. In the past, people usually think about how to create smooth function upon index profile. In this work, we discovered that the smoothness of refractive angle within the coating layer plays an important role over the AR performance, especially for the high-angle incidence.

Since it’s almost impossible to create continuous index profile on fabrication, we discussed how many discredited layers are sufficient to approximate their continuous counterparts and remain good performance. We found out that five layers are already enough to achieve good performance under the index variation between air (n=1) and Aluminum Nitride (n=2.06).

Reference:

[1] W. H. Southwell, “Gradient-index antireflection coatings” Opt. Lett. 8, 584 (1983)

[2] D. Poitras and J. A. Dobrowolski, “Toward perfect antireflection coatings. 2. Theory” App. Opt. 43, 1286 (2004)

6480-17, Session 4

Development of an optical, analog-to-digital converter using photonic crystals

A. S. Sharkawy, EM Photonics, Inc.; C. Chen, B. Miao, S. Shi, D. W. Prather, Univ. of Delaware

Optical or optoelectonic analog-to-digital (A/D) converters have received significant interest due to the development of seamless, ultra-fast optical communication systems. Further, optical A/D converters may offer better performance than conventional electronic A/D converters, because optical signals are not subject to electronic noise and radiation, and are thus immune to electromagnetic interference. Moreover, all-optical A/D converters eliminate the speed and integration limitation of electrical-to-optical and optical-to-electrical conversions in photonic networks. Several optical/optoelectronic A/D conversion approaches have been demonstrated, such as the Mach-Zender interferometer, the optical fiber temporal-spectral mapping converter, the optoelectronic thyristor, and the optical alternating layer A/D converter. However, these designs are either optically or electrically complex or cannot be monolithically integrated. In this paper, we experimentally design and demonstrate a compact, nanoscale, multi-bit, all-optical analog-to-digital (A/D) converter. The converter consists of an array of cascaded splitters constructed in a self-guiding photonic crystal through the perturbation of the uniform lattice. The A/D conversion is achieved through tuning the splitting ratios by changing the degree of perturbation. To validate the proposed design, we fabricated a prototype in a SoI wafer and experimentally characterized the relation between the splitting ratio and the degree of lattice perturbation. Based on this information, we fabricated the multi-bit A/D converter and successfully observed multiple unique states corresponding to different power levels of input analog signal.

6480-59, Session 4

Negative index photonic crystals: new concepts in imaging and negative refraction

S. Sridhar, Northeastern Univ.

We discuss negative refraction at microwave and optical frequencies in 1D and 2D metallic and dielectric photonic crystal media. Here negative refraction is due to the anomalous dispersion characteristics of the medium. The experiments show that materials with tailor-made negative or positive refractive indices over broad spectral ranges can be designed and fabricated. We have also demonstrated that negative refraction leads to some novel optical elements for imaging, such as flat lenses and focusing by plano concave lenses. A general theory of imaging by a flat lens without optical axis has been developed, leading to specification of the characteristics required of the flat lens metamaterial. Features of images formed using negatively refracting optical elements, including subwavelength resolution, are discussed. Potential applications for imaging and communications at microwave and optical frequencies are discussed.

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Collaborators: W.T.Lu, P.Vodo, P.Parimi, Y.Huang, R.Banyal, D.Casse

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6480-18, Session 5

Microfludic ARROW photonic crystal fibers

B. J. Eggleton, The Univ. of Sydney (Australia)

This paper reviews recent progress in developing microfluidic photonic crystal fibres as a platform for integrated tunable optical filters, sensors and nonlinear devices. Specifically, we focus on photonic crystal fibres that are infiltrated with high-refractive index fluids that transform ordinary index guiding fibres into ARROW (Anti-Resonant-Reflection-Optical-Waveguides) fibres. In particular, these fibres exhibit resonant transmission properties and strong dispersion, similar to a hollow-core photonic banbgap fibre and at the same time strong tunability and nonlinearity. We present a basic interpretation of guidance in these fibres based on the ARROW model and review recent results demonstrating tunable soliton propagation and tunable optical gratings incorporated into such fibres.

6480-19, Session 5

Supercontinuum generation in photonic crystal fibers using quasi-CW pumping

M. H. Frosz, O. Bang, P. D. Rasmussen, A. O. Bjarklev, Danmarks Tekniske Univ. (Denmark)

Supercontinuum generation (SCG) is often achieved using pulses from a femtosecond laser. Recent advances in high-power continuous-wave (CW) fiber lasers have made it possible to use these com°(c)pact and rugged sources for SCG. This talk will review the physical mechanisms behind SCG and also treat some of the intricacies of numerically modelling a CW pump. This allows an in°(c)ve°(c)sti°(c)ga°(c)tion of, e.g., how the pump spectral linewidth affects the SC spectrum.

6480-20, Session 6

Improvement of transmission properties and characterization of chalcogenide photonic crystal fiber for the 3-5 μm and 8-12 μm atmospheric windows

P. Houizot, J. Troles, L. Brillant, F. Désévédavy, F. Smektala, Univ. de Rennes I (France)

Two windows are of interest because they correspond to the atmospheric windows of transparency between 3-5 μm and 8-12 μm. These atmospheric windows rise a great interest for the military optoelectronic and lidars systems. The chalcogenide glasses are known for their transparency in the infrared. The major inconvenient of the chalcogenide glasses is the optical losses due to the presence of impurities like water, carbon and oxygen.

In this context, we have developed microstructured fibers for mid IR transmission. We focus in this work more particularly on the improvement of the transmission properties. For the 3 - 5 μm window, we have studied the 2S1G glass composed with sulphur, antimony and germanium. Indeed, this glass presents a transmission window between 0.7 μm and 8 μm. We report the particular efforts that have been performed to reduce the S-H absorption band. This band, which is located around 4 μm, has a high extinction coefficient of 2500 dB/km/ppm. For the 8 - 12 μm window, we study the TAS glass composed with tellurium, arsenic and selenium because this glass has a transmission window between 3 and 12 μm.

We report the improvements that have been achieved in the reduction of the absorption bands and in the attenuation level of fibers from these two glasses. We point out the realisation with stack and draw technique of a microsructured fiber in 2S1G glass and a microsructured fiber in TAS glass. For the first time to our knowledge, a microsructured fiber in 2S1G glass has been characterised at 1.55 μm and 3.39 μm and a microsructured fiber in TAS glass at 10.6 μm.

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6480-21, Session 6

PbTe quantum dot doped tellurite glass photonic crystal optical fiber

G. J. Jacob, E. Rodriguez, E. F. Chillcce, W. M. Faustino, W. L. Moreira, L. C. Barbosa, C. L. Cesar, Univ. Estadual de Campinas (Brazil)

The nonlinear properties of Quantum Dots (QD) has the potential to be used as an ultrafast “all-optical” device, specially if a QD doped core optical fiber can be produced and the absorption bands fall in the near infrared window used for optical communications (1.3-1.5 μm). PbTe QDs absorption band can be controlled by its size to fall in this spectral window. In the past we showed that PbTe QD doped core/undoped clad optical fiber could be produced with tellurite glass. Tellurite glasses have a very high QD solubility compared to other glasses and the right thermophysical characteristics for optical fiber drawing. The difficult to make a conventional core/clad optical fiber was the thermophysical matching of the core and clad glass together with the desirable refractive index mismatch for light guiding. We only succeed after trying with a great number of glass compositions. However, Photonic Crystal Fibers (PCF) presents none of these problems because it uses the same glass, automatically matching the thermophysical properties, while the light guiding is provided by the hollow parts and geometry. For these reasons we decided to produce a PbTe QD doped tellurite glass PCF. The fiber showed the typical attenuation peak shift to the IR with the QD size that has been observed by Scanning and Transmission Electron Microscopy (SEM and HRTEM).

6480-22, Session 6

FEM investigation of leaky modes in hollow core photonic crystal fibers

J. Pomplun, Zuse Institute Berlin (Germany); R. Holzloehner, European Southern Observatory (Germany); S. Burger, L. W. Zschiedrich, F. Schmidt, Zuse Institute Berlin (Germany)

Hollow core holey fibers are promising candidates for low-loss guidance of light in various applications, e.g., for the use in laser guide star adaptive optics systems in optical astronomy. We present an accurate and fast method for the computation of light modes in arbitrarily shaped waveguides. Maxwell’s equations are discretized using vectorial finite elements (FEM). We discuss how we utilize concepts like adaptive grid refinement and higher order finite elements, and adaptive transparent boundary conditions for the computation of leaky modes in photonic crystal fibers. Further, we investigate the convergence behavior of our methods.

We employ our FEM solver to design hollow-core photonic crystal fibers whose cores are formed from 19 omitted cladding unit cells. We optimize the complete fiber geometry for minimal attenuation using multidimensional optimization and taking into account radiation loss (leaky modes) and loss due to roughness at air-glass interfaces which leadsto mode coupling.

6480-23, Session 6

Propagation characteristics of highly elliptical core photonic crystal fiber

R. K. Sinha, A. D. Varshney, Delhi College of Engineering (India)

The propagation of electromagnetic waves in periodic and disordered dielectric media has attracted much attention in recent years. There has especially been a significant interest in a photonic crystal fiber (PCF) consisting of a central defect region surrounded by multiple air holes running along its length. For the analysis of PCF devices, various numerical and semianalytical methods have been proposed so far, such as modal decomposition techniques using sinusoidal function (plane wave expansion method, or PWE)or Hermite-Guassian functions (localized function methods, or LFM). Various numerical techniques have also have also been proposed, such as a finite element method (FEM) and Finite difference time domain (FDTD) method.

In this paper we introduce a semianalytical method for the analysis of the propagation characteristics of elliptical core photonic crystal fibers. The refractive index profile of the PCF is calculated by scalar and vectorial effective index models, and an approximate separable wave equation is found in an elliptical coordinate system for the longitudinal field components. The exact solution to the derived equation is expressed in terms of higher order transcendental function, such as Mathieu functions. After having expressed all the field components, boundary conditions are imposed on the boundaries, and then, a transcendental equation for the propagation constant is derived, which is solved numerically. The validity of the method is ensured by comparing various quantities, such as effective indices and modal birefringence, with those from accurate perturbation approach, showing relatively good agreement between the results.

6480-24, Session 7

Three-dimensional photonic band gap materials: adding optical functionality through novel materials and defined defects

E. C. Nelson, F. García-Santamaría, X. Yu, S. Rinne, P. V. Braun, Univ. of Illinois at Urbana-Champaign

No abstract available

6480-25, Session 7

Core-shell diamond-like silicon photonic crystals from 3D polymer templates created by holographic lithography

J. H. Moon, Y. Xu, Univ. of Pennsylvania; W. Dong, J. W. Perry, A. Adibi, Georgia Institute of Technology; S. Yang, Korea Advanced Institute of Science and Technology (South Korea); S. Yang, Univ. of Pennsylvania

We have fabricated diamond-like silicon photonic crystals through a sequential silica/silicon chemical vapor deposition (CVD) process from the corresponding polymer templates photopatterned by holographic lithography. Core-shell morphology is revealed due to the partial backfilling of the interstitial pores. To model the shell formation and investigate its effect to the bandgap properties, we developed a two-parameter level-set approach that closely approximated the core-shell morphology, and compare the bandgap simulation with the measured optical properties of the 3D crystals at each processing step. Both experimental and calculation results suggest that a complete filling is necessary to maximize the photonic bandgap in the diamond-like structures.

6480-26, Session 7

Two-dimensional diffractive optical element based fabrication of 3D photonic crystal templates

D. Chanda, L. Abolghasemi, P. R. Herman, Univ. of Toronto (Canada)

Recently, two-dimensional and three-dimensional periodic dielectric structures have been directly fabricated by laser holographic lithography (HL) to create novel geometric structures with high-precision tolerances. Multiple beam interference via beam splitting mirrors or diffractive optical elements (DOE) produce isointensity contours that can be accurately recorded in photoresist and subsequently can be used as a template for creating photonic crystals with a complete bandgap. In our previous work, we demonstrated the formation of “Woodpile”-type 3-D photonic crystal templates in photoresist by a new means of diffractive optic holography that was based on two sequential exposures of orthogonal 1D diffractive

optical element using Ar+-ion laser beam. Diffractive optical elements directly generate multiple beams in various diffracted orders which create interference patterns without the use of multiple mirrors and beam splitters required in multi-beam holographic approach. Here, we extend this fabrication technique to two-dimensional diffractive optical elements and thereby generate 3-D photonic crystal structures in a single laser exposure. This approach offers optically robust alignment that provides absolute phase control in placement of the x-z and y-z periodic structures that was not possible with the sequential 1D-DOE technique. 3-D "Woodpile"-type templates, formed in SU-8 photoresist with 5 to 20s laser exposures, show good structural uniformity over large area and resist thickness. Optical characterization of several crystallographic directions verify the presence of several predicted stopbands, demonstrating good prospects for creating devices with complete photonic bandgaps should the templates be double-inverted with high index media like silicon.

6480-27, Session 7

Metallization of 3D photonic crystals with different thickness of Cu thin films

D. Ye, Z. P. Yang, J. A. Bur, S. Lin, T. Lu, Rensselaer Polytechnic Institute

Photonic crystals with a photonic band edge inside the visible wavelengths have extraordinary applications in illuminations, solar cells, and photovoltaic devices by redistributing the energy. However, there is a barrier of achieving such a photonic crystal due to the limitation of fabrication methods and the nature of the dielectric materials used. Recently, we demonstrated that the band edge of a photonic crystal can be modified to be close to visible wavelengths by conformal coating of Cu films [1].

In this talk, we studied the evolution of the band edge with the thickness of the coating layers. We coated the pre-fabricated Si photonic crystals with Cu thin films by chemical vapor deposition. The reflectance of the photonic crystals was measured by a Fourier-transform infrared microscope at room temperature. We observed the coupling of Cu with the photonic band structure of the Si photonic crystals when the thickness of the coating is less than ~60 nm. Complete band gap with the band edge close to 700 nm is developed when the thickness of Cu films is 60 nm. The effect of the adsorption of thin Cu film on the thermal emission is under investigation.

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6480-28, Session 7

Emission spectroscopy of ZnO inverse opal photonic crystals

M. G. Scharrer, H. Noh, M. V. Erementchouk, H. Cao, R. P. H. Chang, Northwestern Univ.

Light emitted within a photonic crystal structure can be used to probe both the photonic density of states and the anisotropic propagation of light through the structure. Most previous studies of emission in three-dimensional photonic crystals have been based on light sources infiltrated into a passive dielectric backbone. Here we present results of angle- and polarization-resolved measurements of photoluminescence from three-dimensional ZnO photonic crystals. The ZnO inverse opals were fabricated by infiltration of polystyrene synthetic opal templates using atomic layer deposition [1]. The resulting nanocrystalline ZnO structures exhibit strong UV emission as well as a broad defect emission peak, allowing us to observe the dispersion of the primary as well as higher-order PBGs over the entire visible spectrum. The spontaneous emission spectrum is strongly modified and anisotropic due to the effect of the PBGs. The observed features are correlated to transmission and reflection measurements as well as calculated band structures and eigenfrequeny surfaces in the -L-K and -L-W planes of the fcc Brillouin zone. Apart from the suppression and redistribution of light near the primary and higher band gaps, we observe a strong enhancement in the PL peaks due to light propagation in higher (e.g. 5th and 6th) photonic bands at frequencies and angles where no PBG exists. The pronounced polarization of these peaks yields information about the symmetry of the involved eigenmodes and their coupling to free space.

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6480-29, Session 7

Porous silicon 2D photonic crystals

N. Tokranova, D. Song, B. Xu, J. Castracane, SUNY/Univ. at Albany

Porous silicon (PSi) is an attractive material for fabrication of multilayer optical devices such as Bragg reflectors, Fabry-Perot resonators and other novel (optical) components. Such devices are characterized by a periodic modulation of the refractive indices in alternating layers and can be classified as 1D photonic crystals. 2D photonic bandgap structures can be also obtained using a variation of applied potential on the back side of the sample during electrochemical formation of the multilayers. This technique allows a fabrication of spatially distributed filters on the millimeter size scale. In this paper, a new method is presented which uses a front side protective mask for the creation of 2D photonic bandgap structures on the micron scale. The devices obtained by this technique can be used for the creation of spatially distributed filers. The front side protective mask controls lateral undercut in multiple ways depending on the mask material. By varying the design and material of the protective mask, PSi interference filters with desired optical parameters across a field of view can be realized.

In this paper, the dependence of filter parameters on mask materials is discussed. In particular, the focus is on the changes in the photonic crystal cavities when various mask materials are used. In addition, initial optical measurements of such prototype PSi components will be presented.

6480-30, Session 8

Broadband and low loss slow light in SOI photonic crystal waveguides

T. F. Krauss, Univ. of St. Andrews (United Kingdom)

No abstract available

6480-31, Session 8

Radiation loss of coupled-resonator waveguides

M. L. Povinelli, S. L. Fan, Stanford Univ.

Coupled-resonator waveguides (CROW's) in photonic-crystal slabs are known to be intrinsically lossy, since the waveguide mode lies above the light line. However, little is understood about the theoretical minimization of these losses. We compare the loss of CROW waveguides to that of isolated cavities (resonators) by means of appropriately-defined Q (quality factor) values. We observe that the CROW and isolated cavities can differ by up to an order of magnitude. We present a case in which optimization of an isolated, high-Q cavity also results in high Q values of the CROW. Moreover, it is found that the CROW loss itself can be an order of magnitude lower than the isolated cavity. We also present a case in which a low-Q isolated cavity can be used to construct a very high-Q (low loss) CROW mode. In general, we find that the intrinsic losses in CROW waveguides have a non-universal dependence on the wave vector of the mode, and so must be taken into detailed consideration in the design and optimization of any future CROW structure.

6480-32, Session 8

Active transmission control based on slow-light photonic crystal waveguide

X. Chen, L. Gu, W. Jiang, R. T. Chen, The Univ. of Texas at Austin

Silicon nanophotonics has recently attracted great attention since it offers an opportunity for low cost opto-electronic solutions based on silicon complementary metal oxide semiconductor (MOS) technology. Photonic crystal (PC) structures with slow photon effect are expected to play a key role in future large-scale ultra-compact photonic integrated circuits. A novel structure that incorporates a silicon PC waveguide with a microelectronic structure for charge injection was proposed to achieve active transmission control via the free carrier plasma dispersion effect. We designed and fabricated a PC waveguide that forms the basis of the aforementioned novel structure on a silicon-on-insulator (SOI) substrate and demonstrated that a defect mode was present in the infrared region. Plane-wave-expansion (PWE)-method-based simulation indicated that the group index of the fabricated PC waveguide was in excess of 100 near the transmission band edge. Further investigation demonstrated that the novel structure that combines the PC waveguide with electronic control would be a good candidate to realize ultra-compact transmission control.

6480-33, Session 8

Meandering photonic crystal delay lines

M. Fakharzadeh, Univ. of Waterloo (Canada)

In this paper we study the characteristics of miniaturized photonic crystal delay lines and propose guidelines for designing photonic crystal delay lines with meandering shapes. We study three structures for PC delay lines, namely serpentine, double spiral and reflective spiral. We show how lattice parameters and refractive index difference affect the bandgap width and suggest a criterion for selecting these parameters. We analyze the effect of the channel length and the inter-channel spacing on the crosstalk between parallel photonic crystal waveguides. We also show corner mitering in meandering structures can reduce the reflection loss significantly. Considering all these guidelines we design different delay lines and examine the propagation of light in these structure through full wave analysis of time delay, loss and bandwidth. We show replacing waveguide channels of a delay line with coupled defect can generate time-delays more than 9ps within a device size less than 27 um, which corresponds to slowing light by a factor of 100.

6480-34, Session 9

Nanowire photonic crystal waveguide and active diode

H. Park, C. J. Barrelet, Y. Wu, C. M. Lieber, Harvard Univ.

We report a novel waveguide structure that couples active semiconductor nanowires and photonic crystal waveguides. Active semiconductor nanowires are used to both generate and inject light into a silicon-nitride two-dimensional photonic crystal slab waveguide structures. Structural parameters of the photonic crystal waveguide are optimized with plane wave expansion and finite-difference time-domain three-dimensional simulation methods. The optimized structure overlaps the electronic semiconductor bandgap of the nanowire with the guided mode of the photonic crystal waveguide. We successfully measure the injection and waveguiding of light from the semiconductor nanowire into the photonic crystal waveguide. In addition, we report the first active nanowire photonic diode structure. Using a CdS/CdSe core/shell nanowires, green and red photons are generated by the respective CdS and CdSe semiconductor materials. Photoluminescence measurements show that this hybrid nanowire/photonic crystal structure selectively waveguides green photons in one direction and red photons in the opposite direction. Since each color of light has a preferred propagating direction, we term this structure ‘active photonic diode’. The progress achieved using hybrid nanowire photonic crystal waveguide represent a significant step toward all-optical processing in the integrated nanoscale photonic systems.

6480-35, Session 9

Optimal photonic crystal bends with linear dispersion

M. Askari, A. Adibi, Georgia Institute of Technology

No abstract available

6480-37, Session 9

Efficient characterization of dispersion in photonic crystal waveguides using spectral interferometery

A. Jafarpour, M. Askari, J. Huang, A. Adibi, Georgia Institute of Technology

No abstract available

6480-61, Session 9

Photonic band structure of Abrikosov lattices in superconductors

H. Zandi, A. Kokabi, S. Khorasani, M. Fardmanesh, Sharif Univ. of Technology (Iran); A. Hosseini, Rice Univ.

We have performed a numerical solution for band structure of an Abrikosov vortex lattice in type-II superconductors forming a periodic array in two dimensions for applications of incorporating the photonic crystals concept into superconducting materials with possibilities for optical electronics. The implemented numerical method is based on the extensive numerical solution of the Ginzburg-Landau equation for calculating the parameters of the two-fluid model and obtaining the band structure from the permittivity, which depends on the above parameters and the frequency. This is while the characteristics of such crystals highly vary with an externally applied static normal magnetic field, leading to nonlinear behavior of the band structure, which also has nonlinear dependence on the temperature. The similar analysis for every arbitrary lattice structure is also possible to be developed by this approach as presented in this work. Some examples are presented and the results are discussed. Similar effects are computed for High-Tc superconductors, in which an anisotropy evolves out of the Abrikosov lattice. As a totally unexpected result, we observe the existence of completely elliptical bands for the first time, and discuss the possible implications.

6480-38, Session 10

Compact photonic crystal demultiplexers and spectrometers

B. Momeni, Georgia Institute of Technology

No abstract available

6480-39, Session 10

3D holographic polymer photonic crystal for superprism application

J. Chen, L. Wang, X. Chen, The Univ. of Texas at Austin; W. Jiang, Omega Optics, Inc.; R. T. Chen, The Univ. of Texas at Austin

Photonic crystal based superprism offers a new way to design new optical components for beam steering and DWDM application. 3D photonic crystals are especially attractive as they could offer more control of the

light beam based on the needs. We employ a holographic method to fabricate 3D polymer photonic crystal. We utilize a top cut prism as the single diffraction element to split the collimated incident laser light (325/422nm He-Cd laser) and combine the beams together to form a 3D interference pattern inside the coated photoresist. Therefore antivibration equipment and complicated optical alignment system are not needed and the requirement of the coherence of the laser source is relaxed compared with the traditional holographic setup. By changing the top cut prism structure, the polarization of the laser beam, the exposure and development conditions we can achieve different kinds of triclinic or orthorhombic photonic crystals on demand. Large area (>1cm^2) photonic crystals with a large range of polymeric matrix volume fraction have been fabricated using optimal conditions from computer simulations. Such 3D polymer photonic crystal would exhibit superprism effects around the wavelength of 1550nm and be suitable for the beam steering usage when refilled with EO polymer.

6480-40, Session 10

Diffraction properties of a photonic crystal

A. Gandhi, X. Sun, Nanyang Technological Univ. (Singapore); M. Yu, Institute of Microelectronics (Singapore); P. Shum, Nanyang Technological Univ. (Singapore)

Photonic Crystals (PCs) are materials with periodic modulation of refractive index. The light propagation in a PC is highly dispersive and it is very different from those of homogenous materials. In this paper we report several novel diffraction properties of a PC. For this reason we fabricated two-dimensional (2D) photonic crystal slab made of silicon nitride (and silicon dioxide) with periodic air holes in triangular pattern with pitches from 400 to 700nm. The out of plane diffraction of these samples are studied. Instead of Fourier optics approach, we adopt a new model based on the theory of equ-frequency surface (EFS) of a PC to support the experimental results.

The experiment is done using either a monochromatic source or a white light source. The diffraction pattern with a collimated light beam and a normal incidence to the 2D periodic plane is dramatically different from those of conventional grating. Several diffraction orders are prohibited. The explicit diffraction condition for a 2D PC is also derived. Interestingly, in some cases the diffraction pattern of hexagonal lattice also consists of a rectangular lattice pattern. This rectangular pattern is intrinsically due to the hexagonal lattice which is also a special type of a centered rectangular lattice. Such a diffraction of rectangular lattice pattern using a hexagonal lattice sample is not visible in all cases. The specific cases are studied and the conditions are derived.

The experiment also was carried out using a monochromatic source with a light beam of ring type of cross section. The circular ring transforms to an elliptical ring after diffraction. Furthermore such an out-of-plane diffraction pattern with a ring kind of beam shape has a direct correspondence to the in plane band structure. The relationships are theoretically derived and experimentally observed. Under specific condition, we showed that the out-of-plane diffraction pattern is actually a scaled version of the iso-frequency contour of the in plane band structure.

6480-41, Session 10

Nonlinear diffraction of second- and third-harmonics in three-dimensional photonic crystals of opals

I. V. Soboleva, S. A. Seregin, A. A. Fedyanin, O. A. Aktsipetrov, M.V. Lomonosov Moscow State Univ. (Russia)

The effect of nonlinear diffraction can be observed in structures with periodicity of dielectric function in two or three directions - two- (2D) and three-dimensional (3D) photonic crystals (PC). In the wave-vector domain 2D and 3D PCs can be described in terms of reciprocal vectors. The enhancement of the optics-harmonic generation in 2D and 3D PCs is observed when the wave vectors of fundamental wave, harmonic wave and reciprocal vector form the triangle - the nonlinear diffraction condition is fulfilled. The directions of harmonic wave propagation defined with the wavelength and propagation direction of fundamental wave and structure period can be differ from fundamental wave propagation direction - the nonlinear diffraction effect is observed. The possibility of nonlinear diffraction effect observation in nonlinear systems, e.g. in opal templates filled with liquids possessing great nonlinearity, highlights their potential use for nonlinear-optics and photonic devices.

In this the new effect of the simultaneous second- (SH) and third-harmonics (TH) nonlinear diffraction are observed in three-dimensional photonic crystals of artificial opals when the second harmonic of fundamental radiation is tuned across the PBG edge. The angular spectra of the second- and third-harmonic intensities are obtained. The directions of second- and third-harmonic waves propagation are determined by the fulfillment of nonlinear diffraction conditions. The SH and TH intensity spectra have peaks at angle values different from one achieved for linear diffraction at the same wavelengths. The SH and TH propagate direction is unambiguously determined using opal reciprocal vector defined by opal refractive index periodicity.

6480-42, Session 10

Systematic synthesis of photonic crystal structures by topology optimization

O. Sigmund, Danmarks Tekniske Univ. (Denmark)

No abstract available

6480-43, Session 11

Inverse design beyond photonic crystals: an introduction to scattering optical elements

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The challenge of making artificial photonic crystals has developed many top of the art fabrication methods. Many of these methods such as lithography or micromanipulation, are so complete that they are not only restricted for crystal fabrication, but also being able to introduce very complex defects into otherwise ordered structures. Taking advantage of this freedom of design one can push this to its extreme, i.e. breaking the symmetry by introducing an excessive number of defects. Within this framework we have introduced a new type of optical devices named Scattering Optical Elements (SOE) [1]. SOEs are computer generated devices where each scatterer is placed in an optimized position with respect to the set functionality. The universality of the inverse design approach makes it very easy to do ‘design on demand’. So far a library of new innovative and high quality devices has been proposed, e.g. optical lenses [2], demultiplexers [1,3] and spontaneous emission controlling elements [4], and we are currently addressing new designs proposals such as cloaking devices [5] or MEMS controlled optical switches.

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6480-44, Session 11

Efficient modeling of spatially incoherent sources for the analysis of photonic crystal spectrometers

M. Badieirostami, H. Zhou, S. N. Chow, A. Adibi, Georgia Institute of Technology

No abstract available

6480-45, Session 11

Investigation on dispersive properties of photonic crystals for employment of Z-scan method

J. Hwang, College of Optics & Photonics/Univ. of Central Florida; J. W. Wu, Ewha Womans Univ. (South Korea)

We investigated the dispersive properties of photonic bandgap structure and the employment of Z-scan method for the determination of the optical Kerr nonlinearity of photonic crystals. Since Z-scan method is based on the dispersion relation of an isotropic nonlinear optical material, we calculated the effective refractive indices of photonic crystals which the material, possessing optical Kerr nonlinearity, manifest via photonic bandgap structure. We adopted the generalized dispersion relation based on transmission coefficient, which involves the dispersive properties of the finite-length material system even in the presence of structural defect. For the one-dimensional photonic crystals of Bragg reflectors and the cavities with defect mode, we calculated transmittance, density of modes, and the effective refractive indices. From these, we discussed the dispersive characteristics of photonic crystals associated with the dispersion anomaly, enhancement of optical nonlinearity, and optical bandgap change, specially focusing on bandgap edges and defect mode. Also we compared the enhancement factor of optical nonlinearity according to the spectral position near bandgap, the structural difference, and the number of layers composing photonic crystal. As a method to determine the effective Kerr coefficients of photonic bandgap structure, Z-scan method was studied. Through the numerical simulation using Transfer matrix method, we found that Z-scan profile has peak at bandgap edges and defect mode: Closed-aperture Z scan reveals the large phase change by the field localization. On the other hand, open-aperture Z scan displays the nonlinear optical change of transmission by all the possible extinction processes, corresponding to the nonlinear absorption of materials and nonlinear reflection by bandgap change.

6480-13, Poster Session

A fluid sensor based on a sub-terahertz photonic crystal waveguide

T. Hasek, Technische Univ. Braunschweig (Germany); H. Kurt, D. S. Citrin, Georgia Institute of Technology; M. Koch, Technische Univ. Braunschweig (Germany)

Recently, photonic crystals (PC) have attracted considerable attention due to their interesting properties and wide application potential in many areas of science and industry. Here, we present two-dimensional photonic crystal waveguides for fluid sensing applications in the sub-terahertz range. The structures are produced using a standard machining process and are characterized in the frequency range from 67 to 110 GHz using a network analyzer. The photonic crystal consists of an air-hole array in high-density polyethylene. A waveguide is introduced by reducing the diameter of the holes in one row. These holes can be loaded with liquid samples. For all structures we observe photonic band gaps between 97 and 109 GHz. While the pure photonic crystal shows the deepest stop band (28 dB), its depth is reduced by 5 dB by the insertion of the waveguide. The depth of the photonic band gap is further reduced by several decibels depending on the refractive index of the liquid inserted. With this type of fluid sensor we can clearly distinguish between cyclohexane and CCl4 with refractive indices of 1.42 and 1.51, respectively. The results are in good agreement with theoretical calculations based on the 2D finite-difference time-domain (FDTD) method with the recursive convolution.

6480-55, Poster Session

Effects of paraffin addition on optical properties and self-assembly of SiO2 photonic crystal

Y. T. O, S. J. Hong, D. C. Shin, Chosun Univ. (South Korea)

The effects of paraffin addition on the optical properties and crystallinity of self-assembled SiO_2 photonic crystal (PC) were examined using a silica nanopowder. The silica nanopowder was fabricated using the well-known Stöber process. During the evaporation process for self-assembly of PC, the nanopowder content was 0.05 or 0.2 wt%, the paraffin addition was fixed to 0.001 wt%, the process temperature was 80°C and the heat-treatment temperature after evaporation was 900°C. The addition of paraffin reduced the defects in the PC layer, thereby resulting in good crystallinity and transmittance. Our results suggested that paraffin can enhance the bonding force between silica nanopowders.

6480-58, Poster Session

Photonic crystal waveguides

J. N. Ptasinski, San Diego State Univ. and SPAWAR Systems Ctr; San Diego

Photonic crystals have been one of the new, exhilarating topics in the last decade. The intent of this work has been to provide an understanding of two dimensional PC waveguides and the guiding mechanism associated with the structures. The basic understanding of two dimensional waveguides can be applied to more complex structures such as those found in three dimensional PCs. Results presented consist of seven different two dimensional waveguide cases, for both the line defect and the coupled cavity variety. It has been shown that PCs do not rely on index guiding, as conventional optical waveguides do, but that they do rely on distributed Bragg reflection. It has also been shown that in the case of defects, such as a waveguide, the size of the photonic bandgap is not the main determinant in the wave confinement of that waveguide. The group index is a good measure of the degree of reflection one expects to see along the propagation direction of a waveguide.

6480-46, Session 12

Adiabatic wavelenegth conversion and optomechanical energy conversion in photonic crystal cavities

M. Notomi, NTT Basic Research Labs. (Japan)

No abstract available

6480-47, Session 12

Investigation of the optical farfield of photonic crystal microcavities

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Photonic crystal membrane microcavities lend themselves to applications like novel higly efficient emitters of incoherent light and sensing devices, and support fundamental investigations on material properties. On the one hand these applications demand a high quality factor at a tailored resonance frequency of the cavity. On the other hand it is important to provide an efficient coupling of the emission to an optical system or waveguide. Another important design issue is the robustness of the cavity with respect to fabrication imperfections to improve the yield. Based on these requirements photonic crystal microcavities have been designed and optimized with a novel 3D Finite Element (FE) Maxwell solver which is capable of solving eigenproblems as well as source problems. The solver features the computation of the farfield to support the investigation of the spatial emission pattern and is applicable to arbitrary 3-dimensional microcavities. Based on the cavity design, photonic crystal light emitters

with quantum dots have been fabricated and characterized in a photoluminescense setup. The good agreement between the characterization results and the model calculations of different photonic crystal microcavity configurations confirms the performance and the accuracy of the 3D FE Maxwell solver. Different photonic crystal configurations have been investigated with respect to their outcoupling efficiency and optimization strategies are proposed.

6480-48, Session 12

Spectrally selective absorption enhancement in photonic crystal defect cavities

L. Chen, Z. Qiang, W. D. Zhou, The Univ. of Texas/Arlington

Infrared (IR) photodetectors with wide spectral coverage (2 to 20∝m) and controllable spectral resolution are highly desirable for absorption spectroscopy gas sensing and hyper-spectral imaging applications [1]. Significant progresses have been made in quantum well and quantum dot based IR photodetectors (QWIPs, QDIPs). The incorporation of photonic crystals (PCs) [2-6] into IR photodetectors can lead to engineered spectral resolution with multi-spectral coverage in IR photodetectors. Simultaneous enhancement and suppression of absorption at different spectral locations is feasible via lithographically controlled photonic bandgap (PBG) and defect mode cavity [7-10].

Detailed simulation has been carried out to investigate the absorption properties based on three-dimensional finite-difference time-domain (3D FDTD) technique with perfectly matched layers (PMLs) at the boundaries of the structure [11]. The simulation was carried out on a symmetric slab waveguide, with a thin absorptive layer in the center of the slab. PC cavities with and without defect were investigated. The simulated absorption results were normalized to the absorption obtained from the same slab without PC cavity (as reference).

For 2D symmetric air hole triangular lattice PC structures, enhanced absorption at defect level was obtained, with the enhancement factor greater than 35. This enhancement factor is largely dependent upon the spectral overlap between the absorption material and the defect mode cavity. Complete absorption suppression within photonic bandgap region was observed in defect-free cavities, and in single defect cavities when the absorption spectral band has no overlap with the photonic bandgap. In single mode cavities (single-defect), similar alternation was obtained for spontaneous emission in lossless cavities and absorption in lossy cavities. However, drastically different behavior observed in multi-defect cavities, where multiple modes exist. Discussions will be given on the defect configuration impact. The Work is ongoing both theoretically and experimentally based on the QDIP materials at center wavelengths of 8∝m (Long-wave IR) and 4∝m (Mid-wave IR).

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6480-62, Session 12

Analytical analysis of tm polarized defect modes in 2D photonic crystals based on hermite expansion of Floquet orders

P. Sarrafi, K. Mehrany, S. Khorasani, Sharif Univ. of Technology (Iran)

Using polynomial expansion of electromagnetic fields has been already reported for extraction of TE polarized defect modes in two-dimensional photonic crystals. This approach is now applied to straight single-line defect optical waveguides, where TM defect modes are analytically extracted for the first time. Electromagnetic fields are expanded in accordance with the Floquet theorem, where each Floquet order is itself expanded in terms of Hermite polynomials and finally a new set of linear ordinary differential equations with non-constant coefficients is obtained. This set of equations is handled by employing differential transfer matrix method. In this fashion, algebraic and easy to solve dispersion equations are derived, where each mode is effectively sought out in the Hilbert space spanned by Hermite polynomials. Finally, the validity of obtained results is confirmed by employing Finite Difference Time Domain approach.

6480-50, Session 13

Multi-layered photonic crystals de novo: new formalism, results, insights, and analytic possibilities

F. Szmulowicz, Univ. of Dayton

A new formalism for calculating the photonic band structure of multi-layered photonic gap (PBG) materials is derived. For theory aficionados, the formalism is compact, algorithmically simple, and physically appealing. Its simplicity makes it possible to represent eigenfrequency conditions using geometric constructs, find a factored form of the secular equation, and derive analytic eigenfrequency conditions and analytic wave functions for multi-layered structures. For the practically minded, the new formalism makes it possible to find the complete band structure of multi-layered PBG materials with integer ratios of optical path lengths (e.g., any combination of quarter-wave,half-wave, etc., stacks) through a single diagonalization of a low order secular equation, the alternative being an implicit root search via the transfer matrix method. The formalism is demonstrated on multi-layered structures arranged in the Fibonacci sequence, a saw tooth-graded dielectric profile, and half-wave-quarter-wave-eighth-wave and half-wave-third-wave-sixth-wave PBGs.

6480-51, Session 13

Correlation between tamm-like and shockley-like surface states in photonic crystals

N. Malkova, C. Ning, NASA Ames Research Ctr.

We investigate surface states, which appear in a complex defect chain embedded in a host photonic crystal. The defect chain contains the two different types of defects and/or different types of bonds. We analyze this structure using empirical tight-binding model and numerical Finite Difference Time Domain technique. We investigate how the spectrum of the structure is changing with termination of the chain. We interpret this effect in terms of the correlation between Tamm-like and Shockley-like surface states.

6480-52, Session 13

Magnetic photonics crystals

S. Yang, H. Horng, National Taiwan Normal Univ. (Taiwan); C. Hong, Da-Yeh Univ. (Taiwan); H. Yang, National Taiwan Normal Univ. (Taiwan)

Magnetic permeability of material plays a role in optical properties at long wavelength region. Thus, the periodic refractive-index variation of photonic crystals is dominated by both dielectric constant and magnetic permeability at long wavelength region. In this work, we develop simulation methods, including modified plane-wave expansion and finite-difference time-domain mehtods, to investigate the effects of magnetic permeability on photonic properties of photonic crystals. The investigated properties are dispersoin realtion, superprismimg effect, birefringence prism, and negative refraction of photonic crystals. The effective medium model is proposed to clarify the physical origin of the contribution of magnetic permeability to these photonic properties.

6480-53, Session 13

Ultra compact photonic crystal polarization mode splitter

R. K. Sinha, Y. Kalra, Delhi College of Engineering (India)

In the recent years Photonic Crystals (PhCs) which are periodic arrangement of two or more materials of different refractive index with the period of the order of wavelength, have gained considerable interest because of their ability to mold the flow of light. A new design of polarization mode splitter based on complete photonic band gap (CPBG), involving coupled photonic band gap (PBG) waveguides operational in the wavelength range from 1.51 micrometer to 1.59 micrometer, has been proposed. . The PBG structure considered is composed of square Si rods (n = 3.42) with lattice constant a =0.86 micrometer and normalized rod length l/a = 0.42in honeycomb lattice which exhibits a complete photonic band gap for the normalized frequency range (a/lambda) from 0.53908 to 0.5745. The proposed CPBG polarization mode splitter is formed by two PBG waveguides placed in close proximity of each other. The finite difference time domain (FDTD) method has been used to model the proposed CPBG polarization mode splitter. Numerical calculations indicate that the size of the polarization mode splitter can be reduced lesser than 30 micrometer using the CPBG effect for the entire operational range. Further, the polarization splitting properties i.e. extinction ratio and coupling efficiency over the entire operational range has been studied. It is shown that the extinction ratios better than -24dB and coupling efficiency better than 83% over a large bandwidth of 80nm can be obtained in the CPBG polarization mode splitter.

Thus, the design parameters of the CPBG polarization splitter can be tailored to make the CPBG polarization mode splitter in the required wavelength range, which can prove helpful in the design and development of ultra compact all optical integrated circuits.

Conference 6481: Quantum Dots, Particles, and Nanoclusters IV

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6481-01, Session 1

Controlling the optical properties of quantum dots and nanocrytals using size, composition, coupling and strain

G. W. Bryant, National Institute of Standards and Technology

Passive control of the optical properties of semiconductor quantum dots and nanocrystals is achieved by controlling dot size, shape, composition, and interdot coupling via the growth. In advanced applications, active, dynamical control of optical properties is also needed. In self-assembled quantum dots and nanocrystals, local strain due to lattice mismatch between the dot core and barrier influences dot electronic properties and optical response. Active control could be achieved by applying external strain to induce or split level degeneracies, polarize optical transitions, or modify coupling in closely spaced dots, all critical capabilities for using dots in quantum information processing. It was also proposed recently that quantum dots could be used in optical cooling schemes to bring vibrating nanomechanical oscillators into the quantum limit.

We exploit atomistic tight-binding theory to describe the effects of dot size, composition, coupling, and internal and applied strain on the confined states in quantum dots. Both types of strain are critical, so we include the atomistic local strain and the externally imposed strain on an equal footing via an atomistic valence force field approach. A full tight-binding model including an sp3s*d5 orbital model and spin-orbit effects is used. Several examples are discussed, including core-shell nanocrystals, quantum dot quantum wells, InP nanocrystals under pressure, arrays of coupled self-assembled dots and self-assembled dots buried in bent nanomechanical oscillators, to highlight the importance of using atomistic models, extending tight-binding models to include d states, and having both internal and applied external strain.

6481-02, Session 1

Stress-engineered self-organized quantum dots: platform for advanced technologies

A. Madhukar, Univ. of Southern California

Spontaneous formation of defect-free three-dimensional nanoscale islands driven by relaxation of lattice mismatch induced strain during overgrowth of a thin film on a crystalline substrate underlies the subject of the so-called self-assembled quantum dots. Separate from this lattice mismatch driven phenomenon, structuring surface morphology introduces spatially varying surface stress which can also be exploited to cause directed-migration of atoms during even lattice-matched epitaxy and thus create regular arrays of quantum confined structures. Combining these two concepts allows manipulating the spatially organized arrangement of spontaneously-formed quantum dots into two- and three-dimensional architectures. In this talk I shall emphasize the underlying framework of surface-stress driven self-organized growth. Time permitting, the applications of such quantum dots to devices such as lasers, optical amplifiers, and photodetectors will be presented.

6481-03, Session 1

Copper selenide nanostructures

G. Statkute, Vilnius Univ. (Lithuania); I. Mikulskas, EKSPLA Ltd. (Lithuania); A. Jagminas, Institute of Chemistry (Lithuania); R. Tomasiunas, Vilnius Univ. (Lithuania)

Nanocrystallized copper selenide manifests itself as a new perspective material in optoelectronic applications for the near infrared, in particular, photovoltaics and laser optics. However, there is lack of experimental results concerning carrier dynamics in this indirect p-type semiconductor.

Investigation of copper selenide nanostructures of different stoichiometries is summarized. The experimental results and theoretical modeling concern carrier photogeneration, recombination and trapping. We present to our knowledge first experimental results on carrier lifetime measurements performed by means of time resolved non-degenerate four wave mixing and pump-probe techniques.

Cu2-xSe nanowires and nanocrystallite samples were prepared by electrochemical deposition of copper selenide into the pores of alumina matrix of various diameter 10 - 70 nm. Samples were charactrized by SEM, TEM, XRD and UV-VIS-IR spectrophotometry techniques.

6481-04, Session 1

Thermal-lens study of thermo-optical properties of CdSe/ZnS quantum dots embedded into PMMA matrix

V. Pilla, E. Munin, L. P. Alves, M. T. T. Pacheco, Univ. do Vale do Paraíba (Brazil)

Recently, semiconductor nanocrystals have generated an increasing interest due to its versatility and flexibility of use. For example, the quantum dots can be mixed into liquid solution, common matrix materials like polycarbonate, polystyrene or polymethyl methacrylate, or films. In this way, joining the advantages and merits of both, the dots and the matrix materials, these new quantum dots composite materials are becoming promising for practical applications requiring excellent transparency, resistance to water, easy thermoforming, casting and brittle properties. They find potential use as biological markers, in non-linear and military applications, in solar cells and photonic switching. The present work reports thermal-optical properties of solutions of CdSe/ZnS quantum dots encapsulated with polymethyl methacrylate (PMMA) dissolved in chloroform, as a function of the CdSe/ZnS concentration, which were measured by using the Thermal Lens (TL) technique. TL transient measurements were performed using the mode-mismatched dual-beam (excitation and probe) configuration. A He-Ne laser (632.8 nm) was used as the probe beam and either a He-Ne laser (543.5 nm) or a He-Ne laser (594 nm) was used as the excitation beam. Thermo-optical properties as thermal diffusivity (D), thermal conductivity (K), the probe beam temperature coefficient of the optical path length change (ds/dT), fraction thermal load and the fluorescence quantum efficiency of CdSe/ZnS/PMMA liquid samples were determined.

6481-05, Session 2

Phonons in semiconductor quantum dot materials

A. A. Balandin, M. Shamsa, I. Calizo, W. Liu, Univ. of California/ Riverside

The proposed applications of the semiconductor quantum dot (QD) materials in optoelectronic and nanoelectronic devices stimulated interest to understanding the properties of phonons, i.e. lattice vibrations, in such nanostructures. Phonons manifest themselves practically in all characteristics of semiconductors: they affect optical response, limit electron mobility, carry heat, etc. [1]. The phonon properties in QD materials differ substantially from those in constituent bulk crystals. In this talk we present our recent theoretical and experimental results pertinent to the acoustic phonons in QD materials. First, we describe the modification of the acoustic phonon dispersion in the ordered arrays of QDs made of InAs/GaAs and

GeSi/Si. We show how the modification of the phonon spectrum can change the interaction of phonons with charge carriers and light. Secondly, we present the results of the experimental study of thermal transport through GeSi/Si QD material performed by the "3-omega" and "hot-disk" techniques. The strain fields, which also affect the phonon transport in QD materials, have been evaluated using the micro-Raman spectroscopy. We offer two model explanations to the observed changes in the acoustic phonon thermal conductivity using the phonon-hopping [2] and Callaway-Klemens approaches. The strong decrease of the thermal conductivity can affect the design of optoelectronic devices made on the basis of QD materials.

The work has been supported, in part, by the MARCO Center on Functional Engineered Nano Architectonics (FENA) and by the UCR-UCLA-UCSB Center for Nanoscience Innovation for Defense (CNID).

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6481-06, Session 2

Maximum operating temperature and characteristic temperature of a quantum dot laser in the presence of internal loss

L. Jiang, L. V. Asryan, Virginia Polytechnic Institute and State Univ.

High temperature stability of threshold current is among the predicted advantages of semiconductor quantum dot (QD) lasers over the other types of diode lasers. Here we study the effect of carrier-density-dependent internal optical loss outside the active region [in the optical confinement layer (OCL)] on the temperature stability of threshold current of a QD laser. Such loss is shown to couple the confined-carrier level occupancy in QDs to the free-carrier density in the OCL. As a result, the level occupancy becomes temperature-dependent, which introduces the T-dependence of the threshold current component associated with the recombination in QDs. The T-dependence of the recombination current in the OCL is also strongly affected by the internal loss. The characteristic temperature T_0 - a figure merit of a diode laser from the viewpoint of temperature stability of operation - is calculated versus the structure parameters (surface density of QDs, QD-size dispersion, cavity less), cross-section of internal loss, and temperature. T_0 is considerably reduced due to carrier-density-dependent internal loss. At room temperature and for the structure emitting near 1.55 micron, T_0 is about twice as low as that in the absence of such loss. The carrier-density-dependent internal loss sets up an upper limit T_max for operating temperatures of a QD laser. For temperatures above the maximum operating temperature T_max, the lasing condition can not be satisfied. At the maximum operating temperature, the characteristic temperature drops to zero; the same happens as any of the structure parameters (e.g., the QD-size dispersion) approaches its critical tolerable value.

6481-07, Session 2

Effect of excited states on light-current characteristic of a quantum dot laser

L. Jiang, L. V. Asryan, Virginia Polytechnic Institute and State Univ.

Comprehensive theory of the output power of a quantum dot (QD) laser is discussed in the presence of excited states in QDs. Depending on the parameters of the structure, the following situations are possible for lasing: (i) ground-state lasing only; (ii) ground-state lasing first and then the onset of also excited-state lasing with increasing injection current; (iii) excited-state lasing only. A simple excess of the maximum gain for ground-state transitions over the mirror loss is not sufficient for ground-state lasing to occur. Likewise, a simple excess of the maximum gain for ground-state transitions over the maximum gain for excited-state transitions is not sufficient for ground-state lasing to occur prior to the onset of excited-state lasing. Strict criteria are formulated for all the above situations. An important parameter in the model is the transition time between the excited- and ground-state. The following characteristics are analyzed versus the injection current and the transition time: occupancies of the excited- and ground-states, carrier density outside QDs, threshold currents for ground- and excited-state lasing, output power and number of photons emitted via the ground- and excited-state transitions, internal and external differential quantum efficiencies. Under the conditions of ground-state lasing only, the output power saturates with increasing injection current. Under the conditions of both ground- and excited-state lasing, the external efficiency is independent of the transition time. Under the conditions of excited-state lasing only, the role of ground-state transitions is simply reduced to increasing the threshold current.

6481-08, Session 2

Cavity QED with quantum dots in semiconductor microcavities

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Cavity QED effects with single self assembled InGaAs/GaAs quantum dots inside both micropillar and photonic crystal cavities are investigated. We measure enhanced and inhibited spontaneous emission lifetimes in both cavity geometries. In addition, we report on the ultra efficient lasing of photonic crystal cavity modes using a low density of quantum dots as gain medium. This surprising result is extended and validated by a systematic study of the lasing transition as measured by the photon statistics of the emitted light field as a function of pump power.

6481-09, Session 2

A GISAXS study of PbTe quantum dots/SiO2 multilayer

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The nonlinear properties of Quantum Dots has the potential to be used as an ultrafast "all-optical" device. A Fabry-Perot cavity can further enhance the nonlinearities if the QDs are placed in the maximum of the electromagnectic fields. For a real application the absorption peaks must be in the near infrared window (1.3-1.5 μm) used in optical communications. We choose PbTe QDs because absorption band can be controlled by its size to fall in the spectral near infrared window used for optical communications (1.3-1.5 μm). Multilayers of PbTe quantum dots embedded in SiO2 were fabricated by alternatively use of Plasma Enhanced Chemical Vapor Deposition and Laser Ablation techniques. This structure was grown inside a Fabry Perot cavity and the transmittance of this one-dimensional photonic crystal was measured, clearly showing the absorption enhancement expected. The morphological properties of the nanostructured material were studied by means of Grazing Incidence Small Angle X-ray Scattering (GISAXS) and Transmission Electron Microscopy(TEM). The GISAXS spectra provided information about the shape, size and size distribution of the nanoparticles. Both GISAXS spectra and TEM images reveled the nanoparticles are 6-8 nm in diameter, consequently appropriate for developing optical devices in the infrared region.

6481-10, Session 3

Pseudopotential theory of interband and intraband transitions in (InGa)As/GaAs quantum dots

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We have calculated interband conduction-to-valence and intraband conduction-to-conduction and valence to-valence optical absorption spectra in self-assembled (In,Ga)As/GaAs quantum dots by adopting an atomistic pseudopotential approach combined with the configuration-interaction method. Several features emerge. Interband absorption: (i) Transitions that are parity forbidden in simple effective mass models with infinite confining wells (e.g., 1S-2S, 1P-2P) become possible because of finite band offsets and orbital-mixing effects. (ii) Light-hole-to-conduction-band transitions, enabled by the confinement of light-hole states. (iii) Transitions that show an enhanced intensity due to electron hole configuration mixing with allowed transitions. Transitions of types (i) and (ii) explain recently observed satellites of the allowed P-P transitions. Intraband absorption: (i) In pure, non-alloyed InAs/GaAs dots, 1S-1P conduction intraband transitions are fully polarized along [1-10] and [110]. But in alloyed dots this polarization is weakened due to the mixing of the two P states that arises from alloy fluctuations. (ii) When charging the dots with a few electrons, the conduction intraband transitions display spectroscopic shifts of ~1-2meV. These shifts are mainly the result of correlation effects. (iii) When charging the dot with holes, valence intraband spectra are more complex than the conduction intraband spectra as hole states are strongly affected by spin-orbit coupling, and configuration-mixing is more pronounced. These predictions could be probed in single-dot spectroscopy of n-doped and p-doped quantum dots.

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6481-11, Session 3

Size effects in silicon quantum dots probed by second-harmonic spectroscopy

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Silicon quantum dots (Si-QDs) have recently attracted much attention for potential application in future nanoelectronic and optoelectronic devices. In centrosymmetric media quadratic polarization becomes nonzero starting only from quadrupole term of its multipole expansion over fundamental field gradients, thus QD-to-substrate signals ratio becomes significantly better for second-harmonic-generation (SHG) than for conventional linear-optical techniques, such as spectroscopic ellipsometry and photoreflection. This makes SHG as an effective tool for studying Si-QDs. In this paper, the size effects in resonant nonlinear-optical response of Si-QDs are studied in the spectral interval of second-harmonic photon energies from 3.0 to 3.5 eV.

A monolayer of Si-QDs was fabricated from the a-SiNx /a-Si:H/a-SiNx samples deposited on quartz substrates by furnace annealing process. The a-Si:H sublayer thicknesses in the series of the samples were 2, 4, 7, 10, 50 and 100 nm. The SHG spectra are measured in the p-in, p-out polarization combination using tunable 100-fs Ti-sapphire laser. The Si-QDs SHG spectra differs significantly from the spectra of the unannealed sample with Si quantum well. The SHG spectra of Si-QDs samples with 100, 50, 10 and 7 nm dot sizes have pronounced resonant character. The spectral maximum demonstrates the blue-shift upon the decreasing of the Si-QDs size. For 10 and 7 nm Si-QDs size samples the SHG maximum is expected to be outside of the Ti:sapphire laser tuning range. The resonance is not observed in the SHG spectra of 4 and 2 nm Si-QDs size samples, where the SH signal becomes comparable with one from fused quartz substrate.

6481-12, Session 3

Modulation spectroscopy characterization of InAs/GaInAsP/InP quantum dash laser structures

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The main driving force of the efforts spent on development of quantum dot (QD) based lasers operating at fibre telecommunication windows is to combine the emission at 1.3 - 1.55 ∝m range and to utilize the unique QDs properties like delta-like density of states or natural nonuniformities of the so called self-assembled systems. We report on the modulation spectroscopy investigation (in a form of photoreflectance (PR)) of self-assembled InAs/GaInAsP quantum dot structures grown by gas source molecular beam epitaxy on InP (100) substrutes and designed for laser applications at 1.55 ∝m wavelength range. The growth conditions led to the formation of elongated islands (dashes) with typical height, width and length of about 2 nm, 20 nm and 200 nm, respectively. The density of dashes per QD layer is about 5Å~1010 cm-2. The dots parameters have been determined by cross-sectional and plane-view transmission electron microscopy (TEM). The advantages of the modulated reflectivity measurements have been used to probe the electronic structure, i.e. to detect the optical transitions, including the excited state ones, related to all relevant parts of the structure like cladding material, quaternary barriers, wetting layer and finally quantum dots. The excited sate spectrum of the quantum dot layer has revealed three well distinguished transitions with the energy separation between the ground state and first excited state ones of about 150 meV, which is very promising value from the point of view of such basic laser properties as temperature lasing stability and high T0 values, i.e. weak dependence of the threshold current on the temperature. Our theoretical analysis based on effective mass approximation calculation within the envelope function approach has shown that the two excited states are related to heavy hole and light hole ground state transitions in the InAs wetting layer. Parameters like wetting layer quantum well thickness and InAs/GaInAsP band offset have been treated as semi-free, and on the base of agreement with the experimental data determined to be 3 monolayers and 70 % for the conduction band, respectively. Our considerations have shown that the confinement potential for the InAs quantum dots of these sizes grown on InP substrate and surrounded by GaInAsP barrier lattice matched to InP (and with band gap energy of 1.07 eV at room temperature) is shallow enough to confine one electron state only and hence a single allowed heavy hole transition has been observed in PR.

6481-13, Session 3

Photoabsorption spectroscopy of InAs/InGaAlAs/InP quantum-dash-in-well laser structure

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Advances in self-assembled semiconductor quantum-dot/quantum-dash (QD) have attracted tremendous attention due to their three-dimensional carrier confinement. These findings have opened up new dimensions in the engineering of quantum nanostructured materials for both electronic and optoelectronic applications. For such applications, a good knowledge of QD structural and electronic properties is essential. Cryogenic photoluminescence (PL) spectroscopy has traditionally been employed to investigate the confined state in QDs, however it only gives only the information of the radiative recombination. The absorption measurements are attractive since they provide fundamental information on interband optical confinement and extended states from epilayers of quantum heterostructures simultaneously related to their electronic structures. The InAs QDs grown on InP substrate are promising candidates to achieve light emission in the 1.3-1.7 μm spectral range, which is suitable for optical fiber telecommunications and various gas sensing applications. Here we report the room temperature photocurrent and surface photovoltage spectroscopy studies of InAs quantum-dash in InAlGaAs quantum-well

laser structure grown by molecular beam epitaxy. The photoabsorption spectra reveal well-resolved excitonic absorption features related to the size quantization and the optical transition in the QDs, QWs, barriers, and separate confinement heterostructures. To complement our study, we extend the investigation to the annealed samples and an energy blue-shift is observed that is attributed to the group-III atoms intermixing after the annealing. The results are compared with PL measurements and the effects of group-III intermixing are discussed. Our results demonstrate that photoabsorption measurements are direct, sensitive, and simple techniques to complementary study low-dimensional nanostructures and interdiffusion.

6481-14, Session 3

Efficient energy transfer in InAs quantum dash based tunnel-injection structures at low temperatures

G. Sek, Politechnika Wroclawska (Poland)

The idea of a laser based on quantum dot (QDot) coupled to the auxiliary quantum well (QWell) has been proposed lately to overcome difficulties typical for standard QDot lasers [1,2]. Generated carriers are collected by the QWell and next they tunnel laterally into the QDot area. This system makes carrier collection more efficient [1], offers much faster carrier injection into QDot [3], solves the problem with carrier relaxation [1], improves the temperature stability [4] and reduces the threshold current [2].

We have investigated InAs/In0.53Ga0.23Al0.24As quantum dash (QDash) coupled to In0.53Ga0.47As/In0.53Ga0.23Al0.24As QWell structures. The samples were grown in a molecular beam epitaxy system on InP substrates. Three samples with various width of a barrier, separating QDash and QWell area, were selected in common with reference QWell and QDash samples. In temperature dependent photoluminescence we have observed two recombination channels - through QWell and through QDash. The relative intensity of both channels depends on the barrier width separating these two systems. At lower temperatures most of the recombination goes through the QDashes while the QWell serves as an reservoir of photogenerated excitons. With increasing the temperature there appears the second channel which is connected with the QWell recombination and it becomes dominant at room temperature (the QDash recombination is then almost negligible). The common tunneling mechanisms have strict restrictions regarding the relative electron and hole energy levels in QWell and in QDash, e.g. direct tunneling (resonant process), photon-assisted tunneling, Auger-assisted tunneling and phonon-assisted tunneling. The exciton tunneling is easier to obtain since only the emission energy difference between QWell and QDash is significant, while the electron and hole separately energy level structure is of a less importance. In our case, the energy difference between QWell and QDash transitions is close to the energy of LO phonon. At low temperatures (< 100 K) we have observed very efficient exciton tunneling which becomes less effective at higher temperatures where excitons are dissociating very effectively (free carriers tunneling prevails).

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6481-15, Session 4

Colloidal quantum dots in optoelectronic devices

V. Bulovic, Massachusetts Institute of Technology

Advancements in chemical synthesis of colloidal nanocrystals (quantum dots, QDs) have made available a plethora of highly engineered nanoscale material systems. Use of such nano-elements in active optoelectronics, however, necessitates development of new methods for layering and patterning QD monolayers, at a precise position within the optoelectronic device layer-stack. The talk will highlight the efforts behind QD layer engineering for development of efficient QD light emitting devices and QD photodetectors.

6481-16, Session 4

Fabrication and characterization of In(Ga)As quantum dot semiconductor optical amplifiers on InP operating at 1.5 μm

N. Kim, J. M. Oh, J. S. Yim, D. Lee, Chungnam National Univ. (South Korea); S. Pyun, W. Jeong, Sungkyunkwan Univ. (South Korea); J. W. Jang, NanoEpi Technologies (South Korea)

Self-assembled semiconductor quantum dots (QDs) have been actively investigated since the high saturation output power, fast gain recovery and low cross-talk are expected when QDs are used as a gain medium for a semiconductor optical amplifier (SOA).

We have grown round and dome-shaped QDs on InP (100) substrate by metal-organic chemical vapor deposition. The barrier was InGaAsP of 1.1 μm energy gap lattice matched to InP and the dot material was InGaAs with gallium content of ~ 0.5%. The diameter, height and density of QDs were 32 nm, 3.4 nm, and 1.1x1011 cm-2, respectively. The full width at half maximum was relatively small, 63 meV at room temperature. The PL peak was controlled from 1.43 to 1.57 μm by adjusting the growth condition. The room temperature PL yield was quite high, about 25% of the low temperature value.

We have fabricated SOAs with 2 ~ 4 μm ridge width using the above mentioned QDs. The QDSOAs had a barrier of 1.1 μm emitting InGaAsP and a simple separate confinement hetero-structure with InP cladding layer. The spacing between adjacent QD layers was 40 nm to ensure no vertical electronic coupling, confirmed by time resolved PL measurements. A tilt waveguide and anti-reflection coatings on both facets were employed to reduce the reflection. The small signal gain was about 20 dB and the typical gain peak was around 1.54 μm, which matches well with the optical communication band. We have also measured 3-dB gain bandwidth with broadband light source of 200 nm and found that it was around 50 nm.

6481-17, Session 4

All-epitaxial VCSELs with tunnel QW-QDs InGaAs-InAs gain medium

V. E. Tokranov, M. Yakimov, J. Van Eisden, S. R. Oktyabrsky, SUNY/Univ. at Albany

Quantum dot (QD) size distribution and limitations in carrier capture and thermalization rates are still limiting the maximum saturation gain in QD-based laser diodes and the utilization of QD-medium in all-epitaxial vertical cavity surface emitting lasers (VCSELs). To overcome these problems structures of tunnel coupled pairs consisting of InGaAs quantum wells grown on top of self-assembled InAs QDs (QW-on-QDs) were employed as a gain medium for VCSELs. Photoluminescence, transmission electron microscopy and electroluminescence were used to study the properties of the multiple-layer QW-on-QDs active medium. QW-on-QDs tunnel structures with 3 - 5 nm tunnel barrier thicknesses and with different ground state (GS) relative separations were grown with varying InGaAs QW while the QD growth process parameters were kept constant. We have developed a tunnel QW-on-QDs structure with a QD PL line red-shifted by 32 meV relative to QW GS line. The narrow linewidth (22 meV) of this QD transition likely indicates an efficient LO-phonon assisted tunneling of carriers from QW into QD ensemble states. Optimized tunnel (with 3 nm barrier thickness) QW-on-QDs structures were evaluated in VCSELs. All-epitaxial VCSELs with triple-pair tunnel QW-on-QDs as active medium demonstrated continuous wave mode lasing. These QD-based VCSELs with n-doped AlGaAs/GaAs mirrors and tunnel n-p junction exhibited 1.8 mA (Jth ~ 800 A/cm2) minimum threshold current at QD GS emission wavelength, 1135 nm, with 0.7 mW optical power and 12% slope efficiency.

6481-18, Session 4

Quantum dot based phase modulator at 1300 nm

S. P. Hegarty, D. Goulding, G. Huyet, Tyndall National Institute (Ireland)

The electronic band structure of quantum-dots (QDs) is fundamentally different to that of traditional quantum well materials as evidenced by phenomena such as 'giant' phase amplitude coupling. Each QD layer contains a finite number of QDs, thus it is quite practical to fully occupy the ground state of a device with a reasonable injection current. Once the ground state is fully occupied, further carrier injection leads to increased occupation of higher energy states and an unchanged occupation and thus an unchanged gain for the ground state. The refractive index of the ground state however is changed by the increased injection due to plasma effects and the asymmetry of the gain change with respect to the ground state. We have therefore the basis for a phase modulator, one that can be fabricated monolithically with the source laser with attendant possibilities for integrated photonic devices.

We demonstrate this principle using a 1 mm long, 10 QD layer SOA with peak gain at 1295 nm and an external probe laser. Each QD layer consisted of 33 nm of GaAs, 0.8 nm of InAs with a 5 nm InGaAs capping layer. Above 50 mA DC bias, the SOA gain was substantially saturated. The SOA was placed in an actively stabilised Mach-Zehnder interferometer so that we could measure phase and amplitude modulation separately as functions of the DC bias. At low DC current we find an alpha factor of less than 5, but at high DC bias alpha exceeds 100, the largest reported value we are aware of for a quantum-dot laser. A large-signal modulation was applied and phase shifts of pi were developed by bias currents of some 10s of mA.

6481-19, Session 4

A two-photon sequential absorption photocurrent generation process in modulation doped InAs/GaAs quantum dots

X. Lu, Univ. of Massachusetts/Lowell; M. J. Meisner, Raytheon Missile Systems

An analysis of a two-photon sequential absorption photocurrent generation process, for modulation doped InAs/GaAs quantum dot (QD) detector material, was performed. Enhanced nonlinear absorption was expected, and demonstrated, due to the long excited sate lifetimes. Ultra-low leakage current has been verified, as well. Consequently, the two-photon sequential absorption photocurrent generation process is promising to achieve thermal-electrically cooled (i.e., high operating temperatures) long-wave infrared (LWIR, 8 to 12∝m) photodetectors, with high photodetectivity.

6481-20, Session 5

Micro-structuring of glass doped with silver nanoparticles

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Ion exchange and subsequent aggregation is a commonly used way to generate noble metal nanoparticles in glass. Using an electric field at elevated temperatures these particles can also be dissolved again - if a structured electrode (Cr-covered Si photonic crystal) is used, this dissolution appears dominantly below the contacted areas. With this method we produced regular patterns of nanoparticle islands (beneath the holes in the photonic crystal) with diameters and distances down to 500nm. The analysis of this process shows, that the depth distribution of the noble metal ions can be controlled by electric field and temperature applied during the dissolution, allowing us to generate 2D photonic-plasmonic structures in the nanocomposite materials.

In a second experiment we have produced inverse structures using a slightly modified procedure, where silver ions were driven from the electrode into the glass. Using again a Si photonic crystal coated with silver as an electrode, the electric field distribution generated a regular lateral variation of the Ag concentration; unexpectedly, in this case the silver concentration below the holes of the electrode structure is higher than below the Ag-covered anode area. By subsequent heating (aggregation) the modulated silver ion concentration leads to the above mentioned inverse nanoparticle distribution.

This technologically rather simple methods have an interesting potential for the production of 2D photonic and plasmonic structures.

6481-21, Session 5

Fabrication and third-order optical nonlinearity of germano-silicate glass optical fiber incorporated with au nanoparticles

A. Lin, B. Kim, P. R. Watekar, S. Ju, W. Han, Gwangju Institute of Science and Technology (South Korea)

Novel germano-silicate glass fiber incorporated with Au nanoparticles was developed for nonlinear optical applications by the modified chemical vapor deposition technique and the solution doping method. The sharp absorption peak appeared near 498.4 nm was found to be due to the surface plasmon resonance absorption of the Au nanoparitcles, which were embedded in the core of the fiber. The diameter of the Au particles was calculated to be 12~27 nm from the accumulative absorption properties of the fibers with different lengths. Third-order optical nonlinearity of the fiber was estimated by measuring the peak shift of the fringes obtained from the long-period fiber grating (LPG) pair upon pumping with Argon laser at 488 nm. The peak shift of the fringes was 0.01~0.29 nm at the pumping power from 0~100 mW, resulting in the third-order optical nonlinearity, n2= 2.0*10^(-16)m2/W.

6481-22, Session 5

Micro-Raman spectroscopic characterization ZnO quantum dots and nanocrystals

A. A. Balandin, V. Fonoberov, I. Calizo, K. Alim, Univ. of California/Riverside

Nanostructures, such as quantum dots (QDs) and nanocrystals (NC), made of ZnO have recently attracted attention due to their proposed applications in optoelectronic devices. Raman spectroscopy has been widely used in order to study the optical phonon spectrum modification in QDs and NCs as compared to bulk crystals. Understanding the phonon spectrum change is important since phonons affect the optical response. Interpretation of the phonon peak position in the Raman spectrum from ZnO QDs and NCs has recently became a subject of intensive debates. In this talk we overview our recent results [1] and present a discussion of the possible mechanisms of the phonon peak shifts in the resonant and non-resonant spectra from ZnO QDs (diameter D~4nm) and NCs (D~20nm). A comparison with the theory developed by some of us [3], allowed us to clarify the mechanisms of the phonon shifts in wurtzite nanostructures. It was found that the phonon confinement results in the frequency shifts of few cm-1 in ZnO QD. At the same time, the local heating of the NC ensemble with UV laser was found to induce large red shifts (>10 cm-1) even for small UV excitation laser power. The results shed new light on the optical phonons in ZnO nanostructures and can be used for their optimization for the optoelectronic applications.

The work has been supported, in part, by the UCR-UCLA-UCSB Center for Nanoscience Innovation for Defense (CNID).

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6481-23, Session 5

Self-assembly of heterojunction quantum dots(HeQuaDs)

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Quantum dots (QDs) have been receiving considerable attention due to the unique properties, which arise due to the confinement of the electron and holes in a lower band gap material. The InAs on GaAs material system is one of the most studied combinations in which quantum dots form during epitaxy. These QDs form in a Stranski Krastanov manner via a self-assembly process in which the dots nucleate at a critical adatom coverage on a wetting layer of InAs. QDs may be vertically aligned by using the residual strain above a buried dot layer to enhance the nucleation of the second layer of dots. In this work, we show the formation of QDs, which are composed of multiplematerials, can be formed through a marriage of these two concepts. In this particular demonstration, we formed InAs dots on GaAs and crowned the QDs with GaSb and encapsulated the entire structure with GaAs. Atomic Force Microscopy shows additional nucleation between the InAs layers has been minimized and cross-sectional transmission electron microscopy shows the formation the composite structure. Transmission electron microscopy indicated a clear boundary between the GaSb and InAs regions. AFM analysis of the HeQuaD structure shows that GaSb material grows mainly on the two (1 1 0) inclined facets. Thus, the HeQuaD is elongated along the (1 1 0) direction. We have also obtained preliminary photoluminescence (PL) from a 3 layer GaS/InAs HeQuaD structure with a peak around 1.3 microns.

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6482-01, Session 1

Time-domain processing of information carried by ultrashort pulses

R. E. Saperstein, Univ. of California/San Diego; D. Panasenko, Lawrence Berkeley National Lab.; K. A. Tetz, Univ. of California/San Diego; R. I. Rokitski, Cymer Corp.; Y. Fainman, Univ. of California/San Diego

Novel approaches to processing information carried by ultrashort pulses in time domain will be introduced and applied to the detection, synthesis and imaging of arbitrary waveforms.

6482-02, Session 1

The homogeneous dispersive lineshape as a wavelet basis

A. E. Craig, Montana State Univ./Bozeman

No abstract available

6482-03, Session 1

Fabrication and plasma spectroscopy of PLD thin film deposition for power-gated holeburning

F. Bezares, Z. U. Hasan, Temple Univ.

No abstract available

6482-04, Session 1

Sluggish-light based true-time-delay multiple beam-forming system for broadband RF phased-array antennas

L. Gao, S. I. Herriot, K. H. Wagner, Univ. of Colorado/Boulder

In conventional Fourier-lens based photonic beamforming systems for RF phased-array antennas, an electro-optical modulator (EOM) is used at each of the antenna elements to modulate the receiving RF signal onto a CW optical carrier. The topology-preserved optical output from the EOMs is then Fourier transformed by a lens onto a photo-detector array. The beamforming angle of the conventional lens-based beamformers depends on the frequency of the receiving RF signal (i.e. beam-squint) and can only be used for narrowband RF phased-array antennas. In this paper, we introduce a novel lens based true-time-delay (TTD) multiple beamforming system for broadband RF phased-array antennas. Such a TTD lens beamforming system is based on recently demonstrated sluggish-light effect, in which a wideband RF signal is modulated onto a broadband optical carrier in a frequency-mapped manner using an acousto-optic tunable filter (AOTF) and a short optical delay of the modulated optical carrier leads to a magnified time delay for the heterodyne-detected RF signal. In this TTD lens beamformer, an AOTF is used at each of the antenna element to modulate the receiving RF signal onto a broadband light source such as a femtosecond pulse train and the output from the AOTFs is then Fourier transformed by a lens onto a photo-detector array in an optical heterodyne configuration with a reference pulse train. The small path-length difference inherent in an optical lens (on the order of mm), therefore, can provide enough time-delay compensation of large RF phased arrays (on the order of km) due to the sluggish-light effect. Proof-of-principle experimental results of the sluggish-light based TTD beamforming of a 2- and 4-channel RF array will be presented in this paper.

6482-05, Session 2

Scalable quantum computing in diamond

P. R. Hemmer, Texas A&M Univ.; F. Jelezko, J. Wrachtrup, Univ. Stuttgart (Germany); P. Tamarat, Univ. Bordeaux I (France); S. D. Prawer, The Univ. of Melbourne (Australia); M. D. Lukin, Harvard Univ.

No abstract available

6482-06, Session 2

Photonic quantum information processing in diamond

C. M. Santori, S. M. Spillane, D. Fattal, R. G. Beausoleil, Hewlett-Packard Labs.; J. R. Rabeau, P. Olivero, A. D. Greentree, S. D. Prawer, The Univ. of Melbourne (Australia)

No abstract available

6482-07, Session 2

Micro-characterization of spectral memory materials using nuclear forward scattering

A. Konjhodzic, Z. U. Hasan, Temple Univ.; E. E. Alp, Argonne National Lab.

No abstract available

6482-08, Session 2

High efficiency DOEs at large diffraction angles for quantum information and computing architectures

A. A. Cruz-Cabrera, Sandia National Labs. Legal Organizations; S. A. Kemme, J. R. Wendt, Sandia National Labs.; T. R. Carter, S. Samora, L&M Technologies

We developed techniques to design higher efficiency diffractive optical elements (DOE) at large diffraction angles for quantum computing and quantum information applications. Qubits in Ion traps architectures are commonly address and read, by lasers. To select the correct qubit, a laser beam usually requires focusing to a diffraction-limited spot. Diffractive optical elements (DOE) are easy to fabricate and can meet the spot size requirement at the intended qubit since; they are usually fabricated using lithographical methods that guarantee fidelity of the lens to their prescription. Another DOE application is the generation of optical lattices for the neutral atom architecture as a trapping mechanism. The main limitation of DOEs is the loss associated with their diffraction efficiency. This limitation is due to requirements for large deflection angles, which leads to extremely small periods in the DOE. If the period size of the diffractive is between one (the working wavelength in free space) and 10 lambda? the diffractive is considered to be working in the vector regime. Diffractives working in this regime and particularly from 1.5 to 4 lambda have unwanted diffractive orders with significant efficiencies. In addition, the optimal depth of diffractives with periods in the vector regime differs from the overall depth of the DOE. We will present results indicating the unique behaviors around the 1.5 to 4 lambda periods and ways to improve the DOE performance.

6482-09, Session 3

Optimizing two-photon optical storage in the presence of hot band absorption

N. S. Makarov, A. Rebane II, M. A. Drobizhev, Montana State Univ./Bozeman; H. Wolleb, H. Spahni, Ciba Specialty Chemicals (Switzerland)

For the two-photon absorption- (2PA) based volumetric storage the accompanying one-photon absorption (1PA) poses a serious problem because it switches chromophores not only in the focus voxel, but rather in the whole illuminated volume. For this reason it was previously assumed that the working frequency is detuned far to the red from 1PA resonance. On the other hand, if the frequency detuning is too large, then the 2PA cross section may become too small for fast reading and writing.

We study optimal conditions for 3D terabit optical disk storage using resonantly enhanced simultaneous two photon absorption in organic chromophores. We simulate signal-to-noise ratio (SNR) and signal-to-background ratio (SBR) for the fluorescence signal read out in the presence of long wavelength 1PA that takes place from thermally excited vibrational states. We show that high molecular 2PA cross section 1000-10000 GM, is required to obtain practical data access rate. The requisite SNR>4 can be achieved by tuning the laser frequency closer to intermediate 1PA resonance, however, at small detuning frequency 2000 1/cm, the 1PA outside of the laser focus causes SBR to decrease. We study the tradeoff between SNR and SBR as function of the detuning frequency, 1PA and 2PA line shape, sample temperature and excitation pulse intensity. We measure 1PA and 2PA properties of a series of asymmetrical phthalocyanines. For the first time we show that depending on absorption line shape there exists an optimal detuning frequency where the SNR and SBR are most favorable. We show that non-symmetrical free-base phthalocyanines possess unique combination of photophysical properties for fast re-writable volumetric 2PA storage.

6482-10, Session 3

Design and implementation of all-optical half adder using cross gain modulation in semiconductor optical amplifiers

S. H. Kim, Korea Institute of Science and Technology (South Korea); J. H. Kim, Korea Institute of Science and Technology (South Korea) and Pennsylvania State Univ.; C. W. Son, G. C. Kim, Y. Byun, Y. M. Jhon, S. Lee, D. Woo, S. H. Kim, Korea Institute of Science and Technology (South Korea)

All-optical logic gates are essential elements for optical signal processors and networks. Several wavelengths conversion techniques using nonlinearities based on semiconductor optical amplifiers (SOAs) have been reported. Comparing to techniques based on fiber, wavelengths conversion techniques in SOAs are attractive because of their high-gain, high-saturation output power, wide-gain bandwidth, compactness and integability with other photonic devices. The cross gain modulation (XGM), one of several wavelengths conversion technique methods based on SOAs, is simple to implement and has shown impressive operation for a high bit rate. Moreover, these show a high conversion efficiency as well as insensitivity to the polarization of input signals.

Our binary half adder has been already demonstrated previously. However, past work utilizes four SOAs for XOR and AND operations, respectively. In this paper, we design a new half adder and experimentally demonstrate an all-optical half adder consisted of three semiconductor optical amplifiers (SOAs) using single mechanism, which is XGM. In addition, we demonstrate an all-optical half adder using commercial VPI simulation tool for knowing a proper switching current in SOA. No additional input beam such as clock signal or continuous wave light, which is required in many other all-optical logic gates, is used in this design concept. The innovation of this AND lies in its optimal design concept and may be used as the basic building unit for half adder, full adder, and binary counter.

6482-11, Session 3

Secure display that limits the viewing space by use of optically decodable encryption

H. Yamamoto, Y. Hayasaki, The Univ. of Tokushima (Japan)

There have been many types of encryption to secure information. Although data-encryption techniques are immune to classic techniques for unauthorized remote access to confidential information, such as wire-tapping of communication links and code breaking, security risks arise with a display that shows decrypted information. These risks include wire-tapping of the electrical video signal, peeping at the screen, and other attacks. This paper describes a secure display that limits the viewing space three-dimensionally by use of optically decodable encryption. A secret image is encrypted into a displayed image and a decoding mask. The decryption process is based on optical logic and performed without calculation. The secret is visible within the limited viewing space. However, the viewed results outside the viewing space look like random-dot pattern. When viewed at a distance different from the designed viewing distance, only the central area of the secret is faintly visible for a limited direction. When a user watches the secure display, in practice, the user?fs head prevents peeping at the secret. The relationships between the size and the position of the displayed image and the viewing space have been analyzed and confirmed experimentally. The proposed technique has been demonstrated by use of two-layered liquid-crystal displays. Furthermore, 3D displacement of the viewing space have been realized only by renewing the displayed image, i.e., without any mechanical movements. By using the decoding mask as the key for decryption, no one can view the secret image without the knowledge of the decoding mask pattern, and the viewed image is secure against prying eyes behind the viewer.

6482-12, Session 3

An evolutionary path toward quantum switching architectures

F. Toudeh-Fallah, M. Carroll, Cisco Systems, Inc.; A. Y. Oruc, Univ. of Maryland/College Park

This presentation explores an evolutionary path in packet switching technology toward Quantum Switching paradigm based on the principles of Quantum Information Processing along with a discussion on the implementation aspects of this concept.

This approach is pursued by researchers as a radical departure in addressing the contention resolution issue, which is one of the main areas of research regarding buffering and scheduling algorithms in packet switching.

6482-13, Session 4

Erbium in silicon nanostructures

Z. F. Krasilnik, Institute for Physics of Microstructures (Russia)

No abstract available

6482-14, Session 4

High directivity of subwavelength wire lasers

E. E. Orlova, Institute for Physics of Microstructures (Russia)

Is it possible to concentrate radiation from a laser with a sub-wavelength cross section into a narrow beam? This would be of interest for numerous applications in optical communications, high density data storage, biological studies etc. Reduction of a laser aperture is known to cause an increase of the beam divergence due to diffraction. However there is a way to break this rule using wire lasers - long lasers with cross section smaller than the wavelength. It has being found out that the far field of wire lasers is analogous to that of traveling wave antennas [1]. Thus radiation of the laser mode with the longitudinal phase velocity close to that

of light in the air can be concentrated into a narrow beam with a divergence determined by the ratio of the wavelength to the length of the laser. Such concentration of the beam is caused by the destructive interference of the radiation from the longitudinal mode distribution in all the directions where the phase difference is nonzero. Antenna model is generally applicable in different spectral ranges and for different kinds of laser media. Theoretical results are compared with the experimental data obtained using terahertz quantum cascade lasers [2]. The ways of control of the longitudinal modes and the influence of the longitudinal phase velocity on the laser gain are discussed.

[1] E. E. Orlova, et al., 2006,Phys. Rev. Lett., 96, 173904.

[2] A. J. L. Adam, et al., 2006, Appl. Phys. Lett. 88, 151105.

6482-16, Session 4

Acceptors in silicon for Tunable THz lasing

E. E. Orlova, Institute for Physics of Microstructures (Russia)

The first silicon THz laser has been realized on donor transitions in silicon [1]. The high threshold and the low gain of lasing on donor transitions in silicon, which limit the applications, are determined by the fast relaxation due to the emission of inter-valley optical phonons. Higher gain can be expected on acceptor transitions, where inter-valley transitions are excluded, while intra-valley relaxation is suppressed due to the momentum conservation law. Experimental investigation using Dutch free electron laser shows that the life times of acceptor states in silicon states are significantly longer than that of donors and the higher gain can be expected [2]. However acceptor lasing has not been realized so far due to complications in the creation of population inversion within the three-level excitation scheme which requires the depletion of the ground acceptor state. Here the four level scheme of lasing on acceptor transitions in silicon is investigated, based on the splitting of the ground acceptor state by external perturbations such as uniaxial stress and applied magnetic field. The fast acoustic phonon assisted relaxation leads to the depletion of the split off s-state, thus providing the possibility of inverse population on transitions to this states from long living p-state. Moreover, the lasing frequency can be tuned as the splitting energy is controlled by external perturbation. Different schemes of pumping can be used to achieve acceptor lasing. Conditions of acceptor lasing in silicon are analyzed for optical, electrical, and cascade pumping scheme.

[1] S.G. Pavlov, R.Kh. Zhukavin, E.E. Orlova, V.N. Shastin, A.V. Kirsanov, H.W. Huebers, K. Auen, H. Riemann, 2000, Stimulated emission from donor transitions in silicon, Phys. Rev. Lett. 84, 5220.

[2] E.E.Orlova, D.V. Kozlov, A.V. Antonov, J.N. Hovenier, T.O. Klaassen, A.J.L. Adam, M.S. Kagan, I.V. Altukhov, Q.V. Nguyen, D.A. Carder, P.J. Phillips, and B. Redlich, 2005, Perspectives of acceptor lasing in strained SiGe structures, Nanostructures: Physics and Technology, St.Petersburg, Russia, June 20-25, 2005, p. 110.

6482-36, Poster Session

Beam pattern investigations for terahertz quantum cascade lasers

E. E. Orlova, Institute for Physics of Microstructures (Russia); J. N. Hovenier, T. O. Klaassen, I. Kasalynas, A. Adam, J. Gao, T. M. K. Klapwijk, Technische Univ. Delft (Netherlands); B. S. Williams, Q. Hu, Massachusetts Institute of Technology; J. L. Reno, Sandia National Labs.

The short range intensity variations have been observed in the far field of the terahertz quantum cascade lasers with subwavelength cross sections and longitudinal dimension much bigger than the wavelength [1]. It was found out that the maxima of intensity form circles in the plane perpendicular to the longitudinal axis of the laser, and the width of the circles grows with the reduction of the length of the laser. The antenna model has been used for interpretation of these results [2]. Due to this model the far field pattern of subwavelength lasers is analogous to that of antennas of traveling wave, and is formed by the interference of radiation from sources along the longitudinal axis of the laser.

[1] A. J. L. Adam, et al., 2006, Appl. Phys. Lett. 88, 151105.

[2] E. E. Orlova, et al., 2006,Phys. Rev. Lett., 96, 173904.

6482-37, Poster Session

Squeezing and squared-amplitude squeezing in a two-atom Jaynes-Cummings model with cavity damping and atomic dissipation

E. K. Bashkirov, M. S. Rusakova, Samara State Univ. (Russia)

In this work we considered temporal behavior squeezing and amplitude-squared squeezing of a two two-level atoms in a finite-Q cavity with atom dissipation. The analytic expressions for mean photon number and squeezing parameters are obtained on the basis of master equation solution for coherent input. Squeezing generation conditions are considered for various dissipation parameters values and coherent and squeezed initial input.

Squeezed states are actively investigated through last decades both theoretically and experimentally. These states attract such considerable attention due to both great advancing in the QED-experiments and due to their possible applications to the precise optical measurements, optical communications and optical processing. Squeezed states in the Jaynes-Cummings model (JCM) are of special interest, cause the JCM is exactly solvable quantum optical model, very reached via quantum effects. Squeezing properties of JCM have been investigated starting with Meystre and Zubairy. Several generalizations of the model, such as, multiphoton, two-mode, two-atom generalizations have been shown to demonstrate squeezing for various field inputs. In the real experimental conditions it is important to take into account cavity damping and possibility of non-emitting atomic interaction with the bath. In this paper we consider squeezing and squared-amplitude squeezing in the system of two-atom JCM with atomic dissipation, interacting with quantum electromagnetic field in non-ideal cavity, for coherent and squeezed initial field state. We investigate the conditions of squeezing generating in the system in the depending of various dissipation parameters values and initial field intensities.

The evolution of the squeezing in a field quadrature components and ASS evolution are considered in the two-atom two-level Jaynes-Cummings model with cavity damping and atom dissipation for coherent and squeezed input. The difference between atom dissipation influence and field dissipation one is obtained: while the former acts onto squeezing constructively, the last acts in a destructive way both for squeezing in quadrature components and for ASS. The dependence of ASS from initial field intensities is also investigated in the work.

6482-38, Poster Session

Nonblocking photonic switching for P2P self-organized optical concurrent communications network using pseudorandom numbers

N. Oshima, Y. Nozaki, W. Sasaki, Doshisha Univ. (Japan)

Peer-to-peer (P2P) optical communication network is presently attracting much attention for the application of small-scale network. We proposed a network element called as a node fabricated by optoelectronics hardware based on the optical bistable devices. These nodes can compose a self-organizing optical network being interconnected with each other. We also proposed an adaptive node with gate function which detects the differences of signal types as to the amplitude modulation (AM) signal in the network and switches their routings. Thus, the adaptive node allows optical P2P concurrent communications between multiple pairs of communicators in the network simultaneously.

Moreover, we have proposed in the present work an optical nonblocking operation using the pseudorandom numbers fabricated into the above mentioned adaptive nodes. We have newly considered a switching scheme which identifies such pseudorandom numbers and forms automatically a signal propagation path so that the nodes with the same input pseudo-

random numbers are to be linked. Since such a pseudorandom-number based switching may also prevent any irregular interception of established links among nodes, our scheme is proved to be a nonblocking operation. Therefore, this scheme allows multiple signals from input nodes to travel in the network simultaneously via only a single propagation path being established by the self-organized adaptive nodes. We have also demonstrated this switching operation experimentally by fabricating it into our optoelectronics hardware based on the optical bistable devices. As a consequence, nonblocking photonic switching scheme for P2P self-organized optical concurrent communications network has been achieved by our pseudorandom-number based adaptive nodes proposed by the present work.

6482-39, Poster Session

Intra-center relaxation in shallow centerrs in silicon

E. E. Orlova, D. V. Kozlov, A. V. Antonov, Institute for Physics of Microstructures (Russia); J. N. Hovenier, T. O. Klaassen, A. Adam, Technische Univ. Delft (Netherlands); M. S. Kagan, I. V. Altukhov, Institute of Radio Engineering and Electronics (Russia); Q. V. Nguyen, D. A. Carder, P. J. Phillips, B. Redlich, FOM-Institute for Plasma Physics (Netherlands)

The first silicon laser has been realized using shallow donor transitions in silicon [1]. The main factor which determined the gain and threshold on impurity transitions is non-radiative intra-center relaxation. We present here the results of investigation of relaxation processes in donor and acceptor centers in silicon. It is shown that the life times of donor states are reduced due to the fast transitions assisted by inter-valley optical phonons. Relaxation in shallow acceptor centers is a cascade of transitions assisted by short-wavelength acceptors, with much longer life times. The results of theoretical investigations of intra-center relaxation in silicon are compared with the existing experimental data, obtained using silicon donor lasers, pump-probe experiments using Dutch free electron laser, saturation absorption spectroscopy [2], transient tunneling spectroscopy [3], relaxation of high frequency conductivity [4], high resolution measurements of the line widths of optical transitions [5].

[1] S.G. Pavlov, R.Kh. Zhukavin, E.E. Orlova, V.N. Shastin, A.V. Kirsanov, H.W. Huebers, K. Auen, H. Riemann, 2000, Stimulated emission from donor transitions in silicon, Phys. Rev. Lett. 84, 5220.

[2] Geerinck K 1995 Doctor degree thesis (Technical University of Delft)

[3] Dargys A, Zurauskas S, and Zurauskiene N 1994 Lietuvos fizikos zurnalas 34 483

[4] Pokrovskii Ya E, Smirnova O I, Khvalkovskii N A 1995 Solid State Commun. 93 405

[5] Jagannath C, Grabowski Z W, and Ramdas A K 1981 Phys. Rev. B 23 2082

6482-18, Session 5

Coherent interactions with atoms and molecules in photonic band-gap fibers

A. L. Gaeta, S. Ghosh, A. Bhagwat, C. Kyle, B. J. Kirby, Cornell Univ.

No abstract available

6482-19, Session 5

Comparing slow-light properties of 10-Gbps RZ data in dispersion shifted fibers and highly nonlinear fibers based on Raman-assisted optical parametric amplification

Z. Hu, Tsinghua Univ. (China); D. J. Blumenthal, Univ. of California/Santa Barbara

No abstract available

6482-20, Session 5

Large widely tunable fractional delays based on wavelength conversion and dispersion

Y. Okawachi, J. E. Sharping, C. Xu, A. L. Gaeta, Cornell Univ.

No abstract available

6482-21, Session 5

Tunable slow light in Bragg-spaced quantum wells

J. P. Prineas, A. L. Smirl, The Univ. of Iowa; R. H. Binder, The Univ. of Arizona

No abstract available

6482-22, Session 6

Demonstration of interferometer sensitivity varying as the inverse of the group index

M. S. Shahriar, G. S. Pati, M. Messal, Northwestern Univ.

Recently, we have shown that group-index engineering can be employed to enhance significantly the sensitivity in several areas of precision metrology, including Sagnac-effect based rotation sensing, and the detection of gravitational waves. In this talk, we will present experimental evidence of the basic mechanism underlying these schemes. In particular, we will describe our experiment that shows that the sensitivity of a ring-configuration interferometer can be tuned by modifying the group index of an incra-cavity rubidium cell, in agreement with our theoretical predictions.

6482-23, Session 6

Optimization of slow and stored light in atomic vapor

I. Novikova, D. F. Phillips, M. Klein, R. L. Walsworth, Harvard-Smithsonian Ctr. for Astrophysics

No abstract available

6482-24, Session 6

Demonstration of a white light interferometer using fast light

G. S. Pati, M. Messal, M. S. Shahriar, Northwestern Univ.

For detection of gravitational waves using the LIGO-type interferometers, as well as other applications in telecommunication, it has been established that a so-called White Light Cavity (WLC) can be of great utility. For detecting gravity waves, insertion of a WLC in front of the so-called signal recycling mirror in the advanced LIGO interferometer is expected to enhance the sensitivity-bandwidth product significantly beyond what can

be achieved without it. In this talk, we will present experimental results demonstrating such a WLC, using a rubidium vapor cell embedded in a ring resonator.

6482-25, Session 6

Large fractional displays in a hot vapor

R. M. Camacho, A. Schweinsberg, M. V. Pack, R. W. Boyd, J. C. Howell, Univ. of Rochester

Using the transparency between two strong absorption resonances we have demonstrated up to 80 fractional delays in a hot Cs vapor with only 50% fractional broadening using 740 ps pulses. Strong saturating beams were used to rapidly reconfigure the pulse delays in the vapor. The method can be generalized to any system with strong resonances.

6482-26, Session 7

Rubidium spectroscopy on a chip

H. Schmidt, Univ. of California/Santa Cruz

No abstract available

6482-27, Session 7

Coherent few-photon quantum transport in one-dimensional systems

J. Shen, S. L. Fan, Stanford Univ.

No abstract available

6482-28, Session 7

Designing optimal gain profiles for slow-light applications

R. Pant, Consultant; M. D. Stenner, M. A. Neifeld, The Univ. of Arizona

Tunable delay using stimulated Brillouin scattering (SBS) in optical fibers is useful for applications such as data synchronization, optical signal processing, etc. Delay-bandwidth tradeoffs result in pulse distortion with increased pulse bandwidth. Fractional delay performance, defined as the ratio of delay ΔT to pulse width Tpulse, can be improved by gain broadening, given a gain and distortion constraint. Various methods for gain broadening such as combining multiple-gain lines, temperature variation, and pump modulation have been studied. We will present a design methodology for creating slow-light optical delay with constrained pulse distortion and system resources such as maximum gain (to avoid nonlinear effects, for example) and pump power. Using this methodology, we will present double-line and triple-line gain systems achieving 1.5 and 1.7 times the delay of single-line systems with comparable distortion. We will also present a medium achievable with SBS pump modulation that produces optimal delay given constraints on distortion, maximum gain, and total pump power. This medium achieves a delay-bandwidth product of ~1.5 for a maximum intensity gain of exp(10). A comparison of fractional delay and distortion performance with other results will be presented.

6482-29, Session 7

Subluminal and superluminal propagation of an optical pulse in an active Raman gain medium

L. Deng, National Institute of Standards and Technology

The rapidly changing region of the refractive index usually overlapped with the peak absorption of the field, preventing the region from being used for active wave propagation control. Electromagnetically induced transparency (EIT), which could circumvent this difficulty, had demonstrated slow optical propagation with many order-of-magnitude reduction of the group velocity in highly resonant medium. In addition, a passive Raman scheme (no gain) had also been demonstrated to be capable of achieving ultra slow group velocity.

In this paper, we experimentally observed the optical velocity modification in the active Raman medium, which was fundamentally different from the usual type of EIT scheme. In the case of two-photon resonance, we achieved ultra slow and distortion free propagation of a pulsed probe field. The velocity showed an inverse quadratic dependence on the driving field Rabi frequency and had excellent S/N ratio due to the Raman gain and the advantage of being widely tunable yet distortion free.

In the case of two-photon detuning, we showed a 220 20ns advance time for an optical pulse of FWHM=15.4us propagating through a 10-cm medium using a single channel active Raman gain medium, where no interference happened. The leading time ratio to the pulse width was comparable to what was previously reported. The superluminal group velocity showed inverse quadratic behavior as the function of the pump field Rabi frequency and quadratic dependence on the two-photon detuning.

6482-30, Session 7

Electromagnetically induced backscatering via slow light

Y. V. Rostovtsev, M. O. Scully, Texas A&M Univ.

We demonstrate a strong coherent backward wave oscillation using forward propagating fields only. This is achieved by applying laser fields to an ultra-dispersive medium with proper chosen detunings to excite a molecular vibrational coherence that corresponds to a backward propagating wave. The physics then has much in common with propagation of ultra-slow light. Applications to coherent scattering and remote sensing are discussed.

6482-32, Session 8

Ultralow-light level saturation spectroscopy and EIT using a tapered fiber in a hot vapor cell

G. S. Pati, M. S. Shahriar, P. Kumar, Northwestern Univ.; S. M. Spillane, R. G. Beausoleil, Hewlett-Packard Labs.

Tapered fibers can be made extremely thin (sub-wavelength) and practically lossless, so that the energy density of the photon field inside the fiber can be made extremely large compared to that in free-space. We have been pursuing applications of a such a system for studying strong light-matter interaction. Unlike the medium-filled integrated waveguides or hollow core fibers used in earlier experiments, in a taper fiber the interaction of photon fields with the atoms is mediated outside the fiber as the fiber allows access to its evanescent field. Small size, reasonably easy integration and fabrication make these promising for real device applications. In this talk, we will describe our experimental results demonstrating ultra-low light level saturated absorption in a tapered fiber embedded in an atomic vapor. This shows the potential for extremely low light level optical switching and quantum information processing with such a device.

6482-33, Session 8

Slow wave atom interferometers for rotation sensing

M. Ozcan, Sabanci Univ. (Turkey)

A gyroscope based on Sagnac Interferometer measures the rotation rate relative to an inertial frame of reference. Originally, Sagnac effect has been derived and experimentally shown with optical waves. In addition, there has been significant activity in development of matter wave based Sagnac interferometers due to inherent sensitivity over a photon based system. However in any case, it has been proven that the resultant phase shift due to counter-rotating waves is independent of the wave velocity.

Here we show that one can have larger phase shifts with slower matter waves using Aharonov-Bohm effect: The phase difference of the counter propagating waves is proportional to the inverse square of the particle velocity.

6482-34, Session 8

An optical prism based on resonance ultradispersive media

V. A. Sautenkov, H. Li, Y. V. Rostovtsev, M. O. Scully, Texas A&M Univ.

We have experimentally demonstrated an ultra-dispersive optical prism made of coherently driven Rb atomic vapor. The prism possesses spectral angular dispersion that the six orders of magnitude higher than the prism made of optical glass; it is the highest spectral angular dispersion that has been ever shown (such angular dispersion allows one to resolve spatially light beams with different frequencies separated by a few kHz). The prism is working near the resonant frequency of an atomic vapor, and its dispersion is optically controlled by coherent driving field.

6482-35, Session 8

Reduced density matrix descriptions for electromagnetic induced transparency and related pump-probe optical phenomena in atomic systems

V. L. Jacobs, Z. Dutton, M. Bashkansky, M. J. Steiner, J. F. Reintjes, Naval Research Lab.

No abstract available

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6483-01, Session 1

Optical trap shaping for binding force study and optimization

M. Guillon, Observatoire de Haute-Provence (France); J. Fournier, École Polytechnique Fédérale de Lausanne (Switzerland)

Light induced binding energy between micron-sized particles in the Rayleigh range in intense laser fields varies as 1/r. This long range dependence suggests a diverging increase of the binding force when the number of interacting particles becomes large. Theoretical studies performed for 1D periodic chains of dipoles reveals large binding field enhancement for an optimum number of interacting particles. When the number of dipoles overshoots this number, the binding intensity collapses. This result is consistent with experimental observations of periodicity defects in large 2D optically built crystals. Some solutions are explored to keep large binding field enhancement for large crystals. Shrinking the coherence length and phase modulating the incident trapping light are among the proposed schemes.

6483-02, Session 1

Forces and binding in a two-mirror system

A. Mizrahi, L. Schachter, Technion-Israel Institute of Technology (Israel)

Two mirrors guiding light experience attractive or repulsive forces according to the eigenmode type of symmetry, but regardless of the specific details of the guiding structure. A transverse evanescent mode (TM or TE) that has a symmetric longitudinal field causes repulsion, while attraction occurs when the mode has an anti-symmetric longitudinal field. Transverse propagating modes, however, are always repulsive. One possible application for this phenomenon is to use an anti-symmetric mode supported, for instance, by two properly designed Bragg mirrors. By varying the wavelength of the mode injected into the waveguide, it is possible to cross the light-line and switch between attraction and repulsion. If the mirror is free to move in the transverse direction, then this is a scheme for controlling its motion.

Another possibility is creating equilibrium with a superposition of transverse evanescent symmetric and anti-symmetric modes. Since one is repulsive and the other is attractive, the ratio of their powers will determine the equilibrium distance between the mirrors. For this purpose, a more appealing configuration than Bragg mirrors is a waveguide that consists of two dielectric slabs where the light is guided by total internal reflection. As a function of the equilibrium distance and the slab width, we show that a stable equilibrium may be formed. Hence, each slab is trapped in a potential well, thus creating a trap or optical binding by eigenmodes. This effect may be viewed as an “all optical spring” where guided light in the longitudinal direction dictates the transverse behavior.

6483-03, Session 1

Optical electrostriction

R. G. Crisp, D. L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

It is well known that the forces which light imparts on micro- and nanoparticles arise due to intensity gradients and dielectric mismatch. For laser-irradiated atoms and molecules, optical forces primarily result from close resonance between the optical frequency and an electronic transition. Recently it has emerged that optically induced pair forces also arise, through a modification of Casimir-Polder interactions; preliminary assessments of the mechanism have largely centred on nanoparticle systems. In this paper, we show that a potentially very significant effect can be anticipated in the condensed phase, an optically induced modification of interatomic forces that is capable of generating anisotropic patterns of laser-induced compression and expansion. This phenomenon, termed optical electrostriction, should be measurable and significant when high intensity laser light is transmitted through even an essentially non-absorptive material. However, the full conditions for observation of the effect are such that some competing interactions might also arise. The experimental challenge of precluding those secondary effects in the condensed phase, allowing unequivocal identification of optical electrostriction, is discussed. Key parameters that determine the size and character of optical electrostriction are delineated and possible applications are considered, including optical actuators for nanoscale electromechanical systems.

6483-04, Session 1

High-speed, dynamic spatial control of cold atoms with combined acousto-optic and spatial light modulation

F. Fatemi, M. Bashkansky, Z. Dutton, Naval Research Lab.

The ability to control the motion of atoms has recently been of interest for possible uses in atom interferometry and quantum information. The success of beam-based atom interferometry for measuring rotations and gravity gradients has encouraged prospects for compact, guided atom interferometry analogous to optical fiber sensing devices.

Optical techniques have been considered as candidates for atom guides and for controlling collisions between individual atoms. Reconfigurable atom traps generated solely by spatial light modulators (SLM) offer the possibility of complex optical potentials or arrays of traps, but have refresh rates limited to ~1-2 kilohertz and can suffer from interframe artifacts. Also, in cases where multiple spots are generated by a single SLM, DC interference between spots may produce undesirable effects when the intertrap distance approaches the trap size.

In this paper, we combine the holographic capabilities of an SLM with the high-speed and resolution of acousto-optic deflectors (AODs) to create and control arrays of atoms confined in optical potentials with individual site addressability. The atoms are trapped in the centers of crossed hollow laser beams that are blue-detuned from atomic resonance, which lowers heating rates and increases trap lifetime. We use the SLM to generate a hollow laser beam, which is then passed through an AOD driven by multiple, independent RF frequencies to create the array of traps. The intensities and locations of the traps can be controlled with much higher resolution than SLMs alone. Each trap is frequency-shifted from its neighbor, reducing interference effects. A second AOD is used to move the traps orthogonally. An AOD that operates in slow-shear mode is especially promising for atom manipulation, as these have high deflection angles, large active apertures (~1 cm) and flicker-free, ~50kHz update rates. We demonstrate these benefits by manipulating three atom traps in parallel, splitting atom clouds into a 1 x 3 array, and moving atom traps in circular trajectories. We discuss effects on the atom confinement due to trap motion.

6483-05, Session 1

Developments towards atomic quantum sensors

W. A. Ertmer, Univ. Hannover (Germany)

Microgravity is expected to be a decisive ingredient for the next leap in

tests in fundamental physics of gravity, relativity and theories beyond the standard model. A promising technique for fundamental tests in the quantum domain are matter-wave sensors based on cold atoms or atom lasers, which use atoms as unperturbed microscopic test bodies for measuring inertial forces or as frequency references. Microgravity is of high relevance for matter-wave interferometers and experiments with quantum matter (Bose-Einstein Condensates or degenerate Fermi gases) as it permits the extension the unperturbed free fall of these test particles in a low-noise environment. We report on the status of our transportable dual atom Sagnac interferometer and a Space atom laser. With the launch of the development of QUANTUS (QUANTen gase Unter Schwerelosigkeit), a mobile platform for microgravity experiments with quantum matter in the drop tower (Bremen) and during parabolic flights within a pilot project the DLR took a major first step to establish this field of research in Germany.

6483-06, Session 1

Single-beam, blue-detuned toroidal optical traps for cold atoms

F. Fatemi, M. Bashkansky, Z. Dutton, S. E. Olson, M. Terraciano, Naval Research Lab.

An optical trap for atoms created by light that is blue-detuned from resonance confines atoms to bounded regions of low intensity. Such dark traps are attractive because they reduce spontaneous scattering rates, AC Stark shifts of the energy levels, and light-assisted collisional loss rates when compared with red-detuned optical traps with equivalent trapping parameters. A complex optical trap can be formed using holographic techniques to define a pattern in a plane, which is then bounded by crossed light sheets to create 3D volumes. Generation of such traps with a single beam would significantly reduce alignment complexity.

In this paper, we demonstrate single-beam and crossed-beam hollow toroidal guides for atoms, which are of interest for neutral atom storage and atom interferometry. We demonstrate experimentally and theoretically optical potentials that contain a ring-shaped intensity minimum, bounded in all directions by higher intensity. We use a spatial light modulator to alter the phase of an incident laser beam, and analyze the resulting optical propagation characteristics. We compare the single-beam results with crossed beam geometries, which we create using a multi-ringed hollow laser beam bounded by sheets of light. The techniques used here can be used to generate other planar trap configurations.

We have also confined ultracold rubidium atoms within toroidal hollow guides using laser beams that are blue-detuned up to 20 GHz from the atomic resonance. We discuss the performance of the atom traps in the context of required laser powers, effective scattering rates, trap depths, and trap potential profiles.

6483-07, Session 2

Exact theory of optical forces of Mie scatterers exposed to high numerical aperture beams examined with 3D photonic force measurements

A. Á. R. Neves, A. Fontes, W. L. Moreira, A. A. d. Thomaz, D. B. d. Almeida, L. C. Barbosa, C. L. Cesar, Univ. Estadual de Campinas (Brazil)

One very important contribution of the Optical Tweezers technique is its ability to extract the missing mechanical measurements in the world of microorganisms and cells that could be correlated to biochemical information. A microsphere displacement is the preferential force transducer for this kind of measurement. However, the geometrical optics is no longer valid for the typical conditions used in Optical Tweezers with very high numerical aperture beams and microspheres with diameters up to ten wavelengths. These conditions require a full vectorial description of the incident beam in partial waves with the origin of coordinate system at the center of the microsphere and not at the focus of the beam. All sorts of approximations and tricks have been used to proceed forward to obtain numerical results. By using the Angular Spectrum Representation of the incident beam and an analytical expression for integrals involving associated Legendre Polynomials, Bessel functions and plane waves we have been able to obtain a closed expression, without any approximation, for the beam shape coefficients of any orthogonally incident beam and even to show how the Spherical Bessel Functions emerge from these integrals. We tested these theoretical results by using a 3D positioned dual trap in an upright standard optical microscope, one to keep the particle at the equilibrium position and the other to disturb it, to obtain the whole curves, instead of isolated points, of the optical force as a function of the microsphere center with respect to the focus of the beam position for different wavelengths.

6483-08, Session 2

Refractive multiple optical tweezers for parallel biochemical analysis in micro-fluidics

F. Merenda, J. Rohner, J. Fournier, R. Salathé, École Polytechnique Fédérale de Lausanne (Switzerland)

We present a multiple laser tweezers system based on refractive optics. The system produces an array of 100 single-beam optical traps thanks to a refractive microlens array, whose focal plane is imaged into the focal plane of a high-NA microscope objective. This refractive multi-tweezers system is combined to micro-fluidics, to perform simultaneous biochemical reactions on ensembles of free floating objects. Micro-fluidics is used both for transporting the particles to the trapping area, and for conveying biochemical reagents to the trapped particles.

Parallel trapping in microfluidics is achieved with polystyrene beads as well as with native vesicles from CHO cells. The traps can hold objects against fluid flows exceeding 100 micrometers per seconds. Parallel fluorescence excitation and detection on the ensemble of trapped particles is also demonstrated. Additionally, the system is capable of selectively releasing particles from the tweezers array after fluorescence detection. Strategies for high-yield particle capture and individual particle release in a microfluidic environment are discussed. A comparison with diffractive optical tweezers enhances the pros and cons of refractive systems.

6483-09, Session 2

Scattering of light at micro- and nanostructures of triangular shape

M. Goncalves, A. Siegel, R. Ameling, O. Marti, Univ. Ulm (Germany)

The development of new photonic and plasmonic devices rely on the new pioneering techniques of micro- and nanofabrication, combining both standard lithography techniques and self-assembly. The combination of colloidal crystals, projection patterning and soft-lithography are examples of fabrication techniques which allow to obtain complex structures of sizes smaller than the wavelength of visible light. In many cases, the structures fabricated by this way are not possible to obtain using standard lithography techniques, like electron-beam and UV-VIS lithography and focused ion beam (FIB).

We have used two-dimensional colloidal crystals as templates to fabricate arrays of isolated metallic particles of triangular shape on surfaces and, as well, two-dimensional gratings of spherical profile. Either dielectric or metallic structures can be obtained. In the later case the coupling between light and the locally confined surface plasmon-polaritons leads to resonances, field enhancements and other related phenomena.

The scattering properties of the particles and gratings have been investigated experimentally, using a confocal, a near-field optical microscope and a spectrometer, and theoretically, using FDTD methods.

We show that triangular particles of noble metals are high sensitive to the relative direction of incidence of light and its polarization. On the other hand, the light scattered in the direction perpendicular to the plane of the particles reveals strong spectral dependency. This dependency can be

exploited to fabricate photonics devices sensitive to the direction of incidence of light.

6483-10, Session 2

Time-resolved evanescent wave-induced fluorescence studies of macromolecular adsorption

T. A. Smith, C. A. Scholes, A. Mularski, M. L. Gee, The Univ. of Melbourne (Australia)

Observing conformational aspects of adsorbed macromolecules in situ is inherently difficult. A range of spectroscopic techniques can be used to obtain information about the conformational state of macromolecules in solution and in this work the Evanescent Wave (EW) is exploited to enable fluorescence spectroscopic studies of macromolecules in an interfacial region. Specifically, time-resolved evanescent wave-induced fluorescence techniques have been applied to the study of the adsorption of dyes, polymers and biomolecules to silica surfaces.

We have extended these EW measurements using polarised excitation and emission detection, and resonance energy transfer studies, to investigate the utility of these methods for probing molecular photophysics, motion and conformational change in the interfacial region. These techniques have been extended further through the development of time-resolved total internal reflection fluorescence (TIRF) microscopy.

We will report on the observation of complex time-dependent fluorescence anisotropy data and its interpretation in terms of rotational motion, excited-state dynamics, and conformational information by probing localized microenvironments. Förster resonance energy transfer studies have been employed to determine changes in macromolecular configurations upon adsorption. The macromolecular-interfacial systems investigated by this evanescent wave approach included polymer film dynamics, adsorbed protein denaturation and oligonucleotide helical rearrangement upon adsorption.

6483-11, Session 3

Assembling mesoscopic systems with holographic optical traps

D. G. Grier, Y. Roichman, New York Univ.

Dynamic holographic optical trapping can organize hundreds of mesoscopic objects into arbitrary three-dimensional configurations. Using the fabrication of three-dimensional quasicrystalline photonic heterostructures as a model, this talk addresses the limits of structural complexity that can be attained by all-optical assembly. We also discuss holographic manipulation of carbon nanotubes and semiconductor nanowires to establish bounds on optical nanofabrication based on sample dimensions and composition.

6483-12, Session 3

Optical manipulation of gold micro and nanoparticles on silicon nitride waveguides: impact of polarization and particle size on gradient forces

S. Getin, S. Gaugiran, J. Fédéli, Commissariat a l'Energie Atomique (France); J. Derouard, Univ. Joseph Fourier (France)

Kawata and Tani's [1] experiments showed that the evanescent field created on the surface of an ion exchanged waveguide could trap and move microparticles. This opened up the possibility of combining conventional optical trapping with integrated optics in order to create new microsystems for the manipulation of particles or biological objects. Recently, the use of strip silicon nitride waveguides increased the performances of these systems enabling higher particles speeds and reduced guided power [2].

Our experiments demonstrate that polarization affects drastically the way particles are propelled along the waveguide surface. For example in TM polarization, 1μm diameter gold particles are moving along the center of the waveguide whereas in TE, they are propelled along its sides. Moreover, it appears that gradient forces involved in this phenomenon depend on the particle size.

To understand this behavior, a numerical approach of the problem based on the finite element method has been developed. This method enables the calculation of the 3D distribution of the electric fields. The resulting optical forces are calculated thanks to the Maxwell stress tensor formalism.

This first experimental and theoretical illustration of repulsive gradient forces on metallic particles opens up perspectives for polarization based sorting systems.

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Optical manipulation of microparticles and cells on silicon nitride waveguides. Optics Express, 13(18): 6956

6483-13, Session 3

Measuring mesoscopic interactions with holographic line traps

Y. Roichman, M. Polin, I. Cholis, D. G. Grier, New York Univ.

We describe methods for projecting holographic optical traps with specified intensity and phase profiles along extended lines transverse to the optical axis. This class of optical traps is useful for manipulating elongated nano-objects, creating anisotropic potential energy landscapes, and in particular for investigating the interactions and dynamics of microparticles in reduced dimensionality. We will present the shape-phase holography technique used to create this new class of traps, as well as three-dimensional characterization of their intensity distribution. We characterize their trapping performance by tracking the motions of a single fluid-borne colloidal particle using digital video microscopy. Trapping two particles on the line provides a rapid technique for measuring the pair interaction potential. We compare the results of such measurements with those obtained by conventional liquid structure analysis of massive two-dimensional data sets.

6483-14, Session 4

Nonlinear effects in the propagation of short laser pulses in air

J. San Román, Univ. de Salamanca (Spain); C. Ruiz, Max-Planck-Institut für Physik komplexer Systeme (Germany); I. Sola, C. Mendez, J. A. Perez, D. Delgado, V. H. Diaz, L. Plaja, I. Arias, L. Roso, Univ. de Salamanca (Spain)

The propagation of ultra-short laser pulses has been a quite intense research field in the last decade. The high intensity of this type of laser has allowed to do nonlinear propagation research in media with quite low nonlinear properties as, for example, the atmospheric air. We have taken advantage of this new possibility to study in detail nonlinear propagation effects under different experimental setups. Our first finding was a precise balance between the self-focusing Kerr effect and the linear diffraction so the pulse propagated forming a quite stable channel of light. This was done by passing the ultra-short pulse through an aperture and a long focusing lens. Using the correct pulse energy and aperture diameter we observed a quite long channel of light corresponding to the first direct observation of the Townes soliton. Furthermore we have investigated the temporal effect of this particular nonlinear propagation obtaining a temporal shortening and cleaning of the pulse. We have also studied other experimental configurations in order to better understand the nonlinear pulse propagation. In particular, we have recreated the Young's double-slit experiment using an ultra-short and -intense laser pulse. The nonlinearities change the interference pattern obtained from the Young's

linear prediction. We concluded that two nonlinear effects were acting together in that experiment: the self-focusing Kerr effect, which was expected to be the main nonlinear contribution, and the self-phase modulation, i.e. the nonlinear phase effect, which was essential to understand the final result. In the range of distances that we studied we observed the formation of two channels of light slightly diverging.

6483-15, Session 4

Multimode fibers: mutual influence of propagation and polarization

B. Y. Zeldovich, College of Optics & Photonics/Univ. of Central Florida

Several effects of classical linear optics were predicted and then observed experimentally. The talk will contain the description of the experiments and of the related electrodynamic theory. The effects include: Berry's phase and polarization rotation inside multimode fibers, Optical Ping-Pong effect (transverse Goos-Hanshen effect), rotation of light ray due to external magnetic field, creation of single wavefront dislocation (optical vortex) via polarization selection, and numerous other effects.

General statement is that the geometric-optical description of the polarizational effects works at much larger distance, than the same description of the rays and transverse patterns of intensity. Pedagogical aspect of the talk will be enhanced by the use of Quantum Mechanics for the explanation of the phenomena of Classical Electrodynamics. Special attention will be paid to separate "kinematical effects", which are governed by spatially-dependent propagation speed v=1/(epsilon*mu)^(1/2) from "dynamic" effects, which arise due to the gradients of the impedance Z=(mu/epsilon)^(1/2).

New scalar wave equation is suggested for the approximate description of DEPOLARIZED WORLD, i.e. of the situation with unpolarized light sources and polarization-insensitive detectors. It corresponds to the medium with inhomogeneous propagation speed, but with constant impedance Z. This Z-Helmholtz equation becomes standard Helmhotz equation in the case of completely homogeneous medium.

6483-16, Session 4

Complex beam sculpting with tunable acoustic gradient index lenses: an alternative to spatial light modulators

E. J. R. B. McLeod, C. B. Arnold, Princeton Univ.

Spatial Light Modulators (SLMs) have been successfully used for beam sculpting in the area of optical manipulation, however in some applications their associated pixelation, slow switching speeds, and incident power limitations can be undesirable. An alternative device that overcomes these problems is the Tunable Acoustic Gradient index (TAG) lens. This device uses acoustically induced density and refractive index variations within a fluid to spatially phase modulate a transmitted laser beam. The acoustic waves within the fluid are generated via a piezoelectric transducer. When driven with a frequency-modulated signal, arbitrary optical phase modulation patterns can be generated at regular time intervals. The resulting sculpted beam is best observed using a pulsed laser synchronized to the frequency-modulated signal of the TAG lens. As this device is purely analog, there is no pixelation in the phase modulation pattern. Also, because the only major requirement on the fluid is that it be transparent, it is possible to select fluids with high damage thresholds and high viscosities. High damage thresholds allow the TAG lens to be used in high power applications that would be unsuitable for an SLM. High viscosities provide fast damping of transient density variations and increase switching speeds between patterns. Discussion here will be limited to axially symmetric beam sculpting, however the results can be generalized to asymmetric cases.

6483-17, Session 4

Spatial structure of cavity modes with general astigmatism

G. Nienhuis, S. J. M. Habraken, Univ. Leiden (Netherlands)

We use algebraic techniques to derive the paraxial mode structure and the frequency spectrum of optical resonators with astigmatic mirrors. The relative orientation of the mirrors is arbitrary, so that we allow for general astigmatism, where the modes are not separable in the two transverse coordinates. The technique is based upon the use of ladder operators that transform fundamental Gaussian modes into higher-order modes. All information that is needed to determine the modes is contained in the four-dimensional ray matrix. This matrix has a purely geometric optical significance, and it describes the change of an optical ray during a roundtrip through the cavity. The full astigmatic mode functions can be expressed in terms of the eigenvectors of the ray matrix, while its eigenvalues determine the frequency spectrum.

For cylindrically symmetric cavities it is known that frequency degeneracy of the modes is needed to allow for closed paths of rays traveling back and forth through the cavity. In the case of astigmatism, the relation between closed paths of rays and frequency degeneracy is more complex, not only since the two transverse dimensions are inseparable, but also due to larger number of eigenvalues of the ray matrix.

The general astigmatic modes have a twisted nature, so that non-vanishing optical angular momentum can arise. This will be discussed in the context of the torque exerted on the mirrors. Moreover, nontrivial effects can occur when one or both mirrors are put into rotation.

6483-18, Session 4

Engineering of illumination and collection field profiles for single-molecule orientational imaging

Z. Sikorski, L. M. Davis, The Univ. of Tennessee Space Institute

Recently, spatial light modulators (SLMs) have been used to generate polarization-engineered laser beams, such as radially polarized doughnut modes, which may provide advantages for excitation of fluorophore dipoles in single-molecule (SM) spectroscopy. Here we investigate the additional use of SLMs for spatially-dependent transformation of the collected fluorescence field with a goal to improve the fidelity of three-dimensional molecular orientation determination. Numerical calculations of a high numerical aperture single-molecule confocal microscope are presented in which a SLM is placed in the back focal plane of the objective. The coherently imaged fluorescence undergoes spatially-dependent phase and polarization transformation by the SLM, before it passes to a polarization beamsplitter, and is subsequently focused onto two pinholes and single-photon avalanche photodiodes. We calculate the electric vector field in the back focal plane of the objective using the Weyl representation and taking into account the forbidden light emitted at angles above the critical angle of the cover glass-immersion fluid interface. The calculated electric field is then subject to the spatially-dependent polarization change implemented by SLM. We numerically study the effects of polarization control on the microscope sensitivity to molecule orientation. We also analyze the combined use of the intensity and polarization information in the back focal plane of the SM microscope for single-molecule orientation determination.

6483-28, Poster Session

Analysis of localization phenomena in weakly interacting disordered lattice gases

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Cold atomic gases in magnetic and optical potentials offer the unique possibility of introducing a well controlled disorder in the system. This situation is known to lead to a number of spectacular phenomena, such as Anderson localization. It is caused by the interference of waves scattered on random impurities or defects within the system.

Several methods have been proposed to produce such disordered or quasi-disordered potentials for trapped gases. We study the addition of small pseudorandom potentials to disturb an ideal lattice configuration. Depending on the experimental parameters this disorder is predicted to lead to the formation of an Anderson-glass phase in the weakly interacting case.

Recent experiments with Bose-Einstein condensates in traps with added disorder have shown the feasibility of this method. We report on the realization of disorder in our experiments and show further theoretical analysis. In particular the use of incommensurable superlattices is shown to lead to localization phenomena. The localisation length and the superfluid faction of the system are investigated as a function of the interactions in the system and the depth of the disorder. It is shown that these parameters suitably reflect the localization within the sample.

6483-19, Session 5

Nonlinear photonic quasi-crystals and Anderson localization

M. Segev, Technion-Israel Institute of Technology (Israel)

No abstract available

6483-20, Session 6

Femtosecond optical vortices: how to make them and what to do with them

C. J. Uiterwaal, J. Strohaber, I. Mariyenko, Univ. of Nebraska/ Lincoln

An optical vortex is a singularity point in a (scalar) electric field where the amplitude vanishes and the phase is undetermined. Instructive examples of modes containing an optical vortex are the so-called Laguerre-Gaussian modes[1]. Characterized by a radial mode number p and an azimuthal mode number L, they form a complete set of solutions of the paraxial wave equation. In cylindrical coordinates (r, phi, z) their azimuthal phase equals exp(-i L phi). We are interested in vortex modes because their photons possess optical orbital angular momentum (OAM)[2]. Our goal is to make strong ultrashort pulses with a vortex, so we can investigate the effect of optical OAM on intense-field ionization. We are motivated by the role of the photon's spin angular momentum: in its manifestation as polarization, this is well-known to affect intense-field ionization. Notable are electron recollision processes, central to many schemes to generate attosecond pulses. What role optical orbital angular momentum plays in intense-field processes is to the best of our knowledge experimentally unexplored territory. In 2005, we were the first to report the generation of a pure femtosecond vortex[3]. Because of the substantial bandwidth (tens of nanometers) that is inherent to femtosecond pulses we needed to pay special attention to spatial chirp. If present, this phenomenon would undermine the usefulness of the produced vortices, giving rise to a chromatic effect[4] in their foci. We avoided this adverse effect by using two holographic masks in our setup. This summer (2006) we have started to explore the production of ultrafast optical vortices with a spatial light modulator (SLM), a PC-programmable hologram[5]. In particular, we investigate the efficiency of this device and its interaction with unfocused amplified Ti:sapphire pulses, with intensity up to 10 GW/cm^2. Using home-made laser-etched holograms, we have already increased the intensity of our femtosecond vortices to the level were intense-field ionization occurs. To demonstrate this, we have started to image focused vortices with our spatially-resolved ion detector. Recent progress will be discussed.

References

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6483-21, Session 6

Coherence measurements for light fields for optical trapping with helical wavefronts

W. M. Lee, A. E. Carruthers, V. G. Garcés-Chávez, K. Dholakia, Univ. of St. Andrews (United Kingdom)

Microparticles in an optical trap may act as a force transducer that has the ability to measure femtoNewton forces for biomolecular studies. Notably, microparticles trapped in a light field may act as scattering and diffracting points that allow us probe the coherence and phase of the trapping light field. In this paper, we describe how forward scattered light from the optically trap microparticles in an optical vortex trap converges in the far-field to create patterns that reveal the helicity and azimuthal phase variation in the vortex beam without prior knowledge. Further, we realise a version of Young's slits experiment with trapped particles. Micro-particles trapped in an optical vortex beam provide a means of studying the phase variation of the vortex beam. This observation can be further extended to the study of the relative phase and spatial coherence of two points in trapping light fields with arbitrary wavefronts.

6483-22, Session 6

Three-dimensional intensity distribution of helico-conical optical beams

C. A. C. Alonzo, P. J. J. L. Rodrigo, I. R. Perch-Nielsen, J. Glückstad, Risø National Lab. (Denmark)

Helico-conical optical beams are a recently introduced class of beams that multiplicatively combine helical and conical phase fronts. Focusing these beams leads to a spiral intensity distribution at the focal plane of the lens. Further theoretical and experimental examination reveals interesting three-dimensional intensity patterns near the focal region, including a cork-screw structure around the optical axis. Variations on these light distributions based on the superposition of multiple helico-conical beams are also presented here. These beams are expected to yield interesting dynamics when applied to the optical trapping of microscopic particles. We are particularly interested in the effect of the two-dimensional asymmetry and three-dimensional variation of the light distributions on dielectric microspheres.

6483-23, Session 6

Stability of powerful tubular pulsed beams in dielectrics with photo-induced ionisation

O. K. Khasanov, T. V. Smirnova, O. M. Fedotova, Institute of Solid State and Semiconductor Physics (Belarus); A. V. Volyar, Taurida National Univ. (Ukraine); A. P. Sukhorukov, M.V. Lomonosov Moscow State Univ. (Russia)

High- power femtosecond tubular pulsed beam dynamics in a dielectric medium like fused silica under photoionization conditions is studied by means of numerical solution of the system of modified nonlinear (3+1)D Schrödinger equation for an electric field envelope as well as kinetic equation for free electron density. The competition of saturable nonlinearity and plasma defocusing are taken into account. It was established, that when a vortex pulsed beam with a near-critical input power propagates through a nonlinear dielectric solid medium, the competition between the 3-and 5-th order nonlinearities leads to the beam structure multifoci behavior. The input beam power increase results in growth of defocusing factors related to the plasma domination. The interaction of a singular pulsed beam with nonlinear dielectric medium stipulates higher plasma

densities in comparison with gaussian pulsed beams, at this the free electron number increases with increasing the beam topological charge. The process of the electron plasma formation due to multiphoton ionisation in this case is responsible for a nonlocal character of the light- matter interaction. This may be the main factor for the attainment of vortex beam stability condition, as the balance between nonlinearities of opposite sign and different magnitude in the case of multiphoton ionisation favours the establishment of a quasi-soliton regime of radiation propagation over a distance exceeding several diffraction lengths. The effect of normal and anomalous group velocity dispersion is considered.

6483-24, Session 7

Laguerre-Gaussian supercontinuum

H. I. Sztul, V. Kartezayev, R. R. Alfano, City College/CUNY

In recent years beams of light that have phase singularities, or optical vortices, have gained much attention. They have been used to study various optical phenomena. More recently, white-light optical vortices have been studied and shown to be more versatile in these applications due to the wide spectral bandwidth and azimuthally varying phase structure. Coherent white-light supercontinuum generated from fs pulses has been investigated since its discovery by Alfano and Shapiro. Supercontinuum has thus far not been shown to propagate with a LG distribution. We demonstrate here the first coherent Laguerre-Gaussian (LG) white-light beam generated from a femtosecond supercontinuum (SC) light source. In the experimental setup to generate a LG SC beam a 100 fs collimated SC beam is used to generate a LG field distribution. We project a computer-generated hologram onto a spatial light modulator and block out all of the reflected beam except the +1st order diffracted beam which leaves only the exp(+i?) phase structure desired. The angular dispersion that this method introduces is neglected, as it has been show that introducing a small angle prism corrects this blur effect.

We demonstrate the first Laguerre-Gaussian supercontinuum beam generated from a femtosecond supercontinuum light source. Supercontinuum plus this extra degree of freedom from the orbital angular momentum can also lead to development towards 100's of terabit data transmission rates.

6483-25, Session 7

Colloidal statistical mechanics in optical vortices

Y. Roichman, S. Lee, K. Xiao, D. G. Grier, New York Univ.

Adaptively optimized optical vortices constitute ideal model systems for studying statistical mechanics in reduced dimensionality. In addition to providing a uniform tangential force, optical vortices can be superposed to create tailored potential energy landscapes. We describe video microscopy measurements of individual colloidal spheres moving through these landscapes. A single driven sphere exhibits normal velocity fluctuations, but with a remarkable hundred-fold enhancement of its diffusion coefficient. Hydrodynamic coupling among multiple circulating spheres drives a transition to chaos, including an experimental demonstration of weak chaos. In addition to presenting the remarkably rich physical insights drawn from this simple optical system, we will discuss the holographic techniques required to create optimized optical vortices.

6483-26, Session 7

Optical taper beams

S. Chávez-Cerda, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); D. P. Caetano, J. M. Hickmann, Univ. Federal de Estado de Alagoas (Brazil)

Using the property of propagation invariance of Bessel beams (BB) stable hollow beams have been created and used as optical tweezers and hollow pipes to guide and manipulate microparticles and atoms. Despite of being diffracting, Laguerre-Gaussian (LG) beams posses other properties that when focused makes them suitable for other applications. In both instances, the propagating hollow beams are due to the presence of a vortex at the centre of the radial symmetric ringed transverse profile. BB and LG beams are, respectively, modes of the wave equation in its full form, the Helmholtz equation, and the paraxial wave equation. In both families of modes the radial solution is linked to the azimuthal solution by the topological charge number or vortex order. For instance, a Bessel mode of order m has the same m topological charge. In this work, we present the results of investigating the violation of such link by setting a different radial mode number with respect to the azimuthal mode number. Our findings are that by conservation of angular momentum the radial solution accommodates to the respective azimuthal vortex mode creating an optical funnel. When the azimuthal order is smaller than the radial mode the hollow beam reduces its diameter while in the opposite case, if the azimuthal order is larger than the radial one, the vortex modifies the radial solution by widening its inner ring diameter to fit the corresponding vortex mode. In both cases an optical funnel is created that can be used to have a further control in applications as atom and nanoparticles guiding.

6483-27, Session 7

Optical vortices in diffracted light beams

E. J. Galvez, S. Baumann, Colgate Univ.

We study the optical vortices in beams produced by diffracted optical elements. The optical beams were prepared by diffraction of a laser beam in the fundamental mode into high orders. We used amplitude binary forked gratings of integral and fractional charge. The resulting beams were imaged by interference. Our observations are in qualitative agreement with recent theoretical predictions and observations.

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6484-01, Session 1

Design and manufacturing of 10G GenX VCSELs at Emcore

N. Li, D. Collins, S. Jatar, O. Lavrova, L. Liu, C. Liu, C. J. Helms, W. Luo, C. X. Wang, EMCORE Corp.

No abstract available

6484-02, Session 1

VCSEL proliferation

J. A. Tatum, Advanced Optical Components

No abstract available

6484-03, Session 1

High output power 670nm VCSELs

K. Johnson, M. K. Hibbs-Brenner, Vixar

No abstract available

6484-04, Session 1

A TCAD approach to robust ESD design in oxide-confined VCSELs

H. Meier, R. Santschi, S. Odermatt, B. Witzigmann, ETH Zürich (Switzerland); S. Eitel, Avalon Photonics Ltd. (Switzerland); G. Letay, F. Nallet, Synopsys Switzerland AG (Switzerland)

Electrostatic discharge (ESD) during production, packaging and application of VCSELs can cause irreversible damage deep within the device. Investigations of these damage patterns inside a real device is a complex and expensive task. Simulation tools can provide insight into the physics during an actual discharge event. This contribution aims to analyze the physics of ESD events using technology computer-aided design (TCAD).

In particular, the impact of current confinement on ESD robustness is investigated. With the help of state-of-the-art TCAD tools virtual ESD tests are performed on oxide-confined VCSELs. The 2D simulation model takes into account high-field effects and self-heating in a hydrodynamic framework that allows time-dependent spatially resolved monitoring of critical quantities (electric field across the oxide, temperature profile, current densities) during the ESD events.

Human Body Model (HBM), Machine Model (MM) and Charged Device Model (CDM) show typical local heating and current crowding effects which may lead to irreversible damage of the device. The results show that for slow ESD events the temperature peak is found near the center of the device's intrinsic region. Faster pulses show maximal heating at the oxide aperture. This difference, which also has been found in experiments, can be explained by a combination of local electric field, heat generation and heat transport.

Design criteria such as oxide aperture, thickness and its position relative to the intrinsic region strongly influence self-heating, electric fields, current density profiles and in consequent the dielectric breakdown conditions. The impact of these criteria on ESD robustness are analyzed and guidelines for robust ESD design in VCSELs are presented.

6484-05, Session 2

VCSELs for atomic sensors

D. K. Serkland, G. M. Peake, K. M. Geib, G. A. Keeler, Sandia National Labs.

No abstract available

6484-06, Session 2

New markets for VCSELS: pulsed operation of high power devices

M. Grabherr II, M. Miller, D. Wiedenmann, R. Jaeger, R. King, ULM Photonics GmbH (Germany)

VCSELs have proven their competitiveness against edge emitting lasers and LEDs in many volume applications like Gigabit per second data transmission or optical PC mice. Due to their uniqueness in spectral and spatial emission characteristics as well as availability of simple mounting technologies, large area VCSELs and VCSEL arrays are getting increasingly attractive for short pulse (10ns..100μs), high power (1W..30W) operation, too. Addressed applications are range finding, object detection and illumination in automotive and industrial environments. Large area VCSELs are discussed in terms of design, production, performance, assembly, and reliability as well as selected application details.

6484-07, Session 2

Heterogenously integrated waveguide-coupled VCSEL-based optical interconnects

J. Cheng, K. Yang, D. A. Louderback, K. M. Patel, X. J. Jin, T. J. Eustis, C. Y. Chao, J. Schoengarth, P. S. Guilfoyle, OptiComp Corp.

No abstract available

6484-08, Session 3

Monolithic integration of VCSELs and MSM photodiodes for bidirectional multimode fiber communications

R. Michalzik, M. Stach, F. Rinaldi, S. Lorch, Univ. Ulm (Germany)

No abstract available

6484-09, Session 3

Modulation properties of VCSEL with intracavity modulator

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We have studied the modulation properties of VCSEL with intracavity multiple quantum well (MQW) electroabsorption modulator integrated into the top distributed Bragg reflector (DBR)[1]. Small signal analysis of the rate equations with loss modulation shows a more gradual intrinsic high-frequency roll-off slope of 1/f instead of 1/f2 in directly modulated laser diodes, and consequently bandwidths in excess of 40 GHz are obtain-

able with this configuration[2]. The limiting factors to high bandwidth have been determined by fitting high frequency characteristics to a multi-pole transfer function, and include hole drift-limited time of flight (TOF) in the modulator intrinsic region, and modulator RC delay. Intracavity loss modulation shows a strong (up to +30 db) relaxation oscillation resonant feature in both theory and experiment. This feature can be significantly reduced in amplitude using the optimization of parasitics. We have extracted relative contribution of TOF and parasitic capacitance by varying the modulator intrinsic region width (100 and 200 nm) and lateral size of the modulator (18 and 12μm). It was estimated that the small size modulator exhibits parasitics f-3dB at 6GHz, while TOF f-3dB is estimated to be at 8 GHz. To further increase bandwidth, low temperature growth of a 200 nm absorber i-region and MQW was employed to reduce photogenerated carrier lifetime. We have used p-modulation doping of the gain region to increase the relaxation frequency. Pronounced active Q-switching was observed, yielding pulse widths of 40 ps at a 4 GHz rate

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6484-10, Session 3

Optical switch and logic gates based on the integration of vertical cavity laser: depleted optical thyristor

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Vertical cavity surface emitting laser (VCSEL) - based optical switches and optical logic gates provide a versatile and promising approach to two-dimensional optical information processing, parallel computing, and interconnection architectures. Latching optical switches and cascadable optical logic gates AND and OR are demonstrated by the monolithic integration of a vertical cavity laser (VCL) with depleted optical thyristor (DOT), which has not only a low threshold current, but also a high on/off contrast ratio. It allows the single-typed VCL-DOT to be demonstrated both the optical AND-gate and OR-gate by simple reference switching voltage changes. All the Boolean logic functions can be constructed by using only two basic logic functions, such as AND or OR, plus the INVERT functions. Any logic function can be implemented by cascading different combinations of these simple gates. The VCL-DOT fabricated using the oxidation process can achieve a high optical output power efficiency, nonlinear S-shaped current-voltage characteristics, very low threshold current and a high sensitivity to the optical input light. The minimum threshold current is 0.65 mA at the mesa size with 37x37 μm and oxide aperture with 2x2 μm. The switching voltage is changed from 5.24 V to 1.90 V, as the optical input light is injected into the VCL-DOT. Our experimental results suggest the potential applications of VCL-DOT in advanced optical communication systems.

6484-11, Session 3

Monolithic integration of VCSEL/PiNs

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No abstract available

6484-12, Session 4

Monolithic, bufferless III-Sb VCSELs on Si (011) wafers

D. L. Huffaker, The Univ. of New Mexico

No abstract available

6484-13, Session 4

Low threshold current, low resistance 1.3 μm InAs-InGaAs quantum-dot VCSELs with fully doped DBRs grown by MBE

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We report InAs-InGaAs quantum-dot vertical-cavity surface-emitting lasers (VCSELs) grown by molecular beam epitaxy with fully doped n- and p-doped AlGaAs distributed Bragg reflectors and including an AlAs layer to form a current and waveguiding aperture. The metal contacts are deposited on a topmost p+-GaAs contact layer and on the bottom surface of the n+-GaAs substrate. This conventional selectively oxidized top-emitting device configuration avoids the added complexity of fabricating intracavity or coplanar ohmic contacts. The VCSELs operate continuous-wave at room temperature with peak output powers of 30 μW and threshold current are about 0.7mA. The peak lasing wavelengths are near 1.28μm with a side-mode suppression ratio of 24dB. The series resistance of the fabricated devices are 83O, which is ten times lower than our previous result, and 2 times lower than intracavity QD VCSELs previously reported. The lower resistance can also improve the high speed modulaiton performance.

6484-14, Session 4

1.3 μm VCSELs: InGaAs/GaAs, GaInNAs/GaAs multiple quantum wells or InAs/GaAs quantum dots: three candidates as active material

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In this article, we report our results on 1.3μm VCSELs for optical interconnection applications. Room temperature continuous-wave lasing operation is demonstrated for top emitting oxide-confined devices with three different active material, highly strained InGaAs/GaAs(a) and GaInNAs/GaAs (b) multiple quantum wells or InAs/GaAs (c) quantum dots. Conventional epitaxial structures grown respectively by MOCVD, MBE and MBE, contain fully doped GaAs/AlGaAs DBR. All three epilayers are processed in the same way. Current and optical confinement are realized by selective wet oxidation. Circular apertures from 2 μm to 12 μm diameters are defined.

At room temperature and in continuous wave operation, all three samples exhibit lasing operation at wavelength above 1 275nm and reached 1 300nm for material (a). Typical threshold currents are in the range [1-5]mA and are strongly dependent firstly on oxide diameter and secondly on temperature. Room temperature maximum output power corresponds respectively to 1.7mW, 0.5mW and 0.6mW. By increasing driving current, multimode operation occurs at different level depending on the oxide diameter. In case (a), non conventional modal behaviors will be presented and explained by the presence of ab normal oxide modes.

Thermal behaviors of the different devices have been compared. In case (a) we obtain a negative T0. By the end, we will conclude on the different active materials in terms of performances with respect to 1300nm VCSEL application.

6484-15, Session 4

1.55μm InP-based electrically-pumped VECSELs: comparison of buried and implanted tunnel junction as current confinement schemes for the realisation of single-transverse-mode large diameter (50μm)

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We present InP-based electrically pumped vertical external cavity surface emitting lasers (VECSEL) operating at 1550nm The half-VCSEL structure is monolithically grown on n-doped substrate. The n-doped bottom DBR consists of 50 InP/InGaAsP quarter-wavelength pairs. A n-i-d junction comprising the nine compressively strained InGaAsP quantum wells, active layer was grown on the top of the DBR, followed by an InGaAsP-based (lg=1.2μm) p/p++/n++/n tunnel junction. For large emission diameters, the current injection homogeneity is a key factor to achieve single transverse mode emission and good external efficiency. We compared buried (BTJ) and ion implanted tunnel junction (ITJ) as two current confinement schemes for devices of 20, 30, 50μm diameters. Thermal resistance values Rth were deduced from the amplitude of the Half-VCSEL electroluminescence peak wavelength shifts measured with both CW dissipated power, and temperature (measured in pulsed regime). Reduced thermal resistance is obtained for BJT devices, but reduced current crowding is evidenced for ITJ for the 50μm emission diameters where a transverse single mode emission is obtained.

6484-19, Poster Session

VCSELs with tunnel-regenerated multiple-active-region structure

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The difficulty in physics to realizing high-power and low-threshold vertical-cavity surface-emitting-lasers (VCSELs) was analyzed. Then the structure of tunnel-regenerated multiple-active-region was proposed, which possessed the unique properties of higher single round-trip gain, lower threshold current, and higher quantum efficiency. The quantum efficiency exceeding 100% with maximum power of about 10 mW @ 20mA of VCSELs with such structure was obtained in this paper.

6484-20, Poster Session

Numerical simulation of temperature-dependence on distributed Bragg reflector (DBR) and performance analyses for proton-implant/oxide confined VCSEL: comparison with transmission matrix, matrix calculating methods and macleod model

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This paper mainly focuses on the simulation for temperature-dependent Distributed Bragg Reflector (DBR) of 850nm vertical cavity surface emitting laser (VCSEL) with Transmission Matrix (TMM), Matrix Calculating Methods (MCM) and Macleod Model and performance for comparison with proton-implant/oxide confined process on VCSEL. Using well-developed temperature-dependent DBR-reflectivity solver with Mathcad simulator, we have successfully compared the Macleod Model simulator with theoretical self-developed solution based on the Transmission Matrix (TMM), Matrix Calculating Methods (MCM) and find very good agreement with previous results while accounting for influences of conjugated part of refractive index and graded Al compositions of DBR materials. Moreover, optoelectronic performance of Proton-Implant/Oxide Confined 850nm VCSEL have been demonstrated on this paper using temperature-dependent power output, voltage/injection current, transverse operating wavelengths, optical spectral characteristics, slope efficiency and transverse optical modes with an approximated Marcatili's method extracted and measurement from systematically measuring experiments. Through adequate and precise LD device design and processes, we have proposed the high performance single-mode proton implanted in contrast to the oxide confined 850 nm VCSEL. Under nominal temperature-variety and keeping operating temperature of 30¢J, the maximum power output of 10 micro-meter aperture proton implanted VCSEL exceeds 5 mW while injecting current of 10 mA, and the threshold voltage, injecting current, peak-wavelength, differential resistance are 1.8 V, 3.2 mA, 851 nm and 36.8 ohm, respectively.

6484-16, Session 5

Progress and issues for high speed vertical cavity surface emitting lasers

K. L. Lear, A. N. Al-Omari, Colorado State Univ.

No abstract available

6484-17, Session 5

Characterization of 1.55 um VCSELs using high-resolution and high-dynamic range measurements of the CW spectrum

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We present a methodology for the characterization of the main parameters of VCSELs for its use in direct modulation: chirp parameter, linewidth, sensitivity to feedback, relaxation frequency and RIN, obtained from measurements of the emitted optical spectrum in carrier wave (CW) operation by means of a high resolution (10 MHz) and high dynamic range (80 dB) optical spectrum analyzer.

Many of the main static and dynamic parameters of VCSEL lasers can be obtained from the analysis of the optical spectrum when emitting in CW operation mode, but traditional spectrum analysis techniques do not achieve enough high resolution and dynamic range and high signal to noise ratio to perform it. Recent developments in high resolution OSA technology allows a deeper characterization of the main properties of VCSELs for its applications in optical communication systems by analysing their CW emitted spectrum.

Commonly it is assumed that intensity noise cannot be measured in the optical domain, due to the resolution requirements for an optical spectrum analyzer and the lack of dynamic range or limiting Free Spectral Range when using interferometric techniques. Measurements in the electrical domain require complex set ups and very precise control of the detection system and calibration of the thermal and shot noise.

Both phase and intensity noise contribution to the emitted spectrum of a CW operated VCSEL are measured. Linewidth enhancement factor is obtained applying a modified version of the linewidth method. Relative intensity noise (RIN) is directly measured from the optical spectrum, avoiding the influence of electrical noise and with a simpler set-up. Relaxation oscillations frequency is measured on its signature over the spectral lineshape of the laser without the need of modulating the laser.

Special focus on the VCSEL sensitivity to undesired optical feedback has been performed. Even when using anti-reflection coating and isolators, feedback issues are found measuring the optical spectrum fast enough. A simple test for detecting feedback issues is presented and the impact of this feedback in the measured parameters is studied.

Conference 6484:
Vertical-Cavity Surface-Emitting Lasers XI

6484-18, Session 5

Single mode proton-implanted photonic crystal and holey VCSELs

P. O. Leisher, D. Siriani, K. D. Choquette, Univ. of Illinois at Urbana-Champaign

No abstract available

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6485-01, Session 1

Tunable broad-area InGaN laser diodes in external cavity

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Semiconductor lasers apart from their applications in a vast variety of commercially utilized optical systems - such as laser printers, CD and DVD players, bar code scanners, optical sensors, telecommunication systems, etc. - are also very convenient and suitable tool for spectroscopy. Thanks to their compactness, low cost and reliable operation, laser diodes can be competitive comparing with expensive and large standard spectroscopic sources (gas lasers, solid state lasers). For high precision atom spectroscopy (gas analysis, absorption spectroscopy) wavelength tuning of the laser is the most required device property. The tunability can be achieved the most easily by using an external cavity scheme. Blue, InGaN - based laser diodes enable the study of optical transitions in many new systems including indium, rubidium, potassium etc... We will present here the use of our broad-area laser diodes (20um x 500um, grown on low dislocation, pressure grown gallium nitride substrates) coupled to Littrow external cavity, for the construction of the tunable, high power laser devices. We demonstrate the tunability range of 5.5 nm (central frequency is 398 nm). The maximum power at single mode operation was around 40 mW indicating the 22% of the extraction efficiency (170 mW of optical power in case of an ucoupled laser diode). We will also present the use of new epitaxy scheme (involving the gain spectrum engineering) for improving the tunability range of our laser diodes.

6485-02, Session 1

Recent progress of high-power GaN-based laser diodes

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No abstract available

6485-03, Session 1

Comprehensive study of reliability of InGaN based laser diodes

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Since 1996 when the first blue laser has been demonstrated, the great efforts have been made to improve the reliability of nitride devices. However, the improvements demonstrated by the leading companies in terms of laser stability are not fully reflected in the published articles. The farther progress in the development of laser nitride devices requires the deeper understanding of physical mechanism lying behind the observed aging processes.

In this work we present a reliability study of InGaN based laser diodes grown on low dislocation density GaN crystals. We observed two modes of degradation. The first one is characterized by increase of threshold current and stable behavior of differential quantum efficiency. It is worth noticing that the threshold current temporal evolution has a characteristic square root dependence what suggests that diffusion may be responsible for the damage.

The second mode concerns the facet areas of the laser diodes which are sensitive to the damage due to high current and photon densities. In our laser diodes we found the examples of damage occurring on the facets in the waveguide area. This type of degradation is depends on the facet coating procedure.

In order to differentiate between various facet related degradation mechanisms we fabricated so called “Non Injected Facet” (NIF) devices in which we eliminate the current injection in the area near the facet. The preliminary results indicates an improvement in the laser diodes lifetime.

Finally, we compare the microstructural measurements (SEM, CL, EBIC) on aged structures and new, non-aged structures.

6485-04, Session 1

High-power operation of inner-stripe GaN-based blue-violet laser diodes

C. Sasaoka, NEC Corp. (Japan)

No abstract available

6485-05, Session 1

Investigation and comparison of optical gain spectra of (Al,In)GaN laser diodes emitting in the 375nm to 470 nm spectral range

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We measure gain spectra for commercial (Al,In)GaN laser diodes with peak gain wavelengths of 470 nm, 440 nm, 405 nm, and 375 nm, covering the spectral range accessible with electrical pumping. For this systematic study we employ the Hakki-Paoli method, i.e. the laser diodes are electrically driven and gain is measured below threshold current densities. We observe a dependency of the internal losses which reflects the increasing losses at the edges of the accessible spectral range. These losses are more pronounced at the short wavelength edge. Inhomogeneous broadening is strongest for the long wavelength laser diode. This 470 nm laser diode also shows a peculiar second gain peak at even longer wavelengths (490 nm) which saturates far below threshold carrier densities. This second peak may be caused by transitions between different levels in the quantum well. A decrease of the internal losses would allow lasing at the technical important wavelength of 488 nm. The gain spectra for the other laser diodes is reasonable for a 2D carrier system and understandable when we take into account inhomogeneous broadening and manybody effects. We also study differential gain and antiguiding factor. We see our measurements as providing a set of standard gain spectra for a set of similar laser diodes covering a wide spectral range which can be used to develop and calibrate theoretical gain simulations.

6485-06, Session 2

Quantum-cascade lasers without injector regions

M. Amann, A. Friedrich, Walter Schottky Institute (Germany)

Quantum-cascade (QC) lasers have been investigated for more than a decade by now and are still gaining increasing interest as light sources for applications like trace gas sensing and free-space communications. Typically, QC lasers rely on a periodic alternating repetition of active sections and so-called injector regions. In the active sections the photons are generated, while the injector regions enable the transfer of the electrons from one active section to the next one. Due to their doping, the injector regions act as an electron reservoir and provide stable current flow. Furthermore, they prevent a thermal backfilling of the lower laser states. However, the main disadvantage of this concept is the lengthening of the active stage with optically passive and slightly absorbing material. QC lasers without injector regions are therefore expected to yield improved performance, provided that the electron transfer can be managed otherwise and thermal backfilling can be suppressed.

We shall present the status of injectorless QC lasers, based on a four- and five-level staircase, respectively. First lasers were realized at a wavelength of about 10 μm. Applying an optimized design, we also achieved high performance injectorless QC lasers emitting at 6.7 μm, exhibiting threshold current densities as low as 1.6 kA/cm(c)¯ at 300 K and a maximum operating temperature of 430 K. Recently, we have further extended the wavelength range even down to 4.3 μm.

6485-07, Session 2

Electronic and thermal properties of Sb-based QCLs operating in the first atmospheric window

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The short wavelength (3-5 μm) operation limit of quantum cascade lasers (QCLs) is related to the conduction band energy discontinuity between the barrier and well semiconductor materials that, in turn, is strongly dependent from the material choice. In0.53Ga0.47As/AlAs0.56Sb0.44 and more recently In0.53Ga0.47As/Al0.62Ga0.38As0.55Sb0.45 heterostructures represent the more attractive candidates for high performance QCL development. We report on the experimental study of the electronic and thermal properties in state of art Sb-based mid-IR QCLs operating in the range 4.3-4.9 μm. This information has been obtained by investigating the band-to-band photoluminescence signals, detected by means of an InGaAs-array detector. We show here: i) the first measurement of the electronic and lattice temperatures and of the electron-lattice energy relaxation rates in Sb-based QCLs based on a quaternary alloy; ii) the electronic spatial distribution and the influence of the growth procedure on the optical properties of In0.53Ga0.47As/AlAs0.56Sb0.44 mid-IR QCLs. This technique allowed to probe the spatial distribution of conduction electrons as a function of the applied voltage and to correlate the quantum design of devices with their thermal performance. We measured a thermal resistance (R = 9.6 K/W) and an electrical power dependence of the electronic temperature (Re = 12.2 K/W) in the lattice temperature range 60-110 K. Our results demonstrate that the process of electron cooling generate non-equilibrium electrons that share an electronic temperature close to the lattice one within (~ 15-18 K). This implies that the e-LO interaction provides a very efficient cooling of the electron gas that thermalizes with the lattice with an electron-lattice energy relaxation rate $\tau E\text{-}1 = 5.7$ ps-1.

6485-08, Session 2

State-of-the-art GaInAs/AlAsSb quantum cascade lasers

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The search for high conduction-band-offset material systems for the fabrication of short wavelength (l<5 μm) quantum-cascade (QC) lasers is driven by the need for robust semiconductor lasers covering the technologically important 3-5 μm atmospheric transparency window. The performance of conventional GaInAs/AlInAs QC lasers towards wavelengths shorter than 5 μm rolls off due to insufficient carrier confinement caused by the limited available conduction-band offset, which is in the 500-700 meV range. The major motivation for using the GaInAs/AlAsSb material system, lattice matched to InP, for the fabrication of QC lasers emitting in the short wavelength range (l~3-5 μm) originates from the high conduction-band offset of 1.6 eV (G-valley) between the quantum well and the barrier. Another attractive feature of GaInAs/AlAsSb heterostructures is their compatibility with the well-established InP waveguide and processing technology.

In this presentation, recent advances in GaInAs/AlAsSb QC laser research will be reviewed, resulting in devices emitting in pulsed mode operation at 4.6 μm up to a maximum operating temperature of >400 K as well as GaInAs/AlGaAsSb QC lasers emitting at 3.7 μm with a maximum peak output power of 10.5 W at 77 K (corresponding to a total power efficiency of 22%). In addition, GaInAs/AlAsSb distributed-feedback (DFB) QC lasers, showing room-temperature single-mode emission at 4.08 μm for pulsed mode operation, have been demonstrated. Furthermore, current limitations and possible improvements of the GaInAs/AlAsSb QC laser technology will be discussed.

6485-09, Session 2

Sub-wavelength antireflection gratings on quantum cascade laser facets

A. O. Dirisu, C. F. Gmachl, Princeton Univ.; D. L. Sivco, Lucent Technologies/Bell Labs.

Quantum Cascade Lasers (QCLs) in external cavity operation are desirable for wavelength tuning, selectivity and beam shaping. They require at least one of the facets to be antireflective in order to suppress the formation of coupled cavities. The currently used conventional thin film antireflection coatings tend to have poor adhesion and can become unstable under thermal cycling. We present the use of sub-wavelength gratings as antireflection surfaces by fabricating the gratings into the QCL facet to eliminate the issues associated with coatings. The grating period is much smaller than the incident wavelength and the sub-wavelength structure acts as a homogeneous medium. Combining thin film theory with the effective medium approach, we computed the grating parameters, such as the fill factor and the depth, to achieve minimum reflectivity. The gratings are etched into the QCL facet using focused ion beam milling with a focused beam of Ga+ ions at an energy of 30KeV. Damage from the ion beam is partly alleviated through thermal annealing after the milling process. The lasers are characterized before and after milling of the gratings by measuring the light-current-voltage characteristics. QCLs emitting at a wavelength of 4.9 μm were tested with grating periods of 0.46 μm and depths between 0.5 μm to 1.3 μm at a fixed fill factor of 0.76. The change in threshold and the corresponding change in reflectivity before and after the gratings were measured. Presently, we have achieved reflectivities as low as 1-2% with the absolute value depending on the measured waveguide loss.

6485-10, Session 3

Toward an AlGaAsSb/GaInAsSb/GaSb laser emitting beyond 3μm

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Gases present in the atmosphere have specific absorption lines. The range between 2 and 3 μm presents a great interest for Tunable Diode Laser Absorption Spectroscopy (TDLAS) because many gas species have strong

absorption lines in this area. Beyond 3 μm, absorption lines are even stronger. Alas, it is hardly possible to go beyond this wavelength using Multiple Quantum Wells laser (MQW) structures. We present here a sum up of GaInAsSb/AlGaAsSb MQW lasers emitting from 2.3 μm to 3 μm made in our laboratory. Structures were grown on GaSb (100) substrates and are composed of cladding layers (Te doped and Be doped), a waveguide made of AlGaAsSb and two quantum wells made of GaInAsSb. If lasers emitting at 2.3 μm have typically 10 nm-thick wells, lasers emitting at 2.6 μm and beyond have thicker wells (around 16 nm). The use of this relatively high thickness goes with the risk of exceeding the critical thickness. We present a study showing that for quantum wells emitting at 2.6 μm with a strain of 1.8 % the critical layer thickness is 16 nm. Eventually, we present a study based on threshold currents computations in order to answer the question : why performances at 3 μm are lower than those at 2.3μm ?

6485-11, Session 3

GaSb-based external cavity laser emitting around 2.3 μm

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There is increasing interest in semiconductor lasers emitting in the 2 μm wavelength range for applications in materials processing, gas spectroscopy, and medical diagnostics. For the latter application, the spectroscopic detection of molecules dissolved in liquids is of special importance. Owing to the broadened absorption lines, laser emission does not necessarily have to be single mode, but a wide tuning range (over 100 nm) of the emission wavelength is required. Furthermore, for practical noninvasive diagnostics a compact laser system is highly desired. These requirements can be fulfilled by an micro external cavity setup incorporating a GaSb-based diode laser.

The external cavity laser (ECL) has been realized in the Littrow-configuration. A GaSb-based quantum well diode laser, mounted on an AlN submount, serves as gain medium. The laser light from the back facet is directly butt-coupled to an multimode fiber. A maximal tuning range of 177 nm (2.212 μm to 2.389 μm) with an output power in the 9 to 19 mW range, has been achieved using a macroscopic setup.

Based on this investigation a micro ECL setup has been realized by employing the diode laser together with a micro lens and an electrostatically actuated Si-grating. The grating has 300 grooves/mm and an etch depth of 400 nm, optimized for high reflectivity in the first diffraction order for the present wavelength range. The micro-mechanical grating system consists of two parts: a Si wafer with the moving rectangle grating and a Pyrex wafer on which the electrodes for electrostatic actuation are placed. A maximum tilt range of 6° has been achieved. The resulting tuning range and output power achieved with this micro ECL-system will be presented.

6485-12, Session 3

Narrow linewidth and high power Al-free DFB laser diodes at 852nm for atomic clocks and interferometry applications

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Single frequency and spatial single mode diode lasers emitting at 852nm are strategic components for systems such as atomic clocks (positioning systems for navigation, in space atomic clock like Galileo or Pharao (cold atom), measurement of fundamental constants), or interferometry applications. We have developed the technological foundations of lasers at 852nm to address these different applications. These include an Al free active region, a single spatial mode ridge waveguide and a DFB (distributed feedback) structure.

The device is a separate confinement heterostructure with a GaInP large optical cavity and a single compressive strained GaInAsP quantum well. For an AR-HR coated ridge Fabry Perot laser, we obtain a power of 230mW with M(c)˜=1.3.

An optical power of 150mW was obtained at 854nm, 20°C for AR-HR coated devices. We obtain a single spatial mode emission and a SMSR over 30dB, both at 150mW.

DFB Lasers at 852.12nm, corresponding to the D2 caesium transition, were then realised with a power of 40mW, 37°C for uncoated devices. The SMSR is over 30dB and the M(c)˜=1.3 at 40mW. We measure a SMSR value much better than 30dB between 10°C and 80°C.

On this last laser run, we obtain very homogeneous spectral linewidth values for five different lasers, measured with a Fabry Perot interferometer. We obtain at 20°C a low average linewidth value of 1.2MHz and 1.3MHz at respectively 40mW and 20mW, together with a low standard deviation of 0.1MHz. At 852.12nm (37°C, 40mW), a low linewidth value of 0.9MHz was measured, for one laser preliminary tested.

6485-13, Session 3

In-phase coupling of tapered lasers in an external Talbot cavity

I. Hassiaoui, N. Michel, A. Gomez, C. Larat, J. Huignard, M. M. Krakowski, Thales Research & Technology (France)

Tapered lasers offer both high-power, together with good beam quality. They contain a ridge waveguide, which acts as a modal filter, and a tapered section of increasing width, which provides high power. Our small aperture (few tens of μm) fully index guided single emitters based on this geometry deliver a maximum power of 1W CW, together with a good beam quality parameter M(c)˜(siegman)=2.8 at lambda=975nm.

In order to obtain higher power, we have realized an array of N=6 fully index-guided tapered diode lasers. At 600mA, 109mW, the low far field angle of the array is 2.7° FWHM and 4.5° at 1/e(c)˜. The emitters of the free-running array are not optically coupled to each other, as a consequence, the array has a highly beam quality parameter M(c)˜ of 19.4 which is larger than N times the single emitter's parameter.

In order to improve beam quality of diode arrays, several approaches have been investigated to combine them coherently, including the Talbot effect. The Talbot effect consists of a reproduction of the field of an illuminated periodic object at multiples of the Talbot distance ZT=2d(c)˜/lambda, where d is the spatial periodicity of the object and lambda the wavelength. It was studied for many kinds of lasers such as gain guided lasers, or fiber lasers. Here, we demonstrate for the first time the coherent operation of an array of tapered diode lasers in an external Talbot cavity. The in phase supermode is selected by tilting the reflecting mirror. The divergence of the central peak is 0.4° FWHM.

6485-14, Session 4

High brightness slab coupled optical waveguide lasers

R. K. Huang, J. P. Donnelly, L. J. Missaggia, C. T. Harris, B. Chann, A. K. Goyal, A. Sanchez-Rubio, T. Y. Fan, G. W. Turner, MIT Lincoln Lab.

We have been developing a high power, high brightness semiconductor diode laser concept, the Slab Coupled Optical Waveguide Laser (SCOWL). This laser concept is based upon slab coupling, in which a large, multimode waveguide is converted to a large, single mode waveguide by means of slab coupling of the higher order waveguide modes. SCOWL devices feature large, nearly circular mode sizes (~4 x 4 micron and larger) and low modal loss, leading to low gain per unit length, allowing for the construction of long (~1 cm cavity length) devices. These characteristics allow for high single mode output power. For 980-nm AlGaAs/InGaAs/GaAs-based SCOWL devices, we have demonstrated > 1 W CW output power in a single spatial mode, with brightness levels of > 100 MW/cm2-str. We

have constructed high power arrays of SCOWL devices with bar widths of 1 cm and cavity lengths of 3 mm, and have demonstrated > 90 W under CW operation. By using the technique of wavelength beam combining (WBC), which is analogous to wavelength division multiplexing in optical communications, we have been able to combine the outputs from the elements of a SCOWL array to obtain 50 W peak power (30 W CW) with nearly diffraction-limited beam quality. These SCOWL arrays combined by WBC have demonstrated record single bar brightness levels, 3.6 GW/cm2-str. The WBC SCOWL approach is inherently scalable, and offers a route to obtaining kW-class, nearly diffraction limited output from an all-diode laser source.

6485-15, Session 4

Very high power 1310nm InP single mode distributed feed back laser diode with reduced linewidth

P. Doussiere, C. Shieh, S. D. DeMars, K. M. Dzurko, JDS Uniphase Corp.

High power single mode InGaAsP/InP DFB laser diodes with narrow linewidth and emitting near 1310nm are key devices for Analog transmission and Sensor applications since they can be rugged and compact sources more suited to harsh environment than solid-state or fiber-based lasers. Typically, the useful output power of DFB sources is limited to about 100mW by the so-called “re-broadening effect” which causes the spectral linewidth to increase due to spatial-hole burning and other effects. We report here sub-MHz linewidth at output power levels exceeding 500mW resulting from cavity design that successfully addresses the concerns of linewidth re-broadening. Single-frequency operation can be maintained from threshold to the high power operating point without mode hops. Side-mode suppression is greater than 55dBc and relative intensity noise is below -150dB/Hz from 0.1MHz to 20GHz. Threshold current under 100mA and electrical-to-optical conversion efficiency of 0.4-0.5W/A result from proper cavity design optimization. Preliminary aging studies demonstrate that the stability of these devices is similar to our 14xx nm Fabry-Perot Raman Pump product, which offers 20-year reliability for telecommunications applications. In this paper we report that a linewidth as narrow as 0.2 MHz can be maintained for a facet power as high as 400mW by using a low loss cavity design allowing thereby high slope efficiency even for long cavity design.

6485-16, Session 4

Wavelength stabilized, narrow linewidth, high power and high efficiency broad-area laser

M. Kanskar, Alfalight, Inc.

No abstract available

6485-17, Session 4

To be announced

J. Farmer, nLight Corp.

No abstract available

6485-18, Session 5

Recombination in quantum dot ensembles

P. Blood, Cardiff Univ. (United Kingdom)

No abstract available

6485-19, Session 5

Characteristics of In(Ga)As/InGaAsP quantum dot laser diodes lasing at 1.55μm

E. Lee, N. Kim, D. Lee, Chungnam National Univ. (South Korea); S. Pyun, D. Ko, J. Yoon, W. Jeong, Sungkyunkwan Univ. (South Korea); J. W. Jang, NanoEpi Technologies Corp. (South Korea)

Due to the zero-dimensionality of quantum dots (QDs), QD laser diodes (LDs) are expected to have the low threshold current, high differential gain and temperature insensitive threshold current. Recently, continuous wave (CW) lasing at room temperature from InP based QD LDs has been reported. However, detailed characteristics of QD lasers and CW lasing at 1.55 μm have not been reported.

We have measured I-V, L-I curves and spectra from In(Ga)As/InGaAsP QDLDs to investigate how to optimize QDLDs for output power. In I-V measurements, the series resistances are from 2 to 5 ohm and voltages are almost constant around 3.5 V at the maximum output power for all QDLDs. The slope of L-I curves, which is proportional to the differential quantum efficiency, after lasing rapidly decreased due to the heat in CW mode. Since the heat can be neglected in pulse mode, the efficiency is constant up to a higher current level. In spite of the heat problem, the maximum output power is over 60 mW in CW mode at 20 C. At the same temperature, the lowest threshold current is around 120 mA with cavity length, width and QD layer of 1 mm, 5 μm and 7 stacks, respectively. Typical lasing wavelengths are around 1.55 μm. The slope efficiency, internal loss and gain are 0.26 W/A, 5.2 cm-1 and 15 cm-1, respectively.

6485-20, Session 5

Robust passively mode-locked quantum-dot lasers with low timing jitter

J. G. McInerney, National Univ. of Ireland/Cork (Ireland)

No abstract available

6485-21, Session 6

High-temperature and high-power terahertz quantum-cascade lasers

B. S. Williams, Massachusetts Institute of Technology

No abstract available

6485-22, Session 6

MOCVD growth and regrowth of quantum cascade lasers

F. Choa, Univ. of Maryland/Baltimore County

No abstract available

6485-23, Session 6

Quantum cascade lasers emitting at wavelengths shorter than 4 microns

M. Razeghi, Northwestern Univ.

No abstract available

6485-24, Session 6

Room temperature, continuous wave operation of distributed feedback quantum cascade lasers with widely spaced operation frequencies

A. Wittmann, M. Giovannini, J. Faist, Univ. de Neuchâtel (Switzerland); L. Hvozdara, S. Blaser, Alpes Lasers SA (Switzerland); D. Hofstetter, Univ. de Neuchâtel (Switzerland); E. Gini, ETH Zürich (Switzerland)

Room temperature, continuous wave operation of distributed feedback quantum cascade (QC) lasers with widely spaced operation frequencies are reported. The relatively small temperature tuning range of a single device usually limits the possibilities of gas analysis. This is particularly true for complex mixtures with multiple absorption lines or in mixtures with very broad lines. A device integrating several lasers emitting at different wavelengths would thus allow for the construction of a multi-channel laser spectrometer suitable for tracing the analytes in those cases. Ideally, such a device would contain a QC structure with a broad gain spectrum and, if possible, using several emission wavelengths in a monolithic integration concept. Owing to the presence of a miniband-type lower lasing level, the bound-to-continuum active region exhibits a gain spectrum with a full-width half-maximum (FWHM) in the range of 200-300 cm-1. This miniband allows for multiple optical transitions with reasonably high oscillator strengths. We therefore investigate the lasing characteristics of a series of monolithically integrated DFB lasers using a boundtocontinuum active region and differing in the grating period only. As a result, first-order DFB lasers employing different periods allowed us to achieve single mode continuous wave emission at several wavelengths ranging from 7.7 to 8.3 microns at a temperature of +30 °C. The frequency span corresponds to 8 % of the center frequency. At gain maximum, the lasers were working up to 60 °C whereas at the limits of the explored wavelength range the maximum continuous operation temperature were only 35 and 45 °C. In addition, hightemperature buried heterostructure QC lasers at the same emission frequency range were also fabricated and results will be presented.

6485-25, Session 7

Nonselective oxidation of GaAs-based III-V compound semiconductor heterostructures for in-plane lasers

D. Liang, J. Wang, D. C. Hall, Univ. of Notre Dame

A nonselective wet thermal oxidation technique for AlGaAs-containing heterostructures has been shown to enable the fabrication of a variety of novel high-efficiency, high-power GaAs-based in-plane laser devices. Applied in conjunction with a deep anisotropic dry etch, nonselective oxidation yields a simple, self-aligned high-index-contrast (HIC) ridge waveguide (RWG) structure. The native oxide grown directly on the waveguide ridge simultaneously provides excellent electrical insulation, passivation of the etch-exposed bipolar active region, and a low refractive index cladding, leading to numerous laser performance benefits. The resulting strong lateral optical confinement at the semiconductor/oxide interface (with refractive index contrast $\Delta n \sim 1.7$) enables half-racetrack ring resonator lasers with a record small 8 μm bend radius. A nearly circularly-symmetric output beam is demonstrated on narrow w=1.4 μm aperture width straight stripe-geometry lasers with single spatial and longitudinal mode total power output of ~180 mW at 228 mA (9x threshold). With the complete structural elimination of lateral current spreading, the excellent overlap of the optical field with the gain region provides high slope efficiency performance (ranging from >1.0 W/A at w=1.4 μm to 1.3 W/A for w=150 μm broad area stripes) for 300 K cw operation of unbonded, p-side up 808 nm InAlGaAs graded-index separate confinement heterostructure (GRINSCH) active region lasers. Using the direct thermal oxidation of a dilute nitride GaAsP/InGaAsN MQW active region, 1.3 μm emission GaAs-based HIC RWG lasers exhibit a >2X threshold reduction and kink-free operation relative to conventional low-confinement devices. Other recent progress on the application of nonselective oxidation to GaAs-based semiconductor lasers will be reported.

6485-26, Session 7

Highly reflective non-alloyed ohmic contacts on n-type GaAs

N. A. Rider, S. Yu, Y. Zhang, D. Ding, J. Wang, S. R. Johnson, Arizona State Univ.

Many modern optoelectronic devices such as high-power semiconductor lasers require that electrical contacts possess low resistivity and high reflectivity to enhance the photon recycling effect and to minimize the absorption losses at the contacts. Unfortunately, most contact recipes for GaAs require annealing, which reduces the optical reflectivity of the metal-semiconductor interface more than 20%. Recently, people reported that excellent ohmic contact is achievable using a thin low-temperature GaAs (LT GaAs) overlayer without annealing. The present work reports the detailed study of the electrical and optical properties of Au/LT GaAs contacts as a function of LT GaAs layer thickness. We have confirmed that through the use of a 3 to 5 nm thick LT GaAs overlayer, non-alloyed ohmic contacts are possible on n-type GaAs. The As defects in the LT GaAs layer facilitate the tunneling of electrons, while the slow oxidation rate and smooth surface offer a highly reflective interface. Consequently, it will be advantageous for laser diodes to use the contact interface to reflect most photons back to the active region to get reabsorbed, resulting in a much lower apparent threshold and less parasitic joule heating at the contacts. Our results have shown 98% reflectance at 980 nm at the Au/LT GaAs interface, much greater than the 75% for annealed Au/GaAs contact. According to our theoretical modeling, such a dramatic improvement of reflectivity enhances photon recycling and results in up to 40% apparent threshold reduction for broad-area-contact high-power laser diodes.

6485-27, Session 7

Room temperature continuous-wave operation of GaInNAsSb laser diodes at 1.55μm

J. A. Gupta, National Research Council Canada (Canada)

No abstract available

6485-28, Session 8

Recent advances in MOVPE-grown high-performance quantum cascade lasers

L. Diehl, Harvard Univ.

No abstract available

6485-29, Session 8

New THz sources for biomedical imaging

J. S. Harris, Jr., Stanford Univ.

No abstract available

6485-30, Session 8

Nonlinear optics with intersubband transitions in high band offset heterostructures

A. A. Belyanin, Texas A&M Univ.

No abstract available

6485-31, Session 8

Mode tuning of quantum cascade lasers through optical processing of chalcogenide glass claddings

S. Song, S. S. Howard, Z. Liu, A. O. Dirisu, C. F. Gmachl, C. B. Arnold, Princeton Univ.

Quantum cascade (QC) lasers have become a central component in the development of mid-infrared sensing applications due to their versatility and high performance. Considerable effort has been put into the research of single-mode operation and good tunability of QC lasers in the interest of better trace-gas sensing capability. In this work, we demonstrate a method of tuning QC lasers by modifying the optical properties of an overlying cladding material. An amorphous chalcogenide cladding layer is deposited through a low temperature, solvent-casting technique that is compatible with current QC laser fabrication and operation. Above band gap illumination (lambda < 530 nm) of this cladding causes a permanent change in its index of refraction leading to a change of the modal refractive index and a corresponding modal shift in the laser. Combined with deep-etched distributed Bragg gratings, a tuning of over 30 nm is obtained at an operating wavelength of 7.9 micrometer for constant current and temperature. Results of the characterization of the response of the refractive index to above band gap illumination and numerical calculation of the modal shift are also presented.

6485-32, Session 9

High frequency nanophotonic devices

D. Bimberg, Technische Univ. Berlin (Germany)

No abstract available

6485-33, Session 9

Plasmonic laser antennas

K. B. Crozier, Stanford Univ.

No abstract available

6485-45, Session 9

High power pure-blue semiconductor lasers

O. Goto, Sony Shiroishi Semiconductor, Inc. (Japan); S. Tomiya, Sony Corp. (Japan); Y. Hoshina, T. Tanaka, M. Ohta, Y. Ooizumi, Y. Yabuki, Sony Shiroishi Semiconductor, Inc. (Japan); K. Funato, Sony Corp. (Japan); M. Ikeda, Sony Shiroishi Semiconductor, Inc. (Japan)

We have successfully developed high-power and long-lived AlGaInN-based pure-blue laser diodes (LDs) with an emission wavelength of 440-450 nm, subsequent to our former report on broad-area high-power LDs in the 400-410 nm range1. The half lifetimes in constant current mode are estimated to be more than 10,000 hours under 750 mW continuous-wave (cw) operation at 35 degrees C.

To realize the high-performance pure-blue LDs, it is very important to reduce (1) defects at active regions2, and (2) the operating current density. Because of the first requirement, we have grown the pure-blue LD structures on GaN substrates with dislocation densities of less than 105 cm-2 by metal-organic chemical vapor deposition (MOCVD). In addition, the MOCVD growth conditions and the layer structures for the active regions were carefully selected to suppress the generations of defects. The density of dislocations newly originating from the multi-quantum wells (MQWs) increased to ~ 108 cm-2 as the In content of the QW was increased to ~ 16%, resulting in poor reliability. By careful analysis of these defects using transmission electron microscope, we will present the defect formation mechanism and the defect reduction methodology.

For supplying the second requirement, the longitudinal layer structure was designed to exhibit an absorption loss of 4.9 cm-1 and an internal quantum efficiency of 91%. We also reduced the operating current density down to 6 kA/cm2 under 750 mW cw operation at 35 degrees C by optimizing the stripe width to 12 um and the cavity length to 2,000 um.

References

[1] S. Goto, et. al, phys. stat. sol. (a) 200, 122 (2003).

[2] S. Tomiya, et. al, phys. stat. sol. (c) 3, 1779 (2006).

6485-35, Session 10

Si/Ge platform for lasers, amplifiers, and nonlinear optical devices based on the Raman effect

R. Claps, Neptec Optical Solutions, Inc.; D. P. Dimitropoulos, V. Raghunathan, S. Fathpour, Univ. of California/Los Angeles; B. Jusserand, Univ. Pierre et Marie Curie (France); B. Jalali, Univ. of California/Los Angeles

The use of a silicon-germanium platform for the development of optically active devices will be discussed in this presentation, from the perspective of Raman and Brillouin scattering phenomena. Silicon-Germanium is becoming a prevalent technology for the development of high speed CMOS transistors, with advances in several key parameters as high carrier mobility, low cost, and reduced manufacturing logistics. Traditionally, Si-Ge structures have been used in the optoelectronics arena as photodetectors, due to the enhanced absorption of Ge in the telecommunications band. The recent developments in Raman-based nonlinearities for devices based on a silicon-on-insulator platform have shed light on the possibility of using these effects in a Si-Ge architecture. Lasing and amplification have been demonstrated using a SiGe alloy structure, and Brillouin/Raman activity has been predicted for superlattices. This talk will present the latest experimental results, and will explore theoretically the outlook of this technology.

6485-36, Session 10

Monolithic integrated ring resonator based silicon lasers and amplifiers

H. Rong, Intel Corp.

No abstract available

6485-37, Session 10

Energy harvesting in silicon Raman amplifiers and lasers

B. Jalali, Univ. of California/Los Angeles

No abstract available

6485-38, Session 10

Laser charactersitics and gain properties of the novel Ga(NAsP)/GaP-material system for the integration to Si

W. Stolz, Philipps-Univ. Marburg (Germany)

No abstract available

6485-39, Session 11

Quantum dot lasers and integrated guided wave devices on Si

J. Yang, Z. Mi, P. K. Bhattacharya, Univ. of Michigan

No abstract available

6485-40, Session 11

High temperature silicon evanescent lasers

J. E. Bowers, Univ. of California/Santa Barbara

No abstract available

6485-41, Session 12

670 nm semiconductor lasers for Lithium spectroscopy

R. Häring, TOPTICA Photonics AG (Germany); B. Sumpf, G. Erbert, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); F. Lison, W. G. Kaenders, TOPTICA Photonics AG (Germany)

Most experiments on laser cooling, magneto-optical trappping (MOT) or Bose-Einstein condensation (BEC) with Rubidium and Cesium rely on tunable, single-frequency diode laser systems. The advantages over other laser systems are their fast and precise tuning of the wavelength, ease of use and an affordable price. For Lithium MOTs the laser light is generally generated by dye lasers or by semiconductor systems with restricted performance in power and beam quality.

In this paper we present a master oscillator power amplifier (MOPA) optimized for the use in Lithium cooling experiments. For the master oscillator a ridge waveguide diode is anti-reflection coated and used in a external cavity diode laser (ECDL) with grating feedback in Littrow configuration. This setup features a narrow linewidth and a mode hope free tuning over 20 GHz by moving the grating slight with a piezo. The ECDL configuration is operated since 5000 h above 25 mW without signs of degradation and the same semiconductor structure but coated for Fabry-Perot operation is running since 6000 h at 100 mW.

Higher power in the range of a few hundred milliwatts are required for Lithium MOTs. Therefore we use a tapered amplifier to boost 20 mW from the ECDL to the desired power level. The 2 mm long amplifier chip shows a thermal roll-over in the range of 800-1000 mW dependent on the taper angle. The beam quality was measured by evaluation of the caustic resulting in M2 values <1.5 for taper angles of 2° and 3° and slightly higher for 4° at 500 mW. The complete MOPA system is operated at 970 mW since 1500 h with a degradation rate as low as 2*10-5 1/h.

6485-42, Session 12

670 nm tapered lasers and amplifier with output powers P > 1 W and nearly diffraction limited beam quality

B. Sumpf, M. Zorn, G. Erbert, J. Fricke, P. Froese, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); R. Häring, W. G. Kaenders, TOPTICA Photonics AG (Germany); A. Klehr, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); F. Lison, TOPTICA Photonics AG (Germany); P. Ressel, H. Wenzel, M. Weyers, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

High brightness red emitting laser diodes are very promising for flying spot display technology and, combined with a small spectral linewidth, also for high-resolution spectroscopy, including laser cooling of Lithium. Furthermore, pumping of fs-solid-state lasers, photodynamic therapy, and Raman-spectroscopy are important applications.

In this paper, data for high brightness 670nm-lasers will be presented. The device structure is based on a GaInP single quantum well embedded in AlGaInP waveguide layers grown by MOVPE. The structure is designed for a vertical divergence below 30° (FWHM). The characteristic data are jT=165A/cm2 transparency current density, hi=0.9 internal efficiency, ai=2.5cm-1 internal loss, and a characteristic temperature T0=96K.

Ridge waveguide and tapered devices were fabricated and mounted 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.

An output power of more than 250mW and reliable operation at 100mW over more than 6000h was obtained for RW-laser with a stripe width of 7.5μm.

Tapered lasers reach output powers of about 1W in a nearly diffraction limited beam (M2<3). The same output power was achieved using tapered devices as amplifiers. At 500mW output power, the MOPA devices showed a nearly diffraction limited beam quality with a M2<1.5 and reliable operation with degradation rates as low as 2x10-5h-1 over 1500h. The spectral linewidth is determined by the master oscillator and suitable for high resolution spectroscopy.

These values show a strong improvement compared to published results of red-emitting tapered devices (700mW, M2 < 3).

6485-43, Session 12

Highly strained InGaAs lasers grown by MOVPE with low threshold current density

W. Chen, Y. Su, R. W. Chuang, M. Tsai, National Cheng Kung Univ. (Taiwan)

Recently, GaAs-based long wavelength lasers have attracted much attention owing to their advantages such as low substrate cost, mature AlGaAs/GaAs DBR and the high conduction band offset. Among the GaAs-based material system, highly compressive strained InGaAs would be a suitable candidate for the 1300nm VCSEL application while combined with the large gain-cavity detuning technique. In this work, we have successfully fabricated the highly compressive-strained InGaAs broad-area lasers grown by MOVPE. After optimized the epitaxial parameters, these lasers were operating at 1219.56nm with narrow line width of 0.08nm. The InGaAs laser could successfully be continuously waving (CW) under 20¢J with low threshold current density Jth =168A/cm2. To our knowledge, the demonstrated InGaAs QW laser has the lowest Jth/QW =56 A/cm2 to date. The fitted characteristic temperature (T0) was 123.9K indicating the good electron confinement ability. In addition, by lowering the growth temperature to 475 ¢J, we have also obtained the InGaAs/GaAs double quantum wells whose PL peak was at 1249nm and FWHM was 52.8meV. These good characteristics indicate the possibility of fabricating InGaAs VCSELs lasing at 1300nm.

6485-44, Session 12

Lifetime prediction of diode lasers with different aging behavior

Y. Li, Symbol Technologies, Inc.

Laser diodes are non-reparable devices, their reliability is defined by TTF (Time to Failure) obtained from the test data collected from accelerated laser reliability test. In such a test a large number of lasers are placed in a thermal chamber simulating the maximum rating operation (i.e., the maximum environmental temperature and maximum optical output power) for a period of several thousand hours. If the lasers in test are operated in a constant output power mode, the operating current Iop increases gradually during the test because of laser degradation an increasing Iop to maintain the constant power output. The generally accepted failure criterion for InGaAlP laser in the APC mode operation is an increase of operating current Iop to 1.2 of its initial value. Here we have implicitly assumed that Iop keeps increase in laser operation. Lasers with increas-

ing Iop are considered as lasers with normal aging behavior.

However another kind of InGaAlP lasers become increasingly common and is now known as the lasers with negative sloping, i.e., their operating current Iop keeps decreasing in APC operation. Lasers with negative sloping are first observed in lasers grown by LPE (Liquid-Phase Epitaxy) technique, and the decreasing operation current was explained as a result of reducing non-radioactive recombination centers in the active region. After production stage by using MOVPE (Metal-Organic Vapor-Phase Epitaxy) technique, effect of negative sloping has been intensified. The root cause is the Zn dopant in the p-cladding layer passivated by hydrogen. The Zn electrical activity is low due to hydrogen passivation for the wide gap materials like InGaAlP grown by MOVPE technique. As laser diode has been operated for a long time, the Zn in the p-cladding layer is depassived from hydrogen and hole-carriers can be injected to the active region more easily. As a consequence of Zn depassived from hydrogen, the effect of negative sloping tends to be diminished as the aging time increases, and then it could finally turn to be a positive sloping laser. However, this kind of test of lasers needs several tenths of thousand hours, which makes laser lifetime evaluation impossible for industrial applications. The aim of this study is to develop a unified technique for laser aging data processing, which allows us to predict correct results for lasers with either a positive or a negative sloping from the same failure criterion.

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6486-01, Session 1

Nitride nano-LEDs

L. Tu, Y. J. Tu, M. Chen, Y. T. Lin, C. L. Hsiao, National Sun Yat-Sen Univ. (Taiwan)

With the possible advantages of less defective structure, higher light extract efficiency and the potential applications of its nano-size in light emitting, nitrides in nanorod structures are investigated in this report. The samples of nanostructures are grown by plasma-assisted molecular beam epitaxy system. Substrate used is Si(111) wafer for its conductive property besides its popularity in chip industry. In a proper growth parameter window with a buffer layer, sparse and well developed nanorods with a hexagonal shape are formed while under another growth condition without a buffer layer, high-density nanorods can be obtained. These nanorods are dislocation free and all aligned along a unidirection of crystallographic c-axis. Fundamental properties are characterized through a series of measurements and analyses including high-resolution transmission electron microscopy, field-emission scanning electron microscopy, photoluminescence, cathodoluminescence, micro-Raman spectroscopy, X-ray diffraction, energy dispersive spectrometer, etc. A double heterostructures of InGaN/GaN are grown under various growth conditions with a basic pn junction structure in a nanorod. Metal contacts are fabricated and electroluminescence is performed. Colors ranging from red to purple in the whole visible spectra are seen.

6486-02, Session 1

GaN-based light-emitting diodes grown on patterned substrates by metal-organic vapor phase epitaxy

J. Chyi, National Central Univ. (Taiwan)

Patterned substrates, such as etched sapphire, silicon, metal-, SiO or SiN-coated sapphire, have been utilized for GaN-based devices. Although they are proposed for different reasons, the resultant positive effects have made this technique very attractive for both device applications and scientific investigations. In this talk, two cases that involve the growth of GaN on wet etched sapphire substrates and SiON-coated sapphire substrates are covered. The effects of these patterned substrates will be addressed in terms of structural properties as well as optical properties. For the former case, the influence of the etched profiles of sapphire substrates on GaN growth is investigated. The performance of LEDs grown on different patterned are also compared and discussed based on the contribution of defect reduction and light-scattering effect. Due to the difficulties involved in producing patterned sapphire substrate in mass production scale, an alternative approach, i.e. the latter case, is proposal to mimic the former case with additional advantages of reducing dislocation via epitaxial lateral overgrowth and enhancing light extraction via light scattering. InGaN/AlGaN multiple-quantum-well LEDs are grown on sapphire substrates with stripe SiON patterns along the <11-20>sapphire direction, which is defined by standard photolithography and dry etching processes. Output power of the LEDs is increased as high as 60% compared with the LEDs on planar substrates. Etch pits density, cathodoluminescence, cross-sectional transmission electron microscopy and two-dimensional electroluminescence emission of the LEDs indicate that the improvement in output power is attributed to both reduced dislocation and enhanced light scattering resulting from the SiON stripe patterns.

6486-03, Session 1

High extraction efficiency light emitting diodes for electroluminescence refrigeration

S. Yu, N. A. Rider, J. Wang, D. Ding, S. R. Johnson, Y. Zhang, Arizona State Univ.

Light-emitting diodes (LEDs) are promising candidates for the development of vibration-free, solid-state, electrically injected optical refrigerators. High luminescence extraction efficiencies are required to achieve electroluminescence refrigeration in semiconductors. To achieve this, InGaAs/GaAs heterostructure LEDs are monolithically integrated with suspended hemispherical lenses. InGaAs quantum wells emitting at 920 nm are chosen as the LED active region for their high internal quantum efficiency, near-index-match to GaAs, and emission energies below the GaAs bandedge; semi-insulating GaAs substrates are used to eliminate free-carrier absorption within the substrate. All of which increase the luminescence extraction efficiency of this device. The hemispherical lens is fabricated on the substrate side of the LED, by first forming a photoresist lens using reflow and then transferring the lens pattern to GaAs substrate using inductive-coupled-plasma etching. An anti-reflection coating layer is deposited on the surface of the lens to maximize the light extraction. The dimensions of the hemispherical lens and the active region are chosen such that luminescence emitted from the active region is inside the escape cone of the GaAs lens. The edge of the flat side of the hemispherical lens is attached to, and thermally isolated from, the surrounding GaAs via four narrow beams fabricated using dry-etching. Based on theoretical modeling, close to unity light extraction efficiency is expected for this structure. Further fabrication details and characterization results will be reported.

6486-04, Session 1

Non-period binary optical structures for enhancing light extraction of emitters

L. Hong, T. Yu, T. Dai, Z. Zhang, J. Xu, G. Zhang, X. Hu, Peking Univ. (China)

A new method of designing binary optical structures to improve light extraction efficiency for emitters is presented. By this method a novel binary optical structure is generated. Such structures with a width of around 300 nm, are non-period and small enough in size that they do not generate diffraction orders other than the zero order, they are also insensitive to polarization. They serve as an antireflection layer, sending light outward that would otherwise be absorbed within the device.

The experimental devices were GaN based LEDs emitting at 460nm. The non-periodic binary structures and some periodic structures such as triangle-lattice Photonic Crystals (PC), 12-fold Quasi-periodic Photonic Crystals (QPC) are fabricated on the same sapphire side of a LEDs flip chip with Focus Ion Beam (FIB) for comparison. The surface profile of the structures was characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM). Near field scanning optical microscopy (NSOM) was used to measure the output spectral properties of the devices. EL measurements show that the greatest enhancement of emission light intensity was achieved in non-periodic binary structures, increased by 60~135% at room temperature. It demonstrates that this Non-Period Binary Optical Structures will be useful for fabrication high efficient GaN-based LED.

6486-05, Session 1

High light-extraction efficiency in GaInN light-emitting diode with pyramid reflector

J. Xi, H. Luo, J. K. Kim, E. F. Schubert, Rensselaer Polytechnic Institute

A new type of reflector with a 3-dimensional pyramidal structure consisting of an array of SiO2 pyramids and a reflective Ag layer is used to increase the light-extraction efficiency of a GaInN LED. The multi-quantum well GaInN LEDs used in this study are grown by metal-organic vapor-phase epitaxy and have a peak emission wavelength of 400 nm. An array of pyramids is fabricated on p-type GaN by plasma enhanced chemical vapor deposition of a 1.2 micron thick SiO2 layer followed by wet chemical etching. Each SiO2 pyramid has a base width of 3.5 micron and a slope angle of 25 degree. The metallized spacing between pyramids is 2.5 micron and serves for ohmic contact formation. Ag is deposited on top of the SiO2 pyramids and used as a reflective layer. A reference multi-quantum well GaInN LED with planar Ag reflector is fabricated for comparison. The GaInN LED employing the pyramid-patterned Ag reflector is demonstrated to have a 14 % higher light-output compared to the LED with a planar Ag reflector. The higher light output of the pyramid-patterned LED is attributed to enhanced light-extraction efficiency enabled by the change in propagation direction of light rays when reflected by the 3-dimensional structure of the pyramid reflector.

Due to total internal reflection, GaInN LEDs with planar reflector have an escape cone angle of 23.6 degree. A GaInN LED with 3-dimensional pyramid reflector is shown to have an additional escape cone of 25.5 degree - 36.0 degree, that is enabled by the 3-dimensional pyramid structure. Optical ray-tracing simulations are performed on both the GaInN LED with a pyramid reflector and the LED with a planar Ag reflector. The simulation results show that the pyramid reflector, with pyramid slope angle of 30 degree, increases the LED's bottom emission by 27.6%, and total emission by 14.1%, consistent with our experimental results.

The current-spreading length for the p-type GaN beneath each SiO2 pyramid is calculated to be few micrometers, which is comparable with the base dimension of a single SiO2 pyramid. This shows our GaInN LED with pyramid reflector has a reasonable current spreading beneath the SiO2 pyramid.

6486-06, Session 1

LEDs engine hosted on a THS

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A ceramic THS cooler solder mounts a broad, regular field of LEDs and the electronics. To collect the lateral emissions, each LED seats on a thermal riser at a focus of its primary mirror. If parabolic, the mirrors deliver collimated beams. The ellipticals focus on phosphor dots, on the window or tipping the delivery FOs. The sealing window, eventually integrating lenses, complete this self-cooled compact unit.

The forced air Turbo Heat Sink / THS is an effective cooler for electronic systems.

AlN, a ceramics, sports low TCE and high thermal conductivity, similar to Al. The deep air-cooling channels and the conical sides of the thermal risers are formed before firing, by milling or compacting the powders; later, the mounting plane and the riser-tips are ground and coated with multilayer tracks.

The mounting plane solders directly the drivers and the LEDs, each seating on a broad shallow cone; the hybrid electronics includes IOs, drivers, controls, Opto and thermal sensors.

Compared with Laser Diodes, current LEDs are cheaper but also far less efficient; extracting most of the light and a weak structure seem the main problems; coupling a thermally effective mount with a collector of lateral emissions can widen the R&D possibilities.

The possible applications are very broad and some have been delineated. An assembly including more secondary mirrors, curved or rotating, can form an RYG traffic light, a beacon / lighthouse, or a smart engine for projection displays. In the UV, the LEDs generate more power than any LDs; here, the not so coarse focus of a compound mirror can cure adhesives, sanitise waters etc.

6486-07, Session 2

Recent progress of high efficiency GaN-based light emitting diodes

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Recently light-emitting diodes (LEDs) are attracting much attentions mainly because of the huge improvement in wall-plug efficiency which is one of the key factors for opening a new era of solid state lighting. Especially GaN-based near-ultraviolet and blue LEDs have been intensively investigated for primary light sources of phosphor-converted white LEDs during last ten years. In this presentation we will report on the recent progress and future aspect of high efficiency GaN-based LEDs. We will propose various kinds of top-down and bottom-up type patterned structures to improve the light extraction efficiency. We also present the characteristics of Ag-based and Al-based metal schemes for p-type reflectors. Regarding internal quantum efficiency, we will discuss about optical and structural properties of AlInGaN nanostructures. Finally the device performance of LEDs will be presented in detail.

6486-08, Session 2

Mass production AIX 2800G3 HT MOCVD reactor in the 42x2 inch configuration for the growth of optoelectronic devices

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Current state of the art technology for the supply of group III and group V precursors for nitride MOCVD involves a gas inlet centered within the process chamber producing a symmetric flow profile directed towards the exhaust. A third inlet above the MO for the supply of group V species was introduced, providing more control over the deposition process by shortening the so-called gas entrance length via re-distribution of some of the group V gas flow to the top inlet. The ratio of the hydride gas flows in the upper and lower group V inlets is now an extra tuning parameter to optimize growth rate uniformity. In addition, the presence of a third gas inlet above the MO pushes ceiling deposition further downstream away from the injector. The growth environment inside the process chamber is further optimized via a water-cooled injector head, which provides a more abrupt transition from the cold inlet zone to the process ambient. This ensures the injector head remains deposition free thereby promoting better growth conditions, in particular for high Al content layers where the risk of adduct formation is extremely high even at low gas phase temperatures. Experimental results using the new injector in the 42x2" configuration show typical peak PL wavelength standard deviations of 1 nm at 470 nm and 492 nm with a wafer-to-wafer standard deviation of 1.44 nm. Run to run reproducibility is reported at a span of 3.9 nm (blue spectral range) and 4.4 nm (green spectral range).

6486-09, Session 2

Dicing of high power white LEDs with heat sink by water-jet-guided laser

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High-power LEDs are compound semiconductor devices and distinguish themselves from conventional LEDs by their brightness levels. They are today used as light sources to replace conventional incandescent and fluorescent lamp technologies. HP LEDs are difficult to manufacture as they must be grown by sophisticated epitaxial growth techniques such

as MOCVD. They are packaged like power semiconductors, using surface mount technology and thermal pads.

After having been successfully applied to GaN scribing for side-emitting LEDs, the Laser MicroJet is today used for cutting heat sinks for HP white LEDs. Indeed, since the emitting light power is high, the generated heat must be drained off through a heat sink. Typical materials are metals with high heat conductivity such as CuW, molybdenum or CVD. Using the Laser MicroJet, the achieved cutting quality in these metals is outstanding - smooth edges, no contamination, no burrs, no heat damage, no warping - all this at high speed.

6486-10, Session 2

Study of wet etching on sapphire by H3PO4 and H2SO4 acid solution

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Currently, wet etching on sapphire has been proposed to apply in two LED fabrication processes, which are sapphire removal and patterned sapphire substrate. Up to now, H3PO4 and H2SO4 are two chemical acids often used to etch sapphire. In this study, we investigated the kinetics and etched morphology on sapphire substrate by three kinds of acid solutions (pure H3PO4 and pure H2SO4 and mixed solution of H3PO4 : H2SO4 = 3 : 1). We found that the etching morphology on sapphire surface is relatively smooth by using pure H3PO4. As for pure H2SO4, the etching surface on sapphire is very rough, yet, the rate is very sluggish. The mixing solution of H3PO4 and H2SO4 showed the fastest etching rate on sapphire. In addition, the etching rate is very sensitive and dramatically increases with temperature. An on-set temperature was found for the sapphire etching by pure H3PO4 and the mixed solution of H3PO4/H2SO4, which is about 260 °C. Detail kinetics and formation of the etching morphology on sapphire substrate will be reported in this talk.

6486-11, Session 2

Integration of high-efficiency PIN organic light-emitting devices in lighting and optoelectronic applications

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Displays based on organic light-emitting diodes (OLED) have rapidly developed and are commercially available since some time. However, in order to achieve large market penetration in new segments like lighting and optoelectronic, it is generally expected that the current status of the field has to advance in terms of manufacturing cost and integration possibilities.

OLED devices with electrically doped transport layers show low operating voltage, high efficiency and long lifetime. In this paper we demonstrate that the concept of p- and n-type electrical doping can be applied under manufacturing conditions on the worldwide first vertical in-line fabrication setup for large area lighting applications. An in-line-manufactured highly efficient white-OLED-system will be presented. The driving of large area lighting tiles defines the resulting OLED lifetime and efficiency. In this paper we will present first results on the driving of large area lighting panels.

Beside the lighting application the integration of highly efficient OLEDs for optoelectronic applications is a new opportunity for innovative new applications. Microdisplays, integrated optocoupler and light barriers are few examples for the potential of OLEDs in optoelectronic applications. We will present first results regarding the integration of highly efficient top-emitting PIN OLEDs(tm) for optoelectronic applications.

6486-12, Session 3

New architectures for high performance polymer light-emitting diodes introducing a solution-processed titanium oxide layer

K. Lee, Pusan National Univ. (South Korea)

We report a novel approach that leads to significant improvement of the performance of polymer-based light-emitting diodes (PLEDs). By introducing a solution-processed titanium oxide (TiOx) layer between the active layer and the aluminum cathode, we have demonstrated that the device performance is significantly enhanced compared with the conventional devices without the TiOx layer. The TiOx layer acts as an electron transport/hole blocking layer in PLEDs, thereby improving the carrier balance in the emitting layer and enhancing the device efficiency. In case of top-emitting PLEDs employing aluminum-doped zinc oxide (AZO) as a transparent electrode, the TiOx layer plays an additional role. The TiOx layer prevents the external damage to active polymer caused by UV radiation and by high energy ions generated during the AZO sputtering, thereby preserving the integrity of the luminescent polymers and consequently the efficiency of the devices.

6486-13, Session 3

OLED lighting - light where it never has been before

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The key challenges for the OLED lighting technology rests on three pillars at the same time. At first, the common lighting requirements, mainly lifetime, efficiency, and color quality, have to be met. Secondly, the intrinsic new OLED features need to be maintained by the manufactur¬ing process and the materials used. Last but not least, all of the above must meet cost targets which are orders of magnitude below the cost of manufacturing OLED displays. Within this talk the status of the technology will be reviewed as well as first potential applications will be discussed.

6486-14, Session 3

See-through OLED displays

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Recently, transparent computer screens have been the vision in Hollywood motion pictures. In reality, see-through displays will open up a large variety of novel applications in daily life: For the automotive sector the integration of transparent displays in e.g. the wind screen to assist the driver with essential informations will be an important issue. In medicine during surgery, transparent screens could supply the surgeon with additional informations in his field of view. Security and defense applications aim at head-mounted displays where the area of “augmented reality” currently is a hot-topic.

Organic light emitting diodes (OLEDs) appear to be the most promising technology for the realization of transparent displays. The organic layers that make up an OLED are transparent in the visible part of the spectrum. If conductive oxides like Indium-Tin-Oxide or doped Zinc-Oxide instead of metallic layers are used as contacts entirely transparent OLEDs with current efficiencies as high as 33 cd/A and a transmissivity of more than 80 % have been realized. Based on this technology Small-sized, low information content displays with moderate pixel counts can be readily fabricated. To accomplish the claim for larger-area, high-resolution OLED displays an active-matrix addressing scheme is mandatory.

In today’s active matrix displays the semiconductor of choice for the pixel-driving thin film transistors (TFTs) is silicon. To allow for transparent displays with opaque silicon drivers, the TFTs and the OLED pixels need to be positioned next to each other compromising the overall display trans-

parency and limiting the displays resolution. Our approach is to use TFTs which are transparent themselves. Rather than silicon these TFTs are based on the wide-bandgap semiconductor Zinc-Tin-Oxide (ZTO), which transmits more than 90 % of the visible light (400-750 nm). The ZTO films are deposited at low process temperatures (< 200°C) which would even be suitable for plastic substrates. The transistors have a field-effect mobility of 11 cm2/Vs and an on-off ratio of 105.

The OLED pixel which needs to be driven may be conveniently positioned directly on top of the driver circuit without interference. This technology allows for the realization of active matrix OLED displays with a high transparency of about 70% in the visible - sufficient even for automotive applications.

6486-15, Session 3

Vacuum fabrication of a functional PLED by IR laser vapor deposition

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Polymer light emitting devices (PLEDs) are attracting increasing interest for potential applications in flat panel displays and solid-state lighting. Currently these devices are fabricated by liquid phase deposition techniques, such as spin coating or ink jet printing, because the thermally labile polymers cannot be deposited by sputtering. This introduces the disadvantages of potential unwanted solvent interactions and ambient air processing conditions. An all-vacuum deposition process would avoid the complexities involved in these techniques, as well as potentially streamline the manufacturing process.

We have successfully fabricated PLEDs in a vacuum environment by resonant infrared laser vapor deposition (IR-LVD), using a picosecond free-electron laser as the light source. The device structure consisted of glass/ITO/MEH-PPV/Al., and was fabricated using the following protocol: The MEH-PPV was dissolved in 1,2, dichlorobenzene (DCB) and frozen in liquid nitrogen to form a solid target. The target was then placed in a vacuum chamber and an infrared laser tuned to a wavelength resonant with a vibrational mode of the target matrix (DCB) was focused gently onto its surface. This generated a plume of vaporized material which was collected on a nearby ITO substrate. After the polymer deposition, aluminum was thermally evaporated as the cathode. Multilayered devices were also fabricated where a hole transport layer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) was first deposited by IR-LVD on an ITO substrate, followed by MEH-PPV and the aluminum cathode. The time to deposit the layers in vacuum was typically a few minutes, at an average FEL power of 300 mW. These LVD deposited devices displayed similar characteristics such as turn on voltage and electroluminescence spectra as conventional spin coated devices.

6486-16, Session 3

Employing a 2D surface grating to improve light out coupling of a substrate emitting organic LED

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The organic LED is a very promising candidate for future lighting applications. One way to achieve high efficiency is by increasing light out coupling. We numerically and experimentally have investigated the effects of a grating attached at the glass substrate of a substrate emitting OLED. This grating eliminates total internal reflection in the glass substrate.

For the organic layer stack of the OLED used in the experiments, we numerically have found an optimal wavelength independent fill factor, grating period and depth. This optimal depth corresponds to a surface corrugation of only 500 nm. These simulations also indicate that light out coupling can be improved by 50% compared to a planar interface.

The grating has been fabricated by reactive ion etching a SiOx deposited layer on top of the glass substrate. The grating pattern in positive resist was defined with our interference lithography setup, which is limited to an area of a few tens of square mm. These gratings were attached to the glass substrate of a given OLED of 9 square mm with an optical contact fluid to minimize reflections at the interface. The spectral output power was measured with an integrating sphere. Our optimal grating experimentally gives an average relative improvement of approx. 30%.

The deviation between simulation and fabrication can be explained by a larger than expected absorption in the organic layer stack.

This work has been performed in the context of the European Union funded project Olla (IST-004607), which focuses on OLEDs for lighting applications. (www.olla-project.org

6486-17, Session 4

Recent progress in understanding and optimizing nitride-based light emitters

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While blue LED's based on nitride heterostructures are approaching 100% internal efficiency, both green and ultraviolet LED's are still much less satisfactory. Based on our novel in-depth understanding of mechanisms suppressing nonradiative recombination in GaInN-based quantum wells, we discuss optimization strategies for nitride LED's. We demonstrate dramatic efficiency improvements both for green-emitting GaInN/GaN quantum wells as well as for UV-emitting GaN/AlGaN quantum wells.

6486-18, Session 4

Measurement of the internal quantum efficiency of InGaN quantum wells

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Light-emitting devices based on InGaN/GaN quantum-well heterostructures exhibit a high external emission efficiency even if they suffer from high defect densities due to heteroepitaxial growth. Apart from light extraction and carrier injection efficiencies, the external efficiency is governed by the internal quantum efficiency (IQE) of the InGaN quantum-well. The IQE thus renders useful in assessing quantum well quality.

Here we report temperature and excitation-power dependent resonant photoluminescence (PL) measurements of InGaN quantum-well test-structures. We determine the IQE as the ratio between PL-intensity at 4K and at room temperature. Our measurements also yield information about luminescence decay-times and the fluctuation induced S-shape of emission-energy over temperature. For different structures, we find IQE-values differing largely. The results correlate with small-current electroluminescence (EL) measurements, where low EL intensity and EL-IQE correlate with low PL-IQE.

We attribute the scattering of the IQE measurements to an undoped interlayer between the active region and the p-side of the structure. We propose a model that relates the existence of a carrier-reservoir near the recombination region to the exciton recombination rate.

6486-19, Session 4

Design and implementation of real-time LED spatial radiance measurement systems

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Light-emitting diodes (LEDs) take advantage of energy-saving, environmental protection, long lifetime, etc., and as a result, they have been considered to replace conventional lighting, as a generation of new light sources. To satisfy the requirements of different applications (e.g., that of LCD back-light modules), the spatial radiance of LEDs is important and

necessary to making use of their lighting efficiency. Our objective is to build up a real-time spatial radiance measurement system for LEDs, on the basis of digital signal processing (DSP) techniques, and thus to improve the luminous efficiency and to lower the cost of manufacturing LEDs. In this paper, the system analysis is given to show the feasibility of this work. Two primary subsystems are devised to perform the real-time measurements. First, in the optoelectronic sensing and signal processing part, a wide-bandwidth photodiode sensing circuit is employed to acquire optical information at a high speed, and a high Q-factor dual lock-in amplifier (LA) is designed to suppress the effect of noise from ambient light. This electronics subsystem is implemented in a DSP chip for high-speed data acquisition and noise supression. Second, a light-source rotation scheme is used in the optomechanical subsystem, and then the computer simulation is performed to simulate the scheme in operation. For performance evaluations, we adopt different kinds of optomechanical configurations to test and verify our system with a calibrating light source. In this work, the proposed system is implemented so that the real-time spatial radiance measurements are achieved for the industrial applications of LEDs. Experimental results indicate that this system gives a satisfactory result.

6486-20, Session 4

Studies of InGaN LEDs degradation

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The idea of the replacement bulbs (incandescent lamps) and luminescent lamps by Light-Emitting Diodes (LED) is very closely for the realization because of the progress of AIIIBV based LEDs [1, 2]. One of the practical significance problems is the degradation of performance LED's characteristics.

We investigated the LED's degradation during 10 000 hours and of the influence of ultrasonics action on the InGaN LEDs (we continued this work[3], which is very interesting because of increasing using LEDs in aircrafts or in medicine in which ultrasonic action can be, also we simulated blue and green InGaN LEDs After even 2 hours of ultrasonic vibrations at both frequencies the signals value decreased noticeably. The broadening at the full width at half maximum also varied. The model of LED degradation is suggested [4].

Some our simulation results correspond with the simulation results of Opto Semiconductors Osram [5]

All this also exactly corresponds with our experimental results of LEDs degradation investigation during 10 000 hours.

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6486-21, Session 4

Prediction of intensity and color degradation of LEDs

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The intensity and color degradation of light-emitting diodes (LEDs) can significantly affect the reliability of demanding lightning products for which a certain level of intensity and color homogeneity is required. Intensity degradation is sometimes characterized by manufacturers in a form of a mean half-lifetime, i.e. a time in which the initial intensity of LEDs decreases to 50 %. However, additional information on intensity and color degradation and corresponding variability in a batch of LEDs is required for designing and maintaining demanding state-of-the-art lightning products.

For this purpose, a current-accelerated method, predicting intensity and color degradation and corresponding variability of LEDs, is presented. The method is based on automated periodical spectral measurements of LEDs and computerized analysis of the acquired data. The information on intensity and color degradation and corresponding variability of LEDs, driven by the above-nominal currents, is extrapolated so as to predict the degradation of LEDs at arbitrary current. The method was validated by comparing the predicted and measured intensity and color degradations and corresponding variability at the nominal current.

The proposed method was tested on 1000 ultra-bright white LEDs (luminous intensity ranged from 5 to 20 cd) from six manufacturers (Seoul Semiconductors, Nichia, Etgtech, Sansen, Daina, and Velleman). The method was proved to be useful for predicting intensity and color degradation of the six tested batches. The results also show that the half-lifetimes specified by manufacturers are usually over estimated. The intensity and color degradation and corresponding variability in the six tested batches is significant. In conclusion, the proposed current-accelerated prediction of intensity and color degradation of LEDs was proved feasible for designing highly demanding lightning products.

6486-22, Session 4

Thermally induced stresses resulting from coefficient of thermal expansion differentials between various LED substrate materials and mounting substrates

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An empirical study has been performed to quantify the mechanical stresses induced from the coefficient of thermal expansion (CTE) mismatch between several light emitting diode (LED) materials and various substrate materials to which the LEDs are mounted. LED substrates under evaluation include: Indium Gallium Nitride (InGaN) on a silicon sub-mount, and Aluminum Gallium Indium Phosphide (AlInGaP) on a silicon sub-mount. The LEDs were directly bonded to typical packaging materials including copper and ceramic. There are several ceramic materials that are commonly used in LED packaging, however, they are typically expensive when compared against copper. The objetive of this investigation was to determine the viability of implementing copper as a lower cost alternative to ceramic. In particular, thermally induced stresses resulting from the higher CTE mismatch between copper and the LED substrate materials were analyzed and compared against the stresses resulting from the nearly ideal expansion coefficient match that is achieved with ceramic.

6486-37, Poster Session

Developing a new supplemental lighting device with ultra-bright white LED for vegetables

Y. Hu, P. Li, J. Jiang, JiangSu Univ. (China)

It has been proved that monochromatic or compound light-emitting diode (LED) or laser diode (LD) can promote the photosynthesis of horticultural crops, but the promotion of polychromatic light like white LED is unclear. A new type of ultra-bright white LED (LUW502A, InGaN,Φ5, 150mW, 15000 mcd, wavelength range: 400~720 nm) was selected to make up of the supplemental lighting panel (200X300 mm2), on which LEDs were evenly distributed with 90 branches. Driving circuit was designed to power and adjust light intensity. System performance including

temperature rise and light intensity under different currents and vertical/horizontal distance were tested. Photosynthesis of sweet pepper and eggplant leaf under white LED was measured with Li-6400 to show the supplemental lighting effects. The results show that LD system can supply the maximum light intensity of 300 μmol/m2•s at the distance of 100 mm below the panel and the temperature rise is higher over 13 ºC on the surface of LED encapsulation, but hardly changes 100 mm far away the panel. For both of the two vegetables net photosynthetic rate became faster when white LED system increased light intensity. Compared with sunlight and plant growth fluorescent lamp, white LED promotion on photosynthesis is inferior because the spectra of white LED is unreasonable with more blue light and less red light. Therefore, the unreasonable spectra become the major constraint of its application. But the prospect of white LED application into vegetable crop production is bright.

6486-45, Poster Session

Development of 140-inch autostereoscopic display by use of full-color LED panel

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LED displays are a preferred technology for outdoor installations, such as stadiums, street advertising, and billboards. Our goal is to realize a stereoscopic large LED display for the general public in the open air. For the sake of realizing such an autostereoscopic (i.e. glass-free stereoscopic) large display, there are three requirements. 1) Plural viewing positions are provided by use of an image-separating device. 2) The image-separating device does not restrict the directivity of a large LED panel. 3) Three-dimensional (3D) images can be perceived under surrounding light conditions.

To meet the three requirements, we propose a parallax barrier by use of an aperture grille. The aperture grille is composed of black stripes and apertures. The parallax barrier separates an interleaved stereoscopic image into both perspective images at plural viewing positions. Experimental results of viewing areas revealed that the use of the aperture grille prevents surface reflection and increases transmitted light.

We have developed a large autostereoscopic display by use of 140-inch LED panel. The LED panel is 512 x 228 pixels. The pitch of the LED panel is 6.0 mm. Each pixel is consisted of a red, a green, and a blue LED in SMD package. The size of the parallax barrier is 4 m x 2 m. The viewing distance is 15 m. Viewing positions are located side by side at the interval of 130 mm within the range of 16 m in the width. Furthermore, we have conducted experiments about the depth-perception. It was confirmed that plural viewers perceive the 3D images under lighting conditions.

6486-48, Poster Session

Nanoparticle-loaded encapsulants for light emitting diodes enhance light extraction via refractive index increase

F. W. Mont, H. Luo, J. K. Kim, E. F. Schubert, Rensselaer Polytechnic Institute

The light extraction efficiency of a light emitting diode (LED) is limited by a large refractive index (n) contrast between the semiconductor and encapsulant, which limits the size of the light escape-cone thus decreasing photon extraction. Nanoparticle-loaded encapsulants can enhance the overall refractive index of the composite material, thus leading to high light extraction efficiency by enlarging the light escape-cone. The successful application of nanoparticle-loaded encapsulants strongly depends on the technique to properly stabilize and disperse the nanoparticles into a polymer encapsulant to minimize optical scattering by aggregation of nanoparticles.

Uniform and stabilized dispersion of TiO2 nanoparticles with a filling factor of 10% in epoxy is demonstrated by using proper fabrication processes including drying and surface modification of TiO2 nanoparticles with the help of appropriate chemical surfactants, and mixing the nanoparticles with epoxy. The refractive index of our TiO2 nanoparticle-loaded epoxy is as high as n = 1.70 at 400nm, much higher than that of the pure epoxy film, n = 1.53, which will lead to much higher light-extraction efficiency in LEDs.

6486-23, Session 5

Interplay between light extraction and generation in photonic crystal GaN LEDs

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In GaN LEDs for blue or white lighting, the issue of extraction by photonic crystals has been tackled by many groups. The main issue is to extract guided modes in the thick GaN layer, where over 60% of the light is usually captured. By paying attention to the full modal structure of usual GaN LEDs, we identified a number of issues that photonic crystals have to fulfill in order to achieve sizable extraction at the device scale. We shall briefly outlined these issues. Of course, the period, depth and arrangement of holes need to be adjusted (e.g. using Archimedean lattices), but the scope of “bright” extraction in a short in-plane length requires modifications of the vertical modal structure, as we demonstrated experimentally. Further along this way, we shall hint at more fundamental modifications of the emission process in textured systems, that could help grabbing useful photons even more efficiently.

6486-24, Session 5

Novel GaN-LED structures for high surface extraction efficiency

H. Jeon, Seoul National Univ. (South Korea)

In this presentation, I will introduce two types of LED structures, both of which aim for high photon extraction efficiency through the surface of GaN-LEDs.

In the first type, two-dimensional (2D) photonic crystal (PC) patterns were integrated onto the surface of GaN LED devices. Laser holography technique was employed for wafer-scale patterning of 2D-PCs at high throughput, a big contrast to the conventional electron-beam lithography used for most PC research. Due to strong light diffractions by the 2D PCs, light output from devices with a square-lattice PC pattern was more than doubled over the conventional non-patterned LED devices.

The second type of the LED structure, named sidewall-deflector-integrated (SDI) LED, has a special feature of angled sidewalls all around the LED mesa edges. Those angled sidewalls efficiently deflect, via total internal reflection, the photons that are guided through the air/GaN/sapphire waveguide structure naturally formed in the GaN LED epilayer structure. Although the structural modification made to the conventional LED was minor, the influence of the angled sidewalls on the LED output was significant; light output from the substrate-side-emitting SDI-LED was doubled over that from the reference LED.

6486-25, Session 5

Manufacturing implications for photonic crystal patterning using imprint lithography

C. Jones, D. Lentz, G. F. Doyle, M. L. Miller, M. Ganapathisubramanian, X. Lu, D. L. LaBrake, Molecular Imprints, Inc.

The Step and Flash Imprint Lithography (S-FILTM) process is a nano-imprint lithography technique based on UV curable low viscosity liquids.1,2,3 S-FIL uses drop dispensing of UV curable liquids to pattern entire wafers with a single imprint. This approach allows for micro and nano-fabrication of devices with widely varying pattern densities and complicated structures over wafers with high nanotopography . Patterning of arbitrary shaped sub-100 nm structures with nanotopography which is

greater than 10 ∝m is not obtainable using DUV stepper technology. Photonic crystal structures, wire grid polarizers and micro lenses are examples for optical components that can be formed using S-FIL technology imprinting on whole substrates.

The authors have devised a beginning to end lithography process which includes: wafer preparation processes for imprint, a high throughput whole wafer step and repeat imprint process and dry etching processes for resists and hard mask patterning. The process is capable of patterning sub-100 nm hard masks on substrates where the nanotopography is in excess of 10 ∝m across the substrate. The imprint process flow uses the Step and Flash Imprint Lithography Reverse (S-FIL/R) tone process which has been demonstrated to be robust at holding critical dimensions for a wide window of etch conditions, wafer topography and defects.1,4,5 The authors describe a photonic crystal patterning process from beginning to end with particular attention to etch selectivity, analysis of cross wafer critical dimensions and a survey of defect requirements for successful high yield imprint patterning.

Step and Flash Imprint Lithography: A New Approach to High-Resolution Patterning

Colburn, M., Johnson, S., Stewart, M., Damle, S., Bailey, T., Choi, B.J., Wedlake, M., Michaelson, T., Sreenivasan, S.V., Ekerdt, J., and Willson, C.G.

Proceedings of the SPIE's 24th International Symposium on Microlithography: Emerging Lithographic Technologies III, Santa Clara, CA, Vol. 3676, Part One, pp. 379-389, March 1999.

Analysis of Critical Dimension Uniformity for step and flash imprint lithography

David P. Mancini, Kathleen A. Gehoski, William J. Dauksher, Kevin J. Nordquist, Douglas J. Resnick, Philip Schumaker, and Ian McMackin.

SPIE Microlithography Conference, February 2003.

Step and Flash Imprint Lithography for sub-100nm Patterning

M. Colburn, A. Grot, M. Amistoso, B. J. Choi, T. Bailey, J. Ekerdt, S.V. Sreenivasan, J. Hollenhorst, C. G. Willson.

2000 SPIE's 25th Intl. Symp. Microlithography: Emerging Lithographic Technologies III. Feb. 28 - Mar. 3, 2000 Santa Clara, CA.

Development of Imprint Materials for the Step and Flash Imprint Lithography Process

Frank Xu, Nick Stacey, Mike Watts, Van Truskett, Ian McMackin, Jin Choi, Philip Schumaker, Ecron Thompson, Daniel Babbs, SV Sreenivasan, Grant Willson, Norm Schumaker.

SPIE Microlithography Conference. February 2004.

Fabrication of Nanometer Sized Features on Non-Flat Substrates Using a Nano-Imprint Lithography Process

Mike Miller, Gary Doyle, Nick Stacey, Frank Xu, S.V. Sreenivasan, Mike Watts, Dwayne L. LaBrake.

SPIE Microlithography Conference, February 2005.

6486-26, Session 5

Photonic quasicrystal LEDs: design, modelling, optimisation and experiment

M. E. Zoorob, T. D. M. Lee, Mesophotonics Ltd. (United Kingdom)

Photonic Crystals have recently been shown by several groups to improve light extraction out of LEDs by up to 2.5 times. In this paper we demonstrate the benefits of the use of highly dispersive photonic quasicrystals (PQC) for the efficient extraction of light trapped in readily available thick (~5 microns) high index LED structures while also revealing the much improved directional far field light emission that exceeds those of regular photonic crystals. High Brightness Photonic Quasicrystal LEDs are demonstrated with greater than 5 times the brightness in a 30 degree emission cone without the use of secondary optics. The potential for 10 times the brightness is investigated by use of tailored LED epistructure incorporating PQC patterns. We also demonstrate the feasibility and low cost large scale manufacturability of the photonic quasicrystal LEDs.

6486-27, Session 5

Modeling of GaN based resonant-cavity light-emitting diodes

Z. Li, Z. S. Li, Crosslight Software Inc. (Canada)

The spontaneous emission of an optically active material can be modified by placing the material inside a microcavity whose fundamental optical mode is resonant with the natural emission wavelength of the optically active material. The changes in spontaneous emission characteristics found in microcavity structures include spontaneous emission lifetime, the spectra purity, and the intensity of the emission along the optical axis of the microcavity. Placing a multi-quantum-well inside a resonant cavity (RC), the RC-LED can achieve high-efficiency for lighting and high directionality for plastic optical fiber.

We have recently extended the theory of Henry [1] to accurately treat the coupling of spontaneous emission noise with microcavity modes. The Green's function method is employed to solve the inhomogeneous wave equation including a Langevin force Fω which accounts for spontaneous emission by carriers at angular frequency ω. The optical wave equation is coupled with the self-consistent calculations of the material spontaneous emission rate of quantum well/dot using envelope wavefunction method. Finally the carrier transport equations are solved within the framework of 2D/3D drift-diffusion model implemented in the Crosslight Softwre package APSYS [2].

The RC-LED simulator can be used for the design of active materials, quantum well/dot, and the microcavity. The analysis of a typical RC-LED [3] will be given in this paper, including 2D/3D distribution of potential, carrier, optical wave-intensity and the standing wave intensity within the cavity etc. The comparison with experiments will also be presented

[1] C.H. Henry, J. Lightwave Tech., vol. LT-4, pp 288-297, 1986

[2] APSYS, Crosslight Software Inc, http://www.crosslight.com

[3] E.F. Schubert, N.E. Hunt, R.J. Malik, M. Micovic and D.L. Miller, J. Lightwave Tech., vol. 14, No. 7, pp 1721-1729, 1996

6486-28, Session 5

A generalized 2D and 3D white LED device simulator integrating photon recycling and luminescent spectral conversion effects

W. Ng, Synopsys, Inc.; G. Letay, Synopsys Switzerland AG (Switzerland)

We report new capabilities in our Sentaurus-Device simulator for modeling arbitrarily shaped 2D/3D white LEDs by coupling novel photon recycling, luminescent spectral conversion effects and electrical transport self consistently.

The electrical transport solves the Poisson, continuity and thermal equations by Newton's method, and it includes a special treatment of carrier scattering into quantum wells (QWs). The QW spontaneous emission, stimulated emission, and absorption spectra are computed with the k.p method that includes many body effects.

Extraction efficiency is generally low in LED structures, implying that most of the light is trapped within the device. The trapped light undergoes spectral evolution as it traverses active QWs and luminescent regions multiple times and successively.

In our simulator, the spontaneous emission spectra are embedded in ray tracing, and are allowed to evolve as the rays traverse regions of stimulated gain, absorption, and luminescence. In the active QW, the spontaneous emission spectra can be partially amplified by stimulated gain within a certain energy range and absorbed at higher energies, resulting in a modified spontaneous spectrum. The amplified and absorbed parts of the spectrum give a net recombination/generation rate that is feedback to the electrical transport via the continuity equations. This conceives a novel photon recycling model that includes amplified spontaneous emis-

sion. The modified spontaneous spectrum can further be altered by spectral conversion in the luminescent region. In this manner, we capture the important physical effects in white LED structures in a fully coupled and self-consistent electro-opto-thermal simulation.

6486-29, Session 6

Statistical analysis and yield management in LED design through TCAD device simulation

G. Letay, Synopsys Switzerland AG (Switzerland); W. Ng, Synopsys, Inc.

We demonstrate the use of Technology Computed-Aided Design (TCAD) simulation to establish a Design for Manufacturing (DFM) environment for optimal LED design. The robust Sentaurus Device simulator incorporates advanced physical models including photon recycling and elaborate spontaneous emission spectra calculations. Extensive device simulation is performed to vary design variables and to extract output parameters such as internal and external quantum efficiencies, wall-plug efficiency, and optical output power. These design variables and output results are subsequently input to PCM Studio, a powerful multidimensional fitting and statistical analysis tool, so that a sensitivity analysis and multidimensional correlation map can be created. Fluctuations of design variables can also be introduced together with cost and manufacturing constraints, tailoring the process compact model (PCM) closer to the manufacturing environment. This approach of encapsulating TCAD-predicted device behavior in an analytic multidimensional surface response model (PCM) provides the manufacturing chain with the possibility to transfer the physics-based models down to the fab and up to the yield management and verification group, and to use them with ease. The PCMs can be easily evaluated by engineers without any TCAD knowledge to optimize their structure and to predict yield. Therefore, the design cycle is accelerated and the optimization cost is reduced through this methodology.

6486-30, Session 6

Self-consistent modeling of resonant PL in InGaN SQW LED-structure

M. Sabathil, A. Laubsch, N. Linder, OSRAM Opto Semiconductors GmbH (Germany)

A popular method to analyze the quality and the physical properties of InGaN QWs is the temperature dependent resonant PL measurement. In this method an excitation energy below the gap of the barrier (GaN) material is used to assure that excitons are created inside the QWs only. The internal quantum efficiency is then estimated from ratio of room temperature to low temperature intensity.

In addition, the measurement of the bias and temperature dependent photocurrent, the decay time and the wavelength shift allows to deduce important physical properties such as barrier height, electron-hole overlap and the magnitude of the Piezo-field. However the analysis of this data demands for a detailed physical model based on a realistic device structure which is able to predict the measured quantities. In this work we present a theoretical model to support the analysis of the PL measurements and to allow for a quantitative interpretation of the results. The model is based on the device simulator nextnano and includes a fully self-consistent solution of the Schroedinger-Poisson and current equation for arbitrary Indium profiles in the QW. In addition to the Stark shift of the emission energy, the model is able to predict the temperature and bias dependent photocurrent resulting from the tunneling and thermionic escape of the photo generated carriers out of the quantum well which is strongly dependent on the band offset ratio of the InGaN/GaN heterojunction. The wavelength shift due to external bias as well as carrier induced screening is calculated giving an upper limit for the expected band-filling effects in inhomogeneous InGaN QWs.

6486-31, Session 6

Phosphor conversion of light emitting diodes

G. O. Mueller, R. Mueller-Mach, Philips Lumileds Lighting

Phosphor Conversion of blue or near-UV emission of Light Emitting Diodes (LED) has become increasingly popular with the increase in efficiency especially of blue LED. The main target is the generation of white light for illumination, camera flashes, and automotive. Conversion Efficiency and the Color Quality of the output light measure the success. Secondary criteria like temperature and drive dependencies shift into the customer interest and put more strain on the selection of phosphors, but also on the way of application within the LED package. Phosphor selections and application methods will be reviewed. Emphasis will be put on the interaction of two and more phosphors in one LED to generate for instance high quality warm white. In general a price in reduced conversion efficiency has to be paid for increased light quality and even in lowering the correlated color temperature (CCT) of the output. However, there is a strong tendency to differentiate importance of specifications in different applications - general illumination, museums lighting and car forward lighting to mention only some - have rather different priorities, which begin to be well recognized by LED manufacturers.

6486-32, Session 6

Production of Color on Demand LEDs with narrow color coordinate distribution

B. G. Braune, K. Petersen, J. Strauss, OSRAM Opto Semiconductors GmbH (Germany)

Phosphor conversion based LEDs can emit white light or any color on demand. For SMD devices, a phosphor filled resin is casted into a cavity containing the light emitting chip. Due to parameters like casting accuracy or material related restrictions such as chip wavelength, a production lot will always result in a distribution of color coordinates in the CIE color diagram. In order to reduce yield losses, a small color distribution is desired in the production process. But due to process and material restrictions, the color distribution cannot easily be decreased.

One way to reduce the width of the color distribution is a wafer level coating technology for white or “Color on Demand” LED production lots. A layer of a hard, phosphor filled resin is applied on top of a wafer. The layer thickness determines the color coordinate. While monitoring the color coordinate, the layer is milled down to the thickness corresponding to the desired color.

This process allows for CxCy distributions which are significantly smaller than color distributions obtained by standard casting processes.

6486-33, Session 6

Reference based optical characterization of glass ceramic converter for high power white light generation

A. Engel, M. Letz, T. Zachau, E. Pawlowski, K. Seneschal-Merz, B. Hoppe, SCHOTT AG (Germany)

Fluorescence techniques are known for their high sensitivity and are widely used as analytical tools and detection methods for product and process control, material sciences, environmental and biotechnical analysis, molecular genetics, cell biology, medical diagnostics, and drug screening.

The fluorescence inherent problems for the benefit of users of fluorescence techniques are to demonstrate the need for an improved quality assurance. According to DIN/ISO 17025 certified standards are used for fluorescence diagnostics having the drawback of giving relative values only. Therefore reference materials for quantitative characterization are related directly to the investigated materials.

In order to evaluate these figures it is necessary to calculated absolute number like absorption/excitation cross section and quantum yield. This

can be done using different degree of dopands in glass, glass ceramics or crystals or nano crystalline material embedded in polymers.

We consider here a special type of glass ceramic Ce doped YAG which inhabits a strong diffuse scattering and a high absorption. This material has been developed for the generation white light from a blue 460nm semiconductor transition using a yellow phosphor.

The Ce doped YAG is a pure solid state solution for a yellow phosphor, which is based on a glass ceramic material. A glass ceramic is made from a glass, in which based on a well controlled thermal treatment specific crystalline phases are grown. In our material Ce doped YAG crystallites of a size of several μm are embedded in a matrix of a residual glass. We present chemical, structural and spectroscopic properties of our material. Based on this we discuss design options for white LED's with respect to heat management, scattering regime, reflection losses, chemical durability and stability to blue and UV radiation, which evolve from our recently developed material.

In this paper we present first results on our approaches to evaluate quantum yield and light output.

Used diagnostics are fluorescence (steady state, decay time) and absorption (remission, absorption) spectroscopy working in different temperature regimes (10 - 350 K) of the measured samples in order to get a microscopy view of the relevant physical processes and to prove the correctness of the obtained data.

Work is funded by BMBF under project number 13N8849

6486-34, Session 7

Requirements on LEDs for advanced optical systems

J. Reill, A. Wilm, OSRAM Opto Semiconductors GmbH (Germany)

The use of LEDs in advanced optical systems such as LED projectors or automotive headlamps is usually limited by the optical extend of the light source. The optical extend (or étendue) is defined as the product of the optical area and the divergence angle of the emission. In our paper, we discuss the consequences of such limitations on the design and performance of optical systems. The system optimization involves the chip technology, package design and the primary optics, producing an optical extend that has to mach with the optical extend of the imager component. It will be shown, how these optical laws put constraints on the LED light source and the design of suitable light engines. The benefits of LED light sources for the above mentioned applications will also be demonstrated.

6486-35, Session 7

White LED lighting over Ra=95 for medical applications

K. Kobashi, T. Taguchi, Yamaguchi Univ. (Japan)

Very recently, we have developed high color rendering white LED, using near ultraviolet LED and three-band (red, green and blue) phosphors. This LED has color rendering index Ra=96. Moreover, special color rendering index R9 (red) is 95 and R15 (face color of Japanese, Japanese only) is 97, respectively. White LEDs that have not only color components of red and green, but also homogeneous distribution of light, is essential for surgical and endoscope lighting.

In this conference, we will discuss results of evaluation of the medical lighting applications such as operation, treatment and endoscope experiments.

6486-36, Session 7

Development of light distribution controllable luminaire using high power LEDs

H. Asakawa, Marumo Electric Co., Ltd. (Japan); J. Baba, A. Yaeda, M. Wakaki, Tokai Univ. (Japan)

The luminaires utilizing high power LED are prevailing for general use. In the application, multiple numbers of LED are required to attain the required brightness. It is important to control the light distribution to combine the luminous flux from each LED. We aim to design and fabricate the optical system to control the luminous distribution using 64 LEDs.

The designed luminaire is composed of 64 LEDs as a light source, a collimator array lens, a condenser lens and the imaging optics. In the system, the light distribution can be controlled by projecting the aperture to the screen. The focal length is possible to adjust with the imaging optics. As a result, we can change the spot size . The internal structure of LED is especially considered in this optical designing.

The uniform light distribution was obtained by the prototype luminaire. By using the system, the spot size

was possible to change over the range from 1.6 to 2.5m for the distance of 5m between lens and screen.

We developed the light distribution controllable luminaire by designing the optical system adapting for the LED array. We will explore the possibility to apply the light distribution controllable luminaire using LED to various fields in the next step. For example, we will develop the luminaire using RGB color LEDs that enables to control the color of the emitted light.

6486-38, Session 7

A novel temperature compensated operation scheme for trichromatic LED backlights

D. Lee, J. Kim, M. Y. Park, H. D. Kim, S. R. Hwang, J. Park, S. Cho, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea)

Trichromatic LED backlight renders higher colour gamut and panel transmittance to the LCDs than the phosphor-converted white LED backlight. In realization, however, several technical challenges arise, such as colour shift, due to the ambient temperature change, brightness decrease along with the temperature increase, colour mixing, minimizing the total number of chips and so on. In this paper we designed and tested the low cost temperature compensating circuit, using a thermistor as a temperature compensating element, for stabilizing the brightness and maintaining the colour coordinates of the trichromatic backlight units. By applying the temperature compensating circuit, the decrement rate of the brightness and colour shift rate were achieved by 54% and 51% respectively comparing with uncompensated case.

6486-49, Session 7

Silicon carbide white light LEDs for solid-state lighting

S. Bet, College of Optics & Photonics/Univ. of Central Florida; N. R. Quick, Applicote Associates; A. Kar, College of Optics & Photonics/Univ. of Central Florida

White light emitting diodes (LEDs) have been successfully fabricated for the first time in silicon carbide substrates (4H-SiC and 6H-SiC) using a novel laser doping technique. The donor-acceptor pair (DAP) recombination mechanism for luminescence commonly observed in SiC has been used to tailor these LEDs. Chromium (Cr), which is an unconventional dopant that produces multiple acceptor sites per atom, was successfully incorporated into SiC for the first time using laser doping. Aluminum (Al) and nitrogen (N) were also laser-doped into SiC. Green (521-575 nm) and blue (460-498 nm) wavelengths were observed due to radiative recombination transitions between donor-acceptors pairs of N-Cr and N-Al respectively, while a prominent violet (408 nm) wavelength was observed due to transitions from the nitrogen level to the valence band level. The red (698-738 nm) luminescence was mainly due to nitrogen excitons and other defect levels. This RGB combination produced a broadband white light spectrum extending from 380 to 900 nm. The color space tri-stimulus values were X = 0.3322, Y = 0.3320 and Z = 0.3358 as per 1931 CIE

(International Commission on Illumination) for 4H-SiC corresponding to a color rendering index of 96.56; the color temperature of 5510 K is very close to average daylight (5500 K). The quantum output of these LEDs was low. Optimization of laser doping to achieve higher dopant concentration levels is anticipated to increase quantum output by increasing the radiative recombination rate and creating a direct bandgap semiconductor band structure in doped SiC.

6486-39, Session 8

Excitonic effects in ZnO nanorods

M. Willander, Linköpings Univ. (Sweden)

Excitonic effects in ZnO nanorods will be analyzed. The excitonic UV-emission is analyzed regarding dimensional effects but also the UV- lasing fron ZnO nanorods grown on Silicon will be experimentally analyzed. Exciton polariton effects related to the Q-factor of the cavity is analyzed. The origin of the Green Band (white light emission) will be discussed from experimental point of view. The electroluminescence from ZnO nanorods grown on different substrates will be demonstrated.

6486-40, Session 8

Use of ZnO substrate for GaN-based devices

F. H. Teherani, Nanovation SARL (France); D. Rogers, Nanovation SARL (France) and Univ. de Technologie de Troyes (France); P. Kung, M. Razeghi, Northwestern Univ.; O. Durand, G. Garry, Thales Research & Technology (France)

GaN-based optoelectronic devices are plagued by a tendency to non-radiative transitions linked to defects in the active layers. This problem has it's origin in a) intrinsic factors such as GaN's relatively low exciton binding energy (~24meV) and b) extrinsic factors including the poor availability of native substrates good enough to significantly suppress the defect density.

Indeed, the quality and availability of large-area bulk GaN substrates is currently considered a key problem for the continuing development of improved GaN-based devices. Since development of bulk GaN substrates of suitable quality has proven very difficult, a considerable amount of effort is also being directed towards the development of alternative substrates which offer advantages compared to those in widespread use (c-sapphire and 6H SiC).

ZnO is promising as a substrate material for GaN because it has the same wurtzite structure and a relatively small lattice mismatch (~1.8%). In this paper, we discuss use of ZnO substrates for GaN based LEDs.

6486-41, Session 8

Fabrication of high power AlInGaP-based red light emitting diodes with novel package by electroplating

K. Chen, Y. Su, National Cheng Kung Univ. (Taiwan); C. L. Lin, Kung Shan Univ. of Technology (Taiwan); J. Q. Huang, National Cheng Kung Univ. (Taiwan)

Thermal management is now a critical problem for applications of high power light emitting diodes (LEDs). This paper develops a novel LEDs (Fig.1a) package technique that can overcome thermal problem, and the ability to drive the red LEDs at higher power. Copper is plated on the AlInGaP-based red LED chip directly, and the thermal resistance from chip to the metal heat sink is decreased greatly. With the copper plating layer, the working current of the AlInGaP-based red LED can be increased from conventional 350 mA to 1650mA in room temperature. It was found that the luminous intensity at 350 and 1050 mA of the novel package LEDs showed 53% and 431% enhancement as compared with those of the conventional package ones (Fig.1b). The electrical and optical characteristics of two kinds packages were shown in Figure 2 and Figure 3, respectively.

6486-42, Session 8

Low resistance and high reflectivity Al based reflectors for p-GaN flip process

S. W. Chae, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea)

We proposed an ITO/Al reflector electrode with thigh reflectance and low contact resistance for the p-GaN (p=5Å~1017 cm-3) flip chip process, which is suitable for the high-power light-emmitng diodes(LEDs), instead of Ag which has been commonly used for flip-chip reflector. The GaN and its related materials have been extensively researched in various applications of future illumination and in high density storage recording systems. However, despite of these possible applications, white LEDs have many weaknesses which must be solved before it can be substituted for the conventional fluorescent lamp. The most critical problem is the output power of LEDs. For increasing the external efficiency and many researchers have reported the flip-chip process based Ag reflector which have the high reflectance. However, Ag reflector has a problem of the leakage current through GaN dislocation due to Ag migration by its low melting temperature, in spite of its high reflectance and work function.

Because Al has been commonly used as n-GaN contact, we prepared that the Cu doped In2O3(5nm)/ITO(380nm) interlayers was first deposited by E-beam evaporator and anealed at 500 oC for 60sec. Then, we deposited Ti-W(30nm)/Al(400nm thick) on the ITO interlayer for preventing Al diffusion and bumping layer, and subsequently annealed at 300 oC for 60sec. The annealed Cu doped In2O3(CIO)/ITO/Ti-W/Al contact gave a specific contact resistance as low as 5.63Å~ 10-3$\Omega\chi\mu^2$, compared to 4.52Å~ 10-2$\Omega\chi\mu^2$ of CIO/ITO contact. The reflectance of electrode based Al was reported ~90% at a wavelength of 450nm, which better than those of Ni/Ag schemes. LEDs fabricated with the annealed CIO/ITO/Ti-W/ Al p-electrodes gave forward-bias voltages of 3.2-3.3V and luminescence of above 60mcd at injection current at 20mA. Moreover Al reflector showed lower leakage currents compared to Ag reflector.

6486-43, Session 8

Fabrication of thin-GaN LED by wafer bonding and electro-plating thick metal film

C. Chang, C. Liu, National Central Univ. (Taiwan)

The recent-developed thin-GaN LED structure has been attracted serious attention, which enables GaN-based LED for the lighting applications. To fabricate thin-GaN LED, it requires the transferring technique of the original epi-GaN layer onto better thermal and electrical conduction substrates. The transferring substrate can be attached with GaN epi-layer by two methods, which are wafer bonding and electro-plating thick metal film. In this talk, we will report fabrications of thin GaN LEDs by using these two methods: (a) A low temperature wafer bonding technique to bond GaN wafer with Si wafer. (less than 150 °C) The low temperature bonding process avoids the thermal stress problem and enhance the better results after LLO process (Laser Litf-Off). (2) Thick Ni film was electroplated on the P-GaN side to serves as the transferring substrate. In addition, electrical and optical performance of these two types of thin-GaN LED will be compared and discussed in this talk

6486-44, Session 8

Fabrication study of thin-GaN LED

C. Lin, C. Liu, National Central Univ. (Taiwan)

Thin-GaN LED structure has attracted serious attention due to its better heat dissipation and lighting performance over traditional LED structures. In this work, we utilized three key processes to fabricate thin-GaN LED, which are Au-Si and Au-Au wafer bondings, LLO (Laser Lift-Off), and PEC (Photo-Enhanced Chemical) surface roughening. According to our preliminary results, different process methods and parameters will strongly affect the electrical and optical properties of the thin-GaN LEDs. In this talk, we will report, (1) Effect of wafer bonding conditions on the performances of thin-GaN LEDs. (2) Comparison study of using ITO and AZO as TCL (Transparent Conducting Layer) on the roughened n-GaN surface of thin-GaN LED. (3) Effect of PEC roughened n-GaN surface on the light extraction.

Conference 6487: Emerging Liquid Crystal Technologies II

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6487-01, Session 1

Optoelectronic and photonic properties of liquid crystals: electroluminescence and photorefractivity

S. A. Benning, Univ. of Paderborn (Germany); M. W. Lauhof, L. Paelke, Univ. Paderborn (Germany); F. Scheliga, E. Thorn-Csanyi, Univ. Hamburg (Germany); H. Kitzerow, Univ. Paderborn (Germany)

The unusual combination of both fluid and anisotropic properties appearing in liquid crystals is known to be very useful for electrooptic effects as used in flat panel displays. Thus, it is not surprising if also other possible applications benefit from the versatile liquid crystalline properties. For example, it has been recognized that liquid crystalline order may enhance the charge carrier mobility - an important quantity in organic electronics - , that luminescent liquid crystals can emit polarized light, or that polymer-dispersed liquid crystals can have interesting electro-optic and photonic properties. However, applications based on these effects may require complex techniques to prepare the samples. The present contribution describes two different types of systems that are based on very thin layers (typically d < 100 nm) and sub-μm sized droplets, respectively. The first study describes electroluminescent samples composed of a stack of very thin organic layers, one being composed of an aligned liquid crystalline p-phenylenevinylene oligomer (OPV). The backbone of the respective OPV derivative contains four (n = 2) to seven (n = 5) benzene rings. Lateral alkyloxy chains are attached to the molecules in order to achieve high solubility in organic solvents. The color of the emitted luminescence varies from green (n = 2) to red (n = 5). Organic light emitting diodes (OLEDs) were prepared by depositing an poly(tetrafluoroethylene) (PTFE) alignment layer, several semiconducting organic layers and a metal cathode on ITO-coated glass substrates. The polarized electroluminescence was measured for different lengths of the emitting OPVs. As expected, the increasing length leads to an increase in the dichroic ratio (from DEL = 1.8 for n =2 to DEL = 8.5 for n = 5). This can be explained by an increasing shape anisotropy of the molecules, resulting in an improved orientational order. A brightness up to 380 cd/m2 at 20 V for n = 5 with an efficiency of 0.02 lm Å~ W-1 Å~ sr-1 could be achieved. The threshold voltage is about 7.3 V. The second system studied consist of very small droplets of a low molar mass liquid crystal that are dispersed in a photoconducting polymer. The latter system exhibits photorefractive properties: Exposing the sample to a holographic intensity pattern leads to the generation of an internal space charge field which in turn leads to a periodic modulation of the refractive index due to the electro-optic effect of the liquid crystal. By two-beam coupling experiments and by measuring the diffraction during a fast lateral movement of the induced phase grating it is possible to measure the gain coefficient and the phase of the induced periodic index modulation with respect to the generating intensity pattern, respectively. From the latter experiment, the amplitude of the internal space charge field can be estimated.

6487-02, Session 1

Thin optical films in LCDs, LEDs and solar energy

C. W. M. Bastiaansen, Technische Univ. Eindhoven (Netherlands)

No abstract available

6487-03, Session 1

Liquid crystal tunable and nonlinear negative-zero-positive index material

I. C. Khoo, A. Diaz, The Pennsylvania State Univ.

We describe conceptually perhaps the most nonlinear optical material possible that possesses a refractive index tunable from negative unity to positive unity value. The tuning can be by an applied electric, magnetic or optical field. In the latter case, the refractive index coefficient characterizing the optical nonlinearity can be an order of magnitude larger than due to the larger than undoped liquid crystals, which rank among the most nonlinear optical materials to date. One possible realization of such supra-nonlinear metamaterial is [semiconductor or polaritonic or metallic] core-shell spheres dispersed in bulk aligned nematic liquid crystal. Although all the constituents are non-magnetic [with permeability~ 1], the dielectric resonances of the core and shell materials can be exploited in conjunction with the tunable dielectric constant of the nematic host to give effective refractive index ranging from negative through zero to positive values. Such supra-nonlinear core-shell Nano-sphere Dispersed Liquid Crystal materials [NDLC] will find application in various optical switches, filters and beam combining and steering devices.

6487-04, Session 1

Chiral SmA* materials for optoelectronics applications

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The potential of chiral SmA* materials for analog optoelectronic applications exploiting the electroclinic effect is great, due to the combination of fast switching speeds and “in-plane” optic axis re-orientation. This potential has not been realized, however, due to several problems; most importantly relatively weak electroclinic coefficients observed for typical materials, and a very strong temperature dependence of the magnitude of the coefficient close to the SmA* - SmC* transition. The structure, characterization, and application of some rare SmA* materials exhibiting large and relatively temperature-insensitive electroclinic coefficients will be described.

6487-05, Session 2

THz time-domain spectroscopy of liquid crystal colloids

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THz time-domain spectroscopy (THz-TDS) has newly been emerged as a spectroscopic technique to measure the optical constants, i.e., the refractive index and the absorption coefficient, in the range of THz frequency. In this frequency region, we can expect the vibrations and rotations of large segments of a molecule, which allows us to interpret intermolecular interaction, and hence molecular assembly and packing structures of molecules in materials. As such, this technique has an advantage to study molecular packing and motion in LC phases.

We use THz-TDS in transmission geometry to obtain the optical constants in the range of THz frequency. First, the optical constants of a pure nematic LC, 4'-n-pentyl-4-cyanobiphenyl (5CB), in the frequency range

0.3-2.0 THz were determined using a 2 mm thick cuvet. The refractive index was decreased accordingly as the frequency was increased, while there was almost no absorption in this range. Second, the LC colloids, in which silica particles were dispersed, were measured as a function of particle volume fraction. We found that the LC colloids gave us very stable and reproducible spectra, implying that the silica particles have an ability to break domains of the LC contained in a cuvet due to the anchoring at the particle surfaces. The effective medium theory allows us to deduce the optical constants for pure 5CB from the obtained spectra of the LC colloids. We discuss on how the obtained spectra can be interpreted by the Debye model.

6487-06, Session 2

Anomalous temperature dependence observed in polarized THz absorption spectra of MBBA and its homologs

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Temperature dependence of polarized absorption spectra of MBBA and its homologous were measured. In the temperature region far from the isotropic-nematic phase transition temperature, strong and little absorption was observed in the THz wave polarized perpendicular and parallel to the nematic director n, respectively. Absorption perpendicular to the director becomes stronger when the temperature of the sample came close to the clearing point and suddenly decreased after the phase transition completed. The anisotropy and the temperature dependence suggests the origin of absorption be molecular rotational and/or librational motions around the molecular long axis.

However, two anomalous features were observed in the temperature dependence of the absorption spectra; (1) The absorption parallel to the director also became stronger when the temperature approached the phase transition point and the reverse of absorption strength was observed in the temperature region a few degrees below the transition point. (2) The peak position of both parallel and perpendicular direction showed only weak temperature dependence. The first feature suggests that the fluctuation of molecules from the averaged orientation causes the absorption in the parallel direction near the transition point. The increase of fluctuation generally comes from the decrease in the force of restitution and causes the huge red shift of the absorption peak. However, such the huge red shift was not observed.

To understand the temperature dependence, we have to consider many factors such as temperature dependence of elastic constants, viscosity coefficients, molecular conformation and so on. Detailed temperature dependence and the mechanism of the dependence will be discussed.

6487-07, Session 2

Effect of permanent dipole moments perpendicular to molecular long axis on terahertz absorption in liquid crystals

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Terahertz (THz) waves are electromagnetic waves that have a frequency of between 100GHz and 30 THz. This frequency region has been known as a fingerprint region, where low-frequency intramolecular vibrational and rotational motions are observed. Recently, THz absorption spectra of some nematic liquid crystals were reported by Pann et al(1). They found the nematic liquid crystal of 5CB is almost transparent in the THz region. While, we have measured the THz absorption spectra of MBBA and its homologous and found that they show absorption in the THz region. The difference of their molecular structure and THz absorption spectra suggest that the permanent dipole moments perpendicular to molecular long axis cause the absorption in THz waves.

To confirm the origin of absorption in the THz region, we have measured the THz absorption spectra of MBBA and its homologous. When the alkoxy side chain becomes longer, the absorption peak position shifts to the lower frequency side. It is caused by molecular rotational mode around its long axis. However, when the alkyl side chain becomes longer, the absorption peak appears in the higher frequency side. It is not clear whether the origin of the peak is the same with that of above one.

In addition, we have been measuring the THz absorption spectra of mixtures of 5CB and CCN47. 5CB and CCN47 have little and large permanent dipole moments perpendicular to molecular long axis, respectively. From the concentration dependence of the absorption spectra, we will discuss the relation between the permanent dipole moments and absorption in the THz region.

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6487-08, Session 2

Liquid-crystal-based electrically tunable THz optical devices

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Recently, Terahertz (THz) technology and its applications have advanced rapidly. Nonetheless, essential quasi-optic components such as tunable THz phase shifters are relatively under-developed. Using magnetically controlled birefringence [7, 8] in a sandwiched dual nematic liquid crystal (NLC) cell, 3 mm in total thickness, a tunable room-temperature THz phase shifter capable of more than 360Ỿ of phase shift at 1 THz was realized. Nonetheless, electrically controlled phase shifters are more desirable for many applications. In this work, report electrically tunable phase compensators operating at quarterwave and halfwave point using a homeotropically aligned NLC cell. Tunable phase shift up to 360° at 1 THz is demonstrated using electrically controlled birefringence in a vertically aligned nematic liquid crystal (E7) cell, 1.83 mm in thickness. The driving voltage and corresponding field required for a phase shift of 360Ỿ at 1 THz are 100 V and 90.5 V/cm, respectively. Similar phase shift can be realized using a sandwiched dual NLC cell, about 2 mm in total thickness, significantly improving the dynamic response of the device.

6487-09, Session 3

Lasing application using cholesteric liquid crystals

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Cholesteric liquid crystals (CLCs) are regarded as a one-dimensional photonic crystal. A photonic band gap (PBG) emerges in a wavelength range that is identical to the optical pitch of the helix for one of the optical eigenmodes, i.e., selective reflection. By utilizing this optical property, lasing from dye-doped CLCs has been extensively studied since Kopp et al. experimentally demonstrated mirrorless lasing at the edge of a PBG. In this paper, we will present two topics for the CLC laser a follows. (a)Tunability of lasing wavelength using a spatial modulated structure of CLCs: In order to realize tunability covering whole the visible wavelength range, we fabricated the spatial helical-pitch-gradient structure of CLCs made by introducing the gradient of chiral dopant concentration and containing two dyes. We could succeeded that lasing emission wavelength covers almost the whole visible light region; i.e., from 460 nm to 660 nm except for the vicinity of 500 nm. (b)Lowering the lasing threshold by fab-

ricating of novel structures: We report a novel cavity structure for defect mode lasing with a lowered threshold. The cell consists of three CLC layers, the middle of which contains laser dyes, has the same or opposite handedness of helix to those in both sides and has narrower PBG than those in both sides. It was found that the defect states emerge, and the photonic density of state (DOS) is resonantly enhanced when the defect mode coincides with the edge mode. The lasing from this enhanced mode was found to show a lower threshold value than the single-layered CLC cell.

6487-10, Session 3

Tunable lasing from cholesteric liquid crystals via in-plane electric fields

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The investigation of dye doped liquid crystals systems for lasing applications has become a burgeoning topic in recent years. Lasing has been achieved in cholesteric and ferroelectric liquid crystals, as well as holographic polymer dispersed liquid crystals and liquid crystal polarization gratings. We report on investigations of dye-doped cholesteric liquid crystals on an in-plane switching substrate. To date, reports of the tunability of cholesteric liquid crystal lasers by means of temperature, photochemical processes and mechanical forces - in cholesteric elastomers. The application of an in-plane electric field on a cholesteric liquid crystal results in an unwinding and elongation of the cholesteric pitch. This change in pitch length shifts the reflection band of the cholesteric liquid crystal. A dye-doped cholesteric liquid crystal laser will shift it's emission according to the location of the edge of the band gap, or reflection band. This simple system has the advantage over other tunable cholesteric liquid crystal lasers in that the application of an electric field is more easily accomplished in an end product as compared to mechanical, temperature and photochemical techniques.

6487-11, Session 3

High efficient photonic band-edge cholesteric liquid crystal lasers

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In this paper, we demonstrated a new dye-doped cholesteric liquid crystal (CLC) photonic band edge laser with emission enhanced by an external cholesteric resonator. As one-dimensional photonic crystal, the 5-μm dye-doped cholesteric liquid crystal cell generates circularly polarized laser emission at its photonic band edge. When sandwiched between two 5-μm cholesteric liquid crystal mirrors whose reflection band reflects the laser emission from the central dye-doped CLC laser, the emission can be enhanced by ~800X. In experiment, a second-harmonic Q-switched Nd-YAG pulsed laser is used to pump the CLC laser assembly at normal incidence. The detected laser emission is elliptically polarized and is still located at the band edge wavelength of the central CLC cell. The beam divergence is decreased by ~10X due to an increased cavity length. Theoretical analysis using 4Å~4 transfer matrix and scattering matrix has shown that the circular resonator produces transmission peaks based on Fabry-Perot effect inside reflection band and, moreover, the transmission peak at the band edge of central CLC can be well-preserved. Both experiment results and simulation results are present in good agreement.

6487-12, Session 3

Fast electro-optic gratings for high energy laser beam attenuations

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This paper provides research progress in the development of fast electro-optic gratings for high energy laser beam attenuations. The electro-optic phase grating is formed by the phase separation of ~100nm liquid crystals droplets from a polymerizing organic matrix using holographic interference technique. The formed grating separates the incident laser beam into the output beams: the transmitted and diffracted beam, whose intensities can be electrically adjusted through electro-optic effect. The fast electro-optic gratings have a very fast electro-optic response time of 50 microseconds with diffraction efficiency up to 99.5%.

6487-19, Session 3

Spatial filter based on azo-dye-doped liquid crystal film

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This investigation establishes the feasibility of exploiting the surface-assisted photoalignment effect in dye-doped liquid crystal (DDLC) films as spatial filters with controllable polarization in optical signal processes. The mechanism relies on the fact that a TN structure can be formed in a DDLC film with a suitable exciting intensity. Illuminating the object with an appropriate intensity enables lower diffracted orders, but not other higher orders, to generate a TN structure. The image can be modulated for a high pass / all pass / low pass/ by changing the angle of the analyzer placed behind the sample. This filter is easy to fabricate, and very convenient to use. It therefore has strong potential for use in practical applications. A simulation is also performed, and the results agree closely with experimental data.

Controlling the spatial distribution of optical information is very important. Such control has been practically applied in the fields of photographic image enhancement, pattern recognition and image-inversion, using a highly nonlinear dye-doped NLC film as a phase-modulation element1. Another form of selective spatial frequency reconstruction was demonstrated using functionalized mesogenic composites with holographic capability2. Recently, the authors reported an electrically switchable spatial filter based on polymer-dispersed liquid crystal (PDLC)3.

This paper reports another method that provides a much better result than that described in Ref. [3]. Details of the experiments and results will be reported.

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6487-13, Session 4

Liquid crystal photoalignment: history and future

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In this original review we briefly consider the novel photo-aligning technology: history and the perspectives for future applications in liquid crystal (LC) devices. The review describes the following items.

The brief introduction to the history of photoalignment and the basic classes of the photoaligning materials: photosensitive polymers, azodyes and monolayers will follow with an introduction to the physical mechanisms of the photo-aligning and photo-patterning technology. Four main mechanisms of the phenomena are discussed: (i) reversible photochemical cis-trans isomerization in azo-dye containing polymers, monolayers and pure dye films; (ii) pure reorientation of the azo-dye chromophore

molecules or azo-dye molecular solvates due to the diffusion under the action of polarized light; (iii) topochemical crosslinking in cinnamoyl side-chain polymers; (iv) photodegradation in polyimide materials. The advantages and drawbacks of various photo-aligning materials are analyzed from the point of view of practical applications. The detail description of the diffusion photo-aligning in azo-dye materials is provided. The perspectives of photoaligning LC technology are compared with already existent and new methods of LC alignment, such as rubbing, ion beam technology or oblique evaporation.

The characterization of LC-surface interaction, such as pretilt angle and azimuthal anchoring energy is discussed. The newly developed materials should have a controllable pretilt angle and anchoring energy, thus enabling to develop a new generation of the LC devices: with low voltage, fast response and wide viewing angles. The problem of image sticking can be considerably reduced due to the high anchoring energy of azo-dye materials. Promising results, obtained for voltage holding Ratio (VHR) and residual DC voltage (RDC) in azo-dye photo-aligning materials are also shown. This implies that the azo-dyes can be applied as aligning layers in active matrix liquid crystal displays (AM-LCDs). The thermal stability of the photo-aligned azo-dye layers is sufficiently high (up to 2500C), while UV-stability is also improved by polymerization.

The possibility to use the photo-aligning layers for new types of liquid crystal displays such as FLCD, VAN-LCD, π-BTN LCD, optical rewritable memory, microdisplays, and TN-LCD on plastic substrates is demonstrated. The photoaligning of liquid crystal polymers (LCP) and the new classes of devices based on them (optical retarders and compensators) is discussed. A tunable waveguide-coupled microresonator switch on a dielectric substrate with superthin photoaligned liquid crystal films as cladding layers is also considered as a new class of voltage controllable photonics LC devices.

New superthin photo-aligned polarizers and phase retarders based on azo-dye layers are demonstrated for the first time. The polarizers are based both on photo-aligned lyotropic LC as well as pure azo-dye layers. The polarizers can be patterned and put inside LC display cell to serve as internal polarizers. Both color and neutral internal polarizers can be fabricated with the thickness 0.3-0.7 $\propto$m. The electo-optic response of TN-LCD with internal polarizers is practically the same as in case of usual external polarizers. The photoaligned LCP films as phase retarders are also discussed.

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6487-14, Session 4

Control of vertical liquid crystal alignment for various alignment surfaces

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A vertically aligned liquid crystal display (VA-LCD) mode has been widely used in various application fields such as large flat-panel displays (FPDs), and front or rear projection systems. This spread in the application fields is mainly due to its excellent high contrast property over a large viewing zone. Research works on LC alignment control for a VA display mode, however, have been limited in a large FPD application field because of the usage of an fringing electric field (FEF) method, but the method intrinsically has a drawback of reducing the aperture ratio of a pixel due to the existence of slit and/or protrusion structure in the pixel. Recent increasing demands for applying a VA display mode to projection display systems activates research works on the LC alignment control for a VA mode, in which a FEF method is difficult to use. In this paper, I introduce several methods to control pretilted vertical LC alignment on organic or inorganic alignment surfaces and some possible alignment mechanisms on the methods will be also given.

6487-15, Session 4

Characterisation of the alignment of liquid crystals infiltrated into porous nanostructured thin films

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The advanced physical vapour deposition technique known as glancing angle deposition (GLAD) can be used to fabricate porous, nanostructured, microcolumnar thin films with complete control over film morphology. Because the films can be easily sculpted into morphologies such as helices or square spirals with precise control over handeness and pitch (leading to tunability of the spectral properties), optical applications such as polarisation-sensitive filters and photonic crystals have been demonstrated by many researchers. The optical properties of GLAD-grown thin films have been studied extensively and often compared to those of many classes of liquid crystals. The porous, columnar morphology of GLAD-grown films suggests their use as a confined medium to impart alignment on LC materials infiltrated into the pores of the film. Previous work by our group has shown that achiral nematic LCs embedded into chiral structured thin films caused reduced scatter and enhanced circular birefringence. The film can be designed to span the thickness of the entire cell and its structure engineered to achieve nearly any type of LC alignment, including the ability to include defects. This is a greater level of control than can be achieved through substrate surface treatments alone.

This paper presents recent results on liquid crystal-infiltrated GLAD thin films including optical properties of basic GLAD structures before and after filling with LCs to study the interaction between the thin film “backbone” host and the LC guest material. Various geometries of GLAD films have been examined including simple tilted and vertical posts, helices, and square spirals. Recent work has made use of a dichroic dye mixed into the LC at various concentrations; as the dye molecules align with the nematic director, the anisotropic absorbtion of the dye+LC mixture reveals insight into how the GLAD film columns influence the LC alignment. Finally, we present also work studying active GLAD/LC devices where the application of an electric field can be used to re-align the LCs, allowing for devices based on switching of linear or circular birefringence and/ or dichroism.

6487-16, Session 4

Lyotropic chromonic liquid crystals as materials for optical and biosensing applications

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Lyotropic chromonic liquid crystals (LCLCs) are formed by molecules with rigid polyaromatic cores and ionic groups at the periphery that form aggregates while in water [1]. Light scattering experiments demonstrate that the isotropic-to-nematic pretransitional behavior does not follow the classic Landau - de Gennes model, as the length of aggregates changes with temperature [2]. Most of the LCLCs are not toxic to the biological cells [3] and can be used as an amplifying medium in real-time biosensors [4,5]. The detector is based on the principle that the immune aggregates growing in the LCLC bulk trigger the director distortions [4]. Self-assembly of LCLC molecules into oriented structures allows one to use them in various structured films. For example, layer-by-layer electrostatic deposition produces monomolecular layers and stacks of layers of LCLC with long-range in-plane orientational order which sets them apart from the standard Langmuir-Blodgett films [6]. We discuss how the properties of the LCLC are changed when the solutions are doped with a variety of salts [7].

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6487-17, Session 5

New developments in flexible cholesteric liquid crystal displays

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Cholesteric liquid crystal displays have been rapidly maturing into a strong contender in the future flexible display market. Encapsulation of the Cholesteric liquid crystal permits the use of flexible plastic substrates and roll-to-roll production. Recent advances include ultra-thin displays, laser-cut segmented displays of variable geometry, and smart card applications. Exciting technologies such as simultaneous laser-edge sealing and singulation enable high volume production, excellent quality control and non-traditional display geometries and formats.

6487-34, Session 5

Development of polymer cholesteric liquid crystal flake technology for electro-optic devices and particle displays

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Liquid crystals have been a large presence in the display industry for several decades, and they continue at the forefront of development as the industry delves into flexible displays and electronic paper. Among the emerging technologies trying to answer this call are polymer cholesteric liquid crystal (PCLC) flakes. The motion of PCLC flakes suspended in a host fluid is controlled with an electric field, whereby the flakes reorient to align parallel with the applied field. A PCLC device easily switches from a bright state, selectively reflecting light of a given wavelength and polarization to a dark, non-reflective state. The device is returned to a bright state when flakes relax to their original orientation after removal of the applied field. Progress has been made in addressing several key device issues: the need to switch flakes back to a reflective state quickly, the development of bistability, the ability to produce flexible devices, the necessity to produce high brightness and contrast ratio. Improvements in the technology have been made by addressing the optical, mechanical, chemical, and electrical features and characteristics of the PCLC flake - host fluid system. The manufacture of custom flakes produces shaped flakes with improved reflectivity and response times along with the ability to respond to both AC and DC fields. Specially designed driving waveforms provide a new measure of flake motion control. PCLC flake microencapsulation allows for the possibility of flexible and potentially bistable devices. Here we report on the wide variety of approaches toward improving PCLC flake devices and their results.

6487-35, Session 5

Bimsogenic flexoelectric liquid crystals: new materials for high-performance photonics devices and displays

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We have recently synthesized and studied novel bimesogenic liquid crystals that have extremely large flexoelectric coefficients. Using these materials we have produced a variety of mixtures suitable for new flexoelectro-optic photonic devices. In this paper we will discuss these materials and describe four main types of device, In the first device we will consider materials aligned, in the so called uniform lying helix mode, that lead to in-plain switching, birefringence (or indeed guest-host) based displays with 100 microsecond switching times at low fields, i.e.2-5 V/micron, wide viewing angle and analogue or grey scale capability. In the second device, also based on these nematogenic materials, we will describe devices, using in-plane fields that have 20 microsecond switching times at similar field strengths, with planar alignment and high optical contrast. The “off state” appears as perfect black irrespective of the alignment quality. This switchable phase device may be used both for telecommunications applications as well as birefringence based displays. In the third main area we will describe wide temperature blue phase materials that lead to polarizer and color filter free fast switching ‘Bragg” diffractive devices and displays. The reflected color is varied as a function of the applied external electric field. Switching times of a few milliseconds at fields of 10 volts / micron are readily achieved. Finally we will mention how these materials have been used to produce high efficiency, wide wavelength range tunable narrow linewidth liquid crystal laser sources with low threshold energies and slope efficiencies of over 30%.We will then discuss potential applications including a next generation of RGB coherent light sources.

6487-20, Session 6

Development of high quality liquid crystal lens

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A liquid crystal (LC) lens with two thin LC layers and is driven by two voltages is reported. The two LC layers are separated by a very thin glass substrate. There are three electrodes in the LC cell, one of which having a circular hole in the center. One of the two driving voltages is kept unchanged and the other one varies to change the focal length of the lens. The focal length simply increases with the increasing controlling voltage. Disclination lines are avoided by forming an initial electrical field in the LC layers spatially uniform. For the LC layers are shielded by the electrodes and the properties of the lens do not be affected by electric charges outside the LC cell. One of the advantages of the two-voltage driving technique is that the focal length of the lens is tunable electrically from negative to positive values, and in this way, the optical anisotropy of the LC material is made the most use of to obtain a wide focus range. The switching times between positive and negative lenses is made very short by using thin layers of LC with low viscosity. They are further shortened by using improved driving voltages. The aberrations of the lens are measured and it is found that they are very small in the whole focus range. With planar thin LC layers, glass substrates, and electrodes, the LC lens is very compact and lightweight.

6487-21, Session 6

Wave guiding with liquid crystals

K. Neyts, J. Beeckman, H. J. Desmet, Univ. Gent (Belgium)

Optical waveguides are widely used in the telecom industry for data transport. The high refractive index region guides the light efficiently and radiation losses can be minimal. Different functionalities have been integrated in waveguides, such as wavelength filtering, amplitude modulation and routing. The optical properties of liquid crystals can be modified by applying a small voltage or by illumination with light. The variation in optical properties can be exploited in different kinds of waveguide systems. This has already been studied in liquid crystal doped fibers, but filling holey fibers is a technological challenge.

It is possible to generate wave guides in bulk liquid crystal by modulating the director orientation in an appropriate pattern. Some guided modes in such pure liquid crystals will be discussed. Several types of hybrid waveguides will be introduced in liquid crystal is used in combination with a material with higher (in the core) or lower (in the cladding) refractive index. Silicon on insulator waveguides are convenient components to study the tuning possibilities in combination with liquid crystals.

6487-22, Session 6

Electrically switchable mirrors based on polymer-stabilized cholesteric liquid crystals

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We developed electrically switchable mirrors based on polymer-stabilized short-pitched cholesteric liquid crystals using electro-optical cells with planar alignment. The devices enable the switching of a pre-selected reflective wavelength of the cholesteric to reflect a different wavelength in corresponding to the magnitude of applied electric field. The principle of the wavelength shift to a shorter wavelength is a result of field-induced pitch shortening near the boundaries. The spectral wavelength shift of the reflected wavelength is about 150nm and the wavelength shift is linearly proportional to the magnitude of applied voltage. Furthermore, the mirror reflects same intensity across the tuned wavelength region. We will discuss the detailed electro-optical properties and potential applications of electrically switchable mirrors in full color reflective displays and optical filters.

6487-23, Session 6

Photonic effects in polymerized cholesteric liquid crystal nanofabricated by direct laser writing

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Liquid crystals including chiral molecule have a self-organized helical structure with nano-scaled periodicity, which can be regarded as a 1-D photonic crystal. We have so far investigated lasing characteristics at the edge of the 1-D photonic band gap of dye-doped chiral liquid crystals such as cholesteric liquid crystal (ChLC) and ferroelectric liquid crystal (FLC) under the field and have demonstrated a wavelength tuning of the laser action upon changing electric field strength. We have also proposed the defect modes characteristic to the helicoidal structure of the chiral liquid crystal and demonstrated the lasing from the chiral defect modes.

Here we propose a novel approach to introduce defects into the helical structure of ChLCs. We cause a local modification of the ChLC helix by performing high-resolution laser-lithography within the polymerizable ChLC material. The femtosecond-pulse laser is tightly focused in the polymerizable ChLC material. Two-photon polymerization occurs at the laser focus, and a locally polymerized ChLC film is obtained at the substrate surfaces, resulting in a hybrid structure where an unpolymerized ChLC region is left between two polymerized ChLC films on the cell surfaces. The advantage of this method is the high versatility in the dimension of the structure to be fabricated. Tunable defect mode characteristics and laser actions based on this nano-modulated chiral helix structurre will be demonstrated.

6487-24, Session 6

Design of liquid crystal cells for the investigation of optical spatial solitons

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In some particular materials, it is possible to compensate for the spontaneous diffraction of a laser beam by using the interplay of optical intensity and material nonlinearity. The resulting self-confined beam is known as “optical spatial soliton” and it has been observed in various bulk media. In Nematic Liquid Crystals (NLC), spatial solitons (“nematicons”) can be obtained at milliwatt optical power and have been investigated in a variety of configurations both for fundamental interest and practical applications. Along with a survey of recent investigations of nematicons, we present an experimental and theoretical approach devoted to highlight the importance of controlling the director orientation at the boundaries of the NLC cell: The cell configuration and the consequent director orientation distribution represent indeed the starting point for the production of several, distinct, phenomena related to optical soliton generation and propagation.

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6487-25, Session 7

Touchless optical control of defects, colloids, and structures in liquid crystals

I. I. Smalyukh, Univ. of Illinois at Urbana-Champaign

Laser tweezing in liquid crystals (LC) exhibits richness of new phenomena, fascinating experimental capabilities, and shows a great promise to become one of the mainstream techniques in the fundamental study and applications. The lecture will discuss experimental results on optical tweezing in LCs. In addition to using single laser traps, manipulation of multiple (tens and hundreds) transparent objects is performed in the framework of such approaches as holographic optical trapping and time-shared laser trapping. Colloidal particles, defects, and director structures are manipulated in LCs of both thermotropic and lyotropic origin. Moreover, employing laser beams with intensity exceeding the threshold for the optical Freedericksz transition, a variety of director structures are first optically generated and then spatially translated, rotated, sorted, and organized into superstructures such as periodic arrays. Optical tweezing is employed to measure the elasticity-mediated forces between colloidal particles in LCs. One of the major challenges complicating the quantitative measurements is the anisotropic nature of LCs, which makes the tight laser beam focusing difficult and considerably weakens trapping forces. Using LCs with low birefringence allows us to mitigate these artefacts. Optical trapping forces and the trap stiffness are first calibrated for different laser powers using viscous drag forces. This is then used to characterize interaction forces between colloidal particles in the nematic bulk. The interaction forces are measured for pairs of solid spheres with dipolar as well as quadrupolar symmetry of director distortions in the uniform surrounding LC matrix; the data are discussed in the framework of the available theories. Finally, optical trapping is employed to characterize LC defects. Disclinations and dislocations are manipulated by either optically trapped colloidal particles or directly by tightly-focused linearly-polarized laser beams. This manipulation allows one to determine the line tensions of topologically stable disclinations in nematics as well as dislocations and oily streaks in lamellar LCs. The measured data are in a good agreement with the theoretical predictions. We conclude that laser tweezing allows one to design well-controlled experiments for fundamental studies and also opens new avenues for LC applications.

This research was supported by the Institute for Complex Adaptive Matter and the International Institute for Complex Adaptive Matter.

6487-26, Session 7

Applications of ferroelectric particles/liquid crystal colloids

A. V. Glushchenko, Univ. of Colorado at Colorado Springs; C. I. Cheon, Hoseo Univ. (South Korea); Y. A. Reznikov, Institute of Physics (Ukraine); J. L. West, Kent State Univ.

Ferroelectric nanoparticles significantly improve properties of existing liquid crystals and benefit the performance of many devices. By changing a concentration and a type of ferroelectric particles one can affect physical properties of the nematic, smectic, and cholesteric liquid crystal materials, including the dielectric constants, the birefringence, the phase transi-

tion temperatures, and even the order parameter. We demonstrate the performance of these new materials in various devices, including displays, light modulators, and beam steering devices.

6487-27, Session 7

Effects of carbon nanotubes on physical properties of nematic liquid crystal and liquid crystal device

S. H. Lee, Chonbuk National Univ. (South Korea); Y. H. Lee, Sungkyunkwan Univ. (South Korea)

Recently, active researches on carbon Nanotube (CNT)-doped liquid crystal (LC) mixtures are progressing. Based on experimental observations, CNTs are known to align parallel to the LC director and experience orientational deformation associated with the LC deformation under an electric field. Theoretical calculation also shows that the LC is strongly anchored on CNT in a way that the LC director is parallel to the CNT long axis. Many experimental results have been reported regarding to CNT effects on electro-optic characteristics of the LC device such as threshold voltage, residual dc and response time, and physical properties of a nematic LC such as rotational viscosity, dielectric anisotropy, elastic constants and clearing temperature, although some are still controversial.

In this talk, historical reviews as well as our achievements on CNT-LC mixtures will be discussed.

6487-28, Session 8

Liquid crystal Bragg gratings: dynamic optical elements for spatial light modulators

R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, Science Applications International Corp.; E. R. Beckel, A. M. Urbas, T. J. Bunning, Air Force Research Lab.

Bragg gratings yield a single diffracted order when irradiated by a coherent beam at the appropriate Bragg angle. In many cases, nearly all of the energy of the incident beam can be coupled to the diffracted beam. Hence these gratings can form many useful optical elements, and this has been realized in 1-D, 2-D, and 3-D photonic crystals. Bragg gratings made with liquid crystals offer the added dimension of dynamic properties through the large electro-optical effect in liquid crystals. Applications for spatial light modulators are numerous, including optical switches, modulators, active optical elements (e.g., lenses), laser sources, and tunable filters. We have been exploring a number of approaches for making liquid crystal Bragg gratings, including holographic polymer-dispersed liquid crystals, cholesteric liquid crystals, and homogenous nematic liquid crystals in hybrid devices. We have studied the dynamic properties of these Bragg gratings by electrical, thermal, and optical stimulation. Modification and control of optical and dynamic properties have been obtained through combinations of liquid crystals with polymers, combinations of various dopant materials, and interactions of liquid crystals with organic and inorganic interfaces. We will discuss the materials, fabrication, characterization, and physics of liquid crystal Bragg gratings and present the results of various devices we have studied in our lab. We will also discuss potential applications.

6487-29, Session 8

Diffraction of polarization gratings

C. v. Heesch, Technische Univ. Eindhoven (Netherlands)

The diffraction efficiency and polarization state of diffracted beams from thin polarization grating has been described in a more general way than is currently in the literature. Using the paraxial diffraction theory a more general transfer matrix is presented to describe the diffraction of polarization holograms in terms of arbitrary orthogonal polarizations, circular and linear birefringence, relative intensities, and a small incident angle. Combining linear and circular birefringent modulations require special materials and techniques to create these diffractive gratings, which are able to diffract linear, circular and (more general) elliptical polarized light in a very efficient way. With the right combination of modulations any state of polarization can be diffracted with 100% efficiency.

6487-30, Session 8

New HDTV phase only SLM

S. Osten, S. Krüger, A. Hermerschmidt, HoloEye Photonics AG (Germany)

We developed a new phase only LCOS (Liquid Crystal On Silicon) spatial light modulator (SLM) based on an electrically controlled birefringence (ECB) liquid crystal mode for dynamic diffractive optics applications, optical tweezing, wave front control, digital holography and beam/pulse shaping.

This device is the first Phase SLM showing HDTV (1920x1080) resolution and a small pixel pitch of only 8μm (87% fill factor) on a digital silicon back plane. Here the LC molecules are aligned parallel to the electrodes and an applied electric field forces them to tilt in the direction of the filed in order to change the refractive index seen by the light due to optical anisotropy. This leads to a pure phase modulation without any polarisation change (<1%) if the linear polarised light is coupled along the director axis of the LC molecules.

HOLOEYE provides two versions of this new SLM, where one is optimized for the visible region (420-800nm) and the other one is designed for 2p phase retardation up to 1064nm. We will discuss the optical modulation and show measurements on reflectivity, diffraction efficiency as well as measurements of the surface quality (flatness).

We demonstrate the graphical user interface (GUI) able to adapt the electro-optical response of the system to different wavelengths and applications. Furthermore, we discuss the optical effect of different sequence encoding for the phase modulation properties.

6487-31, Session 8

A reflective LCOS spatial light modulator controlled by 12-bit signals for optical phase only modulation

T. Inoue, H. Tanaka, N. Fukuchi, M. Takumi, N. Matsumoto, T. Hara, N. Yoshida, Y. Kobayashi, Hamamatsu Photonics K.K. (Japan)

We have developed a phase only modulation type of liquid crystal on silicon (LCOS) device. The device was designed mainly for wavefront control in adaptive optics, optical manipulation, laser processing, etc. In the device a dielectric multilayer mirror was fabricated to enhance reflectivity and diffraction efficiency. The pixel number is 792x612 and the pixel size is 20x20 microns square. The range of the phase modulation exceeds one wavelength. The device is driven by electronics composed of a digital-visual-interface (DVI) receiver, a field programmable gate array, and 12-bit digital-to-analog converters (DACs). In the normal mode the driver receives 8-bit image data from a computer via the DVI cable and transfers them to the DACs after converting to 12-bit signals according to a lookup table (LUT). The LUT can compensate nonlinearity of the device, but it is not pixel-dependent so that non-uniformity cannot be removed. The device has the other special mode where the driver receives 12-bit data and transfers them directly to the DACs. In this mode, users can compensate both of the nonlinearity and non-uniformity by programming pixel-dependent LUTs on the computer. The measured diffraction efficiencies reached approximately 90% of the theoretical one in a low spatial frequency region, and approximately 85% at highest. In the presentation, we report details of the device and some measurement results of the phase modulation characteristics.

6487-32, Poster Session

Multiple-functional and cost-effective liquid-crystal cell parameter measurement system

G. Chang, Y. Lin, Y. Lin, National Taiwan Normal Univ. (Taiwan)

For years, the technology of TFT-LCDs (thin-film-transistor liquid crystal displays) has grown very rapidly, especially in the market share and technical development of FPD industries. To effectively promote the industry¡õs capacity for the mass production and quality control, it is urgent to design and develop LC cell optical parameter measurement systems. The goal of this paper is to develop a multiple-functional and cost-effective measurement system to lower the manufacturing cost for the industry. The optical parameters includes the pretilt angle, liquid crystal (LC) cell gap (or phase retardation), and twist angle, which highly influence the display quality. In this paper, we first study the past approaches and analyze their measurement performance. Then, a simple and cost-effective method is proposed to achieve the multiple functions. That is, in addition to the precise measurement of the three important optical parameters, the proposed system can measure the voltage- transmittance (V-T) curve. In our approach, the theoretical study, simulation, and experiment are performed to show the feasibility of the system implementation. Finally, the proposed system is developed to automatically measure the LC cell parameters. Experimental results indicate that the proposed measurement system gives a satisfactory result.

6487-33, Poster Session

Spatial optical modulator (SOM): high density diffractive laser projection display

S. K. Yun, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea)

Diffractive SLMs (Spatial Light Modulators) with submicro second response time show high-performance light modulation, suitable for next generation laser projection displays. Presented will be a new type of diffractive spatial optical modulators (SOM), developed by Samsung Electro-Mechanics. Much details on the nano-level controls over the microoptical grating device, signal processing, and projection optics will be discussed on the VGA (640x480) SOM for mobile supermini-projector with a optics volume less than 15cc, as well as a full HD (1924x1080) SOM for 60" TV and projector.

Conference 6488: Practical Holography XXI: Materials and Applications

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6488-01, Session 1

Photo-thermo-refractive glass: a new material for high efficiency large aperture optical elements

V. I. Smirnov, OptiGrate; G. B. Venus, L. B. Glebov, L. N. Glebova, College of Optics and Photonics/Univ. of Central Florida

A photosensitive glass demonstrating refractive index decrement after exposure to UV radiation followed by thermal development is used for phase volume hologram recording. This photo-thermo-refractive (PTR) glass is a sodium-zinc-aluminum-silicate glass doped with cerium, silver and fluorine. Spatial modulation of refractive index resulted from precipitation of nano-crystalline phase of sodium fluoride. The main mechanism of refractive index decrement is a photoelastic effect resulted from strong tensions generated in both crystalline and vitreous phases because of strong difference in their coefficients of thermal expansion. Volume Bragg gratings recorded in this glass, show extremely narrow spectral and angular selectivity and have low losses combined with high tolerance to laser radiation. These gratings possess a unique ability to produce laser beam transformations directly in angular space. This feature paves a way to creation of high power semiconductor lasers with stable narrow emission spectra and diffraction limited divergence. This approach is based on three types of holographic optical elements made from PTR glass. They are an output coupler providing single-transverse-mode oscillation for broad area emitters, a phase coupling element providing coherent emission from a number of spatially separated lasers, and a spectral beam combiner summarizing a number of laser beams with different wavelengths within a single beam with diffraction limited divergence.

6488-02, Session 1

Characterization of PVA doped with different metallic salts as conductor polymer and as holographic film sensitized with ammonium dichromate

M. d. l. P. Hernández Garay, A. Olivares-Perez, I. Fuentes-Tapia, J. B. R. Ruiz-Limón, E. L. Ponce-Lee, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

There are a multitude of materials were investigated for holographic recording. Materials and processes are advantageous because its have high exposure sensitivity, high diffraction efficiency, stability, etc.

We report a photosensitive emulsion its electro-optical and chemical properties by mixing PVA with metallic salts and ammonium dichromate. We describe a hypothesis with respect to some mechanisms of photo and thermo sensitivity to different characteristics in emulsions.

6488-03, Session 1

Polyelectrolyte as holographic recording medium

S. Toxqui-López, A. Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Replication holograms with high diffraction efficiency can be generated into polyelectrolyte coating by applying ultraviolet light, this material provides advantages in production time and unit cost to replica, futhermore is nontoxic, soluble- water, clear and cheap. we show technique used to obtained the replication holograms and some experimental results.

6488-04, Session 1

Organic photoluminescent holograms

E. L. Ponce-Lee, A. Olivares-Pérez, J. B. R. Ruiz-Limón, M. P. Hernández-Garay, S. Toxqui-López, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We developed a holographic material based on glucose The material is recorded by its crystalline polymerization when it is radiated with ultraviolet light. Also we doped our holographic material with a colorant, obtaining a parallel photoluminescence phenomenon. Thus, our material is recorded with UV light, and it is reconstructed with a green laser beam, at the same time that it is emitting photoluminescent red light. We analyze the relation of both facts by a diffraction grating generated in a computer and transferred to our material.

6488-05, Session 1

Photopolymers containing epoxy monomers for holographic recording

E. Kim, J. H. Kim, K. Rameshbabu, Yonsei Univ. (South Korea)

A new photopolymer composite containing epoxy monomer was explored as a holographic recording media. Epoxy monomers of s-triazine derivatives were prepared by the reaction of amine and s-triazine derivatives in 3-4 steps. Photopolymer films prepared by mixing epoxy monomers with binder, aromatic acrylic monomer and photoinitiator were sensitive to a visible light and polymerized upon excitation with a 491nm laser light. The optimization of holographic recording media was carried out by controlling the concentration of monomers in photopolymer films to control the diffusion and polymerization. The realtime diffraction efficiency was determined and correlated to the polymerization of the film. Sensitivity, recording time, storage stability and application potential will be presented.

6488-06, Session 1

Pulsed holographic gratings in azo-polymethacrylates with different molecular architectures

P. Forcen, F. Rodriguez, C. C. Sanchez, R. Alcala, L. Oriol, Univ. de Zaragoza (Spain); S. Hvilsted, Danmarks Tekniske Univ. (Denmark)

In the information age, with an increasing demand for optical data storage systems with higher storage density and faster data transfer rates, holography is gaining interest as an alternative to magnetic and conventional optical recording systems. Azobenzene polymers have been intensively studied as holographic media since they can show large, long lifetime photoinduced anisotropy while keeping the possibility of rewrite and erase. Diffraction gratings induced in these materials by interference of two coherent continuous wave (cw) laser beams, have been extensively studied. Much less work has been performed on the recording of gratings under nanosecond (ns) pulsed photo-excitation. In 1999 Ramanujam et al. reported the formation of surface relief and anisotropy gratings with a single pulse of 532 nm light. Later on, a few papers have appeared dealing with the grating production in azobenzene polymers films using ns pulses. In all the reported cases the contribution of the surface relief grating to the diffraction efficiency seems to be the dominant one although phase gratings are more interesting for holographic storage purposes.

In this communication we present the results obtained on the production of holographic gratings using 4 ns pulses of 532 nm light in azo-polymethacrylates with different polymeric architectures. We have used

different illumination patterns (intensity and polarization) to register holographic gratings finding surface and phase contributions for the diffraction efficiency. The time response and stability of this diffraction efficiency have been studied as a function of the recording energy for the different polymers. Stable values of the diffraction efficiency have been obtained in some of the polymers after one single pulse of several tenths of mJ/cm2. We have also estimated the relevance of surface and phase contributions at different recording energy regimes. Polarization holographic gratings with efficiencies of about 0.8% (measured at 632.8 nm) have been registered with no measurable relief contribution. A discussion on the influence of the molecular architecture in the optical response will also be presented.

6488-07, Session 1

Quasi in-situ microscopic study of hologram build-up in LiNbO3 crystal

I. Bányász, G. Mandula, Magyar Tudományos Akadémia Szilárdtestfizikai és Optikai (Hungary)

Phase-contrast and interference microscopy were adapted for quasi in-situ microscopic observation of the temporal evolution of phase holograms in photorefractive crystals.

Phase-contrast and interference microscopy are common methods for studying microscopic phase objects, including holographic phase gratings [1,2]. These methods were used for quantitative analysis of phase gratings in ion-implanted glasses and silver-halides recently [3,4].

First a hologram was recorded in the sample, and diffraction efficiency was monitored during hologram build-up using inactinic laser light. Thus kinetics of hologram build-up could be determined. The initial hologram was erased using white light. Then a series of write-erase cycles were performed with increasing exposure times up to an exposure corresponding to saturation of the grating. Holograms were observed by phase-contrast and/or interference microscope after each exposure. The time elapsed between the exposure and the microscopic observation was negligible compared to the relaxation time of the hologram. Possible erasure during microscopic observation was checked by measuring diffraction efficiency of the gratings after having taken the microphotos. The obtained temporal evolution of grating profile gives a deeper insight into the physical mechanism of hologram formation in photorefractive materials than simple diffraction efficiency measurements.

Congruently grown samples of LiNbO3: Fe, with Fe concentrations in melting of 10-3 and 2x10-4 were studied by the above method. Sample thickness was set to 200 μm to allow correct microscopic observation. Plane-wave holograms were recorded in the samples using an Ar-ion laser at λ = 488 nm. Grating constants were between 3 and 9 μm. Holograms were recorded at several values of interference fringe modulation.

The results show the dependence of temporal evolution of grating profiles on recording conditions. Differences between the measured diffraction efficiencies and those calculated using the Kogelnik-formula are due to nonlinear recording.

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6488-08, Session 1

Study for Bragg detuning effect and asymmetry of diffraction efficiency spectrum on the transmission and the reflection hologram

Y. Kwon, K. Y. Kim, J. Y. Park, Daewoo Electronics Corp., Ltd. (South Korea)

Photopolymer is attractive as a recording material for holographic data storage because of high photosensitivity and grating refractive index. We made experiments with photopolymer for the transmission hologram and the reflective hologram. The optical setup was used in common between the transmission hologram and the reflection hologram except each signal beam. So, we could compare the characteristics between two holograms under the same experimental conditions. We observed the Bragg detuning effect on the transmission and the reflective hologram as it has been pointed out. And that effect was shown up lager on the reflection hologram. Another problem was an asymmetry of the diffraction efficiency spectrum. So, the angle of first null was different between each detuning angle direction. The critical reasons of Bragg detuning effect are known as the bulk refractive index change and shrinkage of material after hologram recording. And the asymmetry of diffraction efficiency spectrum is due to non-uniform grating. However, the trials for analyzing the effects are mainly on the K-sphere and biased on the transmission hologram. So, we approached the Bragg detuning effect and the asymmetry numerically. We added factors that cause the Bragg detuning effect and asymmetry in the numerical model from coupled wave theory. We simulated the modified model for all factors with MATLAB and compared the results with experimental ones. And then, we could apply the analysis model to the transmission and the reflection holograms all together.

6488-09, Session 1

Measurement of refractive index of photopolymer for holographic gratings

E. Watanabe, Japan Women’s Univ. (Japan); C. Fujikawa, Tokai Univ. (Japan); J. Mizuno, K. Kodate, Japan Women’s Univ. (Japan)

Recently, volume phase holographic (VPH) gratings have attracted attention in several fields such as high density optical memory, optical information processing, and telecommunication system. We have fabricated VPH gratings and grisms [1] using liquid photopolymer as photosensitive materials. The refractive index modulation of VPH grating has been indirectly estimated from the wavelength dependence of the diffraction efficiency of VPH grating by comparing with the simulation. Because the refractive index modulation of VPH grating is one of the important parameters, its direct measurement is desired. In this paper, a direct measurement system of the optical path length along the optical axis using phase lock technique was demonstrated. The thickness of the photopolymer between the two glasses was 10 um. The resolution along the optical axis in this measurement system was estimated to be 30 nm. This value corresponds to the refractive index modulation of 0.003. The spatial resolution in the plane perpendicular to the optical axis is dependent on the Rayleigh limit and the sample thickness.

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6488-10, Session 1

Electo-optical characteristics of holographic replication using a photopolymer and ZnCl2

M. d. l. P. Hernández Garay, A. Olivares-Perez, I. Fuentes-Tapia, J. B. R. Ruiz-Limón, E. L. Ponce-Lee, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

There are many polymers applications in the industry, but some polymers can be used also as material for holographic register. Photopolymer materials with others components are promising candidates for holographic

replications. We report in this manuscript the analysis of its electro-optical and chemical properties as; diffraction efficiency, pH, refraction index, resistivity experimental and technique to obtain holograms replication with lithographic techniques.

6488-11, Session 2

Polarization experiments in holographic interferometry

G. K. Ackermann, J. P. Eichler, L. Duenkel, C. Schneeweiss, Technische Fachhochschule Berlin (Germany)

Experiments were performed to study the properties of polarized light using real time holographic interferometry. Circular polarized HeNe laser radiation of different helicity was used for the reconstruction and illumination. The conditions were similar to a quantum eraser experiment. As an eraser a linear polarizer is used. It is shown that the results depend strongly on the structure of the object. Metallic and dielectric surfaces were studied. A theoretical analysis is given based on the well-known Jones formalism. The formalism was extended to the depolarizing effect of dielectrica. Theoretical and practical consequences are discussed that refer to the polarization structure of light and to holographic interferometry.

6488-12, Session 2

Problem of twin-image elimination in 2-D Fourier hologram

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It is well known that one of the basic functions of security holograms is the maximal complication of their non-authorized reproduction, in another words - counterfeiting. For the decision of this problem, into hologram's structure usually are placed concealed images demanding special conditions for their viewing. A popular way to place concealed image in Diffractive Optical Variable Device (DOVID) is integration into DOVID's structure of a Concealed Laser-Readable Image (CLRI). Traditionally CLRI is a 2-D Computer-Generated Hologram (2-D CGH), which is an digitized Interference Fringe Data (IFD) structure, computed under the scheme of Fourier-hologram recording. Such hologram provides second - line inspection with use of portable laser reading devices. While it is read two (+/- 1 order of diffraction) identical static or animated images are forming.

Represents significant interest a synthesis of CGH,which is restore image only in one diffractive order or two different images in +1 and -1 orders of diffraction.

For realization of this task, we have carried out researches of holograms' synthesis with applying of methods of Gilbert-Optics. Computer Synthesized Holograms, calculated on these methods are restoring images on screen without "twin", which can be used for two various images instead of twins images in the +1 and -1 orders of diffraction of laser radiation.

6488-13, Session 2

Non-collinear femtosecond photon echo in dye-doped polymers

O. K. Khasanov, O. M. Fedotova, Institute of Solid State and Semiconductor Physics (Belarus); V. V. Samartsev, Kazan Physical-Technical Institute (Russia)

Today the efforts are made to create compact, high-speed optical echo-processors with high information capacity. Compactness may be achieved only by means of using of solid-state information carriers, which must be cheap also. Dye-doped polyvinylbutural films are numbered among such information carriers. Just now recording the echo-holograms in above films at room temperature by use of femtosecond pulses has been demonstrated. The distinguishing feature of polymer films is their extremely large inhomogeneous width of spectral line. In other words the width of inhomogeneous broadening(IB) and spectral width of exciting pulses(EP) are of the same order. At the non-collinear scheme of echo-hologram recording the inhomogeneous spectral line is excited asymmetrically what may lead to complicated temporal structure echo-signals and their spectral peculiarities.

As our analysis shows, besides the principal response, one can observe up to 8 satellites, whereas an intensity of satellite can exceed an intensity of the main response. Photon echo(PE) signals oscillate with variable-in-time frequency likewise the case of non-resonant excitation of spectral line. The relaxation character is time-dependent obeying the power or by the exponential law. The relaxation rate is a function of Rabi frequency of EP and IB. In a number of cases observable responses can take the form of multiple PE. We analyse the PE spectra as a function of angle above and compare analytical and numerical results with experiment. The possibility of PE-frequency switching between the blue and red spectral ranges is predicted. The red shift of PE-signal is due to its diffraction origin and partial coherence of pulsed beams.

6488-14, Session 2

Development of the electronic speckle shearing phase-shifting pattern interferometer

J. Chao, Y. Zhang, G. Zhou, Tianjin Univ. (China)

The electronic speckle shearing phase-shifting pattern interferometry(ESSPPI) has been developed for strain measuring and nondestructive testing. The electronic speckle shearing phase-shifting pattern interferometer with semiconductor laser is designed in this paper. The Michael interference is adopted for realizing shearography in the interferometer, and the precise Micro-displacement system is developed for achieving phaser-shifting interference. Phase map due to distortion of the objects is presented. The results shows that the electronic speckle shearing phase-shifting pattern interferometer is well suited for strain measuring.

6488-15, Session 2

Adaptive optics for holographic data storage

N. Ishii, N. Kinoshita, T. Muroi, H. Shiino, K. Kamijo, N. Shimidzu, NHK Science & Technical Research Labs. (Japan)

The effects of phase fluctuation on the holographic data recording characteristics are reported by simulation and experiment. In experimentally, adaptive optics is applied for phase compensation and discusses the reproduced characteristics with and without the proposed method.

6488-16, Session 2

Novel diffraction grating light guide for LED backlight

E. Miyamoto, S. Maruyama, A. Nagano, L. M. Murillo, T. Toda, F. Iwata, Toppan Printing Co., Ltd. (Japan)

In conventional LED backlight as that used in the mobile liquid crystal displays (LCDs), typically the structure consists of a light guide, a diffusing sheet, a prism sheet and so on. Here the prism sheets are indispensability to obtain high brightness and high uniformity in front. In this work we would like to propose a novel light guide where we have applied a special diffraction grating technology which provides a high performance with a thinner backlight. The special designed diffraction gratings on the light guide redirects incident light by diffraction to the front direction without the utilization of prism sheets. The diffraction grating pattern was optimized so that the backlight module with the diffraction grating light guide would be bright uniformly in all the emitting area. The advantage of

the diffraction grating is that the angle distribution of the emitting light can be designed as desired. Therefore, although a diffraction grating causes spectrum dispersion and shows rainbow colors, our light guide is not colored significantly because of the optimized diffraction grating pattern. Moreover, we arranged a specific scattering pattern with the grating pattern, so that the backlight shows a white color in the front direction. For testing the performance we made a diffraction grating light guide suited for a 2.4 inch backlight with 4 LEDs in a trial. As a result, the backlight which was consisted of diffraction grating light guide, with either a single or none prism sheet, achieved equivalent performance to conventional backlights. In the future, we think that the novel backlight can achieve a higher performance by further optimization of the design of the diffraction grating.

6488-17, Session 2

Holographic wavefront sensor: fast sensing without computing

G. P. Andersen, U.S. Air Force Academy; F. Ghebremichael, K. S. Gurley, Lockheed Martin Corp.

We present results of a fast holographic wavefront sensor. The device consists of a multiplexed hologram designed to diffract a single input beam into multiple output beams depending on the amplitude of particular Zernike terms. The aberration and amplitude are determined by the spatial location of the reconstructed focused light. The sensing does not require any calculations, so the device is simple, compact and fast. In fact, using several fast position sensing detectors (PSD), a full description of the wave aberration can be obtained at rates in excess of 100 kHz. The holographic wavefront sensor can be reconfigured for any type of basis set, and is easily adaptable to laser mode profiling. In this talk we will present results of the both the theory and operation of our holographic wavefront sensor.

6488-18, Session 2

Gratings-based modified Michelson interferometer for quadrature phase measurements

Z. Yaqoob, J. Wu, X. Cui, X. Heng, C. Yang, California Institute of Technology

Quantitative amplitude and phase measurements of optical signals are important in many applications ranging from metrology to cell biology. Phase-shifting interferometry, a method for quantitative phase imaging (QPI), requires recording of four interferograms with precise pi/2 phase shifts of the reference field, adding complexity to the system. Other techniques for QPI such as digital holography and Hilbert phase microscopy depend on recording of high frequency spatial fringes for successful phase unwrapping. We note that multiport fiber based systems such as 3x3 couplers can provide non-trivial phase difference, which can be manipulated for quadrature phase measurements. However, free space equivalents of a 3x3 coupler do not exist.

We report a new method for obtaining non-trivial phase difference between the output ports of a reflectance-based interferometer through the use of shallow diffraction gratings. We show that as opposed to a single shallow diffraction grating-based interferometer (which provides only trivial phase shifts), a pair of harmonically-related shallow diffraction gratings can be used to realize a modified Michelson interferometer where the phase shifts between different output ports can be adjusted. More importantly, the phase shift can be adjusted by simply shearing one grating with respect to the other. This approach does not change the path length relationships of the different interference beams within the interferometer - an advantage for metrology and low coherence interferometry applications.

In this paper, we will provide a mathematical formulation, explaining the advantage of harmonically-related gratings for quadrature phase interferometry. Proof-of-concept experiments will also be conducted to support our claims.

6488-45, Session 2

Holographic lens array for future display screen

F. C. Fan, S. Choi, K. Ko, Shenzhen AFC Technology Co., Ltd. (China)

Holography is well known as a revolutionary science for imaging and display. With the commercialization of LCD and DMD projectors, the quality of the imaging screen becomes more and more important to the future display technology. In this paper, we propose to use the holographic lens array as the imaging screen of these projectors. Basic principle, details of implementation, and the influence to the future display technology are discussed.

6488-19, Session 3

Holographic video display based on guided-wave acousto-optic devices

D. E. Smalley, Q. Y. J. Smithwick, V. M. Bove, Jr., MIT Media Lab.

We introduce a new holo-video display architecture (“Mark III”) developed at the MIT Media Laboratory. The goal of the Mark III project is to reduce the cost and the size of a holo-video display, making it into an inexpensive peripheral to a standard desktop PC or a game machine, which can be driven by standard graphics chips. Our new system is based on lithium niobate guided-wave acousto-optic devices, which give twenty or more times the bandwidth of the tellurium dioxide bulk-wave acousto-optic modulators of our previous displays. The novel display architecture is particularly designed to eliminate the high-speed horizontal scanning mechanism that has traditionally limited the scalability of Scophony-style video displays.

In our talk we describe the system architecture and the guided-wave device, explain how the device is driven by a graphics chip, and present some early results.

6488-21, Session 3

Holographic color display with wide visual field or viewing zone using in-line holograms

K. Tsuji, Univ. of Hyogo (Japan)

New methods are required for the reconstruction of color images from recorded in-line holograms and for enlarging the viewing zone and the visual field of the display. On the other hand, an ordinary hologram contains far more information than necessary for the purpose to reconstruct virtual 3D images. There are three purposes of this paper. One is to propose a new method for reconstructing 3D images from phase-shifting in-line holograms. Other purposes are to enlarge the visual field or the viewing zone of the display by adopting a multi-channel LCD panel, and to propose a novel 3D display with wide viewing zone using sampled small holograms with reduced information. High-quality color images are reconstructed from the complex-amplitude in-line hologram by using the developed holographic display system. The viewing zone or the visual field of the holographic display is enlarged by adopting a multi-channel LCD modulator. 3D images with motion parallax are reproduced in the wide viewing zone from holograms with reduced information. Since a different image is visible from each viewing position, an observer perceives a 3D image with full parallax and continuous motion parallax. This method uses a parallax-fusing perceptual phenomenon. Observer can perceive motion parallax of the image with wide viewing zone by viewing a pair of stereoscopic images from right-eye and left-eye positions. Observer can also perceive the correct visual depth of images through a parallax-fusing perceptual phenomenon.

6488-23, Session 3

Method of reduction of zero order intensity in computer generated holograms by use of phase addition technique

D. W. K. Wong, G. C. K. Chen, Nanyang Technological Univ. (Singapore)

Computer generated holograms (CGHs) are a type of thin holograms which can be designed mathematically if the diffraction regime is known, without a need to capture the actual object field information unlike conventional holography. CGHs are often used as beam-splitters, and have the advantage of allowing complicated designs and facilitating system integration compared to other beam-splitters. However the fabrication of CGHs requires precision, as variations in the fabricated hologram can lead to a degradation in CGH performance, in particular a large intensity in the zero order. In this Paper, a study is first made on the effect of fabrication errors in the CGH performance. A phase plate is then proposed to be inserted into the system in front of the CGH to reduce the zero order for a fixed fabrication error, and the phase plate parameters are varied to determine the optimum design. The fabrication etch depth error is then allowed to vary, and the use of the phase plate shows a reduction in the zero order intensity by a factor of about seven times relative to the total diffracted intensity, and about 20 times relative to the diffracted spot intensity. The results show that the phase plate has resulted in an increase in the tolerance of the diffracted pattern to errors due to fabrication processes. Some comparison will also be made against other methods of reducing the zero order intensity.

6488-24, Session 3

Full-color image-plane holographic video display

T. Yamaguchi, G. Okabe, H. Yoshikawa, Nihon Univ. (Japan)

In this paper, we have investigated real time calculation and display optics of full color hologram with full parallax. In our previous study, full color hologram was realized as the rainbow hologram which discards vertical parallax to reduce computation complexity. Since the color of the reconstructed image changes when observer moves to the vertical direction even a little, proper color reproduction can be obtained only from narrow viewing area. And this hologram has horizontal parallax only.

In this study, we employ the image hologram for better color reproduction and full parallax reconstruction. When we calculate the image hologram, we use the virtual window to reduce the calculation amount. By using the virtual window, we could achieve 253 times faster the calculation speed compare with Fresnel hologram using the difference method. The full color hologram is displayed on the holographic television (HoloTV), which uses a part of original optics and LCoS panels of the conventional video projector (Cannon POWERPROJECTOR SX50) to separate and combine color components.

From experimental results, computational speed of the full-color image hologram is almost same as the full-color rainbow hologram and color reproduction is better than that of the rainbow hologram. We also could achieve to reconstruct good quality animation.

6488-25, Session 3

Quality evaluation of full color hologram

M. Kurashige, T. Kumasawa, A. Kitamura, T. Yamauchi, M. Watanabe, K. Ueda, Dai Nippon Printing Co., Ltd. (Japan)

Holography has been studied at DNP for more than 30 years. Last 15 years, mass-produced full color Lippmann holograms have been developed. In 1997, DNP succeeded in establishing the methods to mass-produce full color Lippmann holograms for the first time in the world and commercialized under the brand name of TRUE IMAGE. This is a volume-type hologram that diffracts selected wavelengths of the ambient light to desired angles. Recently, color evaluation method of full color hologram was reported at the SPIE Photonics WEST 2006. To mass-produce high-quality full color holograms, it is necessary to evaluate several parameters from various points of view as well as color evaluation.

In this report, the resolution of hologram was discussed as a parameter of hologram recording. The resolution is one of the most important parameters to make clear image holograms. At first, customized models and charts were designed to evaluate resolution efficiently. Secondly, such models and charts were recorded in photopolymers as holographic images using H1H2 method. Finally, the resolutions of images were evaluated using visual and machine observation under specified light source. Another parameters, such as chromaticity, gradation sequence and so on, will be also discussed at the presentation.

6488-46, Session 3

Ethereal presences in holography and photography

K. Byrne, M. J. Richardson, De Montfort Univ. (United Kingdom)

This paper examines the concept of the ‘Presence of Absence’ in post-mortem photography and holography, drawing upon both historical and lesser-known images as reference. To create a photographic negative one needs the presence of light to expose the light sensitive surface, be it glass, a polished plate or plastic. In contrast, a hologram may be created when a coherent light source, for example from a Laser, travels through a light sensitive material and falls upon the subject to be recorded. A holograph is a reflection or a memory of light; the laser light can penetrate human tissue illuminating a few microns of skin to create a waxy complexion in the final hologram. And so the hologram of a live healthy subject is often said to look like a death mask. Certainly, holographers often attempt to overcome this by using cosmetics - similar to the make-up applied to the film stars during early black and white silent movies. Both mediums recall ‘now absent moments’ providing information regarding what is ‘not there’ as much as ‘what is’. The exploration of absence and presence post-mortem photographs exemplify this concept through a richly visceral visual language. A photographic syntax can interpret death as an elegant yet horrific aesthetic, the photograph may be beautify screened and yet obscene in its content. Concentrating on post-mortem photography, one can be a voyeur, experiencing a mere visual whisper of the true nature of the subject. Our Victorian for fathers used post-mortem photography is as an object of mourning, and at the close of the nineteenth century when Jack the Ripper had the inhabitants of White Chapel in a grip of fear; post-mortem photography was used as a documentation of violent crime. Today, within contemporary photography, death is now presented within the confines of the ‘Art Gallery’, as a sensual, and at times, sensationalised art form. In exploring post-mortem imagery, both in 3D and conventional 2D, absence presents an aspect of death as startling in its unanimated form and detailed in its finite examination of mortality.

6488-26, Session 4

Simultaneous recording of practical 3D color images by phase-shifting in-line holography

K. Sato, Univ. of Hyogo (Japan)

One of the purposes of this paper is to develop a holography system for simultaneous recording of practical 3D color images. Another is to propose a one-shot phase-shifting holography for recording moving color images. In this work, 3D images are recorded by in-line holography for effective use of the pixel number of a CCD. The in-line hologram can record 3D images with wider visual field as compared with the off-axis hologram. A phase-shifting recording system is developed using a high-resolution reflective LCD panel, a color CCD, and red, green, and blue lasers. The phase of RGB reference lights is precisely shifted by moving the diffraction grating displayed on a reflective LCD panel in the system. Since the phase shift is independent of the wavelength of the light in the present method, RGB interference fringe patterns for the practical object can be recorded at the same time by adopting a high-resolution color

CCD. A novel method is also proposed in order to realize a real-time recording of phase-shifting holograms of practical moving objects. Fine phase-shifting in-line holograms for reconstruction of RGB images are obtained from recorded fringe patterns, and animated high-quality color images of the practical object are reconstructed from the holograms.

6488-27, Session 4

Digital holographic tomograph: the tool for microelements investigation

A. Jozwicka, M. Kujawinska, Politechnika Warszawska (Poland)

In order to control performance of amplitude-phase microelements it is necessary to receive information about amplitude and phase distribution of the field at each point (x,y,z) of the microelement under investigation. Digital holographic tomograph DHT proposed by our group permits in principle to investigate amplitude, phase and amplitude-phase objects. The capability of registration of several angular views of the object during one registration is the basic advantage of DHT. This is performed by a multiple pass arrangements and later by reconstruction of the object at different distances. It decreases significantly the number of registered images used for determination of 3D amplitude and phase distribution in measurement volume, and may in future shorten significantly the measurement time. The analysis of tomographic algorithm best suited for 3D reconstruction based on few non-evenly captured amplitude and phase information is given. Experimental and numerical reconstruction of phase (plastic fiber) and amplitude-phase (waveguide plate with semitransparent layers) objects using digital holography setup will be presented. For numerical reconstruction the plane wave approximation method was applied. The experiment has proven the possibility of independent reconstruction of phase and amplitude for several different reconstruction distances for a certain class of objects and allows to build compact systems.

6488-28, Session 4

Computer-generated holograms allowing 360-degree viewing

Y. Sakamoto, A. Kashiwagi, Y. Murarya, Hokkaido Univ. (Japan)

Holograms that is allowing 360-degree viewing such as cylindrical holograms, show us 3D images with motion parallax and look-around property. Especially, full parallax holograms - not multiplex holograms - make reproductions with an impressive 3-D feeling. However, it has not been realized by a computer-generated hologram, because it takes huge amount of time to calculate a fringe pattern by a PC. To improve the calculation time, we have studied two types of computer-generated holograms allowing 360-degree viewing: cylindrical holograms and prismatic holograms. A prismatic hologram consists of some plates, and it takes not so much time to synthesize the hologram on each plate, because there are some fast calculation methods on planar shape hologram. For the example of the prismatic holograms, we made hexagonal cylinder holograms that consist of 6 plates. On the other hand, a fast calculation method of cylindrical-holograms has been proposed, theoretically (Sakamoto, 2005). We have implemented the method and verified the efficiency of the method. Both calculated fringe patterns were printed on transparent sheets and were carried out experiments of reconstruction. As the results, the holograms show us 3D images of objects at the center of the hologram. A viewer can see the 3D objects from 360-degree by both eyes. In this paper, we discuss the methods and experimental results.

6488-22, Poster Session

Three-dimensional TV using holographic stereogram

K. Sato, Shonan Institute of Technology (Japan); K. Takano, Tokyo Metropolitan College of Aeronautical Engineering (Japan)

Holographic stereogram is useful for information reduction of hologram data transmission in the case of 3D-TV. Multiviewpoint 2D images are used for recording holographic stereogram. In this experiment 2 LCD panels are used. We consider the efficency of this method for 3D-TV.

6488-29, Poster Session

A system of enlarging visual field and viewing zone simultaneously for electro-holography

T. Nagai, Y. Yabe, Y. Sakamoto, Hokkaido Univ. (Japan)

It is difficult to realize a practical electro-holography, because visual field and viewing zone are limited, which are very narrow to see by both eyes.

The problems are caused by the resolution of devices that display fringe pattern, such as on a SLM (spatial light modulator) and an AOM (acoustic optic modulator).

A low resolution of device occurs ghost images that are high-order diffraction images of reconstructed images. Therefore the ghost images prevent large visual field and large viewing zone.

We propose new configuration of electro-holography using LCD (liquid crystal display) that enlarges visual field and viewing zone simultaneously.

The system consists of an array of reconstruction lights, LCD, electro-shutter that is located between SLM and viewer.

It is possible to prevent the rays from the ghost images by the shutter, to choose appropriate positions of both a reconstruction light in array and an aperture of electro-shutter.

It shows viewers the original 3D objects without ghosts.

Switching the combination of positions of reconstruction light and aperture of shutter for all fringe patterns synchronously is possible to see no-ghost images from any point of view.

Furthermore, to switching very fast by time division multiplexing method, we can get large visual field and large viewing zone simultaneously.

To verify the principle of the method, we made a system and carried out the experiments.

In this paper, we discuss the method and the experimental results.

6488-30, Poster Session

Holographic display system using combination of exchangeable holograms and intelligent illuminations

A. Tanaka, K. Sakamoto, Shimane Univ. (Japan)

A 3D display system is useful technology for virtual reality, mixed reality and augmented reality. We have researched spatial imaging and interaction system. We have ever proposed 3D displays using the slit as a parallax barrier, the lenticular screen and the holographic optical elements(HOEs) for displaying active image. The authors hope that the observer can view virtual images when the user puts the special object on the display table. In this future system, the display system gives users virtual 3D images, which is floating in the air, and the observers can touch these floating images, for example, when kids put objects on the table. The key technologies of this system are the object recognition system and the spatial imaging display. The spatial images are playbacked using the 3D image of a hologram.

We developed a prototype interactive tabletop holographic display system last year. This system consists of the object recognition system and the spatial imaging system. A hologram reconstructs some color images. In this prototype display, we recorded three color (red, green and blue) images on the holographic material. Using each color illumination, a hologram can only reconstruct the one image. The observers can select and view the image when he puts the card which is illustrated with its figure. However, this system has the restriction of the reproducable images. To solve this problem, we developed a new display system. Our new display system has an intelligent illumination unit which can recognize the holo-

graphic material attached an RFID tag. A hologram is exchangeable and the observer puts the hologram on the display table. This system controls the appropriate angle and color of illumination according to the hologram. This display system can playback limitless images because the number of reproducable images is equal to that of special hologram media.

6488-31, Poster Session

Event driven illumination system for image reconstruction of hologram

K. Sakamoto, K. Uchida, Shimane Univ. (Japan)

The research group of the authors has developed spatial imaging and interaction system. We hope that the player can view virtual images when he puts the special object on the display table. One of our products is a prototype interactive tabletop holographic display. In this system, the observers can select and view the image when he puts the card which is illustrated with its figure. This development is to produce a product for education such that this system is in the science and technology museum. The display system gives users virtual 3D images, which is floating in the air, and the observers can touch these floating images, for example, when kids put objects on the table. In this paper, we propose another usage of holographic imaging. The authors developed a new application system of a tabletop holographic display. This product is a puzzle toy for kids. Kids set pieces of a puzzle on the special table. If he will complete doing a puzzle perfectly, the game system produces the spatial images on the display to celebrate the completion of his work. These spatial images are provided by the hologram. This system consists of a tabletop working space, an illumination unit and a recognition system. A player does a puzzle on the working space. The recognition system judges player's work. The illumination light is controlled according to the result of recognition and thus the hologram reconstructs a floating image by an appropriate illumination.

6488-32, Poster Session

Development of lighting system for hologram using high power LEDs

J. Baba, A. Yaeda, Tokai Univ. (Japan); H. Asakawa, Marumo Electric Co.,Ltd (Japan); T. Shibuya, M. Wakaki, Tokai Univ. (Japan)

Three color (R, G, B) emitting LEDs are utilized for the image display system by the development of multi color emitting LED. White LED became to commercial base by combining the excitation blur or UV light and fluorescent materials. A single tip with the power of 5W became the line up for commercial market owing to the research for highly bright LED. In this study, we aim to fabricate the white and R, G, B illumination system using high brightness LED for the hologram illumination instead of the conventional halogen lamp. There are two types of white LED system, one is R, G, B type and the another is the combination of blue LED and fluorescent materials. By using R, G, B basic colors, it is possible to obtain appropriate illumination good for the reproduction of the hologram. In the white light illumination, it might be considered the LED light is luck of the color required for the production of the hologram, especially luck of green color in the quasi- white LED system. The ability for hologram illumination was compared between the LED illumination system and a halogen lamp. In case of LED, it is sufficient for the illumination of a small type hologram, but not sufficient for the large size hologram because the luminosity on the hologram plate is not sufficient. It requires a higher bright LED or a multiple numbers of LED arranged as an array to illuminate a large size of hologram.

6488-33, Poster Session

Holographic data calculating algorithm and new digital hologram recorder

M. Cruz-López, J. Báez-Rojas, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); D. Kang, Holotec Inc.

We report the design of digital data generation and recording of computer generated holograms (CGH) for display, security and diffractive optical device. As an initial experiment, an algorithm of a mathematic model of one-step setup was used for creating a white light reconstruction holographic stereogram. The experimental hologram size is 1cm x1cm using 16 perspective 3D images, with 3200 pixel x 3200 pixel per each image. A novel processing algorithm was introduced for calculating large quantity of data. In addition, a new high speed and high resolution digitized image data recording method was applied in the recording process. The method achieves about 0.4 micron spot size. A digital hologram of 1 in x 1 in size can be written in 5 hours by this method, where an incoherent single beam is used as the light source. Experimental results show that the digital image processing as well as the recording method is useful for display, security holograms, Kinoform and Diffractive Optical Element applications.

6488-34, Poster Session

Nanocrosslinked photopolymers for volume holographic storage

S. Lee, Y. Jeong, H. Hah, J. Park, Korea Advanced Institute of Science and Technology (South Korea)

Dry photopolymers are promising candidates for write once, read many times (WORM) volume holographic storage due to their high energetic sensitivity, high contrast refractive index changes Δn, low cost, and processability. Generally, holographic photopolymers consist of polymer matrix, light-sensitive monomers, and photo-responsible initiator. During holographic recording, interference pattern of two coherent laser beams initiates a periodic photopolymerization - A constructive interference patterns result in a local polymerization which in turn causes a spatial distribution of refractive index. For their application to holographic storage, there is a set of stringent requirements such as low volumetric shrinkage during holographic recording, high optical quality, and adequate thickness enough to facilitate the multiplexing of pages of data.

In this work, we present the new organic-inorganic hybrid photopolymer comprised of Poly(methylmethacrylate) (PMMA), highly surface-photoreactive Polyhedral Oligomeric Silsesquioxane (POSS) inorganic (or organometallic) nanoblocks, and vinyl monomers. POSS inorganic nanoblocks possessing the structure of cube-octameric frameworks surrounded by eight acrylic corner groups were used as the crosslinking agent. By incorporating inorganic nanoblocks into vinyl monomers, nanocrosslinked photopolymer can be prepared via copolymerization of vinyl monomers, and since nanocrosslinked structures significantly restrict the entanglement of polymer chains formed during holographic recording, volumetric shrinkage is reduced while the sensitivity and optical quality is not sacrificed. The POSS-nanocrosslinked photopolymer shows that volumetric shrinkage during holographic recording is noticeably reduced (near zero Bragg angle detuning). The diffraction efficiency approaching near 80% in the 532nm laser and the photosensitivity below 50 mJ/cm2 are also observed.

6488-35, Poster Session

Optical encryption of binary data information with 2-step phase-shifting digital holography

S. Gil, Univ. of Suwon (South Korea); S. H. Jeon, Univ. of Incheon (South Korea); J. Jeong, Suwon Science College (South Korea)

We propose an optical encryption/decryption technique based on 2-step

phase-shifting digital holography for a cipher system. The technique using 2-step phase-shifting digital holography is more efficient than 4-step phase-shifting digital holography because the 2-step method has less data than 4-step method to restore or transmit the encrypted data. In our system, 2-step phase-shifting digital holograms are acquired by moving the PZT mirror with phase step of 0 or $\pi/2$ in the reference beam path and are recorded on CCD device. The information data and the key is expressed with random binary amplitude and random phase. Digital hologram in this method is Fourier transform hologram and digitized with 256 gray-level. DC-term removal is essential to reconstruct and decrypt the original binary data information. The simulation shows that the proposed method gives good results for cipher system. The quantization error is also analyzed.

6488-36, Poster Session

Computer generated hologram for phase-only optical encryption

T. V. Vu, N. Kim, Chungbuk National Univ. (South Korea); S. Gil, Univ of Suwon (South Korea); E. Kim, Yonsei Univ. (South Korea)

An improved image encryption/decryption approach is proposed. In the encryption system, a binary amplitude image is encoded in the Fourier domain. Then, the encoded image is scrambled with a random binary phase image to produce the encrypted image. Both the encoding and encryption processes are done electronically. The encrypted image is stored in an encrypted phase mask of which the transmittance is proportional to the phase components of that image. In the decryption process, the encrypted phase mask is optically descrambled with another phase mask which has the transmittance identical to phase components of the random image used in the encryption process. The descrambled field is inversely Fourier transformed by a Fourier lens in order to reproduce the original image. The simplicity and the misalignment free characteristic are the most significant advantages of our method. The Fourier encoding process using an optimization algorithm with iteration technique is discussed in detail. The effect of image sizes on the quality of the decrypted image is investigated. The innovation of the system is demonstrated through simulations. The most critical issue of our technique is that the encryption process requires an optimization search which consumes some computation time so that the system is expected to be applied for unreal-time applications.

6488-37, Poster Session

Chirp volume grating recorded in photopolymer for the optical demultiplexer

D. Do, N. Kim, Chungbuk National Univ. (South Korea); S. H. Jeon, Univ. of Incheon (South Korea); K. Y. Lee, Sunchon National Univ. (South Korea)

The optical demultiplexer is a key device in the dense wavelength division multiplexing (DWDM) system. Among many technologies including fiber Bragg grating, arrayed-waveguide grating, thin film filter, and virtual-image phase array, the diffraction grating offers the demultiplexer the simplicity and the cost attraction. The structure of the demultiplexer consists of a collimating lens, volume holographic gratings, and an output-focusing lens. The output-focusing lens transforms the angularly dispersed diffraction beams into the spatial separation on the focal plane, where a single mode fiber array is placed. The volume grating can be uniform or apodized to reduce the crosstalk between channels. In this paper, the chirp volume grating recorded in photopolymer for the optical demultiplexer is presented. By using the chirp grating, the spectral response and the spatial distance of fibers are expected to be controllable. The chirp rate of the grating and the focal length of the output lens are also investigated.

6488-38, Poster Session

Field of view extender for a novel camera system

S. H. Lim, R. K. Kostuk, M. A. Neifeld, The Univ. of Arizona

Increasing the field of view (FOV) is an important issue in the thin camera system. A blazed grating can be used for extending the FOV. Computer simulation shows several advantages of the blazed grating for this application. A blazed grating is designed that provides over 70% diffraction efficiency (DE) in the primary order over a 15 degree FOV. High diffraction efficiency is maintained over a wavelength range from 430 to 710 nm. In this paper, the 2D characteristics of blazed gratings are discussed for applications in imaging systems. Experimental results that verify the performance of the grating for extender are also presented.

6488-39, Poster Session

Photoluminescent conductor polymer holograms

J. B. R. Ruiz-Limón, A. Olivares-Pérez, E. L. Ponce-Lee, M. P. Hernández-Garay, S. Toxqui-López, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

An organic conductor polymer was doped with benzalkonium chloride to get a photoluminescent effect and it was used as holographic material. We used a digital image to generate a hologram in a computer and it was transferred by microlithography techniques to our polymer to get a phase hologram. The transference is successful by rubbing, the heat increment produce temperature gradients and the information in the mask is transferred to the material by the refraction index changes, thus the film is recorded. We recorded several gratings to observe the behavior of photoluminescent light with different frequencies when it is radiated with a green laser beam.

6488-40, Poster Session

Hologram's in colored dichromate gelatin with natural colorant

G. P. Trujillo Páez, A. Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The holographic properties of dichromate gelatin (DCG) doped with natural colorants, in order to change the absorbance spectrum profile, and increasing the material sensibility, obtaining a good photo sensibility in other spectral emission line laser as red, orange, yellow. We showed some basics studies referent possible mechanism to storage information with this doping, and reported results. We show a light description technique to obtain holograms with these colored materials, as some experimental results.

6488-41, Poster Session

Processing techniques for quality improvement of phase added stereogram

H. Kang, T. Yamaguchi, H. Yoshikawa, Nihon Univ. (Japan)

In this paper, we propose an improved Phase Added Stereogram (PAS), which is one of the Coherent Stereogram, to display clear 3D object as Fresnel Hologram. Advantages of PAS are to reduce the computation time of Computer-Generated Hologram (CGH) using the Fast Fourier Transform and segmentation, and to display clear 3D object as Fresnel Hologram. However, a defect of the PAS is that if large segmentation is used, blurring phenomenon is occurred as coped image in close distance of reconstructed object. The reason of blurring phenomenon is that large segmentation can not be satisfied changing the spatial frequency of fringe pattern, because differences of spatial frequency between neighboring segments are irregular and larger than those of small segmentation. Therefore, it is need to control the segmentation size according to differences

of spatial frequency between neighboring segments to make symmetric fringe pattern and to remove blurring phenomenon. In additionally, we also propose interpolation and extrapolation methods to generate fringe pattern using neighboring segments and their information. The interpolation is to generate a virtual spatial frequency using the neighboring segments. And extrapolation is to generate fringe pattern of segments around basis segment. Finally, reduction method of phase error in PAS is included. In this paper, we present some experimental data, which supports the rationale of the proposed method.

6488-42, Poster Session

Polyvinyl alcohol and crystal violet as photosensitive film

M. Ortiz-Gutiérrez, K. Alemán, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); M. Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico); J. C. Ibarra-Torres, Univ. de Guadalajara (Mexico); A. Olivares-Pérez, Instituto Nacional de Astrofísica, Optica y Electrónica (Mexico)

In this work we propose a phase material based in Polyvinyl Alcohol (PVA) and Crystal Violet Dye (CV) deposited on a glass substrate with 10 mm of thickness. In this material we record holographic gratings using a wavelength of 598 nm and reconstruct the image with 543.5 nm of He-Ne lasers; the diffraction efficiency was 0.08% for the first order. The material no requires developing process and is very easy to make. Experimental results are shown.

6488-43, Poster Session

Fabrication of high diffraction efficiency DOE using a laser direct lithography system

N. Ikemoto, S. Nakahara, S. Hisada, T. Fujita, S. Shingubara, Kansai Univ. (Japan)

Recently, the demand to the diffractive optical elements is increasing with the developments in the micro fabrication technology. In this research, we created the diffractive optical elements with the use of the laser direct lithography system that has the feature of high-resolution drawing, high-speed drawing, and a high accuracy positioning system. Although it is difficult to draw to a large-sized substrate with electron-beam lithography system, since the laser direct lithography system makes it possible, production of the large diffractive optical elements is expected.

Furthermore, 2 and 4 levels phase-type diffraction optical elements were produced by dry etching processing to the substrate, and comparison of the diffraction efficiency of the amplitude-type diffractive optical element and the phase-type diffractive optical element was discussed.

Conference 6489: Projection Displays XII

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6489-01, Session 1

Dual paraboloid reflector technology development on the commercialization for projection display

K. K. Li, Wavien, Inc.

No abstract available

6489-02, Session 1

Brightness increase in LED by recycling of light for projection applications

K. K. Li, S. Inatsugu, G. X. Ouyang, Wavien, Inc.

No abstract available

6489-03, Session 1

Personal projection with Ujoy technology

H. Moench, U. Mackens, P. Pekarski, A. Ritz, Philips Research Labs. (Germany); G. S'heeren, W. Verbeek, Philips Lighting N.V. (Belgium)

Personal projectors are compact and affordable devices used for gaming, entertainment or photo projection. The new 50W Ujoy lamp system enables efficient projection systems wtht a screen brightness of 200-300lm. Lower cooling requirements, the potential for battery operation and the low voltage input makes it the ideal source for this new category of projectors.

The paper will outline the lamp technology as well as the new application area:

- Maintain all UHP advantages with a simplified concept (burner and electrodes)

- Lamp performance results (light collection, spectra, lifetime)

- 50W benefits for cooling, lamp housing and electronics

- miniature reflector design

- very compact driver for 12-18V input

- not yet decided, but possible in the next months: examples of realised projectors and performance in projection systems (especially the good fit with end-user needs like compactness (incl. the potential for new designs), enough brightness for home use, battery operation etc.

6489-04, Session 2

Measuring screen captures for cross-display technology video motion analysis

J. W. Roberts, National Institute of Standards and Technology

The accurate portrayal of motion video is highly demanding on both playback system and display, particularly for high definition video. Errors such as compression artifacts, skipped frames, image breakup, and interactions with display scaling/driving algorithms and display technology are common, and can significantly degrade both the viewing experience (motion image quality) and the viewer's ability to get information from the video (motion image interpretability). Accurate measurement of motion playback is critical to the development of content, playback systems, and displays that can handle high performance motion video, and to the matching of components that work well together. Screen capture (imaging of the display during video playback) is the only way to fully observe the combined effects of all the factors that can affect motion playback. Previous work at NIST has shown that high speed screen capture (at several times the displayed frame rate) can be used to observe playback motion, and that the use of several techniques in the measurement process provides a high level of assurance of measurement accuracy. While human observation of captured images provides a useful "ground truth" for image motion, the process is time consuming, requiring inspection of each captured frame. This paper compares the effectiveness of automated tracking software to visual inspection of high speed screen captures for the measurement of motion playback. Both commercial tracking software and a set of tracking programs developed at NIST are considered. Display system characteristics (e.g. LCD / DMD / plasma) must be taken into consideration to minimize measurement variations across display technologies, as must the properties of playback system and video test material.

6489-05, Session 2

Recent advances in microlens-based projection display screens

G. M. Morris, T. R. M. Sales, S. H. Chakmakjian, D. J. Schertler, RPC Photonics, Inc.

No abstract available

6489-06, Session 2

High collecting efficiency of an LED projection system

S. Chung, C. Lin, C. Tseng, H. Lo, Industrial Technology Research Institute (Taiwan)

Due to Light Emitting Diode (LED) have the properties of compact size and high efficiency, there have more and more illumination system use it to be a lighting source. In this paper a compact projection system was realized by a simple architecture. For this compact projection system, the prototype has been developed by using a single tranmissive light valve and LED source in it. With a simple collecting reflector, a curved mirror and a light tunnel in the illumination system, the optical efficiency from source to light valve is up to over 70% and the uniformity illuminated on the light valve is over 85%.

Refer to the figure 1, light was emitted from the LED and its intensity distribution was corrected by the collimator. Then the corrected light was redirected to the entrance of light tunnel by the curved mirror. Finally, light was recombined inside the light tunnel and form a high uniform distribution on the light valve. The prototype in this paper has the following benefits:

(1) Compact engine: Due to the collimator can be combined as an array type, the light tunnel can be put on the center of the collimator array.

(2) High efficiency and uniformity: Because lots of light was collected by the collimator, and the area of light entrance is big enough to receive. The light only need to consider the Fresnel reflection loss and few loss form collimator. Due to ray was reflected inside the light tunnel, so the uniformity can be control by the length of light tunnel. Refer to the figure 2, the uniformity on the light valve is approached 86%

6489-07, Session 2

Visible laser sources for projection displays

M. Jansen, B. D. Cantos, G. P. Carey, R. Dato, R. Carico, A. M. Earman, M. J. Finander, G. Giaretta, S. Hallstein, W. R. Hitchens, J. H. Hofler, C. P. Kocot, S. Lim, A. Mooradian, G. T. Niven, Y. Okuno, F. G. Patterson, A. Tandon, A. Umbrasas, Novalux Inc.

Low cost lasers represent a disruptive technology, which enables a number of new display applications including “pico-projection” and Laser TV. Lasers offer many advantages over other light sources including much higher brightness, expanded color gamut, long lifetimes, and lower system costs. In this paper, we present an update of the Novalux extended cavity surface emitting laser (NecselTM) technology. The key features of the technology, such as demonstrated multi-Watt output for Laser TVs, power levels scalable with the number of emitters, speckle suppression due to a multi-emitter array geometry, and a low-cost and compact design are discussed in detail.

6489-08, Session 3

DVimage spatial light modulator: a new real-time interface for the TI DMD 3000 chipset

S. J. Saggese, T. L. Thomas, Apogen Technologies

This paper will present the development of a new driver board for the Discovery 3000 Micromirror Device (DMD) chipset being offered by Texas Instruments. Apogen Technologies conducts research and development on optical multispectral imagers and laser projectors for medical applications. A requirement of our current research is to have a real-time digital interface to a reflective spatial light modulator to project patterns based upon images obtained via a camera system. Current DMD driver boards are configured for batch processing and could not provide the real-time speed and flexibility required for our application. As a result, Apogen developed the DVimage(tm) spatial light modulator driver board based upon the Discovery 3000 chipset. The DVimage(tm) can be run from any computer through the standard DVI port, can display 8-bit grayscale at 60Hz in real-time and can store 4600 full resolution 1-bit images on the board and display them at a maximum frame rate of 15,200 fps. The board also has programmable sync pins to trigger other systems (e.g. light sources, cameras). An SDK and software examples have been developed to allow users to integrate DVImage(tm) into custom applications. This paper will describe the general hardware architecture and software tools along with a number of applications we are investigating for medical, microscopy and spectroscopic applications.

6489-09, Session 3

Latest developments and future opportunities with MEMS based displays

J. Bouchaud, Wicht Technologie Consulting (Germany)

2006 has been a turnpoint in the area of MEMS based displays. One the one hand, major technical and commercial milestones have been reached, on the other hand some negative results or investment-stop decision have been shown. This paper will present latest technical and commercial developments and will analysis applications of emerging MEMS based displays technologies. The paper will also present market forecasts by application and by type of MEMS based displays for the 2006 - 2012 time periods.

Micro-mirror arrays have been exposed as one of the best success stories in MEMS in the last 3 years especially considering the DLP chips from Texas Instrument. However, the DLP revenues have declined by 8% from around $ 870 M in 2004 to $ 800 M in 2005.

Micro-scanners based displays

Three demonstrators of color miniature front projectors using a MEMS scanning mirror and a RGB laser module were shown for the first time at SID 2006 by Microvision, Symbol and Fraunhofer IPMS. Compared to existing pocket projectors using a DLP or LCD chip, micro-scanners should enable to decrease the size and the price by a factor 10. The ultimate goal is even to include the mini-projector into a cell phone.

Line scanned displays

Altough a very impressive demonstrator was shown at the Aishi exhibition by Sony in 2005 leveraging the GLV (Grating Light Valve) technology, WTC did not notice recent progress towards implementing a similar technology in mass products such as Rear Projection TVs and front projectors. Sony already disposes of 2 competing technologies - LCD and LCOS - and will not invest in a technology which would cannibalise its existing market. Kodak stopped investing in its GEMS technology in May 2006 and prefers to focus on its OLEDs activities. Micralyne does not either seem to leverage their SLV technology - originally developed for printing applications - for the display market.

Reflective displays

Recent progress has been made on Microsystems based reflective displays for mobile handsets. The main advantages of reflective type displays is their very low power consumption compared to LCD displays.

6489-10, Session 3

Compact design of a polarized head mounted projective display using FLCOS microdisplays

R. Zhang, H. Hua, The Univ. of Arizona

Head-mounted projective displays (HMPD), deviating from the conventional approaches to the design of head mounted displays (HMD), combine the use of projection optics and a retro-reflective screen. This unique combination enables stereoscopic capability and offers potentials of addressing the challenges of designing wide field-of-view (FOV) optical see-through HMDs. Several prototypes have been developed and explored for a wide range of applications in 3D visualization. However, it is a common challenge that the displayed image is lack of brightness and contrast due to low luminance efficiency. We have previously proposed a novel design of a polarized head mounted projective display (p-HMPD) which significantly improves the light transfer efficiency in an HMPD system by applying polarization techniques to manipulate the polarization status of the projection system. A p-HMPD consists of a pair of projections lenses, microdisplays, polarization control elements, and retroreflective sheeting material as a projection screen. One of the modifications to the existing HMPD designs is to replace a non-polarizing beamsplitter with a polarizing beamsplitter (PBS). Further modification is made to manipulate the polarization status in the projection and retro-reflection paths to gain maximum light reflection and transmission efficiency through the PBS interface. In our previous work, we demonstrated the significant improvement on image brightness and contrast on a bench prototype using a miniature back-lit active matrix liquid crystal display (AMLCD). To further improve the image brightness and design a compact head-mounted prototype, in this paper, we replace the AMLCD with a ferroelectric liquid-crystal-on-silicon (FLCOS) microdisplay and present the design of a highly compact illumination engine for the FLCOS microdisplay and a compact telecentric projection lens. FLCOS displays, which operate in reflection and can be thought of as reflective light modulators, offer bright illumination only in telecentric mode. This telecentric requirement imposes great challenges in designing a compact projection lens for a head-mounted system. We will present a compact illumination engine with double telecentric optics that is designed to achieve high bright and uniform illumination on the FLCOS microdisplay. The key contribution in this design lies in the compactness which is a critical factor in HMD systems. The first order optics and the transformation of polarization in the design will be described in detail. The illumination simulation of the light engine will be shown using LightTools, and light efficiency and uniformity will be discussed. Based on this illumination engine, we will further describe the design of a compact projection lens, which utilizes two aspheric surfaces and is designed in an image space telecentric mode to achieve uniform illumination.

6489-16, Poster Session

Floating-image display based on the combination of two-lens system and the stereoscopic polarization-multiplexing display

G. Baasantseren, N. Kim, D. Do, Y. Lim, Chungbuk National Univ. (South Korea)

Today, there are many kinds of 3D displays used to produce 3D images

but these 3D images are not touchable. Therefore many researchers study how to produce a floating image from 3D image. In floating image display, a large concave mirror or a large lens is used to produce the floating image. However the lens and the concave mirror produce the defected image because magnifications of these two elements are not constant, and an image distance is not linear relationship from an object distance. In this paper we present the stereoscopic floating image system using a stereo display and two lenses. The proposed floating display system provides an impressive feel of depth, and produced image appears to be located in a free space and near the observer. The two-lens system can eliminate all defects of large convex lens because the magnifications are constant and are not related the object distance and the image distance. The experimental result shows that the proposed system successfully makes a touchable stereoscopic floating image.

6489-11, Session 4

Dynamic optics for digital projection

F. P. Shevlin, Dyoptyka Ltd. (Ireland)

We have developed optical systems that include dynamic optical elements for digital projectors in a variety of market niches, i.e. for a variety of different designs and levels of performance.

The high-order aberration correction ability and high-frequency response times of dynamic optical elements facilitate a reduction in the number of optical surfaces required relative to conventional projection optical systems. This allows, for instance, a reduction in the number of lens groups in a projection lens system, a reduction in the number of optical surfaces in each group, and a reduction in the precision required to mechanically position the groups with respect to one another.

For example, consider the management of chromatic aberration in a simplified non-achromatic optical system. If simple field-sequential illumination is used then only one wavelength is present in the system at a given moment. The dynamic optical element can change its characteristics in tandem with the illumination so as to ensure all wavelengths focus to the same point—thus avoiding chromatic aberration. As another example, consider the focus group in a zoom lens system. Its purpose is to allow adjustment of the distance to the source image when the focal length of the zoom system is changed. In a conventional optical system, this requires mechanical motion of the focus group. However a dynamic optical element can be used instead to introduce the appropriate amount of defocus to change the optical path length to the image source.

We discuss the design, implementation, and evaluation of several prototype systems.

6489-12, Session 4

Tilt compensated MOEMS projector as input device

H. Grueger, A. Heberer, C. Gerwig, P. Nauber, M. Scholles, H. Lakner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Laser projection is a promising approach to overcome the limitations of small displays in handheld devices. Fraunhofer IPMS has developed a 2d MOEMS scanner mirror suitable for this task. Laser projection was demonstrated successfully. Nevertheless projection with handheld devices has its limitations. Any movement, especially shaking of the hand, will affect the quality of the picture. Using motion sensors, i.e. acceleration sensors and gyroscopes - so called inertial measurement units (IMU), the movement can be detected and compensated. Even more, movement can actively be used as input device like mouse or game controller.

A combination of a MOEMS based laser projection system and an IMU has been realized. As test object a commercial racing wheel was chosen. Along the axis of the racing wheel the projector was mounted. The position of the racing wheel was measured by an IMU with a three axes acceleration sensor (STM Microelectronics) and three single axis gyroscopes (Epson). The rotation of the wheel was compensated for a stable picture position and used for controlling a car racing game. The frame rate achieved was 20 per second with a resolution of 300 x 300 pixels. Up to now the picture was monochrome.

In future handheld devices, which could be a combination of cellular phone, PDA and game box, using inertial measurement units, tilt compensated projection and input device function will be realized. Current work is aimed at free movement of the device. Progress of the laser projection will be full colour and a higher pixel number.

6489-13, Session 4

A LED-based full color stereoscopic projection system

L. Bogaert, Y. Meuret, B. Vangiel, H. Thienpont, Vrije Univ. Brussel (Belgium)

Three-dimensional (3-D) projection systems are promising to be a great asset in a wide variety of domains; from improved medical diagnostic tools over to 3-D advertisement and 3-D gaming. Yet, they are still far away of being widely adopted by the general public. At the conference we will present a compact cubic polarization splitting color-management system with possible stereoscopic 3-D viewing.

The projection engine is build around four separate polarizing beam splitters (PBS) that are positioned such that their polarization splitting surfaces form a cross configuration. Four liquid crystal on silicon (LCoS) panels are located at the exterior facets of two opposite PBSs and wavelength selective half-wave plates are placed between all PBSs. The LCoS panels are telecentrically illuminated by red, green and blue light emitting diodes, ensuring color uniformity within the projection engine. This configuration offers the possibility to create independent light paths that are modulated with a different information, polarization and temporal content. We implement this approach to enable among others light output enlargement and 3-D visualization. Our simulation model and theoretical calculations also show that these light paths have identical black-white contrasts for all projected colors. When the observer wears polarized glasses, each eye will see a different projected image such that 3-D viewing is perceived. Both images are generated by one of both symmetrical light paths.

6489-14, Session 4

Supercompact projection display for HDTV based on MEMS

S. M. Shamaev, Bauman Moscow State Technical Univ. (Russia)

A rear projection optical system that performs enlarged projection from the primary image plane on the reduction side to the second image plane on the enlargement side without forming an intermediate real image.In the basis of a developed projective objective lays the retrofocus scheme. The base design of the objective will consist of two basic refracting lens groups: the first group which is closer to the screen has the big negative power, a group includes at least one reflective surface (a bending mirror) and the second group which is closer to the microdisplay, has positive power.

6489-15, Session 5

Micro-displacement measurements with Moiré patterns of fresnel zone plates films

M. Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico); M. Ortíz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); J. C. Ibarra-Torres, Univ. de Guadalajara (Mexico); A. Olivares-Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); J. Becerra-Macías, Digital Optics and Quantum Electronics Devices (Mexico)

In this work we propose a technique to measure micro displacements

using Moiré patterns of Fresnel zone plates films. In this technique the pattern is placed on a mechanical mount and the displacements are measured counting the displaced fringes of an amplified moire image as the mount is moving.

6489-17, Session 5

Computer simulation of spatial light modulators with micro-optical elements

M. A. Golub, M. Aloni, G. Manor, Explay (Israel)

Highly efficient liquid crystal transmissive spatial light modulators are the key components of laser projection microdisplays with extended depth of focus. Collimated and spatially coherent laser light sources provide new possibilities for improving a throughput efficiency of microdisplays with the aid of microlens arrays (MLA), which reduce lateral dimensions of a light beamlet passing through each pixel of a spatial light modulator, down to dimensions of a TFT layer micro-diaphragm. We present an advanced method for characterizing diffraction spread effects and complicated surface shapes of microlens arrays and their impact on the microdisplay performance. In this method we exploit physical optics propagation combined with geometrical ray-tracing, for both minimizing a diffraction spread and accounting for aberrations in each lenslet. Modeling the MLA enabled us to predict such parameters as focal spot size and its longitudinal variations, transmission efficiency for a given clear aperture of each pixel, output divergence, a cross talk between adjacent pixels. Comparison of computer simulation results by our method with partial simulation in commercially available software codes confirms the validity and applicability of our method. Simulation data for spherical, elliptical and asymmetrical aspherical lenslet shapes was used as a base for designing advanced spatial light modulators with high throughput efficiency.

6489-18, Session 5

Pseudoscopic-free and multi-view 3D displays using invisible area generated by polarized slit barrier

K. Uchida, K. Sakamoto, Shimane Univ. (Japan)

A 3D display system is useful technology for virtual reality, mixed reality and augmented reality. We have researched spatial imaging and interaction system. We have ever proposed 3D displays using the slit as a parallax barrier, the lenticular screen and the holographic optical elements(HOEs) for displaying active image.

The projection display enables observers to view a large screen. To use the image separating method such as a parallax barrier, the observer perceives a spatial image without special glasses. This parallax barrier 3D display has the demerit that the observer perceives reverse images when he views a left image by his right eye and vice versa. This is called pseudoscopic viewing. To solve this problem, we developed the new slit barrier whose apertures are attached a stripe of polarizer. This polarized slit barrier makes invisible regions in the 3D viewing zone. These invisible regions prevent an occurrence of pseudoscopic viewing because either of an observer's eye is in an invisible region at a conventional pseudoscopic viewing zone, (i.e., the observer only perceives either left or right image in this zone.) Moreover, this paper describes a newly developed 4-views display using this polarized slit barrier technique. A linear polarizer selectively blocks the ray or passes, for example, only the incident light that is vibrating parallel to the polarization direction is allowed to pass. Hence the polarizer controls the parallax ray through the slit aperture one bye one. Then the pixels of 4-views stereoscopic images are aligned in not only horizontal direction but also vertical. As a result, this 4-views 3D display can avoid the horizontal resolution problem of conventional system because the image resolution of each view is reduced both horizontally and vertically. Our 4-views display solves the problem that the resolution of each of the stereo images is reduced only in the horizontal dimension.

6489-19, Session 5

Modulating method of linear and circular polarized illuminations for field-lens 3D display

K. Sakamoto, H. Morimoto, Shimane Univ. (Japan)

Many 3D visualization technologies have been invented, but none ever had a broad success. This paper describes the field lens 3D display for viewing the 2-views stereoscopic images. On the conventional systems, several viewers can perceive a stereo pair simultaneously and they can move independently without special equipment. However these systems have the defect that the single LCD panel serves left and right images with half resolution because of dividing horizontal resolution to provide stereo pair images. To overcome this problem, we developed the dual LCD panel using two liquid crystal layers. This display panel enables observers to view full screen high resolution images. This study shows that it is possible to simplify the optical system.

The field-lens 3D display system consists of the dual LCD panel, the fresnel lens and LED arrays. A field-lens serves to direct the projected illumination beams into the appropriate eye. To separate and display left and right images, the display panel placed close to the field lens, must appropriately be able to modulate polarized illuminations. Our old system utilized pair light sources for left and right eyes which have vertical and horizontal linear polarizations respectively. To display stereo pair images, the first LC cell rotates the angle of linear polarization and the second cell modulates the luminance of left and right images. Hence, each LC cell can't display a left or right image directly because both cells are controlled by the combination signal generated from both images. To solve this problem, we developed new modulation method using both linear and circular polarizations. These linear and circular polarization illuminations can be modulated independently and thus it is possible for the first LC cell to display a left image, for example. To use the combination of linear and circular polarizations, it isn't necessary to convert signals for both panels' inputs.

6489-20, Session 5

Optical design of near diffraction limited

M. Negarchi, Consultant

AS mentioned in reference 1,HUD should have comfort TFOV and IFOV. typical IFOVS range are from about 13? to 18? with corresponding TFOV of about 20? to 25?.

In this refractive HUD a pilot looking through the combiner sees the real world at 70% brightness upon which is superimposed the collimated display at 30% of CRT brightness.

6489-21, Session 5

Research of two issues about true colour digital holography

J. Li, Kunming Univ. of Science and Technology (China); Y. Li, Purple Labs., S.A. (France)

Thanks to CCD technology and improvement of computer sciences, single wave length digital holography is widely studied and applicated. According to theory of object true colour, we know that colours are results of absorbs ion of light waves of different wave length. If we separately apply single wave length digital holography method on three base colour waves, we should be able to study True Colour digital holography by combining the result of three waves. However, we must take in account influence of diffraction of waves of different wave length. Also, some problems about computation complexity and calculation result analyze should be considered in True Colour digital holography. For example:

1. For diffraction calculation we generally use S-FFT and D-FFT algorithm, each of them has some advantages and inconvenient. How to choose a suitable calculation method for the case of True colour digital holography?

2. In theory, for CCD record of the three base colour waves, we should know the exact entrance angle of the reference wave or make sure that all three base colour waves are perfectly parallel when they arrive on CCD. But in reality these conditions are quite difficult to be obtained. How to resolve these problems with experience results?

The article will discuss above questions and demonstrate True Colour Holography Theory with simulation and give some practical application samples.

6489-22, Session 5

Color performance of the color separation gratings

H. Y. Lin, J. Yeh, C. Chen, National Taiwan Univ. (Taiwan)

Among the projection systems, the three-panel configuration is of high cost and the single-panel color-sequential configuration suffers from loss and color break. On the other hand, the optical efficiency of a single-pane sub-pixelated LCD device is limited to be less than 10%. It is due to several lossy optical components. Among them, color filter is the lossiest one since 2/3 of light is absorbed to pass the desired sub-band through the corresponding sub-pixel. The color separation grating (CSG) has been proposed to split different sub-bands of the polychromatic light into the corresponding sub-pixels of LCD. It is advantageous to enhance the optical efficiency as compared with that resulted from using color filter. In this paper, the theoretical optical efficiency can be shown to reach 66-81%, ranging almost from 2 to 2.5 times of that resulted from using color filter. Furthermore, the color gamut can also be improved by properly designing the color separation grating. It is shown to have 20% of improvement as compared with that resulted from using color filter.