OPTO 2006

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Conference 6115: Physics and Simulation of Optoelectronic Devices XIV

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6115-01, Session 1

Ultrafast all-optical switching by gain competition in semiconductors

G. A. Vawter, A. Y. Hsu, E. J. Skogen, K. C. Baucom, G. M. Peake, W. W. Chow, G. R. Hadley, Sandia National Labs.

No abstract available

6115-02, Session 1

High-power low-jitter quantum-dot mode-locked lasers

H. Li, L. Cheng, A. L. Gray, H. Huang, S. Kutty, F. Nabulsi, J. Nagyvary, L. Olona, E. A. Pease, K. Sun, P. M. Varangis, R. H. Wang, C. Wiggins, L. Zhang, J. L. Zilko, J. Zou, Zia Laser, Inc.

No abstract available

6115-03, Session 1

Jitter influence in linear and nonlinear pulse compressors using gain switching laser sources

H. Lamela, R. Sanz Mesa, C. de Dios Fernandez, Univ. Carlos III de Madrid (Spain)

Short pulsed laser sources have recently been under study for applications in optical communications, such as optical time division multiplexing systems. Under this frame, as achieved pulse widths become shorter, time jitter is crucial[1]. Time stability has to be at least ten per cent of pulse width, which leads to values as low as hundreds of femtoseconds.

Previous studies have been made concerning short pulse laser sources based on Gain Switching techniques and compression devices. Linear compressors[2], as well as non linear shaping systems[3] have been theoretically evaluated. The present work opens a new field of interest turning the attention to the influence of timing jitter in characteristics such as compression factor, output pulse shape, time-bandwidth product, peak-power and output chirping concerning pulse compressor performance. Several linear compression techniques are theoretically studied, including linear chirp compensation using dispersion shifted fibers (DSF)[4], coupled waveguide[5] and grating compressors[6]. The results obtained will be the basis for the design of a compact high quality ultrashort optical pulse source at 40 GBs repetition rates with monolithic InP semiconductor compressor, which is under investigation within the MONOPLA project[7].

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6115-04, Session 1

Scalable passively mode-locked semiconductor lasers for microprocessor clocking

J. P. Siepmann, A. Rybaltowski, LightTime, LLC

The integration of photonic clocking in microprocessors is anticipated to occur during a 2008-2012 high-volume manufacturing (HVM) cycle. Though photonic clocking can be achieved through electronic modulation or active modelocking of a laser, a less expensive and better solution would be to use passively modelocked semiconductor lasers. Not only do these lasers offer low-cost, simplicity, and ease of integration, but viable prototypes that are amenable to HVM are currently available. We present such a laser with design scalable clock rates from 9-100+ GHz and wavelengths from 800-1100+ nm. The processed layer thicknesses and materials remain the same for all clock rate and wavelength versions of this laser so that no significant changes in the HVM processing lines are needed, even if a different clock rate and/or wavelength is desired. This laser design utilizes internal saturable absorber(s) to passively modelock a semiconductor laser in single spatial mode operation with high peak powers. Experimental data show an RF spectrum signal peak that is at least 40 dB above the noise floor with a -10 dB width <1 MHz. The RMS jitter as determined with an oscilloscope is ~1 ps. Autocorrelation was used to confirm modelocking and pulse width. In addition to the actual prototype data presented, theoretical and extrapolated data are used to show the expected performance for the different scalable characteristics of these lasers. A theoretical discussion of the design and operational considerations will also be presented for this passively modelocked semiconductor laser and its integration as a microprocessor's photonic clock.

6115-05, Session 1

Mode-locked phenomena of hybrid soliton pulse source

N. Dogru, Gaziantep Univ. (Turkey)

In recent years, several examples of short optical pulse sources using active mode-locking have been proposed. This method provides low timing jitter picosecond pulses, locked to an external electrical reference frequency, for high-speed optical communications systems. Active mode-locking with external cavity gratings is one technique used to generate such pulses from semiconductor lasers by applying an rf drive current at frequency matching the roundtrip of the laser cavity. Fibers grating external cavity lasers have been experimentally demonstrated in the mode-locking regime at 2.5 GHz [1] and 10 GHz [2]. Hybrid soliton pulse source (HSPS) is one such device, developed as a pulse source for soliton transmission system. The HSPS system is made up of a multi-quantum well (MQW) semiconductor laser, a fiber and a FBG. One facet of diode is high reflectivity (HR) coated and the other antireflection (AR) coated. The light from the AR coated facet is coupled to the FBG reflector. The field in this system travels between the HR coated laser end and effective cavity length of the grating. The output power is taken through the grating. A practical soliton transmission system may be required to operate at the 2.488 GHz with a pulsewidth of around 50 ps giving a time-bandwidth product range of 0.3 to 0.5. An interesting feature of these devices is the extremely wide operating frequency range, which can be enhanced by using chirped gratings, as reported in [3]. Calculated and measured results showed that transform-limited pulses are generated over a frequency range of 850 MHz

using linearly chirped Gaussian apodized fiber Bragg grating (FBG) [3]. However, in this paper, it is shown that proper mode-locking range is rises up to 1.3 GHz utilizing linearly chirped raised-cosine flat top FBG, which is very unusual in mode-locked laser system. Also, it produces a shorter pulsewidth than that of linearly chirped Gaussian apodized FBG.

In conclusion, with the use of linearly chirped raised-cosine flat top FBG instead of linearly chirped Gausssian apodized FBG, proper mode-locking range where transform-limited pulses are generated rises to 1.3 GHz.

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6115-06, Session 2

Design and implementation of single-mode Fabry-Pèrot lasers using non-periodic index patterns

R. Fehse, S. O’Brien, S. Osborn, E. P. O’Reilly, Tyndall National Institute (Ireland); J. Patchell, D. Jones, J. O’Gorman, Eblana Photonics Ltd. (Ireland)

The spectral purity of a ridge waveguide Fabry-Pèrot (FP) laser can be improved by introducing non-periodic perturbations into the waveguide. The fairly low density of features required can be introduced when the ridge itself is formed and hence require no additional processing steps [1], an advantage over standard DFB edge-emitters.

We have developed a transmission matrix approach to first order in the effective index step from which we derive the threshold condition as a function of cavity mode index. This allows us to use Fourier techniques to solve the inverse problem, namely to determine the optimum feature positions in order to design a particular modulation of the threshold gain condition [2].

We illustrate the technique here through the implementation of edge-emitting lasers incorporating <20 features and designed to achieve single mode emission at 1547 nm at room temperature. Single mode emission at 1547.0nm is confirmed experimentally, in excellent agreement with the laser design. The high wavelength selectivity of the design manifests itself in a low temperature dependence of the lasing wavelength of 0.1nm/C° without mode hopping up to 100C° while maintaining a high side mode suppression in excess of 35dB.

The extension of this technique to novel applications like coherent multi-frequency lasers, discretely tuneable devices and optical clock generation will be discussed.

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6115-07, Session 2

Investigations of 14xx-nm pump lasers formed by active MMI waveguide

A. Guermache, V. Voiriot, Avanex, Inc. (France); J. Jacquet, Supélec (France)

Recent progress in data transmission systems requires high output power single transverse mode laser diodes for Raman and Erbium-Doped Fiber Amplifier pump sources. Several approaches have shown high output power emission up to 1 Watt for 14xx-nm InGaAsP/InP pump lasers. In these works, the design rules were mainly related to the active volume increase, through large or flared waveguides or through the use of MMI. Such designs lead to electrical and thermal resistance decrease. MMI waveguide have already demonstrated better behavior in comparison with straight active waveguide, but neither experimental comparison nor modelisations between different active MMI structures have been reported.

In this work, we report on 2D-BPM simulations and experimental results between different active MMI 1*1 structures for 14xx-nm pump laser. The MMI 1*1 is a large multimode waveguide connected in both sides center by one single transverse mode waveguide. Several parameters such as p order, wavelength emission, MMI width and MMI length have been studied in order to carry out simple design rules for active MMI waveguide based lasers. Moreover, to achieve high level output power, long lasers are necessary. In this case, we also compare long laser, typically 1.2mm, formed by one long MMI waveguide or formed by several short MMI waveguide.

Simulations show a better behavior for short MMI length (LMMI<250μm) and small MMI width (WMMI<10μm). As expected, experimental results are in good agreement with simulations, and the output power figure is improved using the long laser formed by several short MMI waveguide in comparison with either others MMI structures or with straight waveguide.

6115-08, Session 2

Analysis of surface-normal coupled-quantum-well modulator at 1.55 um

Z. Q. Li, O. Shmatov, S. Z. Li, Crosslight Software Inc. (Canada)

Optical modulators at wavelengths near 1.55um are an essential component of photonics links. Recently, Stievater et al.[1] have demonstrated a surface-normal coupled-quantum-well (CQW) InGaAs-InAlAs electroabsorption modulator that provides optical modulation with a constrast ratio of 1.5 at 6V, which is about two times lower than that of a conventional square quantum-well modulator that has a comparable contrast ratio, due to strong quantum confined Stark effect. In this paper, we present detailed simulation and analysis of a 80-CQW electroabsorption modulator using advanced software package APSYS [2].

The device operates at 1.55um and is based on a strain-balanced layer structure grown on InP. The CQW pair consists of two compressively strained 6.4nm In_0.58Ga_0.42As quantum wells separated by a tensil 1.5nm

In_0.43Al_0.57As barrier. The modal absorptions in the quantum well region have been calculated by solving the Poisson and Shrodinger equations self-consistently.

The excitonic effect which enhances the absorption substantially has been also taken into account. The CQW layers, the p-doped and n-doped layers under different external voltage are studied by solving the drift-diffusion equations. Finally multi-layer-optical analyzer (the MOA option of APSYS) was used to calculate the transmission and reflection. The results from these multi-scale simulations were used to discuss the design issues of electroabsorption modulators.

1 T.H. Stievater, et al., IEEE Photon. Tech. Lett., vol. 16,pp 2036-2038, 2004

2 APSYS User’s Manual, Crosslight Software Inc, http://www.crosslight.com

6115-09, Session 2

Jones matrix analytical models to evaluate higher-order polarized-mode dispersion effects

M. F. Ferreira, Univ. de Aveiro (Portugal)

The phenomenon of polarization-mode dispersion (PMD) is now considered to be one of the main limiting factors for high-speed long-haul lightwave transmission systems, especially for systems with bit rate of 40 Gb/s per channel and beyond (1,2). PMD causes a broadening of the

transmitted optical pulse, which depends on the input field polarization and exhibits a stochastic behaviour. PMD may be usefully described by means of the fiber Jones matrix, which relates the input and output electric fields. Alternatively, PMD may be characterized in the Stokes space by means of the dispersion vector (3). The evaluation of the Jones matrix provides a useful theoretical means of predicting the overall distortion of the transmitted signal, but the statistical characterization of its coefficients is not known. On the other hand, the statistical behaviour of the dispersion vector and its frequency derivative (4) are known, but, working in the Stokes space, only the broadening factor of the optical signal can be evaluated. As a consequence, the knowledge of the analytical relationship between the Jones matrix matrix and the dispersion vector is mandatory. In literature, several analytical models have been developed to extend the PMD representation in Jones apace beyond first order. In particular, the model of Bruyëre (5) that seemed to be simple and effective, has been corrected by Kogelnik at al. (6) and by Penninckx et al. (7). A description of high-order PMD based on an exponential expansion of the Jones matrix has been proposed by Eyal et al. (8). On the other hand, an exact Taylor expansion of the Jones matrix with any order PMD has been recently presented by Orlandini et al. (9).

In this paper a comparative analysis among the Jones matrix analytical models with high-order PMD is done investigating about their precision, both in the Jones and Stokes space. An accurate ans stable tool for the system impairment calculation has been indentified in the model that describes the dispersion vector as rotating on a circumference in the Stokes space. This model, which needs only two PMD parameters, i.e., the differential group delay an the principal states of polarization (PSP) depolarization rate, is exploited to calculate the analytical expression of the pulse broadening and its statistics, giving a significant means of evaluating the system penalties. Moreover, the model can be applied in the calculation of system performance in terms of outage probability on the sensitivity penalty. In spite of its simplicity, the results obtained with this model compare very favourably with those obtained with other analytical models proposed in the literature and to those obtained by numerical simulations.

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6115-10, Session 2

The numerical study of signal degree of polarization

L. Y. Wei, R. Zhang, Beijing Univ. of Posts and Telecommunications (China); L. Chen, Hunan Univ. (China); X. G. Zhang, B. J. Yang, Beijing Univ. of Posts and Telecommunications (China)

Abstract: Considering the polarization mode dispersion (PMD) and nonlinear effect in the WDM system of , we have calculated the signal degree of polarization (DOP) of RZ after transmitting 120km at different input powers with the coupled nonlinear Schr˜dinger equation. All the channels' eye diagrams of RZ and the relationship between the signal DOP and wavelengths in the different input powers were obtained. By comparing the eye diagrams and the DOP~ graphs, we can find that the effects of PMD and nonlinearity on the various channels are different, and an optimal input power for a WDM system can be introduce. We also have verified that the signal DOP can be used in WDM system to detect channels' performance in compensating for the worst PMD in real time.

6115-11, Session 2

Characteristics of long period grating written in 980-nm-pumped erbium-doped fiber

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

In this paper, we provide a quantitative description of a long period grating (LPG) written in a 980nm pumped Erbium doped fiber (EDF). The grating is so chosen that it couples power in the core mode to a cladding mode at the wavelength for which the EDF offers gain to the core mode, i.e., typically around ~ 1.53μm. This leads to new features in the transmission characteristics of the grating; the attenuation at the resonance wavelength can now be controlled by signal power of the EDF. We have reformulated the conventional coupled equations used for the analysis of the long period grating to include the EDF gain, which varies along the propagation length. In a typical calculation, when the grating length is chosen as coupling length for zero signal power the rise or decrease in signal power leads to decrease of core mode attenuation at the resonance wavelength with some amplification at the wavelengths outside the resonance. If the grating length is chosen as coupling length for 100nW signal power, the attenuation dip in the transmission spectrum decreases with increase in signal power. On the other hand, if the grating length is chosen as coupling length for 1mW signal power, the attenuation dip in the transmission spectrum decreases with decrease in signal power. Thus, the grating written in EDF forms a wavelength-dependent loss element, which can be controlled by the signal power. This grating can also be used for gain flattening of Erbium doped fiber amplifiers.

6115-12, Session 3

Nanowire nanophotonics

C. M. Lieber, Harvard Univ.

No abstract available

6115-13, Session 3

One-dimensional nanostructures as subwavelength optical elements for photonics integration

P. D. Yang, Univ. of California/Berkeley

The manipulation of optical energy in structures smaller than the wavelength of light is key to the development of integrated photonic devices for computing, communications and sensing. Wide band gap semiconductor nanostructures with near-cylindrical geometry and large dielectric constants exhibit two-dimensional ultraviolet and visible photonic confinement (i.e. waveguiding). Combined with optical gain, the waveguiding behavior facilitates highly directional lasing at room temperature in controlled-growth nanowires with suitable resonant feedback. The nanowire optical emission has been studied in detail using high-resolution optical microscopy. This concept of using well-cleaved nanowires as natural optical cavities may be extendable to many other different semiconductor systems. We have further explored the properties and functions of individual ultralong crystalline oxide nanoribbons that act as subwavelength optical waveguides and assess their applicability as nanoscale photonic elements. The length, flexibility and strength of these structures enable their manipulation on surfaces, including the optical linking of nanoribbon waveguides and other nanowire elements to form networks and device components. We have demonstrated the assembly of ribbon waveguides with nanowire light sources and detectors as a first step toward building nanowire photonic circuitry.

6115-14, Session 3

Surface states of the wurtzite-semiconductor nanowires

N. Malkova, C. Z. Ning, NASA Ames Research Ctr.

In this work we theoretically study optical properties of the wurtzite type nanowires. Our goal is to develop a comprehensive theoretical model and understanding of surface states in the wurtzite type nanowires. We mostly focus on the states of all the lateral surfaces of {01 $\bar{1}$ 0} or {2 $\bar{1}$ $\bar{1}$ 0} symmetry. Our approach is based on the transfer matrix technique within the semi-empirical tight-binding approximation. Firstly, using the empirical parameters, we calculate the surface states for all surfaces of the semi-infinite crystal. The dangling bonds are shown to give a set of the states inside the band gap. We analyze both the ideal and the relax surfaces. Comparison between the theoretical results and available experimental data validates the developed model. Then using the cyclic boundary conditions which depend on the radius of the nanowire, we find the quantized spectrum for the surface states. The result for the surface states of wurzite GaN, ZnO, CdS, CdSe and AlN nanowires with {01 $\bar{1}$ 0} or {2 $\bar{1}$ $\bar{1}$ 0} surfaces are presented. We analyze the symmetry of the quantized surface states and possible optical dipole transitions between them. Using this model we investigate the optical properties of the nanowires. Our particular interest is the size dependent surface effects on optical properties of the nanowires.

6115-15, Session 3

Mechanisms of nucleation and growth of III- V compound nanowires in reactive vapor transport method

S. Vaddiraju, Univ. of Louisville; A. Chin, C. Z. Ning, M. Meyyappan, NASA Ames Research Ctr.; M. K. Sunkara, Univ. of Louisville

Controlled synthesis of III-V compound semiconductor nanowires such as gallium antimonide (GaSb), indium antimonide (InSb) and indium nitride (InN) is very important for their use in infrared (IR) detection and lasing applications. Reactive vapor transport approach (or self-catalysis approach), involving the vapor transport of low melting metals onto substrates in a reactive environment, is a very useful method for the synthesis of these III-V compound nanowires. Understanding the nucleation and growth mechanisms leading to the formation of these one-dimensional (1-D) structures in these reactive vapor transport approaches is crucial for the controlled synthesis of nanowires.

Indium nitride (InN) nanowire synthesis using indium vapor transport in dissociated ammonia environment (reactive vapor transport) is studied in detail to understand the nucleation and growth mechanisms involved with the so-called 'self-catalysis' schemes. The results showed that the nucleation of InN crystal occurs first on the substrate. This is followed by selective wetting and formation of indium droplets on top of these InN crystals. The 1-D nanowire growth takes place through liquid phase epitaxy with underlying InN crystals. These details about the nucleation and growth aspects within these self-catalysis schemes were further rationalized by demonstrating the growth of heteroepitaxially-oriented nanowires arrays and 'tree-like' morphologies. The results also showed that a second mechanism of growth occurs during direct nitridation of indium droplets for the spontaneous nucleation and basal growth of nanowires directly from indium.

These rationalized growth mechanisms were also employed for the synthesis of gallium antimonide (GaSb), indium antimonide (InSb) nanowires. The diameters of the synthesized GaSb and InSb nanowires varied from few nanometers to few microns, with lengths varying from a few to hundreds of microns. Photoluminescence measurements and other characterizations of the nanowires will be presented.

6115-16, Session 4

Semiconducting and piezoelectric nanoarchitectures of ZnO: Growth, structures, and properties

Z. L. Wang, Georgia Institute of Technology

Piezoelectricity is an important phenomenon that characterizes the electromechanically coupled response of a material, and it has widely been used in science and technology. At nano-scale, most of the studies have been carried out for exploring the semiconducting properties of quantum dots, nanowires as well as nanotubes, but the nano-scale piezoelectric property remains an unexplored field until recently [1-6]. In our laboratory, we have synthesized a series of novel nanostructures of ZnO, a material that is semiconducting and piezoelectric. The piezoelectric coefficient of a piezoelectric nanobelt has been found to be almost tripled compared to the value of the bulk [7], clearly indicating the exciting applications of piezoelectric ZnO nanobelts for nano-scale electromechanical coupled sensors, transducers, switches and resonators. The two important characteristics of the wurtzite structured ZnO are the non-central symmetry and the polar surfaces. The structure of ZnO can be described as a number of alternating planes composed of tetrahedrally coordinated O2- and Zn2+ ions, stacked alternatively along the c-axis. The oppositely charged ions produce positively charged (0001)-Zn and negatively charged (000-1)-O polar surfaces, resulting in a normal dipole moment and spontaneous polarization along the c-axis. The polar surface results in a few interesting growth features. This presentation will focus on the growth mechanisms and potential applications of piezoelectric nanobelts, nanorings and nanosprings.

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8 For details please visit http://www.nanoscience.gatech.edu/zlwang/

6115-17, Session 4

Optoelectronic properties of Si and II-VI nanowires and nanoribbons

S. T. Lee, City Univ. of Hong Kong (Hong Kong China)

No abstract available

6115-18, Session 4

Radius-dependent polarization anisotropy in semiconductor nanowires

A. V. Maslov, C. Z. Ning, NASA Ames Research Ctr.

Quantization of carrier motion in zinc-blende semiconductor nanowires leads to anisotropy of optical properties: stronger absorption for axis-polarized light than that for field polarized transverse to wire axis. The k.p theory involving only the heavy and light hole states in a zinc-blende semiconductor predicts that the lowest transition should have 60% polarization anisotropy, with the dominant absorption for the axis-polarized light[1]. For an infinitely-confined wire, this anisotropy coefficient does not change with radius. We show that, in thin wires, the inclusion of split-off states leads to a significant increase in the polarization anisotropy, that can reach, for example, to 90% for an R=3 nm InP nanowire. We demonstrate this

effect using an 8 band k.p theory as well as a simple analytical model. This result is in qualitative agreement with a recent tight-banding study [2]. We also show that the same increase in polarization anisotropy should exist in nanowires made of wurtzite semiconductors, such as GaN.

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6115-19, Session 4

Light emission and lasing from antimonide nanowires for infrared applications

A. Chin, NASA Ames Research Ctr.; S. Vaddiraju, Univ. of Louisville; A. V. Maslov, C. Z. Ning, NASA Ames Research Ctr.

We will present our studies of antimonide nanowire-based photonic devices for future infrared photonic integrated circuits and systems. Specifically, infrared light emission from individual GaSb nano- and microwires is investigated systematically as functions of temperature and excitation power. We report on our results on possible lasing operation of single wires.

6115-20, Session 5

Semiconductor lasers subject to polarization-rotated optical feedback

P. S. Spencer, R. Ju, Univ. of Wales/Bangor (United Kingdom)

The dynamics of a semiconductor laser subject to polarization rotated (incoherent) optical feedback in the long cavity limit have been numerical and experimental investigated. The results show that the induced dynamics can be grouped into four regimes (stable, chaotic, pulsed and two state) and they also show that the TM mode of the laser never lases, at least in the ring cavity configuration studied. In addition, unlike the earlier short cavity work, the boundaries between the regimes in the long cavity case were found to be independent of the external cavity delay time. By focussing on the effects induced by incoherent optical feedback from long external cavities we will show that four regimes of operation can be accessed by varying the external reflectivity. Calculated Lyapunov exponents and a bifurcation diagram clearly delineate these regimes and experimental verification of the transition from stable to chaotic dynamics will be described. The dynamical behaviour exhibited in each regime will be explained in terms of the memory effect introduced by the time delay associated with the external cavity and the natural relaxation oscillations of the solitary laser. It will also be shown that within the pulsed regime the pulse repetition rate is determined by the external reflectivity and injection current and is independent of the external cavity length.

6115-21, Session 5

Coherence resonances in semiconductor lasers

O. V. Ushakov, H. Wünsche, F. Henneberger, I. Khovanov, M. Zaks, L. Schimansky-Geier, Humboldt-Univ. zu Berlin (Germany)

The semiconductor DFB laser with active optical feedback which is tunable by three dc currents, allows to access different types of bifurcations, among them two types of Hopf bifurcation, torus birth and homoclinic bifurcations [S. Bauer, et al., Phys. Rev. E. 69, 016206 (2004)]. We have experimentally investigated the impact of external broadband electrical noise on the laser emission when the system is located close to torus birth and Hopf bifurcations. Noise-induced oscillations appear in both cases as a Lorentzian-shape peaks in a power spectrum. The coherence factor of the oscillations is determined as product of the height of the peak and the quality factor. It attains a maximum for both cases, indicating coherence resonance. However, the spectral width of the peak demonstrates a different behavior: monotonic increasing for the supercritical bifurcation and a non-monotonic with pronounced minimum for the subcritical case. These experimental findings are qualitatively discussed in terms of generic potential models for noise driven motion near to these bifurcations [V.S. Anishchenko, V.V. Astakhov, A.B. Neiman, T.E. Vadivasova, L.Schimansky-Geier, Nonlinear Dynamics of Chaotic and Stochastic Systems (Springer, Berlin, Heidelberg 2002)].

6115-22, Session 5

Square wave solutions in edge-emitting diode lasers with incoherent feedback

A. Gavrielides, Air Force Research Lab.; D. W. Sukow, G. Burner, T. McLachlan, J. Miller, J. Amonette, Washington and Lee Univ.; T. Erneux, Univ. Libre de Bruxelles (Belgium)

No abstract available

6115-23, Session 5

Characteristics of mutually coupled semiconductor lasers subject to optoelectronic feedback

H. F. Chen, National Yang-Ming Univ. (Taiwan)

Stability of mutually coupled semiconductor lasers subject to optoelectronic feedback is numerically studied here. While the theoretical analysis of the necessary condition to achieve chaos synchronization has revealed that the system can synchronize based on three operating conditions, only the synchronization satisfying two of them is reported in experiment. The numerical simulation studied here has revealed that the synchronization based on one of the three operating condition is rarely stable. Different from the uni-directional synchronization of the optoelectronic system, in which the feedback loop on the receiver deteriorates the synchronbization quality of two subsystems, the numerical simulation on this bi-directionally coupled system showed that the feedback loop built in the system can actually enhance the synchronization quality. It is found that careful choose of the feedback strength is required to achieve stable chaos synchrnization. A comparison between different operating conditions to achieve synchronization is also addressed.

6115-24, Session 5

Evaluation of frequency stability in double optical feedback external-cavity diode laser systems

K. Doi, Y. Kobayashi, S. Maehara, T. Sato, T. Maruyama, M. Ohkawa, Niigata Univ. (Japan); T. Tsubokawa, National Astronomical Observatory of Japan (Japan)

External cavity diode laser (ECDL) systems are presently experiencing a surge in popularity as laser light-sources, in advanced optical communications- and measurement-applications. Because such systems require that their external reflectors be precisely controlled to eliminate low frequency fluctuations (LFF) in optical output, we conducted experiments with a two-cavity version of ECDL system, which was expected to eliminate LFF easily. 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-inver board as the platform for our ECDL system, in order to minimize the influence of thermal expansion. Moreover, our ECDL system combines an Rb cell within an external cavity to improve stability; by restricting the LD frequency to both the external cavity mode and to

the Rb saturated absorption spectrum. We used the square root of the Allan variance to evaluate oscillation frequency stability, observing, in the process, that it improved stability about one order of magnitude.

6115-25, Session 5

Frequency stabilization of a semiconductor laser using the Rb saturated absorption spectroscopy

Y. Ohta, S. Maehara, K. Hasebe, Y. Kurosaki, T. Sato, T. Maruyama, M. Ohkawa, Niigata Univ. (Japan); T. Tubokawa, National Astronomical Observatory of Japan (Japan)

Aiming to employ a semiconductor laser as the light source for an optical frequency- or phase-based system, we stabilized the frequency of a semiconductor laser, using both the Rb absorption line, which provides absolute stabilization points, and the Fabry-Perot Etalon, whose resonance frequencies shift over a wide frequency range, as external frequency references.

In a previous experiment, we took advantage of both the Rb absorption line and an etalon fs spectrum, to achieve a broad, yet stable frequency reference. In this work, we have tried to improve the frequency stability of a semiconductor laser, using the Rb saturated absorption line to obtain a larger control signal for the etalon or to construct highly-stable frequency-reference system than our previous works.

In order to improve overall frequency stability within our system, we adjusted the setup used in Rb saturated absorption spectroscopy and optimized modulation parameters such as modulation- frequency and -width in the task of detecting the error signal.

We are now investigating the use of optical feedback, to narrow the laser diode fs oscillation spectrum and the use of the third derivative signal to obtain the better error signal. These are our hope that by using these methods, we will achieve even higher frequency stability.

6115-26, Session 6

Electromagnetically induced transparency in semiconductors

H. L. Wang, Univ. of Oregon

Electromagnetically induced transparency (EIT) exploits destructive quantum interference induced by a nonradiative coherence to make an otherwise opaque medium transparent. EIT and EIT-related processes provide a powerful and effective mechanism for controlling and manipulating light. Recent successes include the reduction of the group velocity of light by many orders of magnitude, the reversible storage of light as a stationary spin coherence, and the generation of entangled photon pairs with controllable delays. While most EIT studies have thus far been carried out in atomic or atomic-like systems, the basic concept of EIT can also be applied to extended optical excitations such as excitons in semiconductors. EIT studies in semiconductors can further deepen our understanding of quantum coherence and interference in solids and can potentially open up new avenues for applications of EIT and EIT-related phenomena.

There are two major obstacles for realizing EIT and, more generally, for coherent manipulation of quantum coherences in semiconductors. First, coherent nonlinear optical processes in an excitonic system are profoundly modified by manybody Coulomb interactions between excitons, often in a detrimental manner. Second, quantum coherences in semiconductors are typically short lived. With the exception of electron spin coherence, these coherences are extremely fragile against dynamic processes such as exciton-exciton and exciton-phonon scattering.

We have successfully demonstrated EIT in semiconductors by understanding and harnessing manybody Coulomb interactions and by using transient optical techniques to overcome rapid decoherence processes. In this paper, we will present experimental results on EIT arising from exciton spin coherence and biexciton coherence. Experimental studies on EIT arising from the more robust electron spin coherence and its application in slow light will also be discussed.

6115-27, Session 6

Performance limits of delay lines based on “slow” light

R. W. Boyd, Univ. of Rochester

Practical applications of slow light methods require that one be able to controllably delay a pulse of light by many pulse lengths. In this contribution we analyze the possible limitations to the maximum achievable time delay and suggest methods for overcoming these limits.

A key figure of merit for many applications is the normalized time delay, that is, the maximum controllable time delay divided by the duration of the input pulse. This quantity can be thought of as the information storage capacity of the medium, that is, it gives the number of bits of information that can reside inside the delay line at any given time. The best result reported to date is the value 4 reported by Kasapi et al. However, data packets useful for telecommunication systems contain at least 1000 bits. The question addressed in this contribution are the prospects for the construction of slow-light delay lines with 1000 bit capacity.

6115-28, Session 6

Tunable ultraslow light in vertical-cavity surface-emitting laser

C. J. Chang-Hasnain, Univ. of California/Berkeley

No abstract available

6115-29, Session 6

Slow light and fast light in quantum dot semiconductor optical amplifiers

H. Su, S. L. Chuang, Univ. of Illinois at Urbana-Champaign

Controlling the speed of light in optical media is essential for applications such as advanced optical networks, optical data storage, and nonlinear optics. Most of the slow light and fast light experiments reported by now are of either low temperature (several to tens K) or narrow bandwidth (kHz to MHz). In practical applications, however, room temperature and a bandwidth greater than 1 GHz are typically required. Therefore, semiconductor optoelectronic devices are attractive considering their carrier dynamics with a time scale from 100 fs (intra-band) to 1 ns (inter-band) at room temperature. In this paper, we demonstrate fast light and slow light in quantum dot semiconductor optical amplifiers using population oscillation and current injection as optical and electrical control, respectively. Change of effective group index from -0.4 to 1.0 with a bandwidth greater than 13 GHz is achieved under different configurations of current bias and optical pump. The group index change and its bandwidth are found to increase simultaneously when the population oscillation increases, indicating no limitation from the slow-down-factor and bandwidth product. Slow light and fast light in QD and bulk semiconductors are compared experimentally with an emphasis on the effect of linewidth enhancement factor. Finally, we utilize those phenomena to characterize the linewidth enhancement factor, intra-band dynamics, and carrier diffusion in QDs.

6115-30, Session 6

Nonlinear mode interaction as a mechanism to obtain slow/fast light in diode lasers

P. G. Eliseev, H. J. Cao, C. Y. Liu, G. A. Smolyakov, M. Osinski, CHTM/Univ. of New Mexico

No abstract available

6115-31, Session 6

Investigation of single-photon propagation velocity in optical fiber

J. D. Ingham, J. E. Carroll, I. H. White, Univ. of Cambridge (United Kingdom)

Technologies based upon the application of single-photon techniques are of escalating significance. Many of these technologies involve single-photon propagation over optical fiber, e.g. quantum key distribution in quantum cryptography. It is therefore of increasing importance to fully understand the nature of single-photon propagation and elucidate any differences to the classical multi-photon regime. This paper provides an important initial contribution to this topic by investigating the velocity of propagation of both classical and single-photon pulses over standard single-mode optical fiber.

Novel techniques and results will be reported that demonstrate a consistent ability to measure the classical group velocity to an accuracy in the time-of-flight better than 2 ns in 30,000 ns. Identical techniques are then applied to single photons to determine if their velocity is equal to the classical group velocity. Furthermore, a novel theory suggests that the classical group velocity may be fractionally slower than the single-photon velocity in optical fibers. Relative delays between single photons and classical pulses may have implications for secure single-photon communication.

Classically, wave interference is essential to establish the group velocity but it is unclear how single photons interfere with other single photons at a different time and frequency. Steinberg et al.[1] measured the velocity of single photons in centimetre lengths of bulk glass. Their results and tolerances do not rule out the possibility of fractional differences between the classical group velocity and the single-photon velocity that could be significant in fibers. At present, we are able to measure the single-photon time-of-flight to a repeatable accuracy of 2 ns in 30,000 ns. The results indicate, for the first time in optical fiber, that single photons may in some circumstances travel fractionally faster than classical pulses.

1 A. M. Steinberg et al., Phys. Rev. Lett., vol. 68, pp. 2421-2424, 1992.

6115-32, Session 7

Nonequilibrium theory for semiconductor laser systems

A. Traenhardt, S. Becker, S. W. Koch, Philipps-Univ. Marburg (Germany); J. Hader, Univ. of Arizona and Nonlinear Control Strategies, Inc.; J. V. Moloney, Univ. of Arizona

No abstract available

6115-33, Session 7

Investigation of anomalously large band-filling effect in type-II InAs/GaSb superlattices

X. D. Mu, Y. J. Ding, Lehigh Univ.; J. W. Little, Army Research Lab.

For InAs/GaSb superlattices (SL's) the bottom of the InAs conduction band is 143 meV below the top of the GaSb valence band. Therefore, electrons and holes are always spatially separated (i.e. type II). Another inherent feature lies in the extremely light electron mass of InAs (0.026 m0). Its de Broglie wavelength is so long that even for the GaSb layer thickness of about 10 nm, there is considerable interaction between electrons in successive InAs layers, resulting in a substantially wide miniband. Such a large width manifests the quasi-3D properties of the SL's. Since the exciton banding energy is about 1 meV or less, exciton-related effects are negligible for most InAs/GaSb SL's. Here, we report our results on detailed investigation of the InAs/GaSb SL's. We grew a series of the InAs/GaSb SL's with the thicknesses of the InAs well or GaSb barrier layer varying in the range of 2.4-10 nm. As the barrier width is increased while the well width is kept constant the photoluminescence (PL) peak is blue-shifted. In addition, the linewidth is significantly decreased. Furthermore, the PL peak intensity is greatly enhanced. As the barrier width is increased, the miniband width is significantly reduced. Therefore, the electrons behave as those closer to 2-D than 3-D in terms of the quantum confinement, which means that the electrons and holes are further separated in space. On the other hand, as the well width is increased while the barrier width is kept constant the PL peak is significantly red-shifted. Such a shift is due to the reduction of the quantized energy for the electrons inside the well. As the pump intensity is increased, the largest blue-shift due to band-filling effect is measured to be about 25.4 meV. Furthermore, the shift exhibits the strongest saturation. We have also found out whether the nonradiative recombination at interface traps or Auger recombination is present by investigating the dependence of the wavelength-integrated PL intensity on the pump intensity. Finally, we have studied the dependences of the PL spectrum and intensity on the defect density.

6115-34, Session 7

Type-II 450-550 nm InGaN-GaNAs active region for quantum well lasers and light emitters on GaN

R. A. Arif, Y. K. Ee, N. Tansu, Lehigh Univ.

Though blue InGaN-GaN quantum well (QW) light emitting diodes (LEDs) and lasers have been demonstrated with good performance, extending the emission wavelength by solely increasing the In-content in the InGaN QW for green and yellow lasers has been challenging. The longest emission wavelength reported utilizing InGaN QW lasers is at 482-nm (green-blue). As the In-content in the InGaN QW is increased, phase separations and higher defect density lead to reduction in internal radiative efficiency. The polarization field also significantly reduces the electron-hole wavefunctions overlap of InGaN QW to 25-30% for 500-550 nm regime, resulting in low optical gain in this regime.

Here we present a new nitride-based gain media of InGaN-GaNAs type-II QW on GaN for lasers and LEDs. We found that this new gain media offers wide emission wavelength coverage from blue (~450 nm) to yellow-green (~550 nm), with low In-content and dilute As-content (<6-8%). The type II alignment and polarization fields in the InGaN-GaNAs-InGaN QW structures allows wavelength extension, while maintaining significantly larger wavefunctions overlap (65-70% for green-yellow regime) in comparison to that (25-30%) of the conventional InGaN QW. The increase in the wavefunctions overlaps in the type-II InGaN-GaNAs QW results in increased optical gain of up to 8 times for the optimized QW structure emitting at 530-nm, in comparison to that of the conventional InGaN QW approach. Optimization for the type-II approach emitting from 450-550 nm will be discussed. This novel type-II InGaN-GaNAs QW should potentially allow the realization of green and yellow lasers on GaN.

6115-35, Session 7

An investigation into changes observed in the oscillation characteristics of semiconductor lasers exposed to magnetic fields

T. Miyamoto, T. Sato, M. Ohkawa, T. Maruyama, Niigata Univ. (Japan)

The application of magnetic fields to semiconductor lasers gives rise to significant alterations in their oscillation wavelengths. Reports dating back to the 1990's. describe shifts to shorter oscillation wavelengths, at extremely low temperatures (80K) and strong magnetic fields (~4T). These shifts were explained by the effect of the Landau Level. In our preliminary experiments, we exposed bulk-type semiconductor lasers oscillating at 780nm to a relatively weak magnetic field (1.4T), at room temperature (300K), observing, in the process, that the oscillation wavelength shifted to the longer (low-frequency) side. This work looks at the longer side shift, the optical output-power shift on the low-power side, and the terminal-voltage shift seen on the higher voltage side of some multi-quantum-well

(MQW) laser diodes oscillating at 780nm, under the same experimental conditions we employed in previous works. In discussions of shift mechanisms, we consider how wavelength (frequency), optical output-power, and terminal voltage-shifts are correlated. Our expanded knowledge base has forced a complete rethink of the mechanisms we relied upon in the 1960's. Current evidence suggests that the temperature rise and the longitudinal magneto-resistance effect were 'co-conspirators' in the shifts observed in our experiments, when we applied magnetic fields to laser diodes parallel to the injection current. In an upcoming report, we will describe the results of experiments conducted near the threshold current.

6115-36, Session 8

All-optical signal processing based on optical injection-locked two-mode vertical-cavity surface-emitting laser

K. Hasebe, F. Koyama, Tokyo Institute of Technology (Japan)

We have proposed all-optical signal processing using an optically injection-locked two-mode vertical-cavity surface-emitting laser (VCSEL). The operating principle is based on an all-optical inverter using transverse mode switching of an injection-locked VCSEL. The nonlinear transfer function in input-output characteristics enables us to reshape degraded input signal. In addition, the polarization state of the output signal can be tightly controlled by two-mode optical injection scheme. Thus, the polarization state of an inverted signal can be fixed for randomly polarized input light. In addition, 3R regeneration can be achieved with electrically driven clock signal. The proposed scheme gives us novel functions such as all-optical 3R regeneration with optical re-polarization function and NRZ-RZ format conversion. We carried out the modeling based on a multi-transverse-mode rate equation analysis which includes two orthogonal polarization modes, exhibiting a potential of high-speed 4R regeneration and format conversion at 10 Gbps.

6115-37, Session 8

Nonlinear RIN modeling of oxide-aperture vertical-cavity surface-emitting lasers

J. Perchoux, A. Rissons Blanquet, J. C. Mollier, École Nationale Supèrieure de l'Aèronautique et de l'Espace (France)

The steadily increasing performances of 850 nm VCSELs (Vertical Cavity Surface Emitting Lasers) concerning their modulation bandwidth and relative intensity noise (RIN) make them very attractive for a use in analog fiber links. However, applications such as the reference frequency signal distribution in the Radar systems or the telecommunication satellites, need to predict the phase noise and its degradation.

So, we propose a new electrical equivalent circuit of oxide-aperture VCSEL derived from the multimodal rate equations including the contribution of the non-linear gain and the coupling between adjacent modes. This model allows to predict accurately, on the one hand, the RIN in a very large frequency band ranging from less than 1 MHz up to more than 10 GHz, on the other hand, the phase noise degradation of a fiber link using a VCSEL directly modulated by a reference frequency RF signal. The RIN and phase noise measurements on a 1 GHz VCSEL-based optical link show a very good agreement with the theoretical predictions, especially for the low frequency RIN enhancement due to the mode competition in the VCSELs and the upconverted noise sidebands at the 1GHz modulation frequency.

An extension of this model towards the low frequencies is currently achieved. This one is being validated thanks to the RIN measurements below 1 MHz.

6115-38, Session 8

Analysis of the static and dynamic characteristics of 1310 nm vertical-cavity surface-emitting lasers

A. Baecker, S. Odermatt, ETH Zürich (Switzerland); M. Streiff, Sensirion AG (Switzerland); B. Witzigmann, ETH Zürich (Switzerland)

We present the static and dynamic simulation of a long-wavelength Vertical-Cavity Surface-Emitting Laser (VCSEL) operating at around 1310 nm. The device consists of AlGaAs/GaAs distributed Bragg reflectors (DBRs) which are wafer-fused to both sides of the InP-based cavity with InAlGaAs quantum wells, and its structure is similar to the one from references [1] and [2]. A tunnel junction is used for current injection into the active region.

The structure is simulated with a modified version of the commercial device simulator DESSIS-Laser by Synopsys. The fully-coupled electro-opto-thermal multi-dimensional simulations use a microscopic physics based model. Carrier transport is described by the continuity and Poisson equations and self-heating effects are accounted for by a thermodynamic equation. To obtain the optical modes, the Helmholtz equation is solved using a finite element approach. The optical gain model includes many-body effects. The equations are solved self-consistently.

Calibrations of static (L-I, V-I curves) and dynamic characteristics (small signal responses) show good agreement with measurements at different temperatures. On this basis, the simulations reveal the critical factors that determine the bandwidth of the device.

1 J. Piprek, M. Mehta, and V. Jayaraman, "Design and Optimization of High Performance 1.3μm VCSELs," Physics and Simulation of Optoelectronic Devices XII, Photonics West 2004 SPIE Proc. 5349-49, 2004.

2 V. Iakovlev, G.Suruceanu, A. Caliman A. Mereuta, A. Mircea, C.-A. Berseth, A. Syrbu, A. Rudra, E. Kapon, "High performance single mode VCSELs in the 1310 nm waveband", IEEE Photon. Techn. Lett., Vol.17, NO.5, May 2005, 947-949 and references therein.

6115-39, Session 9

Longitudinal photonic bandgap crystal laser diodes with ultra-narrow vertical beam divergence

M. V. Maximov, Y. M. Shernyakov, I. I. Novikov, S. M. Kuznetsov, L. Y. Karachinsky, N. Y. Gordeev, A. F. Ioffe Physical-Technical Institute (Russia); V. A. Shchukin, N. N. Ledentsov, NL Nanosemiconductor GmbH (Germany) and Technical Univ. of Berlin (Germany) and A. F. Ioffe Physical-Technical Institute (Russia); A. Sharon, PBC-Lasers Ltd. (Israel); V. P. Kalosha, Univ. of Ottawa (Canada) and PBC-Lasers Ltd. (Israel)

No abstract available

6115-40, Session 9

Emission from an active photonic lattice: Does it exceed that of the blackbody?

W. W. Chow, I. F. El-Kady, Sandia National Labs.

No abstract available

6115-41, Session 9

Advanced FEM analysis of nano-resonators

S. Burger, B. Kettner, F. Schmidt, L. W. Zschiedrich, Zuse Institute Berlin (Germany)

Miniaturized optical resonators with spatial dimensions of the order of the

wavelength of the trapped light offer prospects for a variety of new applications like quantum processing.

We focus on 3D pyramidal-shaped nano-resonators for optical wavelengths in the vicinity of layered media.

We are interested in light scattering of such devices as well as in an eigenmode analysis.

From a mathematical point of view, this leads to large scaled non-selfadjoint eigenvalue or scattering problems posed on unbounded domains.

For both problem types we construct appropriate transparent boundary conditions taking into account the inhomogeneous exterior domain.

We approach these problem classes with a rigorous finite-element method, incorporating higher order vectorial elements, adaptive mesh refinement, transparent boundary conditions based on the Pole condition.

To solve the scattering problem, we propose a novel method for the solution of the arising discrete problem combining multi-level techniques and time-domain preconditioning.

For the eigenvalue problem it is essential to filter out non-physical discrete eigenmodes caused by the numerical truncation of the transparent boundary conditions. We present new ideas to cope with this problem.

We discuss mode structures of experimentally realized devices and analyze the influences of geometrical and material parameters on the resonance characteristics.

6115-42, Session 9

Pattern formation and cavity solitons in a quantum dot semiconductor microcavity: Microscopic model

T. Maggipinto, M. Brambilla, I. M. Perrini, Univ. e Politecnico di Bari (Italy); R. Kuszelewicz, S. Barbay, Ctr. National de la Recherche Scientifique/UPR20 (France)

We develop a microscopic model to describe the optical response of a semiconductor Quantum Dot (QD) medium in a broad area microcavity driven by a coherent holding beam. This model accounts for the subtle mechanisms coupling the QD itself with the wetting layer (WL), such as thermal capture and emission, and Auger diffusion. It also incorporates the inhomogeneous broadening of the quantum dot linewidth, due to the fluctuations of the quantum dot sizes that arise in self-organized growth. We consider both a passive and an active configuration; in the first, no carriers are injected into the wetting layer while in the second a current provides additional carrier generation. In the active configuration the system is always kept above transparency but below laser threshold.

We are able to properly calculate the optical response and confirm the capability of such a material system to exhibit focusing as well as defocusing nonlinearities, depending on the spectral detuning of light with respect to the line center.

We apply this model to the analysis of spatial pattern formation in the coherent field such as global patterns and cavity solitons. The conditions for the onset of modulational instabilities clearly express the favourable character of focusing nolinearities in assisting the absorption saturation mechanisms in this process. Moreover pattern formation and localisation can still be found in the moderate defocusing case. The inclusion of the QD-WL interaction mechanisms stabilize the pattern formation process through the WL diffusion.

6115-43, Session 9

Phase and polarization control as a route to plasmonic nanodevices

M. E. Sukharev, T. Seideman, Northwestern Univ.

We extend the concepts of polarization and feedback control to develop a general approach for guiding light in the nano-scale via metal nanoparticle arrays. Polarization and phase control are first introduced as a method of controlling branching ratios at array intersections. Genetic algorithms are next applied as a systematic design tool, wherein both the excitation field parameters and the structural parameters of the nanoparticle array are optimized to make constructs with desired functionality. Implications to several fields of research are suggested.

6115-56, Session 10

Laser cooling of semiconductors

M. Sheik-Bahae, B. Imangholi, M. P. Hasselbeck, Univ. of New Mexico; R. I. Epstein, Los Alamos National Lab.; S. R. Kurtz, National Renewable Energy Lab.

Since the first demonstration of optical refrigeration in Yb-doped glass, significant progress has been made in laser cooling of rare-earth doped solids. Net laser cooling in semiconductors, however, has remained elusive. A primary obstacle is external quantum efficiency (EQE), which is a measure of how effectively anti-Stokes luminescence can be generated and removed from the semiconductor. The necessary EQE is obtained by i) defeating total internal reflection and ii) engineering devices with long non-radiative recombination lifetimes for the optically generated electron-hole pairs. A simple analysis reveals that an EQE exceeding 98% is required to cool GaAs from room temperature. Recent measurements have indicated that an EQE of 96% is achievable in MOCVD grown GaAs/InGaP heterostructures. Efforts at increasing this quantity to meet the laser cooling requirements at room temperatures are underway in our laboratories. Luminescence trapping and re-absorption has been identified as the main obstacle. A number of techniques are being pursued to reduce the luminescence trapping, including a vacuum nano-gap. Approaches to increase the non-radiative lifetime are also being explored. Advanced growth techniques to reduce surface defects are being investigated by researchers at UNM and NREL. The requirements for laser cooling are eased at lower starting lattice temperatures. Theory and experiment show that non-radiative contributions from deleterious surface and Auger recombination diminish at low temperatures while the desired radiative recombination is enhanced. This fortunate property can be exploited to enhance EQE. We measure an EQE of 99% in a 2 micron thick GaAs/InGaP heterostructure at 100 K, which is extremely promising for net laser cooling. To our knowledge, this is the highest EQE ever reported for a semiconductor. Observation of net laser cooling as well as accurate measurement of EQE requires a sensitive non-contact temperature probe. We developed a differential luminescence thermometry technique that provides a sensitivity of better than 50 mK in the temperature range 100K-300K.

6115-57, Session 10

Band gap engineering for laser cooling of semiconductors

J. B. Khurgin, Johns Hopkins Univ.

Efficiency of laser cooling of the solid state medium is determined by the relative anti-Stokes energy shift between the absorbed and emitted photons. Typically the Anti-Stokes shift is of the order of kBT - thus the efficiency of cooling is low. The effective Anti-Stokes shift can be increased by reducing the probability of radiative recombination at relatively low energies while enhancing it at higher energies. The radiative recombination rate at a given energy is determined by three factors: density of the emitting electron-hole states, density of photon states into which emission takes place, and, finally, oscillator strength of the transition. All three of these parameters can be changed by means of band gap (electronic of photonic) engineering.

In this talk I will consider impact of three techniques:

1. engineering the density of electron-hole states by means of compensation doping, strain-induced change in valence band effective mass, and using discrete levels in shallow quantum dots.

2. engineering the density of photon states by inhibiting radiative recombination close to excitation energy

3. engineering of the oscillator strength by using indirect transitions in type II quantum dot.

Results of extensive analytical and numerical modeling demonstrate that the impact of band gap engineering is strongly affected by the rate of nonradative recombination. Typically the threshold of cooling gets increased but the slope efficiency of it gets also increased when the band gap engineering techniques are used. Thus for each laser power there exists an optimal design allowing for maximum cooling power. For the realistic GaAs structures three-fold enhancements can be achieved.

6115-58, Session 10

Theory of semiconductor laser cooling at low temperatures

G. Rupper, N. H. Kwong, R. H. Binder, Univ. of Arizona

On the road towards experimental realization of laser-induced cooling of semiconductors, theoretical investigations are necessary for a detailed understanding of the microscopic phenomena underlying the cooling process, and for a prediction of optimal parameter regimes where efficient cooling could be expected. A recent realistic theory for cooling of bulk GaAs by Sheik-Bahae and Epstein [Phys. Rev. Lett. 92, 247403 (2004)] has focused on the high-temperature regime, where the cooling process involves absorption of and luminescence from an electron-hole plasma. Using a microscopy many-particle theory for quasi-thermal equilibrium, we extend the Sheik-Bahae Epstein approach to the low-temperature regime, where excitonic effects become important. In particular, the theory includes effects of bound electron hole pairs and correlated unbound pairs (i.e. the plasma). We use a diagrammatic approach that is non-perturbative in the Coulomb interaction and contains effects of phase-space filling, single-particle renormalization in a partially ionized plasma, and screening. We ensure that our theory contains the relevant limiting cases for (partial) ionization in the low-density regime (Saha equation and Beth-Uhlenbeck formula) as well as the high density regime (Mott transition). Based on our microscopic theory for absorption and luminescence in the quasi-thermal equilibrium regime, we present a detailed study of cooling criteria at low temperatures, focusing mainly on the temperature regime between 5K and 100K. We discuss the transition from the high temperature regime where the absorption and luminescence are dominated by transitions in the electron-hole continuum, to the low-temperature regime dominated by resonant exciton transitions.

6115-59, Session 10

Theoretical limits of electroluminescence refrigeration in semiconductors

Y. H. Zhang, J. B. Wang, D. Ding, S. Q. Yu, S. R. Johnson, Arizona State Univ.

No abstract available

6115-60, Session 10

Differential luminescence thermometry in semiconductor laser cooling

B. Imangholi, M. P. Hasselbeck, M. Sheik-Bahae, Univ. of New Mexico; R. I. Epstein, Los Alamos National Lab.; S. R. Kurtz, National Renewable Energy Lab.

In semiconductor laser cooling experiments, use of contact temperature sensors such as a thermocouple is undesirable because the element can absorb anti-Stokes luminescence and heat up. We have developed a non-contact, spectroscopic technique to measure the temperature change of semiconductors with very high precision. A temperature resolution of 30 mK has been demonstrated with bulk GaAs. The approach makes use of the temperature-dependent direct band gap energy.

A weak cw probe laser excites photocarriers from the valence to conduction band. Recombination radiation is detected in the spectral region around the direct band gap. The luminescence is spatially dispersed by a grating spectrometer and imaged onto a time-gated optical multi-channel analyzer (i.e. CCD array). The luminescence spectrum is captured in a single-shot. Spectra are normalized at the band edge wavelength and recorded; subtraction of two spectra determines whether the semiconductor is heating or cooling and by how much. By carefully controlling scattered light and dark current noise, we obtain a differential temperature accuracy of < 100 mK.

In laser cooling experiments, a high power laser pumps the semiconductor at the band edge. Pump laser light would blind the CCD array, so we employ a time-synchronized, pump-probe arrangement in which the high power beam is disabled during brief intervals when spectra are captured. The system has been used to measure the internal and external quantum efficiency (EQE) of GaAs heterostructures. Internal quantum efficiency describes how effectively pump laser light gets converted to luminescence. EQE modifies the internal efficiency to account for how well the luminescence escapes the device. EQE must always be less than internal efficiency; both depend on device geometry and temperature. By looking at fractional heating (i.e. the complement of laser cooling) as a function of pump wavelength, we measure EQE as large as 99% for a GaAs heterostructure bonded to a ZnS dome lens. This is higher than any value previously reported and should be sufficient to realize net laser cooling in GaAs.

6115-61, Session 10

Electroluminescence refrigeration in semiconductor light emitting diodes

S. Q. Yu, J. B. Wang, D. Ding, S. R. Johnson, Y. H. Zhang, Arizona State Univ.

Vibration-free solid-state optical coolers operating at low temperatures are promising candidates to replace mechanical Stirling coolers for many applications, such as space based satellite systems. Recently, some very promising work by Richard Epstein et al., has demonstrated a cooling temperature decrease of 90 K in optical pumped Yb+ doped glass. Compared to rare-earth doped glasses, electroluminescence refrigeration in semiconductors can be possibly more efficient at low temperatures and furthermore, semiconductor based cooling components are more straightforward to integrate with other optoelectronic devices. In this paper, two fundamental questions will be addressed regarding the electroluminescence refrigeration in semiconductors: 1) does cooling occur as part of the light emission process or is it due to the thermoelectric (TE) effect? and 2) what is the optimal electronic density of states (DOS) for a light emitting active region? The physics of cooling in electroluminescence refrigeration (i.e. the microscopic process where lattice thermal energy is absorbed by the carries) is attributed to the TE effect in a light emitting diode (LED). Nevertheless, electroluminescence coolers have the potential to achieve net cooling while conventional TE coolers can only transfer thermal energy. In terms of the optimal DOS, the net cooling power in electroluminescence coolers with active regions that have bulk (3D), quantum well (2D), or quantum wire (1D) DOS are compared as a function of bias. These results show that the maximum cooling power occurs in bulk material with a large effective mass.

6115-52, Session 11

Recent progress in quantum-dot optical devices: Lasers, amplifiers, and high-speed optical switches

M. Sugawara, Fujitsu Labs. (Japan)

No abstract available

6115-53, Session 11

Analysis of spatially-localized recombination in quantum dot lasers

H. D. Summers, H. J. Pask, P. Blood, I. C. Sandall, P. M. Smowton, Cardiff Univ. (United Kingdom)

No abstract available

6115-54, Session 11

Investigation of phonon bottleneck effect on quantum dot lasers

Y. S. Su, C. F. Lin, Y. Ho, W. C. Chang, National Taiwan Univ. (Taiwan)

The effect of phonon bottleneck effect on the performance of QD devices is studied numerically by the rate equation model. In addition to decreasing the modulation speed, phonon bottleneck effect results in simultaneous laser oscillations of 1st and 2nd quantized states of a QD device. In QW devices, the excess energy of carrier relaxation can be released to other carriers, such as Auger effect, or dissipated as phonons. Thus, strong competition between laser oscillations of 1st and 2nd quantized states will prevent simultaneous laser oscillation. In the case of QDs, the two processes are forbidden because the momentum is not conserved. For an electron to relax from 2nd quantized state to 1st quantized state, excess energy can only be transferred to carriers outside the QD by coulomb interaction Thus, it takes more time for carriers to relax into first quantized state in QD structures.

According to the rate equation model, the carrier relaxation time between 1st and 2nd quantized state must be more than 100ps for simultaneous laser oscillation to occur. This value is far more than the carrier relaxation time of a QW structure. Thus, the existence of phonon bottleneck effect can be confirmed by the observation of two-mode laser oscillation of a QD laser. The rate equation model is also used to analyze the RF modulation response under the condition of simultaneous two-mode laser oscillation. Although phonon bottleneck effect will decrease the modulation response of laser emitted by the 1st quantized state, the modulation response of laser emitted by the 2ndt quantized state can still be fast.

6115-55, Session 11

All optical logic performance of quantum dot semiconductor amplifier based devices

H. Z. Sun, N. K. Dutta, Univ. of Connecticut

The performances of all-optical logic gates AND, OR, XOR, NOT based on quantum dot semiconductor optical amplifier (QD SOA) devices have been simulated. The saturation power, optical gain and optical phase response of a QD SOA has been analyzed numerically using a rate equation model of quantum dots embedded in a wetting layer. The calculated response is used to model the performance of the logic gates. Impacts of injection current and the input signal power on system quality factor have been studied. For the parameters used in this paper, all-optical logic gates using QD-SOA is capable of operating at speeds of ~ 250Gb/s.

6115-48, Session 12

Sub-millisecond spin memory in negatively charged InP quantum dots

Y. Matsumoto, B. Pal, M. Ikezawa, Univ. of Tsukuba (Japan); S. Y. Verbin, I. V. Ignatiev, Univ. of Tsukuba (Japan) and St.-Petersburg Univ. (Russia)

No abstract available

6115-49, Session 12

Anomalous photon echoes and Rabi oscillations of quantum dot excitons

Y. Mitsumori, Tohoku Univ. (Japan); A. Hasegawa, M. Sasaki, National Institute of Information and Communications Technology (Japan); F. Minami, Tokyo Institute of Technology (Japan)

No abstract available

6115-50, Session 12

Single-electron spin switching with quantum dots

I. A. Akimov, D. H. Feng, F. Henneberger, Humboldt-Univ. zu Berlin (Germany)

No abstract available

6115-51, Session 12

Single quantum dot emission after resonant excitation

T. Kuroda, National Institute for Materials Science (Japan) and PRESTO-JST (Japan); K. Kuroda, K. Sakoda, G. Kido, N. Koguchi, National Institute for Materials Science (Japan)

High-precision read-out of a single quantum state is a key technique to realize a quantum computation(QC) using a solid state material. In the framework of QC based on excitons in quantum dots (QDs), several groups have successfully demonstrated the Rabi-oscillations, i.e., single qubit operation and its read out. However, previous works mainly focus on state-control of excited levels, and probe the final state via relaxation from the qubit level to the lowest exciton level, which then emits photons. Since the excited levels easily suffer from decoherence, one should design an alternative way to construct (and read-out) qubits exploiting ground-level excitons.

In this report, we observe single QD emissions from the lowest exciton state after resonant excitation. Making use of narrow-band picosecond pulses, a micro-objective setup, and a relatively low-density QD sample, we can capture the photoluminescence of a single QD which is after perfectly resonant excitation. Great care has been taken to reduce elastic scatterings. Temporal resolving of photoluminescence allows to observe single QD emissions, which decay with 200 ps lifetime, being free from scattering components. The relevant emission intensity shows oscillatory dependence on excitation density, confirming the presence of Rabi oscillations in the lowest exciton level. Through the analysis we can determine the oscillator strength as 11 debye, which is consistent with the value of previous reports.

6115-44, Session 13

Strong coupling in a single quantum dot-semiconductor microcavity system

A. W. Forchel, Univ. of Würzburg (Germany)

No abstract available

6115-45, Session 13

Strong light-matter coupling with a single quantum dot in a planar photonic crystal nanocavity

T. Yoshie, Duke Univ.; G. Khitrova, H. M. Gibbs, Univ. of Arizona

Optical microcavities are anticipated to be key components in future nanophotonic systems including quantum information networks. They offer unique characters for modifying optical processes in small volumes. Photonic crystals can define the smallest cavities with high resonator quality factors. Combined with a single quantum dot, therefore, photonic crystals are excellent test beds for investigating solid-state cavity quantum electrodynamics including highly non-classical states, quantum-classical boundary, and quantum nonlinear optics. In this report, we describe the observation of vacuum Rabi splitting with an InAs single quantum dot in a photonic crystal nanocavity. Our high quality nanocavities are defined in thin membranes with InAs quantum dots by omission of three lattice points and shift of two adjacent points from 2D triangular lattices.

The cavities were weakly pumped to measure emission from single quantum dots. Temperature-scanning was used to change a detuning value, which is single quantum dot emission wavelength minus resonance wavelength. For strong coupling samples, two peaks were clearly observed at small detuning, and they showed anti-crossing curves as a function of the detuning value. The vacuum Rabi splitting 2g was 41 GHz = 0.170 meV = 0.192 nm at zero detuning. Assuming that the quantum dot is on the field maximum, a dipole moment of the dot is 29 Debye and an emission lifetime is 1.82 nsec. The observation of strong coupling, which has been demonstrated here, opens up possibilities of constructing an integrated optics chip based on cavity QED.

6115-46, Session 13

Exciton dephasing in strain-compensated self-assembled InAs quantum dots

J. Ishi-Hayase, K. Akahane, N. Yamamoto, National Institute of Information and Communications Technology (Japan); M. Kujiraoka, National Institute of Information and Communications Technology (Japan) and Sophia Univ. (Japan); K. Ema, Sophia Univ. (Japan); M. Sasaki, National Institute of Information and Communications Technology (Japan)

Semiconductor quantum dots (QDs) have recently been attracting a lot of attentions because of their many novel device applications to photonics and quantum information technologies. Exciton dephasing in QDs plays a crucial role in these applications. In this work, we have investigated the exciton dephasing in strain-compensated self-assembled quantum dots (SAQDs) by using a femtosecond four-wave-mixing (FWM) technique. We observed long-lived coherence of excitons at the excitation wavelength ranging from 1.38 μm to 1.50 um which are suitable for the optical-fiber communication.

A used sample is a layer-stack of InAs SAQDs embedded in InGaAlAs grown on InP(311)B substrate fabricated by molecular beam epitaxy. By using a novel strain-compensating technique, the resonant wavelength of exciton ground state (GS) can be tuned to the optical telecom-fiber communication wavelength. We measured time-integrated FWM signal as a function of time delay between incident pulses in the two-beam self-diffracted geometry. At 6 K, FWM signal attributed to the exciton GS exhibits a long decay time corresponding to the dephasing time of exciton of subnanosecond. We also analyzed the excitation intensity and the temperature dependence of FWM signals and discuss roles of exciton-phonon and exciton-exciton interactions in the dephasing process. Our results clearly indicate that pure dephasing process considerably contributes to the exciton dephasing even at low temperature. Moreover, we discuss an optical anisotoropy and fine structure of bright excitons by analyzing a polarization dependence of FWM signals.

6115-47, Session 13

Cavity-QED effect on nonlinear spectra via biexciton of a quantum dot

H. Ajiki, H. Ishihara, Osaka Univ. (Japan)

A microcavity embedding a quantum dot has been considered to be a promising candidate to achieve strong optical nonlinearity. The resonant frequencies exist at those of the levels in the Rabi splitting if the exciton states can be described by a two-level system. The resonant conditions are derived from the semiclassical treatment. In a four-level system including a biexciton state, however, a cavity QED effect manifests itself at resonant frequencies of applied fields. This fact has been demonstrated experimentally for the four-wave mixing of a quantum well in a cavity. Thus the cavity-QED treatment is indispensable to study the optical nonlinearity through the biexciton state.

In this paper, the cavity-QED treatment is employed to investigate the pump-probe spectra of the four-level system in the cavity. The prominent four peaks appear in the pump-probe spectra when the energy of the pump field is tuned to the lower level in the Rabi splitting. Among the four spectral peaks, two peaks originate from the nonlinear processes associated with the biexciton. We shall show the spectral intensity as a function of the coupling constant, binding energy of the biexciton, and the cavity Q factor extensively, and explore the optimal condition to achieve strong nonlinearity of the system.

The hyper-Raman process via biexciton state is one of the methods to generate correlated two photons, and the cavity system would enhance the efficiency. The present study would be helpful to speculate the resonant condition for the entangled two-photon generation.

6115-89, Session 13

Dephasing effect of single In0.4Ga0.6As QD exciton with interaction between QDs

T. Kutsuwa, H. Gotoh, H. Kamada, NTT Basic Research Labs. (Japan); J. Temmyo, Shizuoka Univ. (Japan); H. Ando, Konan Univ. (Japan)

Semiconductor quantum dot excitons have been attracting considerable attention as possible candidates for the fundamental elements of quantum technology.

In a homogeoneus system, the source of exciton dephasing are either pure dephasing or population decay. We study the dephasing effect of the interaction between surrunding dots on the single quantum dot exciton dephasing process.

To study the exciton dephasing effect of the surrounding dot excitation, we have chosen two types of quantum dots in different enviroments, one is well isolated and other surrounded by other dots. The dynamics of the spontaneous emission in terms of the decoherence was measured by auto-correlation function of a single dot exciton luminescence using Michelson interferometer. The envelope curve of a QD which is surrounded excited dot excitons has a non exponential function, wihch can be fitted a gaussian cuuve. It is suggested that the long-term interaction with the surrounding dots results in single dot emission broadening.

The most probable cause is the Coulomb interact ion between the QD exciton and the charged carriers in the nearby QDs.

6115-74, Poster Session

Ultrafast lasing dynamics in ZnO nanolasers

J. K. Song, Univ. of California/Berkeley

The ultrafast lasing dynamics of single zinc oxide nanotetrapods and nanowires are investigated by two-color femtosecond excitation/optical injection spectroscopy. The transient spectral gain induced by time-delayed optical injection pulses is used to investigate the spectrally- and temporally-resolved lasing properties in a single tetrapod or nanowire laser. The lasing output pulse exhibits a faster lasing decay time than the carrier decays due to the superlinear dependence of the lasing on the carrier density. The change in lasing dynamics as a function of wavelength is affected by band gap renormalization, since lasing in the electron-hole plasma regime depends not only on the carrier density, but also on the band gap shift with carrier density.

6115-75, Poster Session

A simple analytic approach to understanding semiconductor quantum dot lasers

P. Rees, Univ. of Wales Swansea (United Kingdom); H. D. Summers, Cardiff Univ. (United Kingdom)

Semiconductor quantum dot lasers offer significant advantages over traditional quantum well laser diodes. However the advantages due to the discrete density of states of a structure confined in three spatial dimensions are usually not fully realised because of problems associated with the capture of carriers into the discrete electronic states. In this paper we use a simple rate equation model to identify the processes which limit the performance of a quantum dot laser. This simplistic approach while lacking the rigor of more complex models allows us to develop an under-

standing of how the properties of the quantum dot electronic states effect the operation of a semiconductor laser.

The existence of a thermal Fermi-Dirac distribution of carriers is shown to exist only when there are no recombination processes (either radiative or non radiative). In a quantum well laser the rate of thermalisation is much faster than the loss processes and therefore the distribution appears to be close to Fermi-Dirac however in a quantum dot structure the capture/escape rates can act to cause the carriers to form a non thermal distribution.

The interplay of the radiative recombination and capture and escape rates in the dots is shown to define the mode of operation of the laser. The rate of carrier escape from the quantum dot compared with the spontaneous recombination rate at lasing threshold is shown to determine whether the carrier population is coupled and the laser operates in single mode.

6115-76, Poster Session

Optimization study on active layers and optical performance for 1.3-um AlGaInAs and InGaAsN semiconductor lasers

Y. K. Kuo, S. H. Yen, M. W. Yao, National Changhua Univ. of Education (Taiwan)

Semiconductor laser emitting at 1.3 μm is of interest for optical interconnections and optical fiber communications. In addition to the traditional InGaAsP/InP multiple quantum-well lasers, the AlGaInAs/InP and InGaAsN/GaAs material systems have received much attention in the past few years due mainly to their relatively high band-offset ratios. In this work, the peak material gains of 1.3-μm InGaAsP/InP, AlGaInAs/InP and InGaAsN/GaAs semiconductor material systems are numerically studied with a LASTIP (abbreviation of LASer Technology Integrated Program) simulation program. Simulated results show that the AlGaInAs and InGaAsN material systems have better gain performance and smaller transparency carrier density than InGaAsP (InAsP) material system has. It is found that, among the three material systems under study, the InGaAsN material system has the smallest transparency carrier density and the highest peak gain when the carrier density is small while the AlGaInAs material system has the best performance when the carrier density is high. The simulated results also indicate that, with the use of a p-type AlInAs electron stopper layer which is located between the active region and the p-type graded-index separate confinement heterostructure layer, better temperature dependence of slope efficiency in the operating temperature of 298~358 K can be obtained for the ridge-waveguide AlGaInAs/InP laser structure. Moreover, with the use of a strain-compensated active region consisting of InGaAsN/GaAsN, better laser performance and stimulated emission characteristics can be achieved for the ridge-waveguide InGaAsN/GaAs laser structure. Optimization study on active layers and optical performance for 1.3-μm AlGaInAs and InGaAsN semiconductor lasers will be attempted.

6115-77, Poster Session

Self-mixing modulation of semiconductor laser wavelength for detection of motion direction

K. T. Ma, C. K. Li, V. Chiu, M. Yen, W. Wang, K. Lee, BenQ Corp. (Taiwan)

Wavelength of a semiconductor laser is modulated to create the undulation wave using the self-mixing effect. The number of undulations is added to the pulses of Doppler frequency shift generated by moving object that determine the moving direction from the difference between the rising and falling counts of a triangular modulated wave. A theoretical model is proposed to relate the wavelength modulation and number of undulation for a given modulated current based on experimental result. It is very useful for tuning a reliable undulation to judge the moving direction of object.

6115-78, Poster Session

Characterization of the noise spectrum of laterally coupled diode lasers

H. Lamela, R. Santos, C. Roda, P. Acedo, Univ. Carlos III de Madrid (Spain)

In nowadays communications there is an increasing demand of new semiconductor laser devices and structures that somehow overcome the intrinsic bandwidth limitation of laser diodes. In order to give a possible solution to this problem, laterally coupled diode lasers have been proposed. These devices exhibit a second resonance frequency beyond the intrinsic relaxation oscillation frequency and its use as a communication channel has been proved.

The mechanisms that induce the existence of this new resonance frequency have been previously studied, and it is known that it is related with their emission spectrum, since the frequency separation of the fields emitted by each one of the laser ridges is the same of the second resonance [1]. The second resonance also depends in the separation between the laser waveguides and the relative bias applied to the device. This dependence was reported previously where it was demonstrated that these devices present different operation regimes, characterized by the phase relation between the fields emitted by each one of the ridges [2].

The study of noise spectrum, in particular of the RIN, in semiconductor diodes lasers is a powerful tool to determine the proper frequencies [3] and the operation regimes [4] of the device. Following this a study of the RIN is of major importance to characterize these devices.

In this work a study of the noise spectrum dependence with the lateral separation between waveguides as well as its dependence with relative bias applied is made. These results combined and compared with spectrally resolved near and far field allows the definition of whether the device is operating in a locking or beating regime.

1 - H. Lamela, B. Roycroft, P. Acedo, R. Santos, and G. Carpintero, “Experimental modulation bandwidth beyond the relaxation oscillation frequency in a monolithic twin-ridge laterally coupled diode laser based on lateral mode locking”, Optics Letters, vol. 27, no 5, March 2002

2-“Influence of the relative bias current injection in the coupling of twin stripe diode lasers” H. Lamela, R. Santos, G. Carpintero, P. Acedo, Spie Proceedings 5722. January 2005

3-“Ultra-high speed semiconductor lasers”, Kam Lau; Yariv, A.; IEEE Journal of Quantum Electronics, Volume 21, Page(s):121-138, Issue 2, Feb 1985

4-“Noise analysis of injection-locked semiconductor injection lasers” Schunk, N.; Petermann, K.; IEEE Journal of Quantum Electronics, Volume 22, Issue 5, Page(s):642 - 650, May 1986

6115-79, Poster Session

Frequency stabilization of laser diode light-sources in satellite-to-satellite laser interferometers

S. Maehara, Y. Kurosaki, T. Sato, M. Ohkawa, T. Maruyama, Niigata Univ. (Japan); T. Yoshino, H. Kunimori, M. Hosokawa, H. Ito, Y. Li, S. Nagano, National Institute of Information and Communications Technology (Japan); S. Kawamura, National Astronomical Observatory of Japan (Japan)

Still in the initial stages of development, the present endeavor aims to use a satellite-to-satellite tracking laser interferometer-based optical technique in stead of the microwave based technique, to prove that fluctuations in earth’s gravity field reflect ongoing changes in its environment, for example the rises in sea level brought about by polar ice-melt or the redistribution of groundwater on land. This system must be able to measure infinitesimal variations in the relative velocity of satellites flying in tandem, sharing the same orbital path, at better than 10 nm/s in averaging time from 1 s to 100 s. The constraints placed upon the system will ultimately require that the interferometer’s light-source be small, lightweight, ex-

tremely efficient and durable, and possess frequency stability better than 10 13 in the square root of the Allan variance.

While several candidate lasers show promise in certain areas, such as the Nd:YAG laser, the laser diode and the fiber laser, the laser diode has almost all characteristics except for frequency stability, which is the most critical one as the light-source of this system. We are therefore focussing on the problem, the stabilization of the laser diode oscillation frequency. We are currently able to obtain the frequency stability, approximately 10 12 at 40 s averaging time, using the Rb saturated absorption signal.

6115-80, Poster Session

Improving by simulation the pattern dependence response of a semiconductor optical amplifier wavelength converter using a fiber Bragg grating

M. de Pinho Alho, Jr., M. T. M. Rocco Giraldi, Instituto Militar de Engenharia (Brazil)

All-optical wavelength conversion using cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA) is one of the simplest and most common techniques to perform such operation. However, the finite gain recovery time of the amplifier causes severe distortion and pattern dependence at high bit-rates. Through simulation, the present work shows that it is possible to reduce the pattern dependence using a fiber bragg grating (FBG) operating on its transmission edge, at the output of the SOA. The use of a FBG after the SOA improves the wavelength converter modulation bandwidth.

The SOA+FBG system can effectively reduce and even eliminate pattern dependence of a NRZ signal at 10 Gbit/s. The reason for such phenomenon is that a fiber Bragg grating converts the chirp impressed on the probe signal into amplitude modulation which can be appropriately used for correcting the distorted signal.

The present work demonstrates by means of simulation that improvements can be achieved in a XGM-converted signal in a SOA due to the use of a fiber Bragg grating. The enhancement is observed in the pattern dependence of the converted signal, which are reduced. Simulations results also demonstrate improvement on the BER for the converted signal at 10 Gbit/s.

6115-81, Poster Session

Modeling of electroluminescent structures based on variable-gap semiconductors

B. S. Sokolovsky, R. M. Kovtun, V. K. Pysarevsky, Ivan Franko National Univ. of L'viv (Ukraine)

The paper theoretically investigates the electro-lumi-nescent properties of structures based on variable-gap semiconductors with linear coordinate dependence of bandgap. Ohmic and blocking contacts are assumed to be provided at the narrower- and wider-gap faces of the structure, respectively. It has been studied in detail the case of homogenously doped n-type variable-gap structures characterized by large magnitude of the light absorption coefficient. By taking into account quasielectric field occuring in these structure the spatial charge carrier redistrubution caused by electric current has been found what allowed to calculate the spectral and integral intensities of radiative carrier recombination. In the proposed variable-gap structures depending on the current direction positive or negative electroluminescence of wide spectral range has been shown to be observed. Electroluminescent properties of variable-gap structures with and without blocking contact differ substantially. Firstly, in the structures with blocking contact at their wider-gap face the spectra of positive and negative electroluminescence extend in the region of photon energies exceeding maximum value of the structure's bandgap. Secondly, the presence of blocking contact gives rise to increasing the intensity of positive electroluminescence in the whole spectral range, especially in its short wavelength part. The modeling carried out has shown that the integral intensity of electroluminescence can be significantly larger in comparison with the case of the structure with two ohmic contacts. Numerical results are presented for the case of HgCdTe variable-gap solution which is a promising material for creation of IR sources.

6115-82, Poster Session

Photoluminescence refrigeration in semiconductors

J. B. Wang, D. Ding, S. Q. Yu, S. R. Johnson, Y. H. Zhang, Arizona State Univ.

The most commonly used solid-state refrigerator is the Peltier thermoelectric cooler, which can only achieve a limited temperature differential and can not be effectively operated below 200K. Therefore it is highly desirable to develop new solid-state refrigeration technologies that have a greater temperature differential and a broader temperature operating range. Recently, a novel cooler has been successfully demonstrated using photoluminescence up-conversion in doped glass pumped by a solid state laser. However, it is difficult to integrate this device with other devices in its present form. In most practical applications, such as infrared sensors and low-noise electronic circuits, the devices needed to be cooled are built with multiple semiconductors. Also, the most efficient pump lasers are semiconductor lasers. It is then very attractive to develop integrated photoluminescence up-conversion coolers using semiconductor materials. In this paper, the rate equations for both carrier density and photon density as well as photon recycling are used to analyze the cooling characteristics of photoluminescence refrigeration in semiconductors. General expressions for cooling efficiency, cooling power density, and the conditions for cooling are derived. The cooling characteristics are evaluated for an intrinsic GaAs slab at room temperature, which shows that sufficiently high quantum efficiency and luminescence extraction are required to realize net cooling. A maximum cooling efficiency of 1.9% and cooling power density of 1.8 x 10^5 W/cm^3 are obtained when the extraction efficiency of the luminescence is close to unity and the pump laser photon energy is close to the energy bandgap of GaAs.

6115-83, Poster Session

Laser cooling with next-generation crystal hosts

W. M. Patterson, A. Mocofanescu, B. Imangholi, D. V. Seletskiy, M. Sheik-Bahae, Univ. of New Mexico; J. Thiede, R. I. Epstein, Los Alamos National Lab.; S. Bigotta, D. Parisi, A. Toncelli, M. Tonelli, Univ. di Pisa (Italy)

We report progress on laser cooling of Yb- and Tm-doped crystals of Barium-Yttrium-Fluoride composition. This crystal host has the potential to outperform established ZBLAN glass technology in optical refrigeration applications because of its lower phonon energy, high transparency at thermal wavelengths, lower thermal emissivity, high thermal conductivity, and very low parasitic (background) absorption. In addition, its superior hardness allows for high quality polishing of the sample faces for mirror deposition. Low absorption, high reflectivity mirrors are used to recirculate pump laser light in a high performance optical refrigerator. Both Yb- and Tm- doped samples cool more than 1 K from room temperature in proof-of-principle, single pass pump experiments. The Tm-doped crystal is excited in vacuum using a 7 W optical parametric oscillator. Approximately 1.5 K of cooling is observed at 1902 nm. The Yb-doped crystal exhibits cooling in room air when pumped with 3 W of Yb:YAG laser light at 1030 nm in a single pass. Because the operating wavelengths are longer, Tm-doped hosts have the potential to cool with approximately twice the efficiency of Yb-doped materials.

6115-84, Poster Session

Single mode criterion for rib waveguides with small cross sections

P. Müllner, R. Hainberger, ARC Seibersdorf Research GmbH (Austria)

The well-known Soref criterion is the standard tool to determine the width

w and depth h of rib waveguide structures with a given thicknesses H to ensure single mode behavior. However, it is only valid for waveguides with large cross sections.

An emerging field of application for integrated optical waveguides is evanescent wave sensing for chemical and biochemical detection. For most of these applications it is essential that the waveguide structure supports only the fundamental modes. In evanescent wave sensing devices, the maximum sensitivity is achieved with core thicknesses that do not fulfill the condition for large cross sections. Therefore, the Soref single mode criterion cannot be used to determine the parameters w and h.

We modify the Soref single mode criterion such that it can be applied also to waveguides with small cross sections. This is verified for highly sensitive silicon on insulator (SOI) rib waveguides with core thicknesses of 100 nm for TE- and 220 nm for TM-polarization, respectively, at a wavelength of 1550 nm by a fully vectorial finite element method (FEM) eigenmode analysis. The criterion enables an efficient design of rib waveguides for wave sensing devices.

6115-85, Poster Session

A scalar coupled-mode theory with birefringence coupling correction for the anisotropic waveguide

Y. S. Qiu, Fujian Normal Univ. (China)

Scalar coupled-mode theory has been widely used for the analysis of the guided-wave devices in optoelectronics and fiber optics. Some significant improvements for scalar theory have been advanced. One of the works that directly influenced our present study is the perturbation approach presented by Miklos Barabas who determinate the propagation constant in anisotropic rectangular waveguide by using approximate variational analysis with anisotropic as a perturbation. In this letter, a coupled-mode formulation based on scalar modes is developed for anisotropy optical waveguide. In the new formulation, the birefringence property of the material is represented as a additional coupling to that due to the refractive-index perturbations. The theory is applied to the direction coupler made of parallel slab waveguides. The numerical results show that the numerical value of the birefringence coupling correction is around ten percent as much as that of the refractive-index perturbation coupling for the special case.

6115-86, Poster Session

Rigorous vectorial coupled-mode theory for the isotropic waveguide under anisotropic disturbance

Y. S. Qiu, Fujian Normal Univ. (China)

We present the rigorous vector coupled-mode theory for the isotropic waveguide under anisotropic disturbance based on the Maxwell equations. The equation of the coupling coefficient is related to every element of disturbed dielectric tensor. For the special case of the isotropic disturbances and orthogonal modes, our results reduce to the previously derived solution by Marcuse, in which, the coupling coefficient doesn't include the polarization coupling term introduced by Wei-Ping Huang and cited in lots of papers. The difference between our result and that of Wei-Ping Huang is discussed. As an example, we analyze which one of the terms in the coupling coefficient for the single-mode fiber.

6115-87, Poster Session

Numerical analysis of laterally shifted periodic structures using a modified fitting-based effective medium theory

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

In this work, a new approach is introduced to obtaining effective permittivities of general periodic structures that possess lateral shifts which a conventional effective medium theory (EMT) has failed to describe due to the homogenization. Effective permittivities are found by numerically fitting the reflectance characteristics based on Fresnel's coefficients to those from rigorous coupled wave analysis for fundamental layers in the direction orthogonal to the propagation at normal incidence. This fitting approach has been shown to provide valid results that are consistent with experimental data. Even with some variations in design parameters such as grating depths and angles of incidence and in the presence of lateral shifts in structure, more accurate modeling of a periodic structure is possible. Feasibility of the approach is studied by applying it to the calculation of effective permittivities of two- and three-dimensional photonic crystal structures with lateral shifts. It is anticipated that the approach improves the accuracy and benefits the calculation speed as the number of layers is increased. Optical characteristics of an arbitrary physical structure homogenized through conventional second-order EMT equation and fitting-based EMT have been compared to quantitatively depict the difference. A more precise optical analysis based on the fitting-based modified EMT is expected to be an effective tool when analyzing photonic crystals as well as other periodic devices with lateral shift.

6115-88, Poster Session

Timing jitter in dispersion-managed soliton transmission systems

M. F. Ferreira, M. H. Sousa, Univ. de Aveiro (Portugal)

Transmission control in optical soliton communications is quite effective for extending transmission distance by stabilising the soliton pulse against various perturbations (1). Control methods such as the use of guiding filters (with its frequency fixed or sliding) (2) and synchronous modulation (3) were studied not only to stabilise the signal pulse but also to eliminate low-power noise; thereby it is expected that long-distance transmission will be achieved with a large signal-to-noise ratio maintained. In systems using dispersion-managed solitons, such control methods may not be needed because of the enhanced pulse energy and reduced Gordon-Haus timing jitter of such systems (4). However, transmission controls which make use of the nonlinear nature of the pulses are still an effective and natural means to improve the performance of DM soliton systems (5).

An interesting feature of soliton pulse propagation in DM systems in contrast to constant-dispersion systems is that the spectral as well as temporal widths of the pulse are not constant along the fiber. The dynamics of the pulse cause the stability of DM soliton propagation to be dependent on the location of the control devices. As optimization of transmission performance requires lengthly numerical simulations, it is desirable to develop simple analytical procedures that allow one to predict the characteristics of pulse propagation. Moreover, analytical methods let one discern the physical nature of the mechanism that leads to instabilities.

By using a variational analysis, we analytically study in this paper soliton pulse stability and timing jitter in optical transmission systems with periodic variations of power, chromatic dispersion, and the periodic insertion of lumped narrow-band filters and synchronous amplitude modulators (6). We show that, unless the compensating fibers and inline filters are properly arranged, regenerated DM solitons are subject to instabilities that lead to growth of initial small-amplitude or timing fluctuations with distance. Moreover, an appropriate positioning of the modulators in the dispersion map can stabilize in some cases the propagation of DM solitons without simultaneous use of bandpass filters. In the absence of filtering and modulators, the timing jitter of DM solitons shows a cubic growth with distance. However, the jitter is reduced relatively to the uniform dispersion case by the power enhancement factor and it can be further sup-

pressed by reducing the average dispersion. We derive an exact analytical expression for the variance of timing jitter of DM solitons controlled by filters and/or synchronous amplitude modulators. Under these control techniques, the timing jitter shows a linear growth for large transmission distances. Moreover, we show that a complete suppression of the timing jitter can be achieved for a given value of the modulator strength, which depends on the exact position of the modulator in the dispersion map.

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6115-62, Session 14

Modeling of (GaIn)(NAs) and related laser media

I. Kuznetsova, A. D. Thraenhardt, C. Schlichenmaier, S. W. Koch, Philipps-Univ. Marburg (Germany); J. Hader, Univ. of Arizona and Nonlinear Control Strategies, Inc.; J. V. Moloney, Univ. of Arizona

(GaIn)(NAs) lasers of different material composition are considered with respect to their gain properties and radiative losses. Rather than relying on phenomenological parameters, we use a microscopic theory based on the semiconductor Bloch equations. Carrier-carrier and carrier-phonon scattering are treated in second Born and Markov approximation. The only input consists of band structure parameters which can be taken from the literature or determined by independent experiments.

The theory is shown to realistically model experiment by comparison to gain measurements. Inclusion of nitrogen is found to have a considerable influence on the gain and refractive index not only from the point of view of a shifted transition wavelength, but also by reducing the differential gain and refractive index. This results from the nitrogen-induced changes especially in the conduction band structure which are modelled by band anticrossing. Introduction of nitrogen hardly affects the linewidth enhancement factor due to the balancing between gain and index changes.

Radiative losses of different laser structures are calculated using the semiconductor luminescence equations. We find the radiative decay time to vary over several orders of magnitude depending on structural parameters.

One commonly assumes the radiative decay time to be proportional to the inverse carrier density, which, however, the microscopic calculation only confirms for low densities. Above the lasing threshold, the radiative decay time is found to become independent of density due to the change from a Boltzmann-like carrier distribution to a degenerate Fermi distribution where the density at low electron momenta is close to unity and hardly changes with increasing carrier density.

6115-63, Session 14

Beyond the ABC: Carrier recombination in semiconductor lasers

J. Hader, Univ. of Arizona and Nonlinear Control Strategies, Inc.; J. V. Moloney, Univ. of Arizona; S. W. Koch, Philipps-Univ. Marburg (Germany)

A fully microscopic model is used to calculate the density- and temperature-dependence of carrier losses in semiconductor lasers due to spontaneous emission and Auger recombination.

The model is based on generalized quantum Boltzmann type scattering equations in the second Born-Markov approximation. It has recently been shown[1] to give excellent quantitative agreement with the experiment for both these loss processes.

The only input the model requires are, besides the structural information about layer widths and materials, basic bandstructure and material parameters that can be found in the standard literature. Thus it is fit-parameter free and truly predictive.

It is demonstrated that the usually assumed density dependencies, BN^2 and CN^3, for spontaneous emission and Auger recombination processes only hold for carrier densities below threshold. For higher densities, phase space filling reduces the density dependence of spotaneous emission losses to only linear in the density, BN. Predominantely Phase space filling, but also Coulomb screening and carrier leakage reduce the density dependence in the high density regime to only about quadratic, CN^2, or even less. The error of the simple power laws is shown to be typically already a factor of two or more at transparency, and can easily reach an order of magnitude for higher densities.

The temperature dependence of the spontaneous emission losses is shown to decrease significantly with increasing density. For very high densities these losses become almost temperature independent. For Auger recombinations it is demonstrated that phase space filling and the corresponding changes in the predominant selection rules of participating states can lead to the unusual effect of losses that decrease with increasing temperature.

1 J. Hader, J.V. Moloney, and S.W. Koch, accepted for publication in IEEE J. Quantum Electron, June 2005.

6115-64, Session 14

Single-lateral-mode broad-area laser diodes by thermally profiled lateral refractive index: Modeling and simulation

J. Mukherjee, J. G. McInerney, National Univ. of Ireland/Cork (Ireland)

We propose here a method of achieving single lateral mode field patterns in broad area laser diodes. The method relies on laterally profiling the thermal conductivity of the bonding solder layer and thereby thermally controlling the lateral index in these devices.

In conventional broad area laser diodes, a Gaussian near field pattern is not obtained and the far field pattern contains multiple peaks, which can be related to self-focusing and filamentation and which are undesirable for many applications. In this paper we use a steady state thermal model to show that for these wide stripe devices the lateral mode guidance deteriorates even further due to temperature induced index anti-guiding. This occurs because the temperature of the active region is lower than that of the passive regions, due to a high thermal resistance path offered by the insulating SiO2 layer compared to that below the gain region in a p-down bonding configuration. As the change in refractive index is proportional to temperature, positive index guiding can be realized if the thermal conductivity of the solder layer is profiled so as to increase preferentially the temperature under the gain region.

Our 2D FEM thermal model takes into account the effect of current spreading on the temperature profile in the device by self-consistently solving Laplace's equation for the electrical conduction coupled, with the heat conduction equation. Active layer heating due to nonradiative recombination and partial reabsoption of radiation has been considered. Joule heating and radiative transfer of spontaneous radiation through the passive layers have also been taken into account.

The simulation shows that a negative (inverted) Gaussian thermal conductivity profile of the bonding solder, centered at the active stripe, is capable of thermally profiling the lateral index in the device so that positive index guiding can be achieved for the lateral modes. Our results suggest that fundamental lateral mode operation of conventional broad area laser diodes can be achieved at high power levels using this technique. The method should be particularly well suited to laser materials that are highly temperature sensitive, such as InP/GaInAsP and InAs/GaAlAs quantum dots.

6115-65, Session 14

Novel approach for efficient mid-infrared coherent emitters based on continuously phase-matched 'W' optical waveguide

Z. Jin, N. Tansu, Lehigh Univ.

Compact mid-infrared (mid-IR) coherent emitters capable of continuous-wave (CW) operation at room temperature are important for biological- and chemical-sensors, and military applications. The type-II GaSb laser has limitation of the less-mature GaSb technology, and its maximum operation temperature for mid-IR CW lasers is still limited to 220 K. Mid-IR InP-based quantum well (QW) intersubband lasers had been recently demonstrated for CW operation at room temperature. However, QW intersubband laser requires relatively-complex epitaxy and processing steps, and its reliability under CW operation at high temperature is still an issue.

In this work, we present a novel approach for achieving semiconductor-based mid-IR coherent emitters by implementing the continuously-phase-matched difference frequency generation (DFG) nonlinear process of two near-IR lasers in our novel 'W' optical waveguide, resulting in efficient generation of coherent mid-IR radiation. The DFG frequency conversion utilizes W-waveguide, which is formed by conventional GaAs-AlGaAs semiconductor material system. By maintaining continuous phase matching in our W-waveguide, coherent CW power of 1.9mW at wavelength of 4.77μm is achievable at room temperature based on the DFG process of 0.92μm and 1.14μm incident waves with input power of 0.8W. The multi-layered structure of W-waveguide can readily be grown by metalorganic chemical vapor deposition (MOCVD), and the photonic integration of the near-IR lasers and the nonlinear frequency converter is achievable by utilizing the selective-area intermixing and selective-area MOCVD epitaxy. The tunability and optimization of this W-waveguide approach for efficient mid-IR coherent emitter at 4.77μm will also be discussed.

6115-90, Session 14

Numerical studies of effective masses and optical gain in InGaAsN quantum-well structures with self-consistent effects

M. S. Wartak, P. C. Weetman, Wilfrid Laurier Univ. (Canada)

The k.p and envelope function methods were widely used to study conventional III-V semiconductor heterostructures. They have been successfully applied to study quantum well (QW) based structures. Those efforts were mostly motivated by enormous potential applications of those structures in optoelectronic industry. In the case of semiconductor lasers, their continued performance improvements were jointly based on advances in material growth technologies, applying new materials and a theoretical understanding of a new generation of devices based on quantum wells. The progress resulted in improvements in such parameters as low-threshold current, high-speed direct current modulation, ultrashort optical pulse generation, to name just a few.

Hole effective masses are among the important parameters needed to properly characterize any particular device. Systematic numerical analysis for InGaAs/InGaAsP material system has been conducted and results were reported for a large range of material parameters and quantum well widths.

In the submitted work, systematic analysis of the electrostatic effects on the effective masses of holes and optical gain in quantum-well structures were determined and analyzed. A 10-band k.p Hamiltonian matrix was used in the calculations and solved self-consistently with the Poisson equation. Numerical results have been presented for a large range of material and structural parameters. Our results show that significant variation in the effective masses is possible by adjusting the relevant parameters and that the effects due to self-consistency are small.

6115-66, Session 15

Electromagnetic modeling of organic light-emitting devices

H. C. Chen, J. H. Lee, C. C. Shiau, Y. W. Kiang, C. C. Yang, National Taiwan Univ. (Taiwan)

We develop a rigorous and efficient numerical method for simulating the radiation from an organic light-emitting device (OLED) based on general electromagnetic theory. This method can be used to simulate the optical performances with different glass substrate thickness ranging from less than one micron to hundreds of microns. When the glass substrate becomes thinner, a multi-peak spectrum of an OLED is observed due to the strong interference between the signals reflected from the two facets of the glass substrate. The input parameters of the simulation program include the layer thickness, the real and imaginary parts of refractive index of each layer, the position and amounts of the oscillating dipoles, and the photoluminescence spectrum of the emitting layer. The outputs of this program include the radiation spectrum, the intensity and viewing angle of the OLED. From the simulations, we also find that the cathode metal material in an OLED plays an important role which may shift the radiation spectrum and change the optical intensity distribution. The simulation results show similar trends to experimental data.

6115-67, Session 15

Optimized photonic crystal GaN LEDs with tailored guided modes and Archimedean lattices

C. Weisbuch, Ècole Polytechnique (France); A. David, Univ. of California/Santa Barbara

We relate the currently limited efficiency of photonic crystal (PhC)-assisted GaN LEDs to unextracted guided modes. To remedy this, we use structures which modify the distribution of guided modes. We fabricate such LEDs and the tailored PhC band structure is evidenced experimentally. We also use Archimedean lattices to reach isotropic PhC diffraction. We investigate theoretically the perspectives of these improvements, which significantly enhance the potential for light extraction by PhCs.

6115-68, Session 15

Simulation and fabrication of nitride-based moth-eye light-emitting diodes from UV to red region

M. Nakashima, H. Kasugai, A. Deguchi, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan)

Nitride-based LEDs having Moth-eye structure, which shows high-light extraction efficiency was strictly simulated by RCWA method. Experiments have been done to fabricate Moth-eye structure using EB-lithography, laser interference and self-organized nano-mask methods. Details of the effect of Moth-eye structure will be presented.

6115-69, Session 15

Accurate modeling of gain and amplified spontaneous emission in super-luminescent LEDs

M. Loeser, F. Römer, M. Luisier, V. Laino, B. Witzigmann, ETH Zürich (Switzerland); L. Occhi, C. Velez, Exalos AG (Switzerland)

This paper describes a novel model that simplifies the design procedure of next-generation multi-quantum well super-luminescent LEDs (SLEDs). As various applications demand features such as high output power, broad spectral width, and short coherence length, efforts are being made to match all of these needs at the same time.

This new model is designed as an extension of the existing software tool DESSIS, permitting multi-dimensional analysis of active semiconductor devices with ridge structure.

To achieve maximum accuracy the following bottom up approach is chosen: in a first step state-of-the-art kp- and many-body models are utilized for band structure and gain calculations in a single quantum well.

Then microscopic transport equations are employed to account for possible carrier non-uniformities in multiple quantum wells. Based on these findings an accurate model describing the amplified spontaneous emission (ASE) is introduced. Special focus is put on the model's ability to account for non-linear effects, e.g., lateral spatial hole burning.

The model's validity is shown by comparison with measurements. In a first step, the calculated optical gain is compared to Hakki-Paoli gain measurements. Second, the computed and measured spectrally resolved output power are compared. In both cases, the agreement is very good.

This model provides two novel features: first, it allows to investigate and predict the impact of carrier non-uniformities on both gain and ASE spectrum. Second, it provides a tool that can be used at early design phases to maximize output power and spectral width. As these demands are contrary the new model helps to counter-balance these two effects and come up with optimal designs.

6115-70, Session 16

On the dynamics of rapidly tuned ring semiconductor lasers

A. Bilenca, S. Yun, G. J. Tearney, B. E. Bouma, Harvard Medical School

Rapidly-swept ring-cavity semiconductor lasers have received considerable interest for their applications to optical frequency domain imaging. The high small-signal gain, broadband gain spectrum and fast gain response of semiconductor materials allows the use of a variety of intracavity filter configurations to provide a large tuning range and rapid sweep repetition rates (>10 kHz) without spurious relaxation oscillations. Recent experiments have shown that the output characteristics of a semiconductor swept laser varied depending on the wavelength sweep direction [Yun et al., IEEE PTL 2004;16:293]. We have initially attributed this phenomenon to four wave mixing (FWM) mediated by the semiconductor gain medium, however detailed understanding has been lacking. In this talk, we present the results of our theoretical and numerical investigations on the dynamics of the semiconductor swept laser which are in good agreement with experimental data. Using a traveling-wave Langevin model of a semiconductor optical amplifier (SOA) [Shtaif and Eisenstein, IEEE JQE 1996;32:1801], we examine the output power and instantaneous linewidth of the swept laser as a function of the alpha parameter, tuning speed, filter bandwidth, and cavity length. In particular, we show that FWM-induced index modulation as well as self-phase modulation (both associated with the alpha parameter) causes a spectral red-shift of the intracavity light, thereby facilitating unidirectional high-speed sweep operation. We also demonstrate a universal relationship between the output power and the wavelength shift per roundtrip, revealing the advantage of a short cavity for high speed tuning.

6115-71, Session 16

Monolithically integrated twin ring diode lasers with quantum-dot active region

H. J. Cao, CHTM/Univ. of New Mexico; A. L. Gray, Zia Laser, Inc.; L. F. Lester, M. Osiński, CHTM/Univ. of New Mexico

No abstract available

6115-72, Session 16

Influence of straight waveguide back reflection in the dynamics of semiconductor microring lasers

S. S. Mikroulis, I. G. Stamataki, E. Roditi, D. Syvridis, Univ. of Athens (Greece)

Semiconductor ring lasers are ideal candidates for optoelectronic integrated circuits (OEICs) due to the absence of cleaved facet, which makes the fabrication easier to be realized, while being ultracompact. Recently a multimode model has been introduced based on traveling wave formulation for simulation of the spectral characteristics of large diameter InGaAs/InGaAsP ring lasers. In this paper we apply a multimode model based on rate equation approximation for a dynamic simulation of mode dynamics and noise characteristics under different operation and design characteristics. We include both self and cross-gain saturation effects, with the later including symmetric and anti-symmetric terms. The effect of output facet power reflectivity is studied in detail. We perform a complete characterization of the ring laser dynamics including mode spectra, time traces and relatively intensity noise (RIN) calculations. Different operation regions are demonstrated, single mode, stable multimode, and hopping multimode dependent on the injection current and the straight waveguide reflectivity. The transition point between stable and mode-hopping regimes strongly depends on the straight waveguide reflectivity. When both reflectivities increase at the same value, low-frequency (0-2GHz) RIN remains at low values for higher currents, indicating single mode or multimode stable operation. Both counter-clockwise (CCW) and clockwise (CW) waves have exactly the same behavior. When the reflectivity value of one facet is increased with respect to the other a selectivity of the respective wave occurs combined with improved low-frequency noise characteristics. Concluding, straight waveguide backreflection provides a mode-locking mechanism that can be a useful tool for improved dynamic operation characteristics.

6115-73, Session 16

Spectral properties of all-active InP-based microring resonator devices

A. Kapsalis, D. Alexandropoulos, S. S. Mikroulis, D. Syvridis, Univ. of Athens (Greece); M. Hamacher, U. Troppenz, H. Heidrich, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

Microring resonators are excellent candidates for very large scale photonic integration due to their compactness, and fabrication simplicity. Moreover a wide range of all-optical signal processing functions can be realized due to the resonance effect. Possible applications include filtering, add/drop of optical beams and power switching, as well as more complex procedures including multiplexing, wavelength conversion, and logic operations. All-active ring components based in InGaAsP/InP are possible candidates for laser sources, lossless filters, wavelength converters, etc. Our work is based on measurement, characterization and proposal of possible exploitation of such devices in a variety of applications. We investigate the spectral characteristics of multi-quantum well InGaAsP(λ=1.55μm)/InP microring structures of various ring diameters and different configurations including racetracks with one or two bus waveguides and MMI couplers. The latter configuration has recently exhibited the possibility to obtain tunable active filters as well as tunable laser sources based on all-active ring-bus-coupler structures. In the case of tunable lasers single mode operation has been achieved by obtaining sufficiently high side mode suppression ratio. The tuning capability is attributed to the coupled cavities effect, resembling the case of multi-section DBR lasers. However, in contrast to the latter, the fabrication of microring resonators is considered an easier task, due to a single step growth procedure, although further investigation must be carried out in order to achieve wide range tunability. Detailed mappings of achievable wavelengths are produced for a wide range of injection current values.

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6116-01, Session 1

Progress in non-silica microstructured fibres

T. M. Monro, The Univ. of Adelaide (Australia)

The combination of microstructured fiber designs and improving preform fabrication technologies is allowing rapid progress in the development of new classes of non-silica fibers. Recent progress in the fabrication of soft glass and polymer microstructured preforms and fibres will be described. Emerging soft glass fibers are enabling new fiber operating regimes including efficient supercontinuum generation extending beyond the near-IR and extreme nonlinearity. Recent theoretical and experimental results in these areas will be reviewed.

6116-02, Session 1

Changing gears in glass poling: from second-order nonlinearity to engineering of glass-metal nano-composites

P. G. Kazansky, Univ. of Southampton (United Kingdom)

No abstract available

6116-03, Session 1

Waveguide formation in Nd doped YVO4 using multiple implants

G. V. V·zquez, M. E. Sónchez-Morales, Ctr. de Investigaciones en óptica, A.C. (Mexico); H. Márquez, Ctr. de Investigación CientÌfica y de Educación Superior de Ensenada (Mexico); P. Moretti, Univ. Claude Bernard Lyon 1 (France)

Optical waveguides have been formed by proton implantation in Nd:YVO4 crystals using energies from 0.4 to 1 MeV and doses of the order of 10 to the 16th power ions per square cm. double implants were realized in order to generate wide optical barriers and a triple implant produced stacked waveguides. Waveguide characterization comprises propagation modes, refractive index profiles, near field imaging and spectroscopic properties. differences between the waveguides were found in terms of mode confinement which is important for integrated devices.

6116-04, Session 1

Tellurite photonic crystal fiber for amplifier for broadband optical amplifiers of Er3+-Tm3+ emission around 1550nm band

L. C. Barbosa, E. F. Chillcce, C. M. B. Cordeiro, C. H. Brito Cruz, C. L. Cesar, Univ. Estadual de Campinas (Brazil)

In this work we report the tellurite photonic crystal fiber (PCF) fabrication for broadband optical amplifiers of Er3+-Tm3+ emission around 1550nm band. differently from extrusion method frequently used to produce soft glass PCF, this tellurite PCF were obtained from pre-forms whose geometrical structure is basically regular arrays of capillaries and rods within jacket external tube. The capillaries and the rods were drawing in the Heathway optical fiber tower, from tellurite glass tubes with the TeO2-WO3-Na2O-Nb2O5 oxide compound. These tellurite tubes were produced by centrifugation method. The 187nm maximum broadband emission spontaneous amplified (ASE) was obtained around 1550nm band using 15cm optical fiber length and 790nm wavelength Ti: Sapphire pump laser (400mW).

6116-05, Session 1

Theoretical characteristics of optical polarizing films using oblique metal island films

K. Baba, Sendai National College of Technology (Japan)

An ultra-thin optical polarizing film using a periodic multiplayer consisting of oblique metal island (OMI) layers and glass layers has been investigated theoretically. The OMI films are composed of prolate metal nanoclusters (i.e., islands) inclining to one side. The OMI films are fabricated by using a conventional vacuum evaporation system in which a substrate is inclined at 70-80 degrees. The OMI films exhibit resonance-type absorption in visible and near-infrared 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. Therefore, the multilayer using the OMI films can be used as an optical polarizing films at the resonance wavelength. The resonance wavelength depends on the aspect ratio of the prolate islands, distance between the centers of the islands, and choice of the metal. The extinction ratio and insertion loss increase with the number of the OMI layer. In this work, we calculate the theoretical characteristics of the polarizing films using composed of the OMI layers with ideal and homogeneous film structure. We now show an example of calculated optical losses of the multilayer consisting of 10 OMI layers and 9 glass layers for the polarizations perpendicular (x-polarization) and parallel (y-polarization) to the inclining direction. Silver is chosen as metal. We have assumed that the metal islands have the same inclining angle (30 degrees) and dimensions (longer axis of 100 nm and shorter axes of 20 nm). The distance between the centers of the islands in the films is assumed to be 100 nm. We have also assumed that the thickness and refractive index of the glass layers are 100 nm and 1.5, respectively. At the wavelength of 720 nm (the resonance wavelength for the y-polarization), the optical loss for the y-polarization corresponding to the extinction ratio is evaluated as 30 dB. The optical loss for the x-polarization corresponding to the insertion loss is 0.03 dB. The thickness of the polarizing film is calculated as 1800 nm. When aluminum is used as the metal, the polarizing films for the shorter wavelength can be designed.

6116-06, Session 2

Characterization of fiber Bragg gratings using spectral interferometry based on minimum-phase functions

A. Ozcan, M. J. F. digonnet, G. S. Kino, Stanford Univ.

We report a powerful interferometric measurement technique utilizing Spectral Interferometry using Minimum-phase Based Algorithms (SIMBA) to fully characterize the spectrum (either in reflection or transmission) of any fiber Bragg grating (FBG). This complex spectrum information is crucial to recover several important parameters of an FBG, such as its impulse response or refractive index profile. The core of our approach involves sending an unknown short laser pulse, e.g., ~1-30 ps of temporal width, into the FBG of interest, and using an optical spectrum analyzer (OSA) to record the spectrum of the interference between the reflected pulse from the grating and the time-delayed replica of the original pulse. This measured spectrum, which yields the square of the Fourier transform (FT) magnitude of the pulse sequence's electric field envelope, is then processed to uniquely recover both the phase and amplitude of the FBG spectrum. The underlying principle of our approach is that by design of the experimental set-up, the pulse sequence sent to the OSA is close to a minimum phase function (MPF). Thus, it is possible to recover its FT phase spectrum using only the knowledge of its FT magnitude spectrum. This is an important result since by merely measuring an FT magnitude, with a rather simple set-up the full complex spectrum of the grating can

be recovered. This technique has significant advantages over existing techniques, including a higher resolution, a better noise performance, and the ability to use longer laser pulses. It can also conveniently be used to simultaneously characterize more than one FBG, with a single FT magnitude measurement. We demonstrate the validity of our approach with numerical simulations.

6116-07, Session 2

High-speed interrogation of fiber grating sensor arrays with a wavelength-swept laser

E. C. W. Lee, Massachusetts Institute of Technology and Wellman Ctr. for Photomedicine; S. Yun, W. Oh, B. E. Bouma, Harvard Medical School

Fiber Bragg grating (FBG) sensor arrays have attracted much attention for distributed structural health monitoring, hydrophones, and seismic exploration. Among many interrogation techniques that have been demonstrated, time-domain techniques based on rapidly-swept tunable lasers offer several attractive features such as high signal powers, high spectral resolution, and high readout rates. Recently, we have developed a high-speed wavelength-swept laser and applied it to FBG array sensing with a large frequency range from dC to 18 kHz. Our sensor system consists of a swept laser with a tuning range of 47 nm centered at 1.31 um, multiple sensing and reference gratings, standard InGaAs photodetector, and high-speed digitizer. The single-scan strain resolution was measured to be 4.9 microstrain rms. This corresponds to an excellent dynamic sensitivity of 26 nanostrain/sqrt(Hz) at a readout rate of 36 kHz. This result represents a 10 to 100-fold improvement in readout speed compared to previous demonstrations using similar interrogation techniques. In the talk, we will demonstrate the system's functionality as an optical stereo microphone.

6116-08, Session 2

Tunable optical delay generator for phased array antennas

O. K. Okusaga, W. Zhou, Army Research Lab.; G. M. Carter, Univ. of Maryland/Baltimore County

We present an application of fiber Bragg gratings as tunable optical delays in transmission for use as true-time-delay lines in an RF-Photonic phased array antenna. In most delay line applications fiber gratings have been used in reflection mode and provide only discrete values of time delay. The reflection mode requires the use of bulky and expensive optical circulators. We have designed an optical true time delay array generator using fiber gratings in cascading transmission mode for such applications which significantly simplifies the system and lowers the cost. A wavelength tunable dFB laser is used as the light source. The laser light is modulated by an RF-microwave input signal, then enters into the optical true time delay array generator to provide a sequence of time delays $\Delta\tau$, 2 $\Delta\tau$, Ön $\Delta\tau$. The goal is to obtain a large, and continuously tunable, group delay $\Delta\tau$ with minimal loss by tuning the wavelength of the laser. designing such gratings is challenging because of the strict Kramers-Kronig relationship and fresnel-like reflections leading to rapid oscillations in group delay versus wavelength. We combined an apodized grating profile, large index step and increased grating length to achieve delay lines with sufficiently smooth and large group delays over large bandwidths. We fabricated and tested the grating with about 120mm length which showed a $\Delta\tau$ of at least 36 ps tunable time delay range with reasonable loss. These gratings display properties suitable for use as optical delay lines in a phased array antenna system.

6116-09, Session 3

An hybrid organic-inorganic approach to erbium-functionalized nanodots for emission in the telecom window

A. Q. Le Quang, J. Zyss, I. N. Ledoux-Rak, École Normale Supèrieure de Cachan (France); V. G. Truong, A. Jurdyc, B. Jacquier, Univ. Claude Bernard Lyon 1 (France)

A new class of hybrid materials for efficient laser emission and amplification in the 1.55 μm eye-safe telecommunication window has been designed, elaborated and characterized, based on lanthanide-doped yttrium oxide nanoparticle guests embedded in a polymer host matrix. The average size of these nanocrystals can be finely tuned by controlling the relative quantities of an organic fuel (glycine) with respect to the yttrium- and lanthanide-containing reactants involved in the combustion reaction leading to nanoparticle synthesis.

Two complementary sensitizers have been added to Er/Y2O3 nanocrystals in order to improve the Erbium luminescence efficiency : cerium to increase population inversion between the emitting and the ground state by accelerating the de-excitation process from the 4I11/2 initially uppermost excited state at 980 nm down to 4I13/2 state emitting around 1.55 μm, and ytterbium to improve the pumping efficiency of the material owing to its strong absorption cross section at 980 nm and subsequent efficient energy transfer towards the 4I11/2 state of erbium ion.

Y2O3 nanoparticles with an optimized erbium-ytterbium composition have been incorporated in a PMMA polymer matrix, resulting in a hybrid amorphous material displaying high gain coefficient values (up to 30 cm-1 as from Amplified Spontaneous Emission experiments) upon moderate 980 nm pumping intensities. These materials open attractive perspectives in the domain of polymer-based telecom amplifiers, with the additional asset of multifunctional properties whereby gain originating from the inorganic Y2O3 nanocrystals can be associated to nonlinear responses attached to an adequately functionalized polymer host matrix.

6116-10, Session 3

Er-doped InAlP native oxides on GaAs: photoluminescence characterization and annealing optimization

M. Huang, d. C. Hall, Univ. of Notre dame

Er-doped waveguide amplifiers (EdWA) require high doping levels due to their length limit of a few to tens of cm, making the host selection of great importance to avoid deleterious high concentration effects. The wet thermal oxides of InAlP (lattice matched to GaAs) are phosphate rich, making them an attractive rare earth host for EdWAs where monolithic integration of pump lasers may be possible. InAlP epilayers are partially oxidized in water vapor (4 h, 500°C). Er-implantion (300 keV, 1E15 cm^-2 total dose) performed either before or after growth of the 300 nm thick oxide results in a peak Er concentration of ~1E20 cm^-3. Room temperature photoluminescence (PL) characterization shows broad (61 nm FWHM) emission with a long 8 ms lifetime. We present a comparison of PL characteristics of Er-doped InAlP and AlGaAs native oxides, and results of rapid thermal processor (RTP) annealing studies for host optimization. At 683°C, the 3 sec optimal annealing time for post-oxidation-implanted samples is notably shorter than that of the pre-oxidation-implanted samples (20 sec), indicating less thermal energy is required for Er. A spectral line shape changes are also observed for the post-oxidation-implanted samples when over-annealed due to a local environment change of Er ions in the samples. For both post- and pre-oxidation-implanted samples, PL lifetimes remain near 8 ms after RTP annealing over the entire temperature range of 550 to 800°C, indicating minimal Er clustering and suggesting that even higher Er concentrations, desirable for increased EdWA gain, are possible.

6116-11, Session 3

Optical properties of rare-earth-doped chalcohalide glass-ceramics

V. Seznec, H. Ma, X. Zhang, V. Nazabal, J. Adam, Univ. de Rennes I (France)

Chalcogenide glasses have been intensively studied for rare-earth doping due to their low phonon energy, leading to high quantum efficiency. This high photoluminescence efficiency can still be greatly improved by generating nano crystals inside the glass matrix.

In this study, we will present some results concerning Nd3+ and Er3+ doped glass ceramics based on chalcogenide and alkali halides. Glass ceramics generally show better thermomecanical properties compared to the corresponding glasses, and improve optical properties for rare earth ions.

The studied glasses are from the ternary system GeS2-Ga2S3-CsCl. Large glass forming domain has been found. The base glass composition shows a good stability against crystallization. These glasses show a transparency in the visible (from 450nm to 12000nm), which is very important for pumping consideration.

To obtain highly transparent glass-ceramics, the most critical parameter is the crystal size which is typically less than 50 nm in the present case. We have observed that the luminescence efficiency is much higher for the glass-ceramics than in the base glasses, due to the crystalline field effect and confinement. Furthermore, the structure of emission peaks is well define in the glass-ceramics compared to the base glasses.

6116-12, Session 3

Time resolve spectroscopy and energy transfer in Tm3+- Ho3+ and Tm3+-Tb3+ doped tellurite glasses

A. Jha, S. Shen, Univ. of Leeds (United Kingdom)

The radiative transition in Tm3+-doped fibre at 1.46 μm (3H4 * 3F4) remains a potential route for designing efficient fibre and waveguide amplifiers for the S-band (1420-1520 nm). The transition however suffers from a long metastable lifetime (5 times longer) than the 3H4 level, which means that the 3F4 level must be depopulated rapidly for efficient inversion for laser and amplifiers application. One of the known means so far for depopulation of the lower 3F4 level is via co-doping with other rare-earth ions, essential for modest gain. For the Tm3+- Ho3+ and Tm3+-Tb3+ doped tellurite glasses, the IR static and time-resolve fluorescence spectra and the lifetimes of the upper 3H4 and lower 3F4 lasing levels for 1.46 μm of Tm3+ were measured. The non-exponential decay is fitted using the Inokuti-Hirayama equation. The energy transfer parameter, critical ion distance and non-radiative transfer efficiency between donors and acceptors are compared. The quenching mechanism has been explained. Both the Ho3+ and Tb3+ ions reduce the lifetimes of the upper and lower lasing levels, with Tb3+ ions proving more effective than the effects observed for Ho3+ ions.

6116-13, Session 3

Spectroscopy and frequency up-conversion in KPb2Br5:Nd3+ crystal

R. Balda, Univ. del Pais Vasco (Spain); U. Hommerich, E. E. Nyein, Hampton Univ.; J. M. Fernández, Univ. del Pais Vasco (Spain)

The luminescence of rare-earth (RE) ions has been intensively investigated in different crystalline hosts, due to the important applications in lasers and nonlinear optics. To develop more efficient optical devices based on rare-earths doped materials, hosts with low phonon energies are required. An important advance on the search for new low phonon energy materials has been the identification of potassium lead halide crystals KPb2X5 (X=Cl, Br) as new low-energy phonon hosts for rare-earth ions. These crystals are non-hygroscopic and readily incorporate rare-earth ions. Efficient IR to VIS upconversion in Pr3+-doped and Yb3+- Pr3+-codoped KPb2Cl5, in Er3+-doped KPb2Cl5, and Nd3+-doped KPb2Cl5 has been recently reported by some of the present authors and the mechanisms responsible for these upconversion processes have been investigated. The maximum phonon energy in this crystal is 203 cm-1. Potassium lead bromide crystal KPb2Br5 presents similar properties to KPb2Cl5 but with the advantage of even lower phonon energies, due to the higher mass of the bromine constituent. According to Raman-scattering measurements the maximum phonon energy, measured at the highest energy peak of the spectrum, is 138 cm-1. This lower phonon energy reduces significantly nonradiative decay due to multiphonon relaxation, allowing an increased lifetime of some excited levels that can relax radiatively or can store energy for further upconversion, cross-relaxation, or energy transfer processes.

In this work we present a detailed analysis of the infrared to visible upconversion in Nd3+-doped KPb2Br5 crystal by using both steady-state and time-resolved luminescence spectroscopy. The study includes one photon absorption and emission spectroscopy and lifetime measurements for the visible and infrared fluorescence, and infrared to, blue, green, orange, and red upconversion processes. The possible upconversion mechanisms are discussed in terms of excitation spectra, excitation power dependence, and lifetimes of the upconversion emissions.

6116-14, Session 3

The effect of controlled stretch on the luminescent properties of Eu(III)-complex doped polyvinylidene fluoride film

R. M. Pogreb, The College of Judea and Samaria (Israel); V. G. Lirtsman, The Hebrew Univ. of Jerusalem (Israel)

Poly(vinylidene fluoride) (PVdF) films doped with Europium(III) thenoyltrifluoroacetone-1,10-phenanthroline complex were manufactured using an extrusion technique. Temperature regime was maintained from 160 to 170°C during the extrusion process according to heating zones. Europium content in a films was 0.4 wt.%. Thickness of films was 100-200 μm. IR absorption spectra of extruded films were studied. The peaks of b-phase were revealed in the IR spectra. According to these spectra a suggestion was made that the samples comprise inclusions of the polar b-phase of PVdF dispersed in the apolar a-phase. Time-of-flight secondary-ion-mass spectroscopy showed a uniform distribution of Eu(III) through the film. Excitation and emission spectra of the films were studied. Film was irradiated by 10 nsec pulses from Nd:YAG laser at third harmonic (355 nm). The emission spectrum of Eu(III) with the maximum at about 613 nm on account of 5d0-7F2 transition was detected. Emission spectrum of the Eu (III) complex was compared to the spectra of the same Eu (III) complex dispersed in PVdF and polyethylene (PE) matrices. It was revealed that the impact of the PVdF matrix on the emission spectra was stronger than that of PE matrix. Luminescence intensity was studied depending on controlled stretch of the film both for PVdF and PE matrices. The stretch produced a significant increase of emission intensity for PVdF film and decrease for that of PE film.

6116-15, Session 3

Significant increment of photoluminescence quantum yield by efficiently prohibiting fluorescence quenching in erbium (III) organic complexes

Y. Li, H. Yang, Z. He, L. Liu, W. Wang, F. Li, L. Xu, Fudan Univ. (China)

Optical amplifiers play a significant role in optical communication systems. Er3+ ions are used as the active components in Erbium doped Fiber Amplifiers (EdFAs) and other planar active devices in recent decade. There has been a growing interest in integrated optics and waveguide

devices. Polymer-based materials would have advantages over inorganic materials in this field because of their low costs, flexibility, high packaging density and simple processing steps. Instead of rare earth ion salt, erbium organic complexes will provide the Er3+ ions with the necessary solubility to achieve high concentration in polymeric matrices.

In this work, a systematic investigation and comparison of the photoluminescence (PL) quantum yields of six erbium(III) organic complexes are reported. We confirmed from experimental measurement that the quantum efficiencies of usual erbium(III) complexes are only about 0.02%, too low for practical applications. Evidences of both OH and CH quenching effect on the Er3+ luminescence were given. We demonstrated that the PL quantum yield could be significantly improved by getting rid of OH and CH groups in the complexes. Perfluooctanoic acid with neither OH nor CH groups was used as a ligand to form complex with Er3+ and the quantum yield of the newly synthesized erbium(III) complex was found to be as high as 2%, 100 times higher than that ever reported. We believe that this is the correct way to put erbium(III) organic complex in the position to compete with erbium doped inorganic glasses that have been widely accepted as efficient light amplification and lasing materials.

6116-16, Session 4

The potential of direct nanoparticle deposition for the next generation active fibers

S. K. T. Tammela, V. N. Philippov, M. J. Soderlund, J. J. Koponen, P. J. Stenius, Liekki Oy (Finland)

Fiber lasers offer substantial advantages compared to conventional solid-state lasers due to their high efficiency, compact size, diffraction-limited beam quality, tunability, and facile thermal management. A number of important applications require high peak powers and pulse energies, which has generated great interest in Yb-doped, large-mode-area fibers. Liekki has pioneered a new manufacturing technology for rare-earth-doped fibers, direct Nanoparticle deposition (dNd), that is capable of producing fibers uniquely well suited to power scaling. Conventional fiber fabrication methods are characterized by poor process accuracy and flexibility due to the large particle sizes and relatively small number of deposition layers (2*10). On the contrary, dNd provides independent control of the composition of hundreds of layers that make up the core, thereby allowing previously unattainable precision, accuracy, and uniformity in the index and rare-earth-dopant profiles. dNd allows the simultaneous use of both gas-phase and liquid precursors, providing unprecedented flexibility in the glass composition. Furthermore, dNd enables fabrication of fibers with extremely high rare-earth concentrations, which minimizes the required fiber length and correspondingly raises the threshold power for nonlinear processes. Finally, the single-step, direct-deposition process makes manufacturing of fibers rapid and cost-effective, even for fibers with large core diameters or sophisticated geometries and dopant distributions. dNd fibers have shown high conversion efficiency (low clustering), low photodarkening, and high damage threshold. dNd thus promises to revolutionize the use of fiber lasers in applications previously restricted to bulk, solid-state lasers and to enable new applications of high-power lasers.

6116-17, Session 4

High brightness pumps for fiber lasers

S. H. Keeney, nLight Photonics

No abstract available

6116-18, Session 4

Thulium doped germanate glasses and fibers for 2 micron fiber lasers

S. Jiang, NP Photonics, Inc.

Laser action near 2 micron using the 3F4-3H6 transition of Tm3+ attracted significant attention in the last 20 years due to their wide applications in medicine, LIdAR, and materials processing. Efficient flash-lamp and diode laser pumped laser operation was achieved in Tm3+-doped crystals utilizing the so-called cross-relaxation process. The obvious advantage of this cross-relaxation process is that a single Tm3+ ion excited to the 3H4 level generates two Tm3+ ions in the 3F4 upper laser level. The quantum efficiency of pumping into the 3F4 state is nearly 200%.

This cross-relaxation process was observed in Tm3+ doped silica fiber when the doping concentration reached 2.2wt%. However, the benefit is limited due to the restricted Tm3+ doping concentration in silica fibers. Silica glass fiber is not the ideal host for lasers at wavelength of 2 micron and longer. The output power and the quantum efficiency of Tm3+ silica fiber laser at 2 micron are limited due to the high phonon energy of silica glass and the restricted Tm3+ doping concentration. Germanate glass exhibits lower phonon energy of 900cm-1 compared to silica glass of 1100cm-1, increasing the quantum efficiency of 3F4 level of Tm3+ ions. Importantly, Tm3+ can be highly doped into germanate glasses, which results in cross-relaxation, dramatically improving the quantum efficiency.

This paper reports our study on Tm3+-doped germanate glasses, spectroscopic properties of Tm3+ ions, fiber preparation, and efficient fiber laser demonstration. A slope efficiency of 58% and a quantum efficiency of 170% were demonstrated. To the best of our knowledge, it is the first demonstration of such a highly efficient laser in Tm3+-doped multi-component oxide glass fibers.

6116-19, Session 4

All-optical regeneration based on pump-depletion effect in fiber parametric amplification

A. Bogris, H. A. Simos, d. Alexandropoulos, d. Syvridis, Univ. of Athens (Greece)

In future very high bit rate all-optical networking approaches, all-optical regeneration is a very critical function to cope with the signal degradation caused by noise accumulation, jitter and dispersion. Recently, parametric process relying on four-wave mixing (FWM) in dispersion shifted fibers (dSFs), has been proposed theoretically and demonstrated experimentally as a possible candidate for optical regeneration purposes, where the regenerative properties of the higher-order mixing products are mainly highlighted.

Up to now, pump depletion has been investigated only in terms of the amount of the pump energy that can be transferred to the signal and the idler. The aim of this work is to take advantage of the pump wave characteristics at the output of a single-pump fiber parametric optical amplifier (FOPA) operating under the strong pump-depletion regime. Based on the fact that the input signal intensity modulation is inversely transferred to the pump wave through the depleted parametric process, it is demonstrated that a cascade of two such FOPAs operates as an all-optical nonlinear gate with 2R (reshaping and reamplification) regenerative properties. The proposed scheme is suitable for both return-to-zero(RZ)/non-return-to-zero(NRZ) modulation formats providing also the possibility of no-wavelength conversion. The latter feature makes the proposed device convenient for direct deployment in the existing networks as in-line all-optical regenerator.

Numerical simulations are carried out to demonstrate the operation of the above reshaping technique in a long-haul transmission system. The results prove that the transmission distance for which the signal can be detected at the receiver with acceptable signal-to-noise characteristics is over-tripled in the case that the 2R reshaping device is periodically placed along the transmission link.

6116-20, Session 4

Amplifications S-, C-, and L-bands in RE-ion tellurite glass fibres using 800 nm and 980 nm pump wavelengths

A. Jha, S. Shen, P. V. Joshi, Univ. of Leeds (United Kingdom)

Large solubility of rare-earth ions in tellurium oxide (TeO2) glass hosts,

long lifetimes of lasing levels, and large absorption and emission cross-sections provide a unique opportunity for designing broadband amplifiers, which can be efficiently pumped with semiconductor diode lasers at 800 nm and 980 nm. In this paper, we report the results of emission and amplification in Tm3+- and Er3+-fibres for signal gain in the 1420 nm to 1630 nm region, which covers S-, C- and L-bands of silica fibre networks.

The paper explains the mechanism for alleviating the pump excited absorption in Er-doped tellurite fibres for maximizing the pump efficiency at 980 nm using Ce-ions as a co-dopant and via the structural modification of TeO2 glass using B2O3. The spectroscopic data and gain bandwidth of Er-doped fibres are reported in the C- and L-bands. We also report the results of gain measurements in Er-Tm co-doped fibres when pumped with an 800 nm source. Methods to enhance gain in the S-band using the co-dopants with 800 nm and 980 nm pumping schemes are also explained. To date the measured maximum relative gain in short fibres of 5 to 10 cm in length in C- and L-bands are: 30 dB and 15 dB, respectively. By comparison the internal gain in a 20 cm long Tm/Yb ion co-doped fibre pumped with a 980 nm source was 7 dB.

6116-21, Session 5

Semiconductor photonic integrated circuits for wavelength division multiplexing

A. R. Kost, College of Optical Sciences/The Univ. of Arizona

No abstract available

6116-22, Session 5

High-power distributed Bragg reflector lasers for green-light generation

M. H. Hu, H. K. Nguyen, K. Song, Y. Li, N. J. Visovsky, X. Liu, N. Nishiyama, S. Coleman, L. C. Hughes, Jr., J. Gollier, W. Miller, R. J. Bhat, C. Zah, Corning Inc.

Visible laser emission is of great interest for many applications including projection display, sensing and high-density optical storage. Blue lasers based on GaN material system and red lasers based on GaAs material system have become commercial products. However, semiconductor green lasers have yet to be demonstrated. On the other hand, second harmonic generation (SHG) was commonly used to generate green emission by frequency-doubling the 1060nm-wavelength output from a diode-pumped solid state laser or a semiconductor laser. The use of a semiconductor laser for green-light generation offers various advantages such as low noise, high modulation bandwidth, wavelength tunability, compactness, high efficiency, easy integration, and low cost of manufacturing.

In this paper, we report the results of high-power 1060nm distributed Bragg reflector (dBR) lasers for green-light generation. The design of the dBR lasers utilizes highly-strained InGaAs single quantum well and impurity-free quantum well intermixing technique to create non-absorbing grating and phase sections.

The dBR lasers reported here have a number of desirable characteristics. Single-spatial-mode and single-wavelength power more than 400mW at 1060-nm wavelength was achieved. We also obtained continuous wave (CW) green power of 104.6mW by coupling the dBR laser output to a periodically poled Lithium Niobate (PPLN) SHG waveguide. Both powers are the world-record values of their own categories, to the best of our knowledge. A thermal induced CW wavelength tuning of 2.4 nm was obtained by injecting current into the dBR section.

The combination of a dBR laser and a SHG waveguide is well suited for the systems that require high-speed modulation of the green light, such as portable laser projection displays. Under direct-intensity modulation by modulating the gain-section current, a rise/fall time of 0.2ns and an extinction ratio larger than 50dB were obtained. Under wavelength switching by modulating the dBR-section current, a rise/fall time of 0.5ns and a carrier-induced wavelength shift of -0.8nm were measured.

In the full paper, we will discuss in more details the design, fabrication and the performance of the dBR lasers relevant to the green light generation. In particular, we will show that the temperature variation due to the injection current heating causes both optical beam steering and wavelength shift, which produce a detrimental patterning effect for green-light modulation. We will discuss techniques to overcome the patterning effect.

6116-23, Session 5

Side-coupled in-line fiber-semiconductor modulator

A. Khalili, Stanford Univ.

We propose a novel narrowband in-line fiber modulator that results from evanescent coupling between a side-polished single-mode fiber and an active antiresonant semicondcutor waveguide. We achieved more that 10dB modulation contrast in a 5/125μm singlemode fiber at 853nm by drawing a nominal current through our semiconductor waveguides without terminating the fiber. Compared to the conventional fiber-coupled modulator modules, these devices have much simpler alignment and packaging complexity, and can be monolithically integrated with the other components, e.g. in-line lasers, on the same substrate. Here, we process a custom epitaxial structure, grown by metolorganic chemical vapor epitaxy on a GaAs substrate, to realize antireonant reflecting optical waveguides (ARROW), which are used for narrowband coupling into the side-polished fibers in our setup. The small coupling spectrum of this system can be easily manipulated by applying a bias on the semiconductor waveguides. Generated carriers in the active region quantum wells change the loss characteristics of the ARROW and alter its coupling strength to the fiber, hence modulating the signal that travels inside the fiber. In this paper, we present the theoretical and experimental results related to various performance parameters of these modulators.

6116-24, Session 5

Multimode interference couplers for 2x2 high speed GaAs-GaAlAs electro-optic switches

S. Cao, L. Sun, J. P. Noad, R. James, d. Coulas, G. Lovell, E. Higgins, K. Laliberté, Communications Research Ctr. Canada (Canada)

Optical switches based on the electro-optic effect in III-Vs such as GaAs have fast optical switching times, typically shorter than 1 ns, and thus are promising candidates for a wide variety of optical network applications ranging from fault restoration and network configuration to optical packet switching. A Mach-Zehnder interferometer (MZI) is often used to implement a 2x2 electo-optic switch in which two identical multi-mode interference (MMI) couplers are connected by two identical parallel electrodes which provide an optical phase difference of 180 degrees based on the electro-optic effect. In this paper, we report the design, fabrication, and test of MMI couplers and 2x2 MZI-MMI optical switches based on these couplers. The waveguide structure has 5 undoped GaAs-GaAlAs layers with a 1.7um-thick core layer. In both simulation and fabrication, various values of MMI width, MMI length, and waveguide width have been considered. Both simulation and experimental results have indicated that the device performance is most sensitive to the MMI width and is less sensitive to the MMI length. From simulation and experimental results, optimized structures have been obtained for 2x2 MZI-MMI optical switches. devices based on the optimized structure have been fabricated without electrodes. The fabricated MZI-MMI optical switches have shown very promising switching properties such as low insertion loss and high on-off extinction ratio. The propagation loss of straight waveguides is typically around 0.3 dB/cm. There is almost no measurable additional loss due to the MMI couplers. The effects of various material and device parameters on switch performance are discussed.

6116-25, Session 5

All-optical wavelength conversion in a vertical cavity semiconductor switch

C. Porzi, Sant'Anna School for Advanced Studies (Italy); L. Poti, A. Bogoni, Consorzio Nazionale Interuniv. per le Telecomunicazioni (Italy); M. Guina, O. G. Okhotnikov, Tampereen Teknillinen Yliopisto (Finland)

Wavelength conversion with high contrast ratio and low OSNR penalty has been achieved by using a vertical-cavity all-optical switch based on saturable absorption in multiple-quantum-wells. The device was grown by MBE on InP substrate. It comprised a 19.5 pairs n+-Ga0.47In0.53As/InP dBR, 28 Ga0.47In0.53As QWs, and a 50% dielectric coating. The structure exhibited a Fabry-Perot behaviour with a resonant wavelength of ~ 1535-nm. We have carried on conversion experiments between a wavelength-tunable modulated signal (pump) and a CW beam with a wavelength matching the Fabry-Perot resonance of the device. Measurements of the extinction ratio for the converted signal indicated a 15-dB contrast with a pump signal modulated at 622 Mb/s and having an average power of only 6-dBm. The wavelength conversion experiments showed a relative weak dependence of the extinction ratio on the pump signal wavelength. In fact, the 3-dB degradation point for the contrast was obtained when the pump signal was detuned with ~ 10 nm from the resonant wavelength. To our knowledge, these values represent a significant improvement over previously reported results for similar devices. BER/OSNR measurements on the 622 Mb/s wavelength converted data signal indicated an OSNR penalty of maximum 2.5-dB, for 20-nm wavelength conversion, with respect to the original pump signal. Error free operation was observed up to 2 Gb/s but at this data rate the performance of the device degraded due to a relative long absorption recovery time. However, with further optimization, the device recovery time could be reduced to ps range, thus extending its application to much higher date rates.

6116-27, Poster Session

Optical properties and energy-transfer frequency upconversion of Yb3+-sensitized Ho3+- and Tb3+-doped lead-cadmium-germanate glass and glass ceramic

A. S. Gouveia-Neto, A. C. M. Afonso, J. F. Nascimento, E. B. Costa, Univ. Federal Rural de Pernambuco (Brazil); L. A. Bueno, Univ. do Oeste de Santa Catarina/Videira (Brazil); S. S. J. Ribeiro, Y. Messaddeq, Univ. Estadual Paulista (Brazil)

There has recently been a widespread interest in using lanthanide-doped glassy materials as near-infrared pumped luminescence sources of visible radiation. The practical interest is due to the possibility of producing: solid-state color displays, infrared pumped visible lasers, etc. Thus, there exists a demand for novel hosts that produce high upconversion efficiencies and allow suitable combinations of rare-earth luminescence centers which can diversify the visible upconversion emission wavelengths. Glass-ceramics or vitroceramics have recently emerged as auspicious contenders for such photonic devices applications. The advantage of using vitroceramic resides in the fact that the rare-earth doping ions are confined in crystalline environments of low phonon energies, yielding large excited-state lifetimes and optical absorption cross sections when compared to vitreous surroundings. Furthermore, the glass host matrix in which the crystals are immersed, possess the durability and mechanical properties of an oxide glass.

In this report we investigate the optical properties and energy-transfer upconversion luminescence of Ho3+- and Tb3+/Yb3+-codoped PbGeO3-PbF2-CdF2 glass-ceramic under infrared excitation. In Ho3+/Yb3+, green(540 nm), red(650 nm), and near-infrared upconversion luminescence corresponding to the 4S2,5F4 ↑ 5I8, 5F5 → 5I8, and 4S2, 5F4 → 5I7, respectively, was readly observed. Blue(490 nm) signals assigned to the 5F2,3 → 5I8 transition was also detected. In the Tb3+/Yb3+ system, bright emission around 485, 550, 625, and 655 nm, identified as due to the 5d4→7FJ's transitions, was measured. The comparison of the upconversion process in vitroceramic and its glassy precursor revealed that the vitroceramic samples present a much higher upconversion efficiency. The dependence of the upconversion emission upon pump power, and doping contents were also examined. The results indicate that successive energy-transfer between ytterbium and holmium ions and cooperative energy-transfer between ytterbium and terbium ions are the dominant upconversion excitation mechanism.

6116-28, Poster Session

Phonon-assisted blue upconversion luminescence in NaY(WO4)2 crystals co-doped with Tm3+ and Yb3+

J. Su, F. Song, H. Tan, J. Tian, G. Zhang, Nankai Univ. (China)

NaY(WO4)2 crystal co-doped with Tm3+ and Yb3+ were prepared by using Czochralski (Cz) pulling method. Absorption spectra, emission spectra, and excitation spectra of this crystal were measured at room temperature. Such optical parameters as oscillation strengths, rates of spontaneous emissions, integrated emission cross-sections, branch ratios and lifetimes were calculated from absorption spectra with Judd-Ofelt theory. The best set of Judd-Ofelt intensity parameters (W2, W4 and W6) obtained from a least square analysis of the observed oscillator strengths respectively: W2=7.32×10-20cm2, W4=0.83×10-20cm2, W6=1.23×10-20cm2. Intensive infrared-to-visible frequency upconversion has been discovered and investigated under a 974 nm laser diode (Ld) excitation at the room temperature. Much more intense blue upconversion fluorescence of Tm3+ was observed in NaY(WO4)2 crystals with high phonon energies than in other fluoride or fluoroindate glasses with low phonon energies. For the bright three-photon blue upconversion luminescence emission around 476nm identified as due to the 1G4‡3H6 transition of the thulium ions, is analyzed in details. Furthermore, the cross-relaxation: 1G4(Tm3+)+ 3H6(Tm3+)‡3F4(Tm3+) +3F3,2(Tm3+) are put forward and discussed. The experimental results and theoretic analysis suggest that The high phonon energy not only enhances the efficiency of the Yb3+‡Tm3+ energy transfers known as phonon-assisted processes, but it also improves the population on 1G4 level by the MPR process. We conclude that the Tm3+/Yb3+ co-doped NaY(WO4)2 crystal is of interest for design of blue solid-state laser through the upconversion of infrared radiation into visible radiation.

6116-29, Poster Session

1550 nm emission from dy3+ and Nd3+ doped PbBr2, KPb2Br5, and TlPb2Br5

U. Hommerich, J. Freeman, E. E. Nyein, A. Phillips, I. Noor, Hampton Univ.; S. B. Trivedi, Brimrose Corp. of America; J. M. Zavada, U.S. Army Research Office

The infrared emission properties of rare earth doped halides are of significant current interest for applications in optical communications and solid-state lasers. Potassium lead halides (KPb2Cl5 KPb2Br5) have recently emerged as new non-hygroscopic laser hosts with low-phonon energies. In this paper, we report on the near infrared emission properties from dy3+ and Nd3+ doped PbBr2, KPb2Br5, and TlPb2Br5 crystals. Under 808 nm excitation, the bromide crystals exhibited efficient 1550 nm emission from the 6F5/2 - > 6H11/2 transition of dy3+ and 4F3/2 - > 4I15/2 transition of Nd3+, respectively. The observation of 1550 nm emission from dy3+ and Nd3+ is rather unusual and reflects on the low phonon energies of lead bromide based hosts (<150 cm-1), which leads to small non-radiative rates and efficient emission from closely spaced excited states.

6116-30, Poster Session

Cathode luminescence of epitaxial layers Ga1-xAlxP

T. Jakhutashvili, B. Mikhelashvili II, N. P. Kekelidze, E. Tulashvili, M. Chkhaidze, Tbilisi State Univ. (Georgia); R. Chikovani, Georgian Technical Univ. (Georgia)

Influence of the degree of dope by tellurium and zinc on cathode luminescence (CL) properties of epitaxial layers of Ga1-xAlxP in a range of structures 0,22 ≤ x ≤ 0,71 is researched. CL spectra consist of two bands: short-wave green and long-wave red or infra-red. Energy of maximum of short-wave bands for undoped and Zn doped layers when having identical structures coincide. As for the layers doped by tellurium, they are a little bit lower. Energy of the maximum of the green band linearly depends on composition. Accordingly, the energy of the maximum of the long-wave bands together with the increased degree of doping is displaced from 1,72 eV to 1,82 eV and from 1,69 eV to 1,3 eV in the layers doped by zinc and tellurium. The optimum concentration of tellurium and zinc in the solution melted and, accordingly, in Ga1-xAlxP layers are determined at temperature of their growth. In this field the peak efficiency of CL is reached. The decrease of the intensity of green band of CL was revealed by increasing the contents of aluminum in undoped and Ga1-xAlxP:Zn layers as opposed to its abnormal increase in Ga1-xAlxP:Te layers. The possible mechanisms are discussed about the influence of impurity on the efficiency and spectral structure of radiation. On the basis of high relative and absolute intensity of the green CL band and uniform character of its distribution according to thickness of the grown layers, helps to make sure they are of high quality.

6116-31, Poster Session

Measurements of non-elastic frozen-in residual stress near the cleaved end of an optical fiber by the inverse linear polarizing method

I. Shin, d. Y. Kim, Gwangju Institute of Science and Technology (South Korea)

Few years ago, the inverse linear polarizing method(ILPM) has been suggested as an effective measurement method for the residual stress of optical fibers by Y.Park et al. and it has been used as an important tool to study photo-elastic and birefringent characteristics of optical fibers. Non-elastic frozen-in residual stress was only recently found to be an important draw-induced inelastic strain that can significantly perturb the refractive index profile and hence the waveguiding properties of optical fibers. We have investigated non-elastic frozen-in residual stress profiles of optical fibers drawn at various drawing forces by using the ILPM. By measuring the non-elastic residual stress profiles of a fiber near the cleaved end of a fiber, we have found that the elastic strain of a fiber is mostly released within 20 micrometer distance from the cleaved end. We have verified that the average non-elastic residual stress along the cross section of a fiber increases as the drawing force of a fiber increases.

6116-32, Poster Session

Gradient of the residual stress distribution in the mechanical defect on the optical fiber surface

I. Shin, d. Y. Kim, Gwangju Institute of Science and Technology (South Korea)

Optical fibers are composed of the core and the cladding that are covered by the polymer coating to be protected. Sometimes, this polymer coating, however, should be removed to fabricate optical devices involving the optical fiber such as Bragg grating, optical coupler, optical sensor and optical connector. In general, the mechanical stripper is used to remove this polymer coating. In this case, the mechanical stripper may cause mechanical defects on the surface of the optical fiber and also, mechanical defects make the optical fiber weak. We have researched relation between these mechanical defects and the residual stress gradient in the optical fiber. We have made a mechanical defect on the surface of a single mode fiber with a mechanical stripper and measured the residual stress distribution along the axial direction of the optical fiber. From this research, we have observed that at the position with the mechanical defect, the residual stress in the core was converted to the compressive residual stress (about 15Mpa) and the residual stress in the cladding was converted to the tensile residual stress (about 7Mpa). We suggest that measurement of the residual stress in the optical fiber can be used as a tool to find out the mechanical defects on the surface of the optical fiber.

6116-33, Poster Session

Simplified transformation circle theory in analyzing laser resonator

Y. Wu, Nankai Univ. (China)

As a method to analyze laser resonator, transformation circle theory is simple. In this paper, further simplification was made and only σ circles in the theory and simple mathematic knowledge were used to analyze the stability and to calculate the parameters of the laser resonator, which further simplifies the transformation theory. The results agree with the well-known matrix theory. A two-mirror and three mirror(including a thermal lens) laser resonators were illustrated to give the stability formula and Guassian beam dimensions on the mirrors. Furthermore, we give a common used example when the laser medium is close to the cavity mirror.

6116-34, Poster Session

Photothermal spectroscopic characterization in tellurite glasses codoped with rare-earth ions

V. Pilla, E. Rodriguez, E. F. Chillcce, C. L. Cesar, L. C. Barbosa, Univ. Estadual de Campinas (Brazil)

Recently, Tellurite glasses have generated an increasing interest due to its high rare earth ions solubility and large amplification bandwidth, for examples, becoming promising for practical applications as: optical amplifiers, laser active media and infrared-to-visible converters. The present work reports thermal-optical and spectroscopy properties of Tellurite glasses codoped with rare earth ions, applying Thermal Lens (TL) and Fluorescence techniques. Tellurite samples, with nominal composition of 70TeO2-19WO3-7Na2O-4Nb2O5 (%mol), were prepared mixing 1.19x1020 ions/cm3 of Er+3 and varying Tm+3 concentration between (0.34 to 1.60) x1020 ions/cm3, respectively. TL transient measurements were performed using the mode-mismatched dual-beam (excitation and probe) configuration. A He-Ne laser (*p= 632.8 nm) was used as the probe beam and either an Ar+ laser (*e= 488 nm) or a Ti-sapphire laser (*e= 785 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 Tellurite glasses were determined.

1 W. Ryba-Romanowski, Journal of Luminescence 46, 163 (1990).

2 S. M. Lima et al, J. Non-Cryst. Solids 273, 215 (2000).

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4 V. Pilla et al., J. Opt. Soc. Am. B. 21, 1784 (2004).

6116-35, Poster Session

Temperature dependences of optical path length in fluorine-doped silica glass and bismuthate glass

A. Koike, N. Sugimoto, Asahi Glass Co., Ltd. (Japan)

Temperature dependences of optical path length (dS/dT; calculated using the equation, dS/dT = dn/dT + na, where a is coefficient of thermal expansion, n is refractive index and dn/dT is temperature coefficient of

refractive index) in various inorganic glasses were investigated. The dS/dT is generally difficult to adjust by change of glass composition because dn/dT and a are interrelated. However, low dS/dT materials are desired for photonic applications such as athermal devices, and high dS/dT materials can be used for thermo-optic devices. Pure silica glass is well-known as a typical low dS/dT material but still not sufficient. Fluorine-doped silica glass showed a lower dS/dT value than that of pure silica glass. By fluorine-doping in silica glass, n and dn/dT decreased but a near room temperature stayed at the same level. As a result, the dS/dT decreased with increasing fluorine concentration. On the other hand, bismuthate glasses showed the highest dS/dT value in this study. Most glasses having high a such as tellurite glass showed negative dn/dT. However, bismuthate glasses showed positive dn/dT values in spite of high a. As a result, bismuthate glasses showed quite high dS/dT values which were comparable to those of organic materials. These results indicate that dS/dT of the glass can be controlled and that fluorine-doped silica glass and bismuthate glass are appropriate candidate materials for optical applications.

6116-36, Poster Session

Glass waveguides produced by ion-exchange in Er3+-doped tellurite glass

L. C. Barbosa, V. V. Anthony Garcia Rivera, E. F. Chillcce, E. Rodriguez, Univ. Estadual de Campinas (Brazil)

Tellurite glasses show very high rare earth ions solubility and amplification bandwidths as large as 180 nm, becoming promising for practical applications such as: optical amplifiers, laser active media and infrared-to-visible converters. Although these application could be performed with optical fibers, there are great advantages to perform them also in integrated optics devices which requires planar and channel waveguides. This work reports the preparation of planar waveguides by Ag+ - Na+ ion exchange in an Er3+-doped tellurite glass with a composition of 75TeO2-2GeO2-10Na2O-12ZnO-1Er2O3 (mol %). The glass was chemically stable during both the ion-exchange process. We have been able to produce single and multi-mode planar waveguides controlling the depths of the waveguides by varying ion-exchange temperatures, from 250 to 280°C, and times, from 3 to 12 h. We also show preliminary results of channel waveguide fabrication with the same technique. The waveguide effective refractive index curves and attenuation (11 dB/cm) at 1536 nm were measured with a metricom prism coupler. The Amplified Spontaneous Emission (ASE) spectra showed a 152 nm bandwidth when pumped with 120 mW at 980 nm.

6116-37, Poster Session

Er3+-doped tellurite glass waveguides produced

V. V. Anthony Garcia Rivera, E. F. Chillcce, C. L. Cesar, L. C. Barbosa, Univ. Estadual de Campinas (Brazil)

In recent years, integrated optics-a new branch in the field of optoelectronics-has been progressing rapidly. The optical waveguide represents the main components of integrated optical circuits. This work report the production of Er3+-doped tellurite glass channel waveguides using the novel concept of T. M. Benson et al[1] of fiber on glass (FOG). In this method the channel waveguide is formed by thermally binding optical fibers onto the substrate glass. To succed with this technique it is important to correlated the main thermophysical characteristics of the substrate and the fiber, which are the transition temperature Tg, the temperature of the onset of crystallization Tx, the maximum crystallization temperature Tc and the thermal expansion coefficient. The Tg, Tx and Tc values were determined by differential Thermal Analysis (dTA), while the thermal expansion coefficient was determined by Thermal Mechanical Analysis (TMA). For the FOG purpose the thermal stability range, Tx - Tg, is an important temperature region which defines if the glass will have enough viscosity to shape in the FOG concept. We used the TMA equipment itself to produce the channel FOG waveguides by pressing an Er3+ doped tellurite glass optical fiber against the also Er3+ doped tellurite glass substrate kept under Tc ± 30°C temperature. The optical characterization was performed with luminescence and waveguide effective refractive index. Scanning electron microscopy was used to observe the structure obtained.

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6116-38, Poster Session

Optical backplane based on substrate optical interconnects technology

M. B. Tayahi, Univ. of Nevada/Reno

Optical networks now mainly serve very high data rates and long distances while short reach communication and low data rates is dominated by electronics. We examine the optical backplane technique based on substrate guided optical interconnects technology. The fulfillment of this architecture, including the implementation of equalized fan-outs across the entire optical interconnects layer using volume holographic gratings and developing of electro-optical interface modules are being investigated.

Conference 6117: Organic Photonic Materials and Devices VIII

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6117-01, Session 1

Advances in third-order NLO materials

S. R. Marder, S. Chung, S. Zhang, T. Odani, J. Cho, S. Barlow, Georgia Institute of Technology; E. W. Van Stryland, D. J. Hagan, J. Fu, College of Optics and Photonics/Univ. of Central Florida; J. M. Hales, M. Rumi, A. Biesso, S. Chi, J. W. Perry, Georgia Institute of Technology

In this talk recent advances in third-order nonlinear optical materials will be described.

6117-02, Session 1

Merging quantum dots, biomolecules, and polymers for record performance from solution-processed optoelectronics

E. H. Sargent, Univ. of Toronto (Canada)

No abstract available

6117-03, Session 1

Unprecedented electro-optic activities through molecular design and controlled assembly

A. K. Jen, Univ. of Washington

No abstract available

6117-04, Session 1

Advances in nonlinear molecular photonics at the nanoscale

J. Zyss, École Normale Supérieure de Cachan (France)

We will review and discuss a currently ongoing revival of molecular nonlinear optics due to the opening up, both experimental and conceptual, of a submicron barrier that was beyond the reach of classical optical methods prior to the advent of 'single molecule' spectroscopy and the ensuing revolution.

Current experiments and related models will be called upon to illustrate the development of powerful nonlinear optical methods either to probe and image materials at the nano-scale or as active engineering tools to tailor refined distributions of molecules. Both approaches will be shown to make extensive use of powerful tensorial symmetry considerations applied jointly to laser fields and molecules.

In order to meet the increasing demand for new photonic structures and labels for nanotechnologies and biotechnologies, molecular engineering for nonlinear optics is being downscaled to the nano-scale, leading to the design of supra-molecular arrangements, nano-crystals and hybrid organic-inorganic nanoparticles which will be reviewed.

So as to check and monitor the activity and relevance of the current wealth of propositions, a major stake is the development of new nonlinear nanoscale imaging techniques capable to map-out artificially engineered materials as well as biological media at unprecedented levels of resolution while being able to retrieve crucial structural and electronic information which is not accessible to the more classical linear approaches.

In this perspective, we will outline the unique potential of nonlinear multiphoton excitation microscopy combining two-photon excitation fluorescence (TPF) and second harmonic generation (SHG), in order to probe, and optically control molecular organization and nonlinear optical responses at sub-wavelength scales in various environments. The local polarization analysis of these optical processes is shown to contain information which cannot be retrieved from averaged measurements on large ensembles.

We will also discuss complex molecular distributions generated by use of the all-optical poling technique, which requires the excitation of nonlinear photoisomerizable molecules by the conjunction of interfering mutually coherent fundamental and harmonic radiations. In addition to the possibility to access controlled multipolar orders governed by the poling fields polarizations, this method can be downscaled to the nano-scale in a polymer medium and lead to applications in high density encrypted optical data storage.

At a more fundamental level, such studies open up the possibility to target challenging applications such as the development of new nonlinear nano-probes, and the electrical or optical monitoring of molecular assemblies in sub-microscopic size structures down to the single molecule level.

6117-05, Session 1

To be announced

T. Wada, Riken Electric Wire Co.,Ltd. (Japan)

No abstract available

6117-06, Session 1

Recent advances in organic photorefractives and organic nonlinear optics and their applications

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

No abstract available

6117-07, Session 1

Liquid crystals for optoelectronics

K. D. Singer, Case Western Reserve Univ.

No abstract available

6117-08, Session 1

Organic light-emitting diodes for displays and solid-state lighting

Z. H. Kafafi, Naval Research Lab.

No abstract available

6117-10, Session 2

Novel two-photon absorbing styrylpyridine-based multibranched dyes

A. Attias, F. Mathevet, D. Kreher, Univ. Pierre et Marie Curie (France); P. L. Baldeck, Univ. Joseph Fourier (France)

We report on the design, synthesis and optical properties of new two-photon absorbing multi-branched chromophores, based on a pyridine

core. Measurements of TPA using the two-photon fluorescence method in the fs regime indicate that these chromophores exhibit two-photon absorptivity. 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. These molecules can serve as pH-sensitive TPA dyes.

6117-11, Session 2

A large aperture laser beam variable attenuator using electro-optic Bragg gratings

J. J. Foshee, Air Force Research Lab.; S. Tang, Y. Tang, X. Wang, Crystal Research, Inc.

A large aperture laser beam variable attenuator is developed for airborne laser applications. This variable attenuator divides the incident laser beam into a transmitted beam and a diffracted beam using electro-optic Bragg gratings. The diffraction efficiency of the electro-optic Bragg gratings can be adjusted, by means of the applied voltage, over a continuous range from essentially zero to near 100%. Depending on the voltage applied to the device, light intensities of both the transmitted and diffracted beams can be electrically controlled through electro-optic effect. The developed laser beam variable attenuators show fast electro-optic response time of 50 microseconds, large optical attenuation range of 25dB, and small transmission loss of 0.5 dB.

6117-52, Session 2

Fluorescence modulation by photoisomerization of diarylethene

E. Kim, Yonsei Univ. (South Korea)

A reversible modulation of fluorescence accompanied by photochromic changes has been one of the important tool for organic switches and recording. Such a function can be introduced into a molecule by incorporating a photochromic unit plus fluorophore. Diarylethene (DA) polymers modified by a fluorophore such as (p-phenylenevinylene) gave alternative copolymers, DA-PPV. The fluorescence of DA-PPV was high in the bleached state but very low in the colored state. A reversible modulation of the emission properties could be achieved through photoisomerization of DA unit by irradiation at selected wavelength. DA-PPV polymers modified by a trimethylsilyl substituted PPV showed higher fluorescence contrast between the colored and bleached state. Fluorescence of the DA polymers in a colored state was greatly increased by oxidation of DA, to yield O-DA polymers. O-DA polymers showed high fluorescence in the colored form but low in the bleached form as contrary to that of DA-PPV polymers. The fluorescence intensity of O-DA polymers was modulated reversibly by the photochromic conversion of DA units. Characterization and optimization of fluorescence modulation from DA polymers will be discussed.

6117-12, Session 3

Functionalized photopolymers for integrated optical components

A. F. Fort, S. Klein, J. Bombenger, K. Dorkenoo, A. Barsella, L. Mager, D. Gindre, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

Organic photosensitive polymers are of special interest for their potential applications in optical integrated devices due to the relatively easy control, at a microscopic scale, of the modulation of the refractive index by an appropriate laser beam. This characteristic is especially useful for the creation of optical components based on photopolymerization processes in diacrylate photopolymers. We describe some examples illustrating the interest of functionalized photopolymerizable materials to realize permanent optical wave guides, fibres connection, distributed feedback dye lasers and optical circuits. Finally, we demonstrate that methods combining one- and two-photon absorption techniques for the polymerization in functionalized matrices open the possibility to create passive or active optical integrated components.

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6117-13, Session 3

Fabrication and evaluation of dye doped polymer strip waveguides

B. Coleman, M. A. Reilly, Univ. of Cambridge (United Kingdom); E. Y. Pun, City Univ. of Hong Kong (Hong Kong China); R. V. Penty, I. H. White, Univ. of Cambridge (United Kingdom)

Polymer optical fiber (POF) is increasingly being deployed in short-haul communication networks, but amplifier devices will be required to overcome relatively high optical losses if the range of POF is to be extended. Devices fabricated from dye-doped polymers have the potential to fulfill this need[1]. We present a study of various dye/polymer combinations and compare their suitability for such applications.

A number of dyes which emit in the visible range are dispersed in both SU-8 (Microchem Corp) and poly(methyl methacrylate) (PMMA) polymers. The solubility of each dye/polymer combination is examined, along with optical properties in thin-film form. We find that the most promising dye from the perspective of its readiness to dissolve in SU8 is Rhodamine 640 Perchlorate, while DCM is found to most readily dissolve in PMMA.

Photolithography is used to fabricate rib waveguides using the negative photoresist SU-8 and the effects of UV exposure on the absorption and photoluminescence spectra of the various dyes are presented. The presence of laser dyes has a significant impact upon the exposure time required to cure the SU-8 due to absorption in dye molecules leading to a significant retardation in the rate at which photoinduced curing proceeds. The consequent increase in exposure required to cure the material caused degradation of the laser dyes.

References

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6117-14, Session 3

Tailoring of organic nanofiber growth for a new type of waveguides

F. Balzer, L. Kankate, H. Niehus, Humboldt-Univ. zu Berlin (Germany); H. Rubahn, Syddansk Univ. (Denmark)

It has been shown recently, that organic nanofibers grown from para-hexaphenyl and -sexithiophene molecules can be used as a new type of nanoscopic waveguides[1]. Their growth is due to a self-assembly process, thus large quantities of aligned nanofibers can be fabricated simultaneously. The fibers can be detached from the mother substrate and dispersed in liquids or transferred to arbitrary substrates[2]. Because of the growth mechanism of the nanofibers, their widths and heights are limited to a few 100 nm and a few 10 nm, respectively. For their use in specific applications, as e.g. single- and multimode waveguides, a wide range of independently controllable morphological parameters is preferable. In this paper we show how this kind of control has been obtained via modification of the bare muscovite surface before organic molecule deposition. Introducing e.g. a thin layer of Au islands before nanofiber growth results in an up to 15-fold increase in height, whereas the mean width and the optical properties of the fibers remain almost unchanged. Au films of varying thickness lead to tailor-made height profiles along the

fiber. Using atomic force microscopy the details of these Au/organic heterostructures are examined and the growth is compared to growth on untreated mica. An alternative way to steer the fiber direction is the use of substrate surfaces with electric fields in arbitrary directions. First results for para-hexaphenyl grown on pyroelectric substrates are presented.

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6117-15, Session 3

Refractive index imaging via a chemically amplified process in a solid polymeric medium

D. R. Robello, Eastman Kodak Co.; S. Farid, J. P. Dinnocenzo, T. G. Brown, Univ. of Rochester

We will describe a new refractive index imaging system in a solid organic polymer medium, based on the photoinitiated isomerization of Dewar benzene derivatives. The system exhibits a refractive index contrast of >0.02, with very low dimensional changes on recording. Furthermore, the medium is highly sensitive because the recording process is chemically amplified, (i.e., many product molecules are formed per photon absorbed). The change in refractive index occurs spontaneously under blue or UV irradiation; no subsequent processing of any kind is required. This system may find applications in holographic recording and for integrated optical devices. For example, >50 spatially overlapping diffraction gratings were recorded in the material in +/- 2 degrees.

6117-16, Session 4

Strong photomechanical effects with diarylethene microcrystals

P. L. Baldeck, I. Colombier, S. Spagnoli, Univ. Joseph Fourier (France)

Microcrystals of a diarylethene {1,2-bis[5´-methyl-2´-(2´-pyridyl)thiazolyl] perfluorocyclopentene} undergo jumps upon photoirradiation. These photochromic crystals present molecular structural changes upon irradiation with ultraviolet light because of reversible photocyclization reactions. When the phototransformation ratio reaches about 10%, the uniaxial stress induced in the crystal lattice relaxes through directional jumps. If we prevent crystals from jumping, parallel, equidistant cracks appear on crystal surface. These photomechanical effects could result from a Grinfeld surface instability.

6117-18, Session 4

Measuring of high nonlinear optical properties in novel liquid crystals by Z-scan technique

R. F. Dominguez-Cruz, A. L. Mendez-Perez, M. A. Panduro-Mendoza, G. Romero-Galvan, Univ. Autónoma de Tamaulipas (Mexico); R. Ramos-Garcia, D. Iturbe-Castillo, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Abstract. Numerous applications of nonlinear optical materials in several photonics devices are based on the change of refraction index induced by the illumination intensity. Liquid crystals are an attractive option due to potential use as inexpensive nonlinear optical element, the possibility of optimization of their composition and particularly to heir colossal optical nonlinearity.

In this paper we report measurements of the nonlinear refractive index using Z-scan in dye-doped liquid crystal 5CB with methyl-red at 1% wt as function of the temperature by using a low power He-Ne laser. We observe a large negative nonlinearity in the sample. It is found that the nonlinear refractive index change depends stronger on the temperature as we approach the nematic-isotropic phase transition. It decreases considerably at the isotropic phase and becomes almost temperature independent.

6117-19, Session 5

DNA: new class of polymer

J. G. Grote, Air Force Research Lab.

No abstract available

6117-21, Session 5

Development of an all-DNA-surfactant electro-optic modulator

E. M. Heckman, Univ. of Dayton and Anteon Corp.; P. P. Yaney, Univ. of Dayton; J. G. Grote, F. K. Hopkins, Air Force Research Lab.

Marine-based deoxyribonucleic acid (DNA), purified from waste products of the Japanese fishing industry, has recently become a new material of interest in photonics applications. The water soluble DNA is precipitated with a surfactant complex, cetyltrimethl-ammonium chloride (CTMA), to form a water insoluble complex, DNA-CTMA, for application as a nonlinear optical material. It is possible to fabricate an all-DNA-CTMA waveguide by crosslinking the DNA-CTMA. Crosslinking causes the material to become resistant to its initial solvents upon curing; this allows a core layer of crosslinked DNA-CTMA-chromophore to be spin coated directly on top of a cladding layer of crosslinked DNA-CTMA. The chromophore dye is added to the core layer to raise the index of refraction of the core layer above that of the cladding. The dye also allows for an electro-optic coefficient to be induced through contact poling. Progress on the development of this all-DNA-CTMA electro-optic modulator will be presented.

6117-22, Session 5

Optically controlled photonic switches based on spiropyran-doped marine-biopolymer DNA-lipid complex films

J. Yoshida, A. Watanuki, H. Takano, S. Kobayashi, H. Ikeda, N. Ogata, Chitose Institute of Science and Technology (Japan)

DNA-lipid complexes have attracted attention due to their functionality produced by the doping of various organic dyes. We have already reported on basic optical characteristics as well as the effect of lipids and type of dopants on the photochromism of spiropyran-doped DNA-lipid complex films. Our results showed that the photochromic effect in DNA-lipid complexes have promising potential for optical switching, optical signal processing, and photonic memories, though the performance of them should be improved to compete with conventional materials and components. In this paper, we report on switching characteristics of absorption type optical switches based on the photochromic reaction of spiropyran-doped DNA-lipid complex films. We found that the photochromic reaction of those films strongly depended on not only the type of spiropyran but also the excitation intensity. Increasing the excitation intensity both 360-nm UV light for turn-off and 532-nm laser light for turn-on operations resulted in accelerating the response speed in both operations. Response times are almost proportional to the excitation intensity; stronger the intensity, faster the response times. At present, 200-300 ms of response times have been obtained, which is limited by the power of our light sources. Since the proportional tendency has not been saturated yet, even under maximum radiation power of our equipments, much faster response similar to conventional TO switches could be expected. However, strong irradiation of the excitation light generally induces some degradation of the photochromic operation of the dyes. Therefore, there may be some tradeoff between excitation power and response times. In conclusion, all our results indicated the potential of DNA-based optical switches by proper selection of the type of spiropyran with proper combination of the control light intensity.

6117-23, Session 6

Red photoluminescence emission of laser dye doped DNA

Z. Yu, J. A. Hagen, W. Li, Univ. of Cincinnati; J. G. Grote, Air Force Research Lab.; A. J. Steckl, Univ. of Cincinnati

DNA material has shown better photoluminescence performance than polymethyl-methacrylate (PMMA) when both are doped with small and large organic dyes. DNA material also has a very low optical loss (<0.5dB/cm) in both visible and infrared ranges and this combination makes it an ideal candidate for many optical device structure fabrications.

Sulforhodamine 640 is a laser dye used mostly in aqueous form for laser emission from 610 nm to 650 nm pumped by different laser sources. In this research, sulforhodamine 640 was doped into surfactant modified salmon sperm DNA (DNA-CTMA) and thin films were formed by spin coating. We will review the photoluminescence (PL) emission characterization performed by exciting the thin film with a He-Cd laser at 325 nm. In our experiments, a strong red emission around 605 nm was observed. The spectra also show the relationship between PL intensity and doping concentration. This strong emission in a thin film device suggests the possibility of using DNA as a host material for light emitting devices, such as a solid-state thin film dye laser.

6117-24, Session 6

Development of the BioLED: Electroluminescence from organic light emitting diodes using marine derived DNA

J. A. Hagen, Univ. of Cincinnati; J. G. Grote, Air Force Research Lab.; A. J. Steckl, W. Li, Z. Yu, Univ. of Cincinnati; F. K. Hopkins, Air Force Research Lab.

Marine derived DNA, extracted and purified from salmon, has been investigated for incorporation in organic light emitting diodes (OLED). OLED devices consist of multiple thin films, each with its own role within the structure. These include the hole transport (electron block), emitting, and electron transport (hole block) layers. Properties of interest for all layers are high optical transparency, low electrical resistivity, and good film forming characteristics. Modification of the purified DNA material by a cationic surfactant reaction with hexadecytrimethylammonium chloride (CTMA) results in a molecule which is soluble in common organic solvents, such as butanol and methanol. This solution has produced high quality thin films by spin coating that have excellent optical and electrical properties, both of which suit OLED devices.

Further processing of DNA-CTMA includes the reduction of molecular weight and narrowing of molecular weight distribution by sonication. The sonic energy applied to the DNA molecules has successfully reduced the molecular weight from over 8,000,000g/mol to 145,000g/mol. Electrical resistivity is dependent on molecular weight, with a reduction of 7 orders of magnitude from 10^15 down to 10^8 Ω*cm.

DNA-CTMA has a large band-gap of 4.3eV, which lends itself to use as either an electron blocking or hole blocking layer. Including a 20nm film of DNA-CTMA into a device with Tris-(8-hydroxyquinoline) aluminum (AlQ3) as the emitting layer has shown a 10x increase in efficiency when used as a hole transport (electron block) layer.

Small planar aromatic molecules, such as 4-[4-(dimethylamino) stylyl]-1-dococylpyridinium bromide (DMASDPB), have the ability to intercalate between base pairs of DNA. This intercalated molecule has shown an enhancement in photoluminescence of 132x when compared to polymethylmethacrylate. This phenomenon is currently being studied for use as an emitting layer in OLED devices.

6117-25, Session 6

Photoluminescence and amplified spontaneous emission studies of [2- methoxy-5-(2'-ethylhexyloxy)-1,4-phenylenevinylene] in solution and films

A. Mahfoud, Univ. of Dayton; T. R. Nelson, Jr., Air Force Research Lab.; A. M. Sarangan, Univ. of Dayton

The photoluminescence (PL) and amplified spontaneous emission (ASE) spectra of the conjugated polymer [2-methoxy-5-(2'-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) is investigated under different conditions such as thin film and solution, solvent type and concentration. Results indicate that aggregation has a pronounced effect on the measured spectra, particularly in the ASE spectra. In solution form, as concentration was increased and thus the proportion of aggregates, a decrease in the ASE emission bandwidth and a red shift of the ASE peak was observed. The ASE emission in solution was assigned to the second vibronic transition of the polymer chains. For the thin film samples, the ASE spectra show two emission bands which we assigned to the first and second vibronic transition of the polymer chains.

This study reveals a strong dependence of the ASE on different types of solvents and their concentrations under visible excitation. Gilch-type MEH-PPV was purchased from Aldrich with average molar number Mn=70,000-100,000 g/mol with a polydispersity value (Mw/Mn=1.52). MEH-PPV solutions were prepared from chlorobenzene, toluene, and tetrahydrofuran (THF) at three different concentrations (0.38, 2, and 5 g/dm3).

In solution, the PL profiles show two emission peaks. The first one is located at 557, 561 and 566 nm in THF, chlorobenzene and toluene respectively. The second peak was found to be dependent on solution concentration and appeared at 596, 604 and 599 nm respectively and is due mainly to the second vibronic transition of the polymer and to a less extent to the formation of aggregated species. Amplified spontaneous emission was observed by pumping the solution at higher energy densities beyond photoluminescence. As concentration was increased, a decrease in the ASE emission bandwidth and a red shift of the ASE peak was observed. The reduction of the ASE bandwidth at higher concentrations is an indication of increment in the proportion of aggregates and interchain species.

The photophysical properties of the samples in the films appear to be quite different from that of the solution. Due to the strong dependence of the polymer (and its aggregates) on its surrounding, we expected different emission characteristic in films from the polymer chains that lay closer or in contact with the glass substrate compared to the rest of the polymer. To study the ASE emission in both situations, the samples were characterized immediately after they were spun, so that the properties under study were mainly of the outer polymer chains. Later the outer polymers were removed carefully through laser ablasion, by increasing the laser power which caused the evaporation of the outer layers of the polymer (about 45-60 nm). The excitation of the outer polymer results in ASE peaks around 640-644 nm roughly 10 nm red shifted from PL emission peaks of the second vibronic transition (0-1). The excitation of the polymer after the laser ablation produced an ASE emission around 605 nm, also 10 nm red shifted from the first PL peak of the polymer chains. This emission was associated with the first vibronic transition (0-0) of the polymer

6117-26, Session 6

Investigating conformational dependent energy transfer in photoluminescent conjugated polymers with time-correlated single molecule spectroscopy

S. Fore, Y. Yeh, Univ. of California/Davis; C. W. Hollars, T. R. Huser, S. M. Lane, Lawrence Livermore National Lab.

We have studied the photophysics of conjugated polymer conformational changes at the single molecule level. Single polymer photoluminescence

spectroscopy provides a fundamental toolkit to elucidate their complex photophysical behavior and the corresponding impact on optoelectronic device performance. Spectroscopic evidence from single polymer molecules of MEH-PPV (poly[2-methoxy,5-(2´-ethyl-hexyloxy)-p-phenylene-vinylene) indicated that only a few centers(only 2-3 active sites), i.e. those with the lowest transition energy, dominate the photoluminescence of the entire chain in samples prepared from non-polar solvents such as toluene. These results were obtained through the observation of photon antibunching, a characteristic feature of photon-emission from just one or few independent centers, from single, isolated molecules of collapsed-chain MEH-PPV. These previous results indicated that MEH-PPV molecules exhibit considerable intrachain energy transfer. These prior studies were conducted with continuous wave excitation which limits the number of detected coincident events. We show that conducting photon antibunching measurements with pulsed excitation dramatically increases the rate of detected events such that we can expand on these preliminary studies. This new approach allows the analysis of the number of active sites for each individual polymer chain. We report on the distribution of these values for the MEH-PPV system. In addition, improved timing resolution of our measurement system has allowed us to more accurately measure the photoluminescent lifetime, averaged over several individual molecules. The controlled tuning of the number of active sites, if combined and addressed in an electroluminescent device, could find applications as a source for single or few photons in quantum cryptography, quantum computing, and data storage.

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6117-27, Session 6

Ambipolar transport in semiconducting polymer transistors through the engineering the top contact device geometry as a platform for a light emitting transistor

J. S. Swensen, A. J. Heeger, Univ. of California/Santa Barbara

A process is demonstrated that allows for the deposition of a low work function electrode and a high work function electrode to serve as the source and drain contacts respectively in a top contact semiconducting polymer field-effect transistor (FET). In this manner, polymer light emitting diode technology is transferred to transistor geometry. The low work function electrode allows for efficient electron injection into the semiconducting polymer while the high work function electrode allows for good hole injection. We refer to this geometry as two-color electrodes. Using the two-color electrodes geometry, ambipolar transport is shown for poly(2-methoxy,5-(2´-ethyl-hexoxy)-1,4-phenylenevinylene) (MEH-PPV). In order to observe electron transport in MEH-PPV, non-polar, low dielectric constant gate dielectrics such as tetramethylsiloxane-bis(benzocyclotutene) (BCB) and polypropylene-co-1-butene were used, either to pasivate an inorganic gate dielectric such as silicon nitride or as the gate dielectric itself, with a patterned chromium gate. The channel width for these devices ranges from 500 to 2000 microns. The channel length is 10 to 20 microns. As device performance is improved, it is expected that light emission will be observed in the channel region of these ambipolar semiconducting polymer FETs and that the gate bias will control emission location and intensity.

6117-28, Session 7

Photolithographic patterning of conjugated electroluminescent liquid crystalline materials for full-color organic light emitting diode displays

A. J. McGlashon, A. J. Campbell, D. D. Bradley, K. S. Whitehead, Imperial College London (United Kingdom); I. A. McCulloch, M. J. Heeney, Merck Chemicals Ltd. (United Kingdom)

Displays based on polymer light emitting diodes are attractive due to their emissive nature, their wide viewing angles and the ability of electroluminescent conjugated polymers to be solution processable at room temperature and pressure. However, it is difficult to deposit separate red, green and blue (RGB) pixels and to maximise performance by making the devices multi-layered. Here we present recent results on a new class of semiconducting conjugated reactive-mesogen OLED materials which are solution processable, can be patterned by photolithography and can form multi-layer devices. These materials consist of conjugated phenyl and thiophene cores with reactive end-groups. Spectroscopy, calorimetry and microscopy show that they form crystalline, aggregate, liquid-crystalline and isotropic phases at a range of different temperatures. The materials are deposited by spincoating from solution. Low density doping with a cationic photointiator and exposure to a specific UV wavelength to avoid damage to the conjugated core leads to cross-linking into an insoluble network. Current-voltage-luminosity and spectral measurements in standard OLED device structures show that cross-linking does not effect the transport and injection properties of the material but does quench electroluminescence from the conjugated core. Insertion of lower-energy gap, fluorescent small molecules can then be used to tune the emission to any desired colour. The effect of conversion temperature and exposure time will be discussed. Initial results for photolithographic patterning in a conventional mask-aligner and multilayer devices may also be presented.

6117-29, Session 7

New architecture for high-efficiency polymer photovoltaic cells using solution-based titanium oxide layer

K. Lee, Pusan National Univ. (South Korea); J. Y. Kim, A. J. Heeger, Univ. of California/Santa Barbara

Despite being considered as promising potential sources of renewable energy, the device efficiency of polymer-fullerene photovoltaic cells is still not sufficient to meet realistic specifications for commercialization. One of the major limiting factors is the ‘optical interference’ between the incident and back-reflected light at the metallic electrode, such that the light intensity is extremely low for a relatively large fraction near the metallic electrode. The need to avoid such drawback in current device configuration requires the implementation of new device architectures with new materials. Here we report that high efficiency polymer photovoltaic cells of ~6% power conversion efficiency have been achieved using sol-gel processed titanium oxide (TiOx) as an ‘optical spacer’ between the active layer and the electron collecting aluminum electrode. The TiOx layer increases the efficiency approximately 50% by modifying the spatial distribution of the light intensity inside the device, thereby creating more photogenerated charge carriers in the bulk heterojunction layer.

6117-31, Session 7

To be announced

M. F. Durstock, Air Force Research Lab.

No abstract available

6117-32, Session 8

Novel functionalized polymers for applications in quadratic nonlinear optics

I. Rãu, P. Chollet, P. Armatys, F. Kajzar, CEA Saclay (France); R. Centore, A. Carella, Univ. degli Studi di Napoli Federico II (Italy); A. Attias, Univ. Pierre et Marie Curie (France)

The synthesis, thin film processing, poling and characterization of novel polyurethane and polystyrene based polymers functionalised with noncentrosymmetric chromophores is described and discussed. The polystyrenes, functionalized with disperse red #1 chromophore, form good

optical quality thins films, what is not the case of polyurethane. The refractive indices of thin films and their dispersion were determined by the m-lines techniques. The films were poled by corona and electrode poling techniques and their second order nonlinear optical properties were measured by the optical second harmonic generation technique and by the modulation ellipsometry. The obtained results will be presented and discussed, particularly from the point of view of possible application of these materials in electro-optic modulators.

6117-33, Session 8

Characterization of NLO polymer materials for optical waveguide structures

P. P. Yaney, E. M. Heckman, Univ. of Dayton and Anteon Corp.; A. A. Davis, Univ. of Dayton; J. A. Hagen, Univ. of Cincinnati; C. M. Bartsch, G. Subramanyam, Univ. of Dayton; J. G. Grote, F. K. Hopkins, Air Force Research Lab.

Polymers have a number of attributes that make them highly desirable for use in the design and fabrication of optical waveguide devices, such as modulators and directional couplers. They have relatively low (1.5-1.7) refractive indices, low (3.1-3.5) dielectric constants at gigahertz frequencies, stable at high (150-190C) temperatures, resistivities that can be tailored by adding guest molecules and electro-optical responses via the addition of chromophore molecules. These materials are easily spin coated on glass, quartz or silicon wafers to form optically conducting films that have low (1-2 dB/cm) optical loss at the near-IR communication wavelengths. In this paper we review basic characterization methods that we have used to provide that data needed to fabricate polymer waveguide devices. This will also include descriptions of the LabView vi's that were developed to pole polymer films and to measure resistivity.

6117-34, Session 8

Electrooptic polymer grating and its applications

D. Y. Zang, IPITEK, Inc.

No abstract available

6117-35, Session 8

Effects of conductive cladding layers on the performance of poled-polymer waveguides

A. A. Davis, P. P. Yaney, E. M. Heckman, Univ. of Dayton; J. A. Hagen, Univ. of Cincinnati; C. M. Bartsch, G. Subramanyam, Univ. of Dayton; J. G. Grote, D. E. Diggs, F. K. Hopkins, Air Force Research Lab.

One of the major issues in the development of wide bandwidth EO modulators is to minimize operating voltages (<1 V) and device length (<3 cm). Improvement in an optical communication link depends on decreasing the operating voltage, because link gain is inversely proportional to the square of the half-wave voltage (Vp) and the noise figure is directly proportional to the square of Vp in the low-gain limit. If this goal is accomplished, photonic devices could become operable via electronic driver chips and incoming radar signals. The effects of various cladding materials with different conductivities and dielectric constants to improve characteristics of poled-polymer waveguide EO modulators were studied. The ability to maximize EO coefficients using conductive cladding layers and different poling techniques will be presented. Modulation performance data, such as Vp, bias voltage stability and insertion loss were measured and compared for different waveguides.

6117-45, Poster Session

Observation of defects in polymeric optical waveguide using polarized guide-collection-mode near-field scanning optical microscopy

T. Mitsui, K. Sakoda, G. Kido, National Institute for Materials Science (Japan)

We fabricated original probes for the near-field scanning optical microscopy (NSOM) with polarization-preserving optical fibers, and succeed polarization observation in guide-collection-mode near-field scanning optical microscopy. In order to characterize the influences of defects and weak stresses within a polymeric optical waveguide, the author intentionally printed an indentation in the vicinity of the waveguide, then evaluated the resulting influences using the polarized guide-collection-mode NSOM images taken around the indentation. When transverse magnetic (TM) polarized light enters a waveguide, the light intensity becomes greater on the near side of the indentation than on the far side, as measured by a linearly polarized component perpendicular to the direction of light propagation. Under the polarization conditions of incident light and collection, it is expected that only the polarization-independent component will be observed and the electric field therefore does not become large. However, if scattering phenomena are present, the electric field should have a non-zero value. The most likely origin of this scattering is microdefects in the polymer generated by the stress-strain field at the interface between the waveguide and the cladding region around the indentation. These microdefects, which are generally a disorder in molecular chains, cause Rayleigh scattering. Finally, it is important to keep in mind that the polarized guide-collection-mode NSOM technique is capable of detecting defects or weak stresses in the nanoscale range within an optical waveguide.

6117-46, Poster Session

Fabrication of waveguide core by a simple vacuum method

H. Mochizuki, T. Mizokuro, N. Tanigaki, T. Hiraga, National Institute of Advanced Industrial Science and Technology (Japan)

We have developed a dye-doping process into a polymer, termed the 'vapor transportation method. This method enables us to prepare a favorable doped layer in the polymer, possessing both a uniform dye concentration and a smooth surface. In this method, a dye is first sublimated in a vacuum ampoule. Then, gas molecules of the dye fill the vacuum ampoule under thermal equilibrium. Finally, the molecules of the dye are dispersed into the polymer. As one of developments of the vapor transportation method, the optical waveguide could be prepared. In fabrication, sulfur compounds showing the higher refractive indices were dispersed in a matrices polymer (such as poly(methyl methacrylate)) through a mask by the developed method. After dispersion, we removed the mask and put the similar polymer on the doped polymer by vacuum press. A double-layered structure of doped and non-doped regions was observed in the cross section and the two regions described were transparent. We confirmed that a beam incident on the edge of the doped region of the prepared sample emerged from the other edge, indicting that the doped region acted as a core.

6117-47, Poster Session

Stabilization of the bias point of an electro-optic modulator based on polymer material

C. Nguyen, A. Clouqueur, R. Hierle, B. A. Journet, École Normale Supérieure de Cachan (France); P. Labbe, Motorola, Inc. (France); J. Zyss, École Normale Supérieure de Cachan (France)

Electro-optic modulators based on polymer material are very promising devices because of the expected very high modulation rate and low cost

fabrication process. These modulators are mainly based on Mach-Zehnder structure, but phase modulators associated to polarizer and analyzer can also be used. Until now there are no real devices commercially available. One of the problems concerns the temperature stability. Because of the optical power of the laser beam and the absorption of the polymer material used for the optical waveguide there is a slight temperature evolution of the modulator leading to a change in the bias point of the modulator and then to slow drift of the bias point leading to a dissymmetry of the optical modulated signal. This evolution can be compensated by adding a small DC value to the voltage applied to the electrodes.

A control loop has been designed and tested in order to stabilize the bias point of the modulator. This loop acts as a synchronous detection with a low frequency modulation at 500Hz and a practical detection at 1kHz. By this way it is in fact the first order derivative of the signal which is stabilized leading to the signal symmetry control. This low frequency signal can be added without any problem to the informative modulating signal. By using this control loop the modulator can be used for a very longer time than without it. Of course a temperature control of the modulator by a Peltier effect module can also be implemented for a better and complete stabilization.

6117-48, Poster Session

Influence of various doping consistence in EML on the optical and electronic performance of multilayer structure OLED

J. Zhong, J. Cheng, W. Chen, Y. Gang, J. Quan, Univ. of Electronic Science and Technology of China (China)

In this study, four kinds of organic light-emitting diodes were developed using vacuum deposition technique. The typical multilayer structures of OLED are ITO / CuPc(200 ≈) / α-NPD(600 ≈) / Alq3(400 ≈) : C545T(X%) / Alq3(200 ≈) /LiF(10 ≈) / Al(1000 ≈) , X% is the doping consistence in Emitter Layer of OLED. The value is change from 1% to 4%. In this letter, the optical and electronic performance including brightness, efficiency, spectrum etc. was change with the doping consistence. When X% is 1%, the steady voltage of device start working is lower the other structures, only 2.5V. When X% is 3%, the brightness of the device was measured to be 10,500cdïm-2 at the drive voltage 20V, CIE coordinates x=0.331, y=0.625 and maximum luminous efficiency 3.92 lm-W-1. When X% is 4%, the green emission spectrum peak is 550nm, almost reach 555nm (standard green spectrum peak).

6117-49, Poster Session

Enhanced electron injection in organic light emitting diodes

J. Lee, Pohang Univ. of Science and Technology (South Korea)

Achieving improved organic light-emitting diodes (OLEDs) performance requires metals having a low-work function, such as Li, Ca and Mg, for electron injection into organic materials. However, OLEDs with these electrodes exhibit poor device reliability due to the reactive nature of these metals. The use of high work function metals, such as Al, though less reactive, actually hurts the device efficiency due to less efficient electron injection. In this work, we present the recent advance of electrical properties of OLEDs using Mg-Al cathode.

The glass coating with indium tin oxide (ITO) was used as the starting substrate. The 4'-bis[N-(1-naphtyl)-N-phenyl-amino]biphenyl (α-NPD, 70 nm) and tris(8-hydroxyquinoline) aluminum (Alq3, 60 nm) layers were deposited in sequence using thermal evaporator, on which a Mg-Al alloy is deposited as a cathode.

The current density-voltage curves show that the operation voltage at the current density of 5 mA/cm2 is 10.4, 5.3, 5.0, and 4.9 V for 0:10, 2:8, 5:5, and 8:2 samples, respectively. Luminescence-current density curves show that the luminance at the current density of 128 mA/cm2 is 1400, 3500, 3800, and 2000 cd/m2 for 0:10, 2:8, 5:5, and 8:2 samples, respectively. X-ray diffraction data show that Al peak shifted to Mg peak with Mg contents, indicating the formation of complete solid solution. Secondary electron emission spectra show that the relative work function decreased as a function of Mg contents. Therefore, it is considered that Mg decrease the work function of Al, enhancing the electron injection from cathode to organic material and improving device performance.

6117-36, Session 9

The side-scattering properties of a novel waveguide multilayer memory

T. Yang, Z. Liang, Nanjing Normal Univ. (China)

The side-scattering effect plays a key role in the data readout of the novel waveguide multilayer memory (WMM). In this paper, we propose a model to study the side-scattering properties of the novel waveguide multilayer memory. We not only confirm theoretically and experimentally the exponential attenuation distribution of the side-emission scattering light intensity of a waveguide with fixed attenuation coefficient, but also deduce an expression about the relation between attenuation coefficient and light propagation distance of a waveguide with distributed attenuation coefficient when the side-scattering light intensity is uniform.

In order to improve the performance of the WMM, some feasible optimizations are designed. Especially the expression about the uniformity of the side-emitting light intensity is deduced here, which makes a good preparation for the fabrication of a high-performance WMM in the future. The obtained model expressions were in general agreement with the experimental results and more detailed future studies will lead to new interesting results on this item.

6117-37, Session 9

Synthesis of well-defined NLO polymers by controlled radical polymerization (RAFT process)

A. Attias, D. Kreher, M. Save, B. Charleux, C. Bui, J. Buffet, Univ. Pierre et Marie Curie (France); F. Kajzar, I. Rau, CEA Saclay (France)

In a first step, a novel macroinitiator containing a DR1 units in the main chain has been synthesized; in a second step, this polymeric precursor was applied to the synthesis of a sequencially ordered polymer by controlled insertion polymerization of styrene or methyl methacrylate into the main chain by a RAFT mechanism. SEC, NMR data revealed that the insertion reaction and the size od the PMMA or polystyrene segments was accurately controlled. Whatever the DR1 incorporating rate, all the polymers are soluble in common solvents; Second-order optical nonlinearity in corona-poled thin films has been evaluated; second harmonic coefficients up to 50 pm/V have been determined. For the first time, polystyrenes bearing DR1 dyes covalently bounded were obtained.

6117-38, Session 9

Organic Chiral salts for optical second harmonic generation

M. Sylla, Univ. d'Angers (France); O. Castellano, Univ. del Zulia (Venezuela); M. Giffard, G. Mabon, Univ. d'Angers (France); H. Soscun, Univ. del Zulia (Venezuela); N. P. Xuan, Univ. d'Angers (France)

This work is addressed to the investigation of the second harmonic generation ability of new chiral thiolate salts. Indeed, aromatic thiolate anions ArS- are expected from a semi-empirical calculation with FM3 parametrisation of the MNDO Hamiltonian, to possess higher intrinsic polarizabilities than the parent neutral thiols ArSH. In this way, salts asso-

ciating (hyper)polarizable aromatic thiolate anions with chiral cation which ensure the noncentro-symmetry necessary to have second order nonlinear optical effects, are synthesized. The first hyperpolarizabilities b of the salts are measured by using hyper-Rayleigh scattering (HRS) technique.

Although the hyperpolarisabilities of salts are different in nature from those of the anions thiolates, one observes despite everything a good agreement between values of b calculated and measured. For this reason, the theoretical calculation of b is used as valuable guide for the synthesis of materials having good second order nonlinear properties.

The second harmonic generation powder tests (Kurtz and Ferry method) carried out on various salts studied, were positive. This indicates that these materials crystallize in noncentrosymetric space groups.

6117-39, Session 9

Optical to microwave conversion in a traveling wave electro-optic polymer based device

F. Duport, C. Nguyen, R. Hierle, B. A. Journet, École Normale Supérieure de Cachan (France); P. Labbe, Motorola, Inc. (France); J. Zyss, École Normale Supérieure de Cachan (France)

This paper describes the design of an optical to microwave converter. The physical effect used for the conversion is based on the non-linear behavior of an electro-optic polymer material. The microwave frequency is generated by the way of an optical waves mixing process, which means by the frequency difference of two optical waves propagating simultaneously inside an optical waveguide. If one of these optical waves is modulated by an informative signal, the microwave signal will infer the modulation. The converter is designed for working at the 1.55 μm optical telecommunication wavelength. The active waveguide is built with the crosslinked PMMA-DR1 electro-optic copolymer, and the cladding layers are made of NOA material. For the first characterizations there is no need of a master-slave configuration for the sources, and the two optical waves are produced by highly stable and fine tunable lasers. The microwave signal is collected on a stripline which characteristic impedance has to be adapted to the conversion process. Simulations have been conducted showing the feasibility of the method and by matching the velocities of the microwave signal and of the optical signals it is possible to create constructive microwave photonic mixing at more than 60 GHz. To achieve the conversion it is necessary to work with a traveling-wave configuration. Some special test devices have been built for the determination of the NOA material permittivity leading to a precise adjustment of the effective index of both optical and microwave waveguide. From all these measurements it has been possible to design completely the device, which is now under test.

6117-40, Session 9

Broadband electric field sensor with electro-optic polymer micro-ring resonators on side-polished optical fiber

H. Sun, A. Pyayt, J. Luo, A. K. Jen, L. R. Dalton, A. Chen, Univ. of Washington

Electro-optic sensors are extensively used for noninvasive sampling/imaging of electric fields in high-speed ICs and microwave/millimeter-wave devices. A lot of previous implementations are based on inorganic EO crystals with Mach-Zehnder modulator structure or polarization modulation. In this paper, a novel EO E-field sensor based on polymer micro-ring resonator directly coupled to the core of optical fiber is proposed and demonstrated. A flat is made on the side of optical fiber by polishing. The depth of the polishing can be carefully monitored until the flat is within a few micrometers of the core of the fiber. An electro-optic polymer waveguide in the shape of a ring is subsequently fabricated on the polished flat using soft lithography. One side of the ring is directly above the core of the fiber. Because of the small separation between the core of the fiber and the ring waveguide, the light of certain wavelengths in the fiber can evanescently couple into the ring resonator to form resonance modes. External electric fields change the index of refraction of the ring resonator and therefore its resonant wavelengths. Since electro-optic polymers have higher electro-optic coefficients, lower dielectric permittivity and faster electro-optic responses than inorganic crystals, higher sensitivity, lower invasiveness and higher bandwidth of E-field sensing can be achieved. The sensor with EO polymer micro-ring directly coupled to side-polished fiber eliminates unreliable and possibly lossy fiber to waveguide coupling as well as the high propagation loss which comes from the long straight EO polymer waveguides. Unlike devices based on waveguide technology, supporting substrate is not necessary in this device. This leads to sensors of small size and low disturbance to the electric field to be sensed.

6117-41, Session 10

Photonic engineering of molecular materials

F. Kajzar, CEA Saclay (France); J. G. Grote, Air Force Research Lab.

The observed recently fast development of photonics, comprised as science and technology connected with handling of photons, can be compared to what electronics has known in the last centaury. This is not only due to the immense development and large needs for information processing, transmission and storage, but also to the increasing use of photons in the everyday life. Indeed, photons are successfully used for atom cooling, material processing, in medicine, dentistry, biology, industry, on battlefield, etc. They become also to be largely used in the material engineering. In this talk we will describe and discuss some aspects of this approach with very recent developments in photonic engineering such as control of molecular order in polymeric media, important for practical applications of these materials in e.g. optical signal processing as well as the way how photons can be used to move molecules, or their parts, thus to create well defined structures or mechanical functions.

6117-42, Session 10

Molecular engineering for two-photon absorption

C. Girardot, C. Barsu, G. Lemercier, C. Andraud, École Normale Supérieure de Lyon (France); P. L. Baldeck, Univ. Joseph Fourier (France)

Oligomers of fluorene are of great interest for the design of molecules with enhanced TPA cross-sections in the visible. Molecules are colorless whatever the length of the oligomer, and TPA properties lie between 450 and 650 nm. Their high TPA efficiency may be interpreted in terms of coherent coupling of transition dipole moments in oligomers.

The linear polyfluorenes family (n = 2 to 60) was studied experimentally. Enhanced TPA cross-sections values were obtained for these systems with a weak red-shift of absorption bands ; an order of magnitude in TPA efficiency could be gained with respect to substituted molecules optimized for this range of wavelength. The considerable increase of the TPA amplitude with the conjugation length was rationalized using an analytic excitonic model, in which each monomer is considered in close interaction with its closest neighbors. Analytical expressions of parameters involved in the well-known three level model could be expressed as a function of n in good agreement with experimental data.

2D and 3D dendrimeric polyfluorene derivatives were also investigated and their TPA properties were interpreted using theoretical calculations.

6117-43, Session 10

Synthesis of a zero-birefringence polymer by doping with a nano-size birefringent crystal

H. Ohkita, A. Tagaya, Y. Koike, Japan Science and Technology Agency (Japan) and Keio Univ. (Japan)

Birefringence of polymers degrades the performance of optical devices that require focusing by lenses or maintaining the polarization state of incident light. The birefringence is mainly caused by polymer chain orientation during polymer processings.

In this report, we describe the birefringent crystal dopant method to compensate for the orientational birefringence of a polymer. A rod-like birefringent crystal which is nano-size (< optical wavelength) is doped in a polymer in this method. When the polymer molecules are oriented, the doped crystals are also oriented, and their opposite birefringence compensates that of the polymer. Strontium carbonate (SrCO3) crystal was selected and synthesized, with an average length of about 200 nm and an average aspect ratio of about 3.

SrCO3 crystals were doped into poly(methylmethacrylate-co-benzylmethacrylate)=78/22(wt/wt) film. The polymer film was uniaxially drawn at 130°C and 4 mm/min. The observation of TEM micrographs of the doped film confirmed the SrCO3 crystals in the film were oriented to the draw direction. The orientational birefringence of the drawn films at a wavelength of 633 nm was compensated by doping with 0.3 wt% of the SrCO3 crystal. The orientation function of the main chains of the polymer was measured by analyzing the IR dichroism. The orientation function of the doped film was about a half as large as that of the undoped film. Furthermore, we estimated that the orientation function of the crystal was about 12.0 times larger than that of the polymer in our drawing condition. The IR analyses showed that the birefringence of the film was compensated by the orientation reduction of the polymer and the high orientation degree of SrCO3 crystal.

6117-44, Session 10

Light-modulated interactions of azobenzene-derivative molecules in polymer films and liquid crystalline matrices

K. Matczyszyn, Politechnika Wroclawska (Poland) and CEA Saclay (France); L. Rocha, CEA Saclay (France); C. Hubert, Univ. de Technologie de Troyes (France); C. Fiorini-Debuisschert, P. Raimond, CEA Saclay (France); S. J. Bartkiewicz, Politechnika Wroclawska (Poland)

Recently a large interest in the study of the nanoscale behavior of different photoactive materials exploited in photonics has been put. Among interesting photoactive molecules are well known azobenzenes, which undergo reversible photochromic reaction. The shape modification from its rod-like to a bent form can imply interesting behavior of the more complicated systems. Those molecules can be doped to liquid crystals and create photoactive panels used in holographic applications. The azopolymer films can be structured in the nanoscale and exploited for aligning other materials.

Photochromic liquid crystal panel built of E7 and 4-fluoro-4'-methoxyazobenzene shows very good photorefractive properties. Such panel was used for optical information processing in two wave mixing experiment, where the light induces isomerisation of azobenzene and in consequence, changes the order parameter of the liquid crystal. The dependence of diffraction efficiency on applied voltage, grating period and light intensity was measured. The diffraction efficiency, main parameter describing utility of the holographic devices, was found to be of a few per cent, which is a very good result.

Photomodulation of surface of azo-polymer films is demonstrated. Polymer films containing azobenzene were irradiated with two interfering polarized laser beams at a wavelength near the chromophore absorption band. Under the illumination the film surface undergoes a direct, reversible and controlled topographic modification. The influence of parameters such as the light intensity, the irradiation time, the thickness of the polymer film but also the irradiation wavelength is studied towards a better understanding of the process.

Understanding and controlling of the mechanisms at the origin of such processes could permit a complete manipulation of the molecular ordering. Nanostructuraction of the azobenzenes films opens new ways towards construction of effective materials with the use in the photonic devices.

6117-51, Session 10

Low sheet resistivity patternable conducting coating on textile by inkjet in-situ polymerization

Y. Yoshioka, G. E. Jabbour, Arizona State Univ.

Wearable electronics have recently become of more significance for many applications. There is a need for fabricating conducting textile with simple, reliable and low cost methods that allow the assignment of the conductive parts of the textile according to a design that can be changed whenever needed without requiring a significant alteration or downtime in the fabrication process. Recently, we were successful in fabricating conducting textile with sheet resistivity lower than 30 ohms/sq. which can be ironed, washed and ultra-sonicated without loosing its conductive properties. Our approach allows us to pattern the textile using inkjet printing chemical approach which open the door for a wide range of applications for smart textile ranging from military to civilian ones. In addition to our results in this exciting area, we will demonstrate few examples of the conductive textile and its robustness.

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6118-01, Session 1

Photoinduced magnetization wave in diluted magnetic semiconductors

V. A. Stephanovich, Univ. Opolski (Poland); Y. G. Semenov, North Carolina State Univ.

We derive an evolutional equation incorporating the processes of spin-polarization transfer from an electron to a magnetic ion subsystem of a diluted magnetic semiconductor along with spin-lattice relaxation and spatial spin diffusion. Above equation has been obtained for nonequilibrium magnetization due to exchange scattering of photoexcited charge carriers by magnetic ions. We show that the mechanism of a band gap narrowing due to exchange scattering requires relatively low optical power to reach an optical bistability for pump frequency range close to crystal band gap. In a bulk crystal, only relatively small local area with essential magnetization enhancement can absorb optical power, thus forming a photoinduced magnetization wave. Spatial spin diffusion can be responsible for a motion of such magnetization wave. We solve above derived equation both analytically for one-dimensional case and numerically otherwise and perform its stability analysis. We also evaluate numerically possible threshold of photoinduced magnetization wave excitation for typical diluted magnetic semiconductor A1-xIIMnxBVI and estimate its length and velocity of propagation.

6118-02, Session 1

Spontaneous magnetization patterning in paramagnetic diluted magnetic semiconductors: theory and experiment

M. Vladimirova, F. Teppe, D. Scalbert, Univ. Montpellier II (France); C. Misbah, Univ. Joseph Fourier (France); T. Wojtowicz, J. Kossut, Instytut Fizyki (Poland)

Diluted magnetic semiconductors (DMS), that is semiconductors alloyed with transition metals, are attracting considerable attention due to very rich physics which follows from the unique combination of magnetic and semiconductor properties coexisting in these materials. This means that one may control their magnetization via injection of the nonequilibrium carriers, which affect the magnetization via mutual carrier-magnetic ions spin-flips. We show that in paramagnetic DMS, the injection of nonequilibrium electron spin in the presence of magnetic field may not only alter the magnetization but also induce a spontaneous magnetization patterning. This phenomenon can be understood as a dynamical phase separation in DMS and it is studied both experimentally and theoretically.

We show that the spontaneous magnetization patterning does occur in CdMnTe quantum wells (QW) subjected to the in-plane magnetic field under femtosecond pulsed excitation, resonant with the QW fundamental optical transition. Using the time-resolved magnetooptical Kerr rotation technique we provide a direct evidence of 'hot' (low magnetization) and 'cold' (high magnetization) domains formation and determine both magnetization and total areas of these domains, as well as the magnetic field intensity threshold for domain formation.

The linear stability analysis of the rate equations describing the coupled electrons-magnetic ions spin system allows to determine the stability map in the parameter space suggested by the experiment, namely the external magnetic field, and the carrier generation rate. It reveals the presence of multiple bifurcation points, i.e. at a given value of the field, the system is unstable against the magnetization fluctuations between two threshold values of the carrier generation rate, and vice versa, at a given generation rate two threshold values of the field show up. The model developed suggests also that the critical instability wavelength, that is domain sizes, are determined by magnetic ions spin diffusion length. The numerical simulation and nonlinear analysis indicate the subcritical nature of the bifurcation points, which means the hysteresis behaviour.

The predictions of the theory suggest further experimental work in order to complete the diagram of stability, detect the hysteresis loop and measure the pattern sizes. Finally, the investigation of electrically induced magnetization patterning in the magnetic resonant tunnel diodes and related structures offers the new direction for further research.

6118-03, Session 1

Sub-picosecond exciton spin-relaxation in GaN

A. Tackeuchi, T. Kuroda, H. Otake, Waseda Univ. (Japan); K. Taniguchi, T. Chinone, N. Horio, Stanley Electric Co., Ltd. (Japan)

Exciton spin relaxation in bulk GaN was directly observed with sufficient time resolution. The obtained spin relaxation times are 0.47 ps - 0.25 ps at 150 K - 225 K. These are at least one order of magnitude shorter than those of the other III-V compound semiconductors. The spin relaxation time is found to be proportional to T -1.4, where T is the temperature. The spin relaxation time of the acceptor bound exciton at 15K is measured to be 1.05 ps.:The spin relaxation in semiconductors is of interest from the viewpoints of fundamental physics as well as the possible applications of spin-dependent optical nonlinearity such as all optical ultrafast switching, vertical cavity surface emitting laser diode and quantum computing. The spin-dependent pump and probe reflection measurement enables us to observe the spin relaxation process with an extremely high time resolution of 0.18 ps[1]. The sample is 2.2 μm thick GaN grown on a sapphire substrate following a 40-nm-thick GaN buffer layer by metal-organic chemical vapor deposition. Frequency-doubled femtosecond optical pulses generated from a Ti:sapphire laser are used as the pump and probe pulses. The circularly polarized pump pulse initially excites spin-aligned carriers, and then the circularly polarized time-delayed probe pulse detects the population change of the spin polarized carriers.

To excite the A-free excitons (FEA) resonantly, the energy of the excitation laser pulses was matched to the FEA PL peak (3.47 eV at 150 K). The spin polarization is clearly observed. The single exponential fitting gives the spin relaxation time of 0.47 ps[2]. This relaxation time is at least one order of magnitude shorter than 5.2 ps in InGaAs/InP multiple quantum wells (MQWs) and 32 ps in GaAs/AlGaAs MQWs[3]. The observed sub-picoseocnd spin relaxation shows the high potential of GaN as a promising material for the ultrafast optical devices. The spin relaxation time of the acceptor bound exciton at 15K is measured to be 1.05 ps.: The spin relaxation mechanism is known to be greatly affected by the band structure. The candidates of the spin relaxation mechanism revealing the strong temperature dependence are D'ya konov-Perel (DP) process which is induced by spin orbit-splitting and Elliott-Yafet (EY) process which is caused by carrier scattering. The fact that the spin relaxation time in GaN is shorter than that in GaAs, in spite of the small spin-orbit splitting, suggests that the spin relaxation is dominated by the EY process, which is considered to be strongly enhanced by the defects.:[1] A.Tackeuchi, S. Muto, T. Inata and T. Fujii, Appl. Phys. Lett. 56, 2213 (1990).

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6118-04, Session 1

Spin depolarization in semiconductor spin detectors

W. M. Chen, I. A. Buyanova, Linköpings Univ. (Sweden); Y. Oka, Tohoku Univ. (Japan); C. R. Abernathy, S. J. Pearton, Univ. of Florida

All-semiconductor spintronics has attracted increasing attention due to its promise to combine new spin enabling functionality with well-established electronic and optical properties that have widely been explored in the present microelectronics and optoelectronics. Among many challenges, efficient spin injection and reliable spin detection are among the key elements required for the success of future semiconductor spintronic devices. Non-magnetic semiconductor quantum wells and quantum dots have recently attracted great interest not only because they can be employed as convenient spin detectors to investigate spin injection efficiency from adjacent spin aligners based on e.g. diluted magnetic semiconductors (DMS), but also they form active regions of potential spin light-emitting devices such as spin-LEDs. Reliability and efficiency of a spin detector are determined by spin relaxation and depolarization processes within the spin detector, which still remain poorly understood to a large extent. Currently there is a great need to fully understand spin dynamics of spin detectors. In this talk we shall review our recent results from in-depth investigations of the degree of spin depolarization and the underlying physical mechanisms within semiconductor spin detectors based on II-VIs (e.g. Zn(Cd)Se) and III-Vs (e.g. Ga(In)N), by employing cw and time-resolved optical orientation spectroscopy in combination with tunable laser excitation. These spin detectors are relevant to applications for spin-LEDs based on ZnMnSe/Zn(Cd)Se and GaMnN/Ga(In)N. We shall show that spin depolarization within these spin detectors is very efficient, which is an important factor limiting efficiency of spin detection. Detailed physical mechanisms leading to efficient spin depolarization will be discussed. Effects of reduced dimensionality and quantum confinement on spin detection will also be examined.

6118-05, Session 1

Subpicosecond Faraday effect in Cd(Mn)Te diluted magnetic semiconductors

R. Sobolewski, D. Wang, Univ. of Rochester; A. Mycielski, Instytut Fizyki (Poland)

Diluted-magnetic semiconductors are natural materials-of-choice for spintronics and spin-related magneto-optic applications. Among them, the most studied is the Cd_1-xMn_xTe [Cd(Mn)Te] compound that can be produced both as single crystals and as nanostructures of the highest quality, even for very high Mn substitutions. We review here our research on time-resolved spin dynamics in Cd(Mn)Te single crystals with the Mn doping concentrations ranging from 9% to >50%. Our crystals were grown by a modified Bridgeman method and the x-ray diffractometry data were used to control the material stoichiometry and lattice uniformity. Using sub-picosecond electromagnetic transients generated by low-temperature-grown GaAs photoconductive switches, we have studied Mn spin dynamics via the measurement of the Faraday effect. Upon application to the Cd(Mn)Te crystal of a ~500-fs-wide magnetic transient generated by the GaAs switch, we observed a 860-fs-wide magneto-optic transient that can be considered as the upper limit of the Faraday response of the Cd(Mn)Te system. The current sensitivity of the measured magneto-optic effect was found to be 0.1 mA. The subpicosecond Faraday response was observed in all our Cd(Mn)Te samples and the amplitude of the effect was enhanced as we moved from room temperature to cryogenic temperatures. The observed ultrafast spin dynamics in Cd(Mn)Te is a combination of the rapid alignment of Mn spins by an external magnetic field, followed by almost instantaneous loss of the ìmagnetic memory.î The above behavior, combined with the Cd(Mn)Te giant magneto-optical effect, makes this material an excellent candidate for ultrafast nanostructured spintronic and magneto-optic devices and systems, including subpicosecond magneto-optical samplers and imagers, and ultrafast magneto-optical transducers and modulators.

6118-06, Session 2

Detection of high frequency acoustic transients using coherent EUV light

R. I. Tobey, M. E. Siemens, M. M. Murnane, H. C. Kapteyn, Univ. of Colorado at Boulder; K. A. Nelson, Massachusetts Institute of Technology

Light in the extreme ultraviolet (EUV) region of the spectrum is ideally suited for studying nanometer-sized features due to its short wavelength. Application experiments range from high-resolution imaging or microscopies, to various types of spectroscopies where the EUV light allows one to gain access to the core levels in many atoms, molecules and materials.

Traditionally, light in the EUV region of the spectrum has been generated using either synchrotron or laser plasma-based sources. More recently, the process of high harmonic generation (HHG) has received considerable attention, because it can generate beams of coherent EUV light up to keV photon energies, in an ultrafast pulse duration of femtoseconds-to-attoseconds. In the HHG process, intense visible-wavelength pulses are coherently upconverted into the EUV by focusing the fundamental laser into a gas. The ultrashort time duration of the generated harmonics, together with the compact nature of the source, is enabling several new dynamical imaging and spectroscopy experiments.

In this talk I will first discuss high harmonic generation as a light source. I will also present the first application of HHG for studying high-frequency surface acoustic waves in thin films. In these experiments, radiation at the laser fundamental frequency irradiates a sample in an interference pattern in order to generate the acoustic waves. The time delayed EUV light then probes the sample and diffracts from the surface acoustic waves. Using EUV radiation as the probe for such dynamical acoustic experiments has unique advantages over visible-wavelength probing of acoustic waves. The reduced wavelength allows one to probe higher frequency acoustic excitations, corresponding to shorter acoustic wavelengths. Furthermore, probing with EUV light provides large signal levels and excellent sensitivity to the surface modulation.

6118-07, Session 2

Thermal effects in 3D recording by femto/picosecond pulses

S. Juodkazis, H. Misawa, Hokkaido Univ. (Japan)

Thermal effects are unavoidable in laser material processing and are present, to some extent, even in the case when ultra-short (sub-picosecond) pulsed irradiation is utilized. We discuss here the matters of high-precision energy delivery into micrometer-sized volumes for three-dimensional (3D) laser microfabrication. Precise account of the absorbed energy, pulse duration, and focal spot size allows to control laser processing parameters and design required conditions for a particular laser microfabrication task. Examples of 3D nano/micro-structuring of resist, glass, and crystalline materials will be presented.

6118-08, Session 3

Thermal effects in femtosecond laser ablation of metals

C. Guo, Univ. of Rochester

Short-pulse laser ablation has found numerous applications in micromachining, thin-film deposition, laser microanalysis, and nanotechnology. These applications often require a detailed knowledge of thermal effects following laser ablation. Recently, we have systematically studied thermal energy effects in metals following femtosecond laser ablation. Our results show drastically different behaviors compared to some common beliefs in the field of ultrashort-pulse laser ablation. Furthermore, our study also characterizes experimental conditions to obtain technologically valuable surface micro- and nano-structures induced by femtosecond laser radiation.

6118-09, Session 3

Efficient frequency conversion of femtosecond and picosecond pulses into the visible and ultraviolet in novel quasi-phase-matched and birefringent materials

M. Ebrahim-Zadeh, Institut de Ciëncies Fotúniques (Spain) and ICREA-InstitucioCatalana de Recerca i Estudis Avancats (Spain)

Efficient second harmonic generation of ultrafast femtosecond and picosecond pulses into the visible and near-ultraviolet is reported using quasi-phase-matched nonlinear material, periodically-poled KTP and the new birefringent nonlinear crystal BiB3O6. Second harmonic average powers of nearly 1 W in the blue, tuning throughout 370-450, single-pass conversion efficiencies in excess of 50% and pulse durations from 200 fs to 3 ps have been achieved. Third harmonic generation of high-energy picosecond pulses at 355 nm at record conversion efficiencies of nearly 50% is also reported in BiB3O6.

The development of new nonlinear crystals with improved optical characteristics is of vital interest for a wide range of frequency conversion devices and applications. Over the past decade, a large number of birefringent materials including *-BaB2O4 (BBO), LiB3O5 (LBO), KNbO3 (KNB) and KTiOPO4 (KTP) have been successfully developed and utilised in variety of nonlinear optical applications. For visible and ultraviolet (UV) generation, BBO and LBO have been established as materials of choice, because of deep UV transparency well below 400 nm, high optical damage threshold, low cost and ready availability. However, the relatively low effective nonlinearities (deff~1-2 pm/V) render BBO and LBO particularly suitable for applications involving high pulse energies or limited phase-matching geometries.

For frequency conversion of continuous-wave (cw) lasers or low-intensity high-repetition-rate pulses, material requirements become substantially more stringent. The low available intensities necessitate higher material nonlinearity to compensate for reduced gain and the added requirements for tight focusing and long interaction length place further demands on the material for large angular acceptance bandwidths, low spatial walkoff, and often a noncritical phase-matching (NCPM) capability.

Quasi-phase-matched nonlinear crystals provide an important class of materials, offering large effective nonlinearities and flexible phase-matching properties, including NCPM. Of these, periodically-poled KTP (PPKTP) represents an attractive material candidate for the visible spectral range, due to increased resistance to photorefractive damage, high effective nonlinearity (deff~8pm/V), and transparency to below 400 nm. The advances in poling technology have now the fabrication of shorter grating periods of improved quality and uniformity, thus allowing the use of PPKTP for first-order QPM frequency conversion at lower wavelengths into the blue and the near-UV. At the same time, the recent development of new birefringent materials such Bismuth triborate, BiB3O6 (BIBO), with unique optical and phase-matching properties and improved nonlinearities compared with BBO and LBO have paved the way for efficient frequency conversion of ultrafast femtosecond and picosecond pulses into the visible and near-ultraviolet.

Here, we report efficient generation of high-repetition-rate femtosecond as well as high-energy picosecond pulses at wavelengths down to 355 nm based on second and third harmonic generation in PPKTP and BIBO. We have achieved second harmonic power and efficiency in the blue with PPKTP, providing 320 mW of average power at 20% conversion efficiency in ~700 fs pulses at 76 MHz. High-average-power second harmonic generation of picosecond pulses is also achieved in BIBO, providing nearly 1 W of average power at record conversion efficiencies in excess of 50% in ~3 ps pulses at 76 MHz. We also report similarly high conversion efficiencies, average powers, and output pulse energies with ultrafast femtosecond and picosecond pulses in different operating regimes and the results of these studies will be presented.

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6118-10, Session 3

GHz repetition-rate femtosecond sources with desired repetition-rate and wavelength

T. Liu, C. Yu, C. Sun, National Taiwan Univ. (Taiwan); F. X. Kartner, J. G. Fujimoto, Massachusetts Institute of Technology

In this talk, we will review our recent works about the GHz-repetition-rate (GRR) femtosecond lasers. These works make GRR femtosecond lasers more flexible in the manipulation of pulse repetition-rate and the operating wavelength. We first demonstrate a phase insensitive way to multiply the repetition-rate of a passive mode-locked laser in femtosecond regime. By inserting an intracavity flat surface with low reflectivity, we multiplied the repetition-rate of a femtosecond Cr:forsterite laser by ten times. It provides a simple and stable way to modify MHz-repetition-rate femtosecond lasers into GRR lasers. To achieve desired wavelength, which can't be directly generated by a gain medium, nonlinear conversion is required. But for GRR femtosecond lasers, the efficiency of single-pass conversion is low due to its low pulse energy. In order to increase the yield, we adopt the method of resonant-enhanced external cavity. With a resonant cavity matched to a 2-GHz repetition-rate Ti:sapphire laser, we demonstrated a high power femtosecond blue source at 2-GHz repetition-rate.

6118-11, Session 4

Ultrafast carrier dynamics in nano-clustered InGaN

H. Wang, Y. Lu, C. Chen, F. Jen, C. Yang, National Taiwan Univ. (Taiwan)

Because of the large lattice mismatch between GaN and InN, nano-scale indium composition fluctuation (or clustering) in an InGaN compound has been widely observed. This process leads to carrier localization and hence radiative efficiency improvement. For understanding the optical properties of such a material, ultrafast carrier dynamics observed with fs pump-probe experiments has been an effective tool for exploring the photon emission mechanisms. In this study, we perform fs degenerate and non-degenerate pump-probe experiments on an InGaN thin film, in which indium composition fluctuations have been identified with high-resolution transmission electron microscopy. In the degenerate pump-probe experiment for the thin film sample, we observed temperature-, pump-power-, and pump-photon-energy-dependent variations of carrier dynamics that are attributed to the variation of space-average density of state, transient carrier screening, local band gap renormalization, and band gap shrinkage in increasing temperature. In the non-degenerate experiment, when the pump is at 390 nm and the probe is at 400 nm, a fast increase of probe intensity in one ps and then a decay of tens ps in decay time constant are observed. As the probe level becomes even lower (with wavelengths at 410 and 420 nm), after the fast increases within one ps range, the differential transmission keeps increasing with a relatively shallower slope. The observed oscillation with a period of about 2.5 ps is similar to what we observed in the degenerate study on the same sample. It was attributed to the interaction of coherent acoustic phonon with carriers. It implies that a certain periodical structure with a scale of about 10 nm exists in the sample. In all these experiments, two-stage carrier thermalization processes can be observed. The first one is completed in 1 ps. It corresponds to the local thermalization process. The second one describes the global thermalization process. It takes a few ps near the free-carrier states. However, such a process takes a few hundred ps near the localized states.

6118-12, Session 4

Ultrafast intersubband relaxation dynamics and coherent nonlinearity in GaN/AlN multiple quantum wells

J. Hamazaki, Sophia Univ. (Japan) and Hokkaido Univ. (Japan); K. Ikuno, H. Kunugita, K. Ema, A. Kikuchi, K. Kishino, Sophia Univ. (Japan)

The electric relaxation process of intersubband transition (ISBT) is ultrafast due to strong electron-LO-phonon interaction. Recently, ISBT energies in GaN/AlN in multiple wells have covered optical communication wavelength. Therefore, ISBT has attracted much attention as promising candidate for all optical ultrafast devices. In the previous work, we clarified that ISBT relaxation dynamics contains two components, which are ultrafast (~140 fs) and slower (~1.3 ps) components corresponding to intersubband LO-phonon scattering time and carrier cooling time with hot-phonon effect, respectively.

In this paper, we have investigated ISBT optical nonlinear effect, using two-color pump-probe technique at room temperature. The pump and probe pulses were the signal and the idler pulses, respectively, produced by optical parametric amplifier (OPA). The temporal width of the optical pulse was approximately 100 fs. We have measured time-integrated pump-probe signal spectra, with 0.5 nm resolution. We have found a drastic spectrum change as a function of the delaytime. For delaytime of $t < 0$ ps, coherent spectrum oscillations have been measured. For $t \sim 0$ ps, the symmetric coherent oscillation is replaced by an asymmetric dispersive spectrum, while no spectrum change has been observed for $t > 0$ ps. From the detail analysis of these results we have investigated the coherent nonlinear properties and estimated some material parameters.

6118-13, Session 4

Ultrafast Raman scattering studies of electron transport in a thick InN film grown on GaN

K. Tsen, D. K. Ferry, Arizona State Univ.; W. J. Schaff, H. Lu, Cornell Univ.

Non-equilibrium electron distributions and electron drift velocities in InN have been studied in a thick InN film grown on GaN by using picosecond/subpicosecond transient Raman spectroscopy at T = 300 K. The built-in electric field, which is of the order of 100 kV/cm and mostly due to the spontaneous polarization effects of the sample, was utilized as the applied electric field for the electron transport measurements. Electron drift velocity as large as 7.5 x 10 ** 7 cm/sec was observed for excitation laser with pulse width of about 600 fs. Our experimental results suggest that InN has great potential for the manufacturing of ultrafast electronic devices.

6118-14, Session 4

Time-resolved photoluminescence of Mg-doped AlN epilayers

N. Nepal, M. L. Nakarmi, J. Y. Lin, H. Jiang, Kansas State Univ.

AlN is emerging as an important semiconductor material due to its applications in deep ultraviolet (UV) optoelectronic devices. For device applications, conductive AlN and AlxGa1-xN alloys with high x are essential. Compared to n-type doping, p-type doping in AlxGa1-xN alloys with high x has been proven to be extremely difficult due to high activation energy of Mg dopant. Due to good insulating nature of high x Mg-doped AlxGa1-xN alloys, a useful characterization method is to study optical properties of these materials. Understanding optical properties not only helps to characterize materials but also is very useful to probe their fundamental properties. Mg-doped AlN epilayers grown by metalorganic chemical vapor deposition have been studied by deep UV time-resolved photoluminescence (PL) spectroscopy. A PL emission line at 6.02 eV has been observed at 10 K in Mg-doped AlN, which is about 40 meV below the free-exciton (FX) transition in undoped AlN epilayer. Temperature dependence of the PL intensity of this emission line also reveals a binding energy of 40 meV. This transition line is believed to be due to the recombination of an exciton bound to neutral Mg acceptor (I1) with a binding energy of, Ebx = 40 meV. The recombination lifetime of the I1 transition in Mg doped AlN have been measured to be 130 ps, which is close to the expected value. Excitation intensity dependence of time-resolved PL for Mg-doped AlN epilayer is also measured to understand carrier and exciton dynamics.

6118-15, Session 5

Femtosecond spectroscopy of unipolar nanometer-scale high-field transport in GaAs

M. Betz, Technische Univ. München (Germany)

Femtosecond high-field transport in GaAs is investigated tracing ultrafast modifications of the Franz-Keldysh absorption spectrum of AlGaAs heterostructure diodes. A sophisticated sample design allows to isolate unipolar contributions to the transport dynamics in combination with a nanometer scale definition of layers for both photoexcitation and detection of the propagating carriers. This novel all-optical technique is applied to various aspects of ultrafast charge dynamics in semiconductors:

(i) Isolating the contribution of nonequilibrium holes, we directly measure transient carrier velocities and spatial broadening of a hole ensemble for electric fields between 15 kV/cm and 200 kV/cm. Especially, we compare room temperature operation to results for T = 4 K. Even at low temperatures, the transient hole velocities are found not to exceed a value of 1.2 x 10^7 cm/s which is a result of ultrafast optical phonon emission with a surprisingly small scattering time below 25 fs.

(ii) For the case of unipolar electron transport, we find an ultrafast velocity overshoot and quasi-ballistic electron motion with an average velocity of 5.4 x 10^7 cm/s over distances as large as 300 nm.

(iii) For electric fields F > 350 kV/cm the dynamical build-up of a nonequilibrium carrier avalanche due to impact ionization is directly analyzed in the time domain. Most interestingly, the timescale of the carrier multiplication is found to be in the order of 10 ps depending on the applied bias.

Monte Carlo simulations in a simplified band structure agree well with the experiment.

6118-16, Session 5

Analysis of photoluminescence decay of excitons in CuInS2 crystals

K. Wakita, Osaka Prefecture Univ. (Japan)

The ternary semiconductor CuInS2 has attracted interest as a promising material for nontoxic, high-efficiency, thin-film solar cells. However, basic physical and defect-related properties of this compound have not been clearly understood. Although we have investigated excitonic properties of CuInS2 crystals with the aid of measurements of photoluminescence, photoacoustic phenomena and resonant Raman scattering, the knowledge obtained from such steady-state measurements is limited.

In order to obtain a basic understanding of recombination processes in CuInS2 we have used pico-second time-resolved photoluminescence spectroscopy to study the decay of excess electrons after pulsed excitation.

Samples used for the measurements were bulk-single crystals of CuInS2, grown by the traveling heater method, where crystals are grown from solution. In the near band-edge region, the observed photoluminescence spectrum consists of three bound exciton peaks at 1.530 eV, 1.525 eV and 1.520 eV and a shoulder of free excitons at 1.535 eV at 10 K.

The decay of free exciton emission exhibits a double exponential curve at low temperature. The decay-time constant of the fast component increases monotonically with excitation density, whereas that of the slow component appears to be independent of excitation density. From this result, the fast and slow components are attributed to nonradiative and radiative

recombination processes, respectively. The radiative lifetime of free excitons is estimated to be 320 ps at 10 K. In order to confirm our estimated value of the radiative lifetime, we have also investigated temperature dependence of the free exciton photoluminescence.

On the other hand, it is found from the analysis of bound exciton decay that radiative decay of the bound exciton at 1.530 eV is exponential with two characteristic decay-times, while that of the bound excitons at 1.525 and 1.520 eV is well-represented by a single exponent at low temperatures. The radiative lifetimes of the bound excitons at 1.530, 1.525, and 1.520 eV have been measured as 500 ps, 2.1 ns, and 3.5 ns, respectively. According to our estimates, a neutral charge should be assigned to the defect centers associated with the observed bound excitons.

6118-17, Session 5

Study of the dynamics of cold excitons in Cu2O

M. Kuwata-Gonokami, The Univ. of Tokyo (Japan)

Photo-generated electrons and holes in semiconductors provide a unique opportunity to examine macroscopic quantum phenomena such as Bose-Einstein condensation (BEC) of excitons. The 1s para-excitons of the yellow series in Cu2O have completely parallel electron-hole spin states and an extremely long lifetime. Although much effort has been devoted, para-exciton dynamics is still not well understood since there is no sensitive method for the direct detection of para-excitons, since there is no sensitive method for the direct detection.

We developed a time resolved mid-infrared pump and probe spectroscopy to detect para-excitons by measuring the absorption associated with internal excitonic transitions (1s to np). Because of the large difference in the electron-hole exchange energy between the 1s and 2p excitons (12 and nearly 0 meV respectively), we can distinguish ortho-excitons and para-excitons. By using a two-photon resonant excitation scheme of 1s-ortho-excitons, we successfully observed excitonic Lyman transitions from 1s to np (n=2,3,4,5) with a high spectral resolution. We confirmed that 1s ortho-excitons are excited in a super-cooled state, colder than the lattice temperature (4.2K). We examined the wave function of the 1s exciton state and found a 7.9 ≈ Bohr radius from a systematic analysis of the absorption lines. [1] We also found efficient ortho to para-exciton transformation. [2] Based on these results, we discuss possible scenarios to reach exciton BEC.

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6118-18, Session 6

Femtosecond buildup of phonon-plasmon coupling in photoexcited InP observed by ultrabroadband THz probe

R. Huber, Technische Univ. München (Germany); C. Kübler, Univ. Konstanz (Germany); S. Tübel, Technische Univ. München (Germany); A. Leitenstorfer, Univ. Konstanz (Germany)

Optical phonons in polar semiconductors may couple to density waves of a carrier plasma via their longitudinal electric field, leading to the formation of phonon-plasmon hybrid modes[1]. Quantum kinetic calculations have suggested that this mixing should not occur instantaneously after femtosecond photogeneration of an electron-hole plasma[2]. In our contribution, we report on the first direct observation of the ultrafast transition of an optical phonon resonance to a coupled phonon-plasmon system[3]. The experiment is based on latest developments of ultrabroadband THz spectroscopy and high-repetition-rate femtosecond amplifier technology[4,5].

After ultrafast photoinjection of a dense electron-hole plasma (N = 2 x 1018 cm-3) in i-InP, we employ the two-dimensional multi-THz spectroscopy developed in references 3 and 6: The polarization response of the non-equilibrium semiconductor is probed in real time by a single-cycle electromagnetic pulse of a duration of 27 fs and a central frequency of 28 THz, at time delay tD after excitation. Ultrabroadband electro-optic detection allows us to monitor both amplitude and phase of the probe electric field as a function of a second delay time T[4,5]. We directly observe the delayed buildup of coherent beats of the emerging hybrid modes. The femtosecond dynamics of the complex dielectric function of the excited semiconductor is retrieved at frequencies between 7 THz and 60 THz[3,6]. The imaginary part of the inverse dielectric function reflects the buildup of dissipation in the non-equilibrium lattice-plasma system: A quasi-instantaneous response immediately following photoinjection characterizes a yet uncorrelated many-body ensemble. Within 150 fs two maxima corresponding to the lower and upper branch of the phonon-plasmon mixed modes develop simultaneously. The real part of the inverse dielectric function describes the renormalization of electric fields via screening by the many-body system. Quasi-particle cor˙relations which are a prerequisite for well-defined collec˙tive hybrid modes are observed to form on a delayed femtosecond time scale. Varying the excitation density over two orders of magnitude, the anticrossing of the coupled modes is mapped out as a function of time and density. The buildup time of phonon-plasmon coupling is measured to be one oscillation cycle of the upper branch of the hybrid modes. The observations have been quantitatively reproduced by recent quantum kinetic calculations[3].

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6118-19, Session 6

Terahertz radiation from semiconductor surfaces in magnetic fields at high-density excitation

M. Nakajima, The Univ. of Tokyo (Japan)

We investigated the radiation mechanisms of THz radiation from semiconductor surfaces at high-density excitation under a magnetic field. Excitation density dependences of radiation intensity and the waveforms of the terahertz radiations from InAs and semi-insulating InP surfaces were investigated with and without magnetic fields (0, 2T, and -2T). Substantial changes of the intensity and the waveforms including a polarity reversal were observed. In InAs, the enhancement of the radiated energy is observed under a magnetic field of ±2T and the radiated energy increases quadratically with increasing the excitation density below 0.1 microJ/cm2. The behavior of the dependence for ±2T changes clearly around 1 microJ/cm2. The radiated energy for 0, ±2T cross each other around 1.0 microJ/cm2. The radiated energy for +2T is smaller than that without the magnetic field above 1 microJ/cm2 while that for -2T is larger than that for 0T. In order to clarify the origin of this anomaly, we have done the THz radiation waveforms measurement, and particularly we focused the waveform polarity which is determined by the direction of the transient photocurrent. We extracted the magnetic field induced (B-induced) component and it is found that the waveform polarities of the B-induced component for 2T and -2T reverse at 1 microJ/cm2. The anomalous excitation density dependence can be explained by the combination of the B-induced component and the component without the magnetic field. The polarity reversal indicates that the dominant radiation mechanism of the B-induced component changes around 1 microJ/cm2. At the conference, we will also show the results for semi-insulating InP.

6118-20, Session 6

Terahertz wave generation and propagation in thin film ferroelectric crystals

D. W. Ward, E. Statz, Massachusetts Institute of Technology; R. M. Roth, R. M. Osgood, Jr., Columbia Univ.; K. A. Nelson, Massachusetts Institute of Technology

Terahertz phonon-polariton generation and real-space imaging with femtosecond optical pulses are demonstrated in thin films (10-50 microns) of single-crystalline lithium niobate and lithium tantalate. The thin film dispersion properties were characterized throughout the polariton wavelength range of 5-100 μm, revealing substantial slab waveguide behavior at the longer wavelengths.

6118-21, Session 6

Carrier dynamics in ion-implanted semiconductors studied via simulation and observation of terahertz emission

J. Lloyd-Hughes, E. Castro-Camus, Univ. of Oxford (United Kingdom); M. D. Fraser, H. H. Tan, C. Jagadish, The Australian National Univ. (Australia); M. B. Johnston, Univ. of Oxford (United Kingdom)

Broadband sources of terahertz (THz) radiation have enabled terahertz time-domain spectroscopy to become a valuable tool in condensed matter physics, with industrial applications in medical and security imaging. High power THz radiation can be obtained from emitters based on the ultra-fast separation of photo-excited carriers under an electric field, which typically produce single-cycle electromagnetic pulses.

In order to increase the application of these emitters it is desirable to widen their spectral range. One method of decreasing the pulse duration (and thus broadening the spectrum) is to reduce the electric field decay time after excitation by choosing a semiconductor with a short carrier trapping time and/or a large momentum scattering rate. We obtained such a material using high energy ion implants to create defects to trap and scatter carriers. By using two implants at different energies a uniform damage profile was created, extending over the absorption depth of the semiconductor.

We have experimentally measured the THz radiation from a series of ion-implanted semiconductors, both from the bare semiconductor surface and from photoconductive switches. GaAs was implanted with As+ ions, and InGaAs and InP with Fe+ ions, and all samples were annealed post implantation. An increase in THz power at high frequencies is observed, which we attribute to the ultrafast trapping of carriers. We use a three-dimensional carrier dynamics simulation to model the emission process. The simulation accurately predicts the experimentally observed bandwidth increase, without resorting to any fitting parameters.

6118-22, Session 6

Extraordinary single cycle terahertz transmission through ensembles of sub-wavelength size metal particles

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

We report on experimental observations of coherent electromagnetic energy transmission through three-dimensional random metallic media having sub-wavelength heterogeneity (i.e. metallic powder). Single cycle terahertz pulses are shown to propagate coherently over sample distances that are orders of magnitude greater than the skin depth. Collectively, the metal particle ensembles behave like a dispersive, lossy dielectric. A non-exponential inverse dependence of the transmission power on the sample thickness departs from predictions for both diffusive and ballistic photon propagation. The preservation of the radiation polarization state in addition to strong dispersion of the transmitted pulse suggest that the transmission is mediated by near-field coupling of surface plasmon modes across the extent of the system. These modes, propagating with measured velocities of approximately 0.5 c, transport electromagnetic energy across the system such that the metallic medium exhibits unusually high transparency. To fully explore this phenomenon, we investigate the effects of particle size, shape, metal type, and conductivity on the temporal characteristics of the transmitted radiation. Finite difference time domain simulations of electromagnetic wave propagation support the experimental observations and show that electromagnetic energy transport is due to near-field plasmonic coupling between particles. The model also predicts the existence of near-field localized electromagnetic modes that are not observable in the far field. These findings pave the way for new studies of electromagnetic interaction in dense random metallic systems. Possible applications are discussed.

6118-23, Session 6

Photonic anisotropic magnetoresistance in sub-wavelength size Co particles

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

Metallic powders exhibit high terahertz electromagnetic transparency due to coherent near-field coupling of surface plasmon across the extent of the medium. As electromagnetic conduction in these dense metallic particle collections is solely mediated by coupled surface plasmon oscillations, such media exhibit global optical properties that are highly sensitive to the particles' electrical and magnetic characteristics. This sensitivity allows active control of plasmonic propagation. Here, we experimentally investigate single cycle terahertz pulse transmission through dense, random ensembles of sub-wavelength ferromagnetic Co particles. Due to the magnetoresistance inherent to the ferromagnetic metal, the optical properties of the Co particle ensembles are shown to be strongly magnetically dependent. In particular, time domain characterization of the terahertz transmission reveals that the pulse propagation time and pulse amplitude depend strongly on the orientation of a biasing magnetic field relative to the incident pulse polarization. We show that this anisotropy maps itself onto an apparent terahertz optical birefringence of the metallic powder. Using a two-dimensional finite difference time domain simulation, the results are qualitatively understood as arising from the cumulative effect of anisotropic magnetoresistance acting on surface plasmon oscillations on individual Co particles. The findings represent the first integration of magnetoresistive effects into plasmonic systems. This novel magnetic effect will have potential application in active terahertz photonic devices.

6118-41, Session 6

Photon-excited fluorescence of rare-earth ions-doped gasses by femtosecond laser irradiation

M. Nogami, Nagoya Institute of Technology (Japan)

Fluorescence properties of rare-earth ions doped in glasses have stimulated much interest because of their fundamental and applicable studies. Here, I report the enhanced- and up-converted-fluorescence properties of the Eu3+ ions-doped Al2O3-SiO2 glasses by femtosecond laser irradiation.

When the glass was irradiated by the femtosecond-pulsed laser with a 800 nm wavelength, strong emissions were observed at 577, 589, 614, 651 and 700 nm which are assigned to the transitions from the 5D0 to 7FJ (J= 0, 1, 2, 3, 4) of the Eu3+ ions, respectively. The dependence of the intensity of the Eu3+-emission on the pump power reveals that the three-photon excitation is dominant in the up-conversion process. The analysis of the up-conversion mechanism indicates that the up-conversion fluorescence comes from the three-photon simultaneous absorption that leads to the population of the 4f levels via the excitation of the charge transfer state of the Eu3+ ions.

The glasses, prepared to codope Sn4+ and Eu3+ ions by a sol-gel method, were irradiated by femtosecond-pulsed laser. Upon laser irradiation, the Sn atoms were activated to react with oxygen, resulting in the formation

of SnO2 nanocrystals. The precipitated SnO2 crystals grew up to ca. 5 nm size by the Joule-heating effect of the laser. The fluorescence intensities of the codoped-Eu3+ ions were enhanced higher than 100 times that of the glass without nanocrystals by exciting with the energy corresponding to the absorption edge of the SnO2 nanocrystals, the energy of which is effectively transferred to the Eu3+ ions.

6118-24, Session 7

Optical nonlinearities and the ultrafast phase transition of VO2 nanoparticles

R. Lopez, R. F. Haglund, Jr., L. C. Feldman, Vanderbilt Univ.; L. A. Boatner, T. E. Haynes, Oak Ridge National Lab.; M. Rini, A. Cavalleri, R. W. Schoenlein, Lawrence Berkeley National Lab.

We study the ultrafast insulator-to-metal transition in nanoparticles of VO2, obtained by ion implantation and self-assembly in silica. The nonmagnetic, strongly correlated compound VO2 undergoes a reversible phase transition, which can be photoinduced on an ultrafast time scale. In the nanoparticles, prompt formation of the metallic state results in the appearance of a surface plasmon resonance. Z-scan and pump probe measurements were used to compare the optical nonlinearities of the VO2 nanoparticles with thin films in both semiconducting and metallic states. In the metallic state, both the nanocrystals and thin films exhibit a positive, intensity dependent nonlinear index of refraction. However, the nonlinear effects are relatively larger in the VO2 nanocrystals, which also reveal a saturable nonlinear absorption. When the semiconductor-to-metal phase transition is induced by the laser pulse, VO2 thin films exhibit a negative equivalent nonlinear index of refraction while the nanocrystals exhibit a smaller but still positive index. Both the VO2 nanocrystals and thin films undergo the phase transition within 120 fs.

6118-25, Session 7

Time-resolved and time-integrated spectroscopy studies of the optical properties of silicon quantum dots

D. V. Lap, X. Wen, P. Hannaford, Swinburne Univ. of Technology (Australia)

At present the growth and study of quantum structures based on Si, the most technologically important material for electronic device in the 20th century, attracts great attention. Efficient light emission from Si quantum structures has led to the current interest in Si for optoelectronic devices, but the origin of the light emission from an indirect band-gap semiconductor is still under debate. Using of time-resolved, time-integrated photoluminescence and three pulse two colour photon echo we study the dephasing time, the state-filling effect and the carrier lifetime of quantum dot energy states. In these experiments the femtosecond pulses are generated by two independently tunable optical parametric amplifiers (OPA) pumped by a 1 mJ amplified pulse (80 fs, 800 nm, 1 kHz) with wavelengths in the region 400-800 nm and a pulse energy of 1-100 mJ. The filling of low energy states and the parabolic confinement of quantum dot structures can be inferred from the dependence of photoluminescence intensity on the excitation intensity. The emitted intensities from different quantum dot levels decay with a stretched exponential function in the range 2 - 100 ms depending on the observation wavelength and the dot size. The dephasing time of 1-1.8 ps which is slightly dependent on quantum dot energy states can be measured. We show that dephasing time of the electrons in quantum dots is strongly influenced by the density of excited carriers.

6118-26, Session 7

Direct observation of the electron spin relaxation induced by nuclei in quantum dots

X. Marie, Institut National des Sciences Appliquées de Toulouse (France)

We have studied the electron spin relaxation in semiconductor InAs/GaAs quantum dots by time-resolved optical spectroscopy. The average spin polarization of the electrons in an ensemble of p-doped quantum dots decays down to 1/3 of its initial value with a characteristic time T~500 ps, which is attributed to the hyperfine interaction with randomly oriented nuclear spins. We show that this efficient electron spin relaxation mechanism can be suppressed by an external magnetic field as small as 100 mT.

6118-27, Session 7

Ultrafast deformation dynamics of silver nanoparticles in glass induced by femtosecond laser pulses

G. Seifert, A. V. Podlipensky, H. Graener, Martin-Luther Univ. Halle-Wittenberg (Germany)

Glass containing spherical silver nanoparticles shows a strong extinction band in the visible range due to the surface plasmon resonance (SPR) of the particles. Irradiating this material with intense, ultrashort laser pulses with a wavelength close to the SPR leads to permanent changes of its optical properties. In particular, using linearly polarized pulses, we observed strong dichroism; the latter is nanoscopically caused by deformation of the particles to ellipsoidal shapes with an additional halo of small silver particles around the central one, with a preferential orientation. In case of a single laser shot of sufficient intensity this orientation is orthogonal to the laser polarization, whereas multi-shot irradiation usually causes preferential orientation along the laser polarization. This effect is quite useful for the production of dichroitic or polarizing microstructures, and optical elements or optoelectronic devices.

In this paper we describe the results of a variety of experimental studies (mostly femtosecond laser pump-probe, electron microscopy, photoluminescence) on the understanding of the physical processes, which show clearly that ultrafast ejection of electron and silver ions into the glass matrix is the starting mechanism, whereas in the course of deformation diffusion processes controlled by the local temperature play a decisive role for the final particle shapes (and thus the optical properties after laser treatment).

6118-28, Session 7

Time-resolved spectroscopy of metal nanoellipsoid

L. H. Acioli, M. H. G. Miranda, E. L. Falcão-Filho, J. J. Rodrigues, Jr., C. B. de Ara˙jo, Univ. Federal de Pernambuco (Brazil)

Metallic nanoparticles (NP) draw intense scientific interest due to their unique physical properties, which differ from those of bulk and atomic species. Nowadays, the aim of this research area is focused, for example, in the nonlinear (NL) optical properties of NP, the dynamics of confined electrons and the possibility of photonic applications. In this work both the nonlinear optical properties and the transient response of non-spherical nanoparticles are studied.

Exploiting the large sensitivity of the Z-scan technique, we have studied the high order NL response of silver colloids. The third-, fifth-, seventh- and ninth-order of NL response were observed. A comparison of the results with the predictions of an effective-medium theory is made and values for the NL susceptibilities are obtained. To provide a quantitative description we consider the intrinsic third- and fifth-order nonlinearity of the silver NP.

Regarding the transient response, two differently prepared colloids are examined: one sample has a broad distribution of sizes and shapes of silver nanoparticles, while the second sample, which is processed by laser ablation, presents a more uniform size and shape distribution (greater fraction of spherical particles). The experiments are performed with a Ti:sapphire femtosecond laser using a two-color, polarization-resolved, pump-probe setup. The pump pulse at ≈ 800 nm excites intraband transitions, heating the electronic distribution, while the probe pulse is scanned

around the peak of the Surface Plasmon Ressoance (SPR): ≈ 400 nm. It is observed that for the pristine colloid (non-spherical) the signal amplitudes of the probe polarizations parallel and perpendicular to the pump polarization present different behaviors as a function of the probe photon energy. The same effect is not observed for the laser ablated samples, which is isotropic. The temporal response of the samples is also different, with the laser ablated samples presenting faster electronic cooling rates. A model describing the induced dichroism that takes into account the shape of the colloid particles is presented. The effects of the size distribution on the nonlinear optical response are also discussed.

6118-29, Session 7

Magnetization-induced second-harmonic generation of cobalt and cobalt oxide nanoparticles

Y. Chang, National Taiwan Univ. (Taiwan)

Magnetization-induced second-harmonic generation (MSHG) in transverse Kerr configuration is used to explore the nonlinear magneto-optical properties of cobalt (Co) and cobalt oxide (CoO) nanoparticles at room temperature. The nanoparticles are deposited on Si (001) substrate by a RF magnetron sputtering system at room temperature. The STM image of the studied sample indicates that the cobalt particle size is in the range of 15 nm to 25 nm. MSHG technique can investigate their magnetic property and determine their crystal and magnetic symmetry. Pure cobalt nanoparticles behave a large nonlinear Kerr rotation response with a low external magnetic field. The increase of coercivity field, Hc, in the cobalt - cobalt oxide nanoparticles, can be attributed to the strong interaction between the ferromagnetic cobalt and anti-ferromagnetic cobalt oxide interface. It is found that the magnetic anisotropy is due to the shape anisotropy of cobalt nanoparticles. MSHG measurement furthermore reveals that the magnetization reversal process of cobalt nanoparticles involves the rotation of the magnetic moment in the surface plane but not the surface normal plane.

6118-30, Session 8

Nanoscale coherent acoustic phonon imaging

B. C. Daly, T. B. Norris, Univ. of Michigan; S. Pau, College of Optical Sciences/The Univ. of Arizona; D. M. Tennant, J. A. Taylor, J. E. Bower, Lucent Technologies

It is apparent that advances in nanoscience and nanotechnology are dependent on improving our capability to image objects at the nanoscale. One particular challenge that must be overcome is how to image subsurface or buried nanostructures. Toward that end, we have developed an ultrafast opto-acoustic technique for imaging nanoscale objects deposited on crystalline substrates.

When an ultrashort (~100 fs) optical pulse is absorbed in a thin metal layer, the resulting thermal expansion launches a broadband acoustic pulse with a peak frequency and bandwidth on the order of 100 GHz. These high frequency acoustic waves (also called coherent acoustic phonons or picosecond ultrasonics) have wavelengths of less than 100 nm in crystalline solids, and so the possibilities for high-resolution imaging are very real. The acoustic waves cause reflectivity changes in the sample that are detectable by time-delayed optical probe pulses. Previous work has established that this technique is ideal for measuring the thickness of thin metallic and insulating films in microelectronic structures. More recently, we have shown that by allowing the coherent acoustic phonons to propagate, and thereby diffract across a macroscopically thick (~ 1 mm) layer, that 2-D imaging with sub-micron resolution is possible.

Here we present 2-D acoustic images of lithographically patterned Al film structures grown on a Si substrate with ~700 nm resolution. Plans for improving resolution down to the acoustic phonon diffraction limit of ~ 50 nm are also described. Finally, we present our first data from a subsurface object, showcasing the exciting possibilities of nanoscale sub-surface acoustic imaging.

6118-31, Session 9

Picosecond x-ray studies of coherent folded acoustic phonons in a multiple quantum well

P. Sondhauss, J. Larsson, M. Harbst, O. Synnergren, Lunds Univ. (Sweden); A. Plech, Univ. of Konstanz (Germany); G. A. Naylor, K. Scheidt, M. Wulff, European Synchrotron Radiation Facility (France); J. S. Wark, Univ. of Oxford (United Kingdom)

Coherent zone-folded longitudinal acoustic phonons (ZFLAPs) in a multilayered GaSb/InAs epitaxial heterostructure were detected via time resolved X-ray diffraction (TRXD)[1].

Ultrafast TRXD is a novel technique to study interatomic processes, such as chemical reactions or lattice dynamics in real-time. It has become feasible by recent developments in X-ray source and detector technology. Unlike techniques probing with visible light, IR or UV radiation, TRXD supplies direct evidence for the atomic structure. This in combination with being a real-time technique gives the most straightforward and unequivocal view on atomic motion.

Coherent ZFLAPs were generated by rapid heating of the heterostructure's cap layer with femtosecond laser pulses. According to Newton's third law the quick onset of thermal expansion leads to a sonic wave, i.e. a coherent set of phonons. These phonons were detected via time resolved X-ray diffraction[2-5]. X-rays were delivered from an undulator in the ESRF electron synchrotron storage ring. Subpicosecond time resolution was obtained via an ultrafast X-ray streak-camera[6].

From a comparison with simulations it was found that the laser penetration depth was shorter than one would expect if interband absorption was the only absorption mechanism. The reduction of penetration depth is most likely due to free-carrier absorption by photo-excited carriers.

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6118-32, Session 9

Engineering quantum evolution in nanostructures: from ultrafast control to sustainability

A. Matos Abiague, A. S. Moskalenko, J. Berakdar, Max-Planck-Institut für Mikrostrukturphysik (Germany)

The ultrafast, coherent control of the evolution of quantum systems constitutes an issue of particular relevance from both the fundamental and practical viewpoints, with some important potential applications for the design of efficient optoelectronic devices and in quantum computation. In this talk we discuss the possibility of controlling the electronic motion in semiconductor nanostructures by driving the system with appropriately designed, external time-dependent fields. We also investigate the important question of how to make the control process sustainable in time. After a general analysis of the geometric properties (geometric phases and quantum lengths) of quantum evolution, we deduce necessary and sufficient conditions for achieving a time sustainable control process. These conditions constitute the basis for engineering the evolution of quantum systems and are in turn used for determining the field parameters capable of inducing sustainability. On the basis of our general predictions we demonstrate theoretically the possibility of an efficient subpicosecond manipulation of the electron motion in AlxGa1-xAs based multiple quantum wells by driving the system with appropriately designed, state-of-the-art, time-dependent fields. Furthermore, the dynamics of driven semiconductor quantum rings as well as the generation of photo-induced charge polarization and magnetization in such heterostructures

are particularly addressed. Potential applications in designing new artificially nanostructured materials will also be discussed.

6118-33, Session 9

Coherent plasmons in InSb

M. P. Hasselbeck, D. V. Seletskiy, M. Sheik-Bahae, R. Dawson, The Univ. of New Mexico

We study coherent plasmons in semiconductors by measuring the far-infrared electromagnetic radiation they emit. Collective oscillations are excited by ultrashort laser pulses (mode-locked Ti:sapphire laser generating near-infrared pulses of duration ~ 50 fs) and detected in the far-field with a Michelson interferometer arrangement and a Si bolometer detector cooled to 4 K[1]. The interferometric scheme provides broadband, high frequency response compared to gated photoconducting antennas. In addition, there is no Reststrahl absorption and dispersion often encountered in electro-optic sampling of THz pulses. Our technique does not, however, provide phase information of the THz electric field relative to the excitation laser pulse.

Measuring the light radiated by coherent dipoles has a distinct advantage compared to pump-probe experiments involving only ultrashort laser pulses, i.e. reflective electro-optic sampling. Because of the small penetration depth, probe laser pulses detect both cold background carriers and hot photocarriers injected by the pump pulse at the semiconductor surface[2]. Separating hot and cold carrier contributions to the plasma dynamics can be difficult. THz radiation experiments, in contrast, only detect the coherent motion of cold plasmons[3,4].

Coherent bulk plasmons are characterized by measuring the frequency and coherence length of the emitted far-infrared radiation as a function of temperature, doping, crystal orientation to the laser field, and pump irradiance. The semiconductor InSb is an attractive crystal for studying coherent plasmons because its high mobility leads to long-lived oscillations. It can be grown very pure, which allows the intrinsic carrier concentration to be adjusted by many orders of magnitude by changing the sample temperature. In this way, the center frequency of the radiation can be temperature-tuned. Our experiments provide insight on the starting mechanism of the coherent oscillations, their spatial extent, and rate of damping[5].

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6118-34, Session 9

Optical quantum control using quantum dots

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

The control of quantum states is a key prerequisite in quantum information processing. Owing to the large Coulomb energies, the exciton-biexciton system in II-VI quantum dots is well suited to study and to implement optical concepts for this control.

The exciton, split by anisotropic electron-hole exchange in a fine structure doublet, enables to prepare a quantum bit by proper photon polarization. Distinct quantum beats in the exciton emission confirm indeed the formation a coherent superposition. The quantum coherence times are longer than the radiative life-time of the exciton.

Entangled states that have no classical counterpart are of particular importance in quantum information. The biexciton is an entangled state of two excitons and exhibits a binding energy as large as 20 meV in II-VI quantum dots. Direct coherent control of the biexciton is achieved by using resonant two-photon excitation with a pair of phase-correlated ultra-short pulses. On the other hand, by stimulating the biexciton-exciton transition with a subsequent pulse, the biexciton can be disentangled in a controlled way. Applications in quantum logics as well as how this allows to trigger single-photon as well as photon-pair emission are discussed.

Charged quantum dots enable the control of the carrier spin. The potential of the trion state, representing the fundamental optical excitation in these dots, is investigated. Novel optical and magnetic anisotropies are observed that are crucial for the spin manipulation. The low-temperature spin relaxation times are on the 10 ns-time scale.

6118-35, Session 10

Nonradiative recombination effect on photoluminescence decay process in GaInNAs/GaAs quantum wells at low temperature

Z. Y. Xu, Z. Sun, B. Sun, Y. Ji, H. Ni, Z. Niu, Institute of Semiconductors (China)

Nonradiative recombination effect on photoluminescence decay process in GaInNAs/GaAs quantum wells at low temperature

Z.Y.Xu,* Z.Sun, B.Q.Sun, Y.Ji, H.Q.Ni, and Z.C.Niu

State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
* zyxu\@red.semi.ac.cn

GaInNAs/GaAs heterostructures have received increasing attention in the past few years due to their potential applications in optical fiber communications. However, an increase in N composition, needed for reaching the desired long wavelength, has been found to induce large number of non-radiative recombination centers, resulting in the degradation of material quality and consequently a poor luminescence efficiency.

In this work, we have performed temperature-dependent photoluminescence (PL) and excitation-power-dependent time-resolved PL (TRPL) to study the nonradiative recombination effect on the optical properties of GaInNAs/GaAs quantum wells (QWs). The samples were grown by solid source MBE. It is found that the integrated PL intensity decreases more than one order of magnitude even in a small temperature range from 10K to 25 K under low excitation. This result is in striking contrast to many other semiconductor compounds, where the PL intensity almost keeps unchanged in the low temperature range, as the PL at low temperature is usually dominated by radiative recombination. The rapid decrease of PL intensity indicates that the nonradiative recombination process plays a very important role even at low temperature in GaInNAs.

In the TRPL measurement, we have found that the PL decay process of GaInNAs QWs shows a significant difference under different excitation power. First, the PL decay time is short under low excitation and becomes longer under higher excitation. These results can be well understood by nonradiative recombination effect. A short PL decay time at small excitation power could be caused by the dominance of nonradiative recombination, and the increase in PL decay time at higher excitation power due to saturation of the nonradiative centers so that the PL lifetime tends to the longer radiative lifetime. Second, the shape of PL decay curves is changed under different excitation power. At small excitation, the decay curve displays a straight line and can be well fitted by a single exponential function with a time constant of 280 ps. As the excitation power increases the decay curves become non-exponential and show convex shape. The PL decay displays a straight line again under high excitation. We believe that the above results are related to the different involvement of nonradiative recombination centers, which makes the overall probability of luminescence be a function of time. We have used the rate equation to numerically calculate the PL decay process. In the calculation, the ratio between the effective density of nonradiative centers (Neff) and the photoexcited carrier density (N0) is used as a fitting parameter. According to this model, PL is dominated by radiative recombination as Neff/N0 ~0, and controlled by nonradiative recombination when Neff/N0 ~1. The decay curves display straight lines for above two extreme cases, while the decays show more or less convex shape in between. The detailed fitting process and underlying physics will be discussed.

6118-36, Session 10

Time-resolved photocurrent spectroscopy of optically excited superlattices and the prospects for Bloch gain

A. Lisauskas, C. Blöser, R. Sachs, H. G. Roskos, Johann Wolfgang Goethe-Univ. (Germany); A. Juozapavicius, G. Valusis, Puslaidininkiu fizikos institutas (Lithuania); N. Demarina, Nizhny Novgorod State Univ. (Russia); K. Köhler, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

We report on the evolution of the electric field in undoped GaAs/AlGaAs semiconductor superlattices subjected to femtosecond optical excitation. The drift of the charge carriers after the optical excitation leads to the build-up of an inhomogeneous electric field which was experimentally deduced from spectral changes of Wannier-Stark transitions. We used a modification of the time-resolved pump-probe technique and measured the photocurrent generated by a spectrally narrowed probe beam as a function of delay time, pump power and bias field. Although the photocurrent spectra by themselves only yield information on the absorption integrated spatially over the superlattice, we extract information on the local electric fields and charge carrier densities by a comparison of the measured data with the results of numerical simulations. We find that even at moderate excitation densities (< 10^16 cm^-3) the superlattice rapidly splits into two moving field regions, one with strong field gradient and low electron density, the other with partially screened field at low gradient and high electron density. The field across the superlattice becomes most inhomogeneous where the electrons are already swept-out. The initial homogeneous electric field distribution is restored on a much longer time scale which is defined mostly by the drift of the holes.

This study was performed as part of the preparation for terahertz-pulse-amplification experiments employing the so-called Bloch gain. We intended to address the question to what extent dynamical field inhomogeneities are tolerable in such experiments. Our calculations show that Bloch gain in optically excited semiconductor superlattice is quite robust against field variations. It is expected in spite of the inhomogeneous field if the electron-rich region is not heavily screened. The time window during which Bloch gain exists is determined by the sweep out of the electrons and can be found on the time scale of 10-30 ps depending on the superlattice parameters and the excitation conditions.

6118-37, Session 10

Dynamic quantum wells on highly electronically excited surfaces of crystalline semiconductors and semimetals

S. I. Kudryashov, Arkansas State Univ.

Appearance of dynamic quantum wells with tunable optical spectral response at high electronic excitation levels of surfaces of semiconductor crystalline materials by intense femtosecond laser pulses is theoretically predicted, being directly supported by recent experimental data. The microscopic mechanism of this phenomenon involving quantized coherent deformation-potential electron-optical phonon interaction, and its potential applications in nano-photonics are discussed.

6118-38, Poster Session

Ultrafast frequency dynamics of coherent phonons in Te under high density photoexcitation

M. Kandyla, C. A. Roeser, E. Mazur, Harvard Univ.

We report on the ultrafast dynamics of large amplitude A1 coherent optical phonons in Te after excitation with femtosecond laser pulses. Using time-resolved pump-probe dielectric tensor measurements on a single crystal Te sample we can monitor the excitation of the A1 phonon mode due to photoexcited carrier density redistribution. By performing a short-term Fourier transform of the observed dielectric tensor oscillations we can track the evolution of their local frequency and determine the time-resolved frequency response of the photoexcited A1 phonon mode.

The purpose of the experiment is to determine if mode anharmonicity (due to the large amplitude of the induced oscillations) or phonon mode softening (due to perturbation of the harmonic potential by the photoexcited carriers) dominates the frequency dynamics of the coherent phonons. Reflectivity-based studies of coherent phonons in Bi reveal a linear relationship between the local frequency and the square amplitude of the oscillations, which is expected for an anharmonic potential. Softening is also observed but is significantly weaker than anharmonicity. In contrast, we do not observe any anharmonic behavior in our data, but only mode softening. Therefore, in agreement with theoretical predictions, mode softening is more important in Te than mode anharmonicity.

6118-39, Poster Session

Effects of spatial reproduction at the interference of the electron waves in semiconductor 1D nanostructures with parabolic quantum wells

V. A. Petrov, A. V. Nikitin, Institute of Radio Engineering and Electronics (Russia)

Effects of spatial inhomogeneity for the probability current density jx (x, z) (or a quantum - mechanical current density ejx (x, z), e is the electron charge) in the semiconductor 1D nanostructures in the form of joints in the direction of propagation of the electron wave (the x-axis) of narrow rectangular and wide parabolic (on the z-axis) quantum wells (QWs) (z-axis is the axis of the quantization) have been theoretically studied. Special attention is given to effects of spatial reproduction for electron waves in such nanostructures. It is shown that transverse distribution jx (0, z) existing at the entry of the wide QW is reproduced with some accuracy at a definite distance L from the joint. This picture is reproduced periodically in cross-sections M(p) = pL (p are integers). The inhomogeneous distribution of the jx (x, z) arises because of the interference of electron waves spreading in the wide QW simultaneously in different electron subbands in the ballistic regime. The results of numerical calculations of this effect in symmetric structure and its modification in asymmetric (on the z-axis) nanostructure are given. This work was supported by the Russian Basic Research Foundation, grant 01-02-17450.

6118-40, Poster Session

Contact resistance dynamics at bimetallic interfaces investigated by ultrafast terahertz surface plasmon-mediated transmission spectroscopy

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

Particles composed of more than one noble metal species are the subject of increasing research interest in the field of plasmonics. Particularly, multi-metallic multi-layered structures exhibit tunable plasmonic properties that strongly depend on the composition and distribution of the constituent metallic species. However, the precise influence of the metallic interface on the plasmonic dynamics remains an unresolved issue. At optical frequencies, the role of the interface in bimetallic nanoparticles and its inherent contact resistance has yet to be elucidated. This difficulty arises from challenges in assembling nanometer sized bimetallic layers on the order of the optical penetration depth (~10 nm) while maintaining the nanoparticle dimensions. In addition, inter-metallic diffusion over nanoscale distances prevents the formation of a well-defined interface and affects the interfacial chemistry. Here, we employ terahertz time domain spectroscopy to investigated the surface plasmon propagation through random ensembles of Cu microparticles partially coated with an Au nanoshell. We find that increased Cu-core Au coverage not only drastically reduces the transmitted terahertz electric field amplitude, but also significantly modifies its phase. The amplitude and phase behaviour in the bimetallic particles is attributed to the inherent contact resistance between dissimilar metals at the nanoshell-core interface. These findings provide a macroscopic analogue of plasmonics in bimetallic nanoparticles and pave the way for novel terahertz spectroscopic studies of bimetallic nanolayers.

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6119-01, Session 1

Solar-blind AlGaN 256x256 p-i-n detectors and focal plane arrays

M. B. Reine, A. W. Hairston, P. Lamarre, K. Wong, S. P. Tobin, A. K. Sood, C. Cooke, BAE Systems; M. Pophristic, S. Guo, B. Perez, EMCORE Corp.; R. Singh, C. R. Eddy, Jr., Boston Univ.; U. Chowdhury, M. M. Wong, R. D. Dupuis, The Univ. of Texas at Austin; T. Li, S. P. DenBaars, Cree Lighting

We have developed 256x256 solar-blind UV Focal Plane Arrays (FPAs). These hybrid UV FPAs consist of a 256x256 back-illuminated Al(x)Ga(1-x)N p-i-n photodiode array that is bump-mounted to a matching 256x256 silicon CMOS readout integrated circuit (ROIC) chip.

The first layer in the back-illuminated AlGaN p-i-n photodiode is a silicon-doped n-type AlGaN window layer that serves as the common n-side contact to all elements in the 256x256 array. The alloy composition of this layer determines the cuton wavelength. The next layer is an unintentionally-doped n-type AlGaN absorber layer, with a smaller band gap than the window layer, that forms an isotype heterojunction with the window layer. The alloy composition of the absorber layer determines the cutoff wavelength. The final layers include a Mg-doped AlGaN p-type layer that forms a p-n homojunction with the n-type absorber layer, and a Mg-doped GaN layer that facilitates the p-side contact.

The x-values for the Al(x)Ga(1-x)N window and absorber layer in these solar-blind arrays are set at x=0.60 and 0.47 to provide cuton wavelengths of 260 nm and cutoff wavelengths of 280 nm. The solar-blind spectral region is generally defined as wavelengths less than approximately 280 nm. At these wavelengths, atmospheric ozone strongly absorbs solar radiation, preventing it from reaching the earth's surface.

The back-illuminated AlGaN p-i-n photodiode operating at zero bias voltage has a number of advantages. Because it operates at zero bias voltage, 1/f noise is not an issue. Because the device is designed so that the absorber layer is fully depleted at zero bias voltage, quantum efficiencies are high; photocarrier collection does not depend on carrier diffusion, which is an important consideration for a material such as AlGaN in which the reported diffusion lengths are quite short (<0.1 μm).

Our back-illuminated AlGaN p-i-n mesa photodiode arrays were fabricated from multilayer heterostructure AlGaN films grown by MOCVD onto 2 inch dia. c-plane double-side-polished sapphire substrates. Mesas were etched by the Inductively Coupled Plasma (ICP) process to assure minimal damage at the mesa surface.

This paper summarizes the results achieved in this three-year program.

We have improved MOCVD growth conditions and designs for high-x AlGaN films grown on sapphire in multi-wafer (3-6 films per run) reactors to achieve:

• Spectral response in the 260-280 nm band;

• High conductivity in silicon-doped n-type AlGaN (x up to 0.60): n=4e18 cm-3 and μH=25 cm≤/V-s for x=0.60;

• High quantum efficiency and high R0A products in back-illuminated p-i-n AlGaN photodiodes: QE(external) up to 51.5% at 272 nm for zero bias voltage (no A/R coating); and R0A products >3e10 ohm-cm2

We have implemented 2" dia. full-wafer processing, with excellent uniformity and control of ICP dry etch depth. We use probe features to measure I(V) and QEversus wavelength for wafer mapping and array screening. We have formulated analytical and numerical (Silvaco) models to fit QE data versus wavelength and voltage. We have designed and implemented a new low-noise input circuit in 256x256 CMOS readout chips that has achieved 9 noise electrons rms measured at 12 Hz frame rate.

We have demonstrated high-operability solar-blind AlGaN UV FPAs. These are data for one of our recent FPAs:

Format	256x256 with 30x30 μm≤ unit cells;
Spectral band	cuton=262 nm, cutoff=278 nm;
QE(external) at V=0	44.5 % at 270 nm (no A/R coating);
Response uniformity	6 %;
Response operability	99.8 %;
R0 (median)	4.3e15 ohm; and
R0A product (median)	3.1e10 ohm-cm≤

This paper will discuss these results, and will present performance data for 256x256 UV FPAs formed by hybridizing recently fabricated, solar-blind back-illuminated AlGaN p-n-N arrays to our new low-noise 256x256 silicon CMOS ROIC chips. We will include AlGaN UV FPAs, all hybridized at BAE Systems onto ROIC chips, with AlGaN solar-blind arrays coming from four different sources. AlGaN p-i-n films (2" dia.) were grown at Emcore and at the University of Texas, and were processed at BAE Systems into 256x256 arrays. AlGaN films were grown and partially processed at Cree and at the University of Texas with a BAE Systems mask set, and processing was completed at BAE Systems.

6119-02, Session 1

Long wavelength MSM photodetectors fabricated on InGaNAs

F. L. Gouin, J. P. Noad, E. Higgins, D. Coulas, Communications Research Ctr. Canada (Canada)

Recently there has been a great deal of interest in the growth of dilute nitride quaternary alloys, such as InGaNAs, on GaAs substrates for the fabrication of GaAs-based components and optoelectronic integrated circuits. The addition of indium to the binary compound GaAs produces a ternary with a lower bandgap and larger lattice constant. The incorporation of nitrogen in this ternary further decreases the bandgap while reducing the lattice constant. This makes it possible to grow material lattice-matched to a GaAs substrate but with a narrower bandgap offering the possibility of growing materials suitable for opto-electronic devices on a GaAs substrate while operating at wavelengths used in long-distance optical communication. These devices can then be integrated with mature GaAs device technologies (MESFET, HBT) in photoreceivers and receivers/transmitters for improved functionality and reliability, lower cost, reduced size, etc.

We have fabricated MSM photodetectors on 1-μm thick In. 11Ga.89N.04As.96 epi-layers, a composition that results in a bandgap in the 1.3 μm region. We report on the DC characteristics, frequency dependence and wavelength dependence of the photoresponse. The results are compared to MSMs fabricated on GaAs and InGaAs-on-InP. The temporal response is not as fast as that of GaAs MSMs and may be related to low carrier mobility. This shortcoming has been reported as the cause for the lower-than-expected efficiency of solar cells fabricated using this quartenary. The effect of material and device layout on detector characteristics such as bandwidth and dark current were investigated. The challenges associated with the use of InGaNAs in photodetectors (such as defects, response speed, requirement for thermal anneal) will be discussed.

6119-03, Session 1

Enhancement of the D* of quaternary GaInAsSb 2.0-2.5 micron P-I-N detectors by light doping of the absorbing region

J. Yager, C. Cao, M. Reddy, J. Olesberg, J. P. Prineas, The Univ. of Iowa; M. Santilli, L. Olafsen, Univ. of Kansas

Quaternary GaInAsSb semiconductor alloys are a promising material for detectors in the 2.0-2.5 micron wavelength region, also called the combination region. The combination region is an important wavelength range in the optical sensing of biomolecules, such as glucose, both due to the transmission window in water as well as the unique optical (vibrational-

rotational) transitions that occur for e.g. glucose at those wavelengths. The band gap of GaInAsSb can be varied over the combination range while keeping the material lattice matched to the GaSb substrate. Lattice matching is important for the reduction of dark current in detectors, and for high-yield fabrication of pixels in focal plane arrays.

It has been hypothesized that light doping of the intrinsic region (hereafter referred to as the absorbing region) of a p-i-n quaternary GaInAsSb detector should enhance the D*, an important figure of merit. To test this hypothesis, a series detector structures were grown by molecular beam epitaxy with varying doping levels in the absorbing region and processed into mesa diodes by wet etching. Results show an enhancement in D* for both light p- and n-doping of the absorbing region.

6119-04, Session 1

Influence of nonradiative surface recombination on the performance of superlattice InAs/InGaSb mid- to long-wave infrared P-I-N mesa diode detectors

J. P. Prineas, J. Olesberg, C. Cao, M. Reddy, J. Yager, M. E. Flatte, The Univ. of Iowa; M. Itzler, M. Maiorov, Princeton Lightwave, Inc

In recent years, research on type-II superlattices that consist of thin layers of InAs/InGaSb has shown the potential for high-sensitivity, high-temperature operation that can outperform existing long-wave infrared detectors. These binary/ternary superlattices have great design flexibility that allows engineering of both the band gap and the band structure. For example, by varying layer thicknesses within a superlattice period, bandgaps can be achieved from 0 meV to 400 meV. Indium content in the GaSb layer can be used to engineer the energy of conduction and valence subbands in order to suppress Auger scattering rates, which are the predominant mechanism for nonradiative recombination in the long-wave infrared. By controlling interface type and indium content, superlattices can also be lattice-matched to GaSb substrates over the whole range of bandgap energies.

A potential limiting mechanism to the high performance of small, mesa-processed diodes is surface recombination, in which electrons and holes recombine nonradiatively either on sidewalls or the top of the mesa. Here, we report on the impact of nonradiative surface recombination on the performance of superlattice InAs/InGaSb mid- to long-wave infrared mesa-processed detector diodes. For this study, a series of 4- and 8-micron p-i-n superlattice structures were grown by molecular beam epitaxy both with and without a degenerately-doped top GaSb window layer. Wafers were processed into mesa-diodes by wet-etching with varying perimeter-to-area ratios to characterize surface recombination and extract device intrinsic performance.

6119-05, Session 1

Electronic characteristics of doped InAs/GaAs quantum dot photodetector: temperature dependent dark current and noise density

C. Liau, Chung-Cheng Institute of Technology (Taiwan); S. Tang, Chung-Shan Institute of Science and Technology (Taiwan); T. Chen, Chung Cheng Institute of Technology (Taiwan); C. Chiang, S. Yang, Chung-Shan Institute of Science and Technology (Taiwan)

The noise characteristics associated with dark current, photoconductive gain (PC), capture probability in doped InAs dots embedded in GaAs spacer layer have been proposed. The photoconductive and photovoltaic behaviors of the InAs/GaAs quantum dot infrared photodetector (QDIP) from the intersubband transition measurements are also clearly observed. Through noise measurement in dynamic signal analyzer (HP35670A), the electronic bandpass filter frequencies are set up ranging from 3 to 10 KHz in a low noise current preamplifier (SR570). The lock-in amplifier (SR830) can be also used to measure and calibrate the noise density by means of the mean average deviation (MAD) contrast with noise spectra from HP35670A. The InAs/GaAs QDIP studied in this work belongs to n+-n-n+ structure with the top and bottom blocking barrier layers. It is observed that the two blocking layers of QDIP not only suppress dark current successfully but also probably reduce the photocurrent. By systematically optoelectronic measurements and simulations, the modified model of noise current, photoconductive gain, and capture probability in the quantum devices have been proposed. It is shown that photoconductive gain is almost independent of bias under the lower bias, then increasing exponentially under higher bias and below the temperature of 80K. In contrast to quantum well infrared photodetector (QWIP), a higher photoconductive gain of the quantum dot infrared photodetector has been demonstrated and attributed to the longer lifetimes of excited carriers in quantum dots. At 77K, a photoconductive gain of tens of thousand is shown in the regions of higher biases. With increasing temperature from 20 to 300K, the QDIP dark current density increases exponentially from 2.6E-8 to 47.3A/cm2 under the bias of 0.2V, while the noise current density from 2.0E-18 up to 2.0E-16 A/Hz1/2.

6119-06, Session 2

Development of a solid state photomultiplier based on an array of Geiger mode CMOS avalanche photodiodes

W. G. Lawrence, C. Stapels, Radiation Monitoring Devices, Inc.; F. Augustine, Augustine Engineering; J. F. Christian, Radiation Monitoring Devices, Inc.

We report the development of a photon-counting solid-state photomultiplier which consists of an array of Geiger mode CMOS avalanche photodiodes (APDs). The detector is based on the design described by Buzhan et. al.[1] in which the individual outputs of an array of Geiger APDs are coupled together to drive a common output signal. The total output signal is a sum of the Geiger outputs of each individual pixel in the array. For a large array, the sum of the discrete pixel signals is an analog representation of the flux on the detector. We present results for a 48 element array of Geiger mode APDs that is fabricated using standard CMOS processes. We will also describe the effort to maximize the dynamic range using integrated active quenching, and minimize the optical cross-talk between array elements.

(1) Buzhan, P. et al. Nucl. Ins. Meth. Phys. Res. Sec.A, vol 504, 2003

6119-07, Session 2

Developments in single photon avalanche photodiodes with fast timing resolution

N. Bertone, OptoElectronic Components (Canada)

Until very recently Single Photon Avalanche Diodes (SPAD), which yield high detection efficiency in the visible spectrum, provided poor timing performance. This paper will review the current state of the SPAD technology and review new SPAD developments that provide; sub 50ps-timing resolution, are stable with count rate, and yield high detection efficiency. Examples will be provided; comparing timing resolution of PMTs and solid-state photon counting modules, effect of count rate on timing resolution, thus illustrating the stability of these newly developed SPAD's.

In addition, the paper will review the basics of photon counting using SPAD's and illustrate how these SPAD's are used in Time-Correlated Single Photon Counting (TCSPC) and the results from these experiments.

6119-08, Session 2

Design and development of scalable 4096x4096 single photon detection UV focal plane array with high quantum efficiency

A. K. Sood, E. J. Egerton, Y. R. Puri, Magnolia Optical Technologies, Inc.; T. A. Cook, Boston Univ.

In this paper we will present design approach for UV Photon Counting Focal Plane Array that is buttable to make 4096x 4096 UVFPA.This Focal Plane includes building of a large area silicon microchannel plate (MCP) using GaN photocathode.

In this paper, we will show the Design and simulation of silicon microchannel plate with GaN photocathode in large area array with 2 micron pores and 3 micron pitch.

We will also discuss the ICP-RIE (Inductively Coupled Plasma) process to fabricate 2 micron pores. We will also discuss the approach for Growth of high conductivity GaN photo-cathodes using MOCVD to produce 40% QE.

We will also present the approach for development of readout architecture and circuit for Silicon based MCP 4096x4096 UV FPA.

6119-09, Session 2

Scalable Geiger/APD/PIN multichannel sensing platform

S. Buckley, R. Wilcock, A. Mathewson, J. C. Jackson, SensL Technologies Ltd. (Ireland)

Previous generation low light detection platforms have been based on the photomultiplier tube (PMT) or the silicon single photon counting module (SPCM) from Perkin Elmer. A new generation of silicon CMOS compatible photon counting sensors are being developed offering high quantum efficiency, low operating voltage, high levels of robustness and compatibility with CMOS processing for integration into large format imaging arrays. This latest generation yields a new detector for emerging applications which demand photon counting performance providing high performance and flexibility not possible to date.

We describe a 4-channel photon detection platform which allows the use of 4 separate photon counting detectors in either free space or fibre coupled mode. The platform is scalable up to 16 channels with plug in modules allowing active quenching or Peltier cooling as required. A graphical user interface allows feedback and control of all device parameters. We show a novel ability to integrate separate detection modules to extend the dynamic range of the system. This allows a PIN or APD mode detector to be used alongside sensitive photon counting detectors. An advanced FPGA and microcontroller interface has been designed which allows simultaneous time binning of counting rates and readout of the analog signals when used with linear detectors.

This new architecture will be discussed, presenting a full characterisation of count rate, quantum efficiency, time binning and sensitivity across the broad spectrum of light flux applicable to PIN diodes, APDs and Geiger-mode photon counting sensors.

6119-10, Session 2

Study of the properties of new SiPM detectors

F. Quinlan, L. Wall, A. Mathewson, J. C. Jackson, SensL Technologies Ltd. (Ireland)

Due to their large active area, robustness, low operating voltage and ability to withstand large magnetic fields, silicon photomultipliers (SiPM) have emerged as a new generation of detector for high energy physics, medical imaging and other light sensitive detection applications. These applications have historically been served by photomultiplier tubes (PMT). In particular SiPM's low sensitivity to magnetic fields is important for many high-energy physics experiments where they can be used to realise new detection platforms combining positron emission tomography (PET) with magnetic resonance imaging (MRI). The SiPM is based around the parallel implementation of a number of individually operating Geiger-mode pixels. Each pixel incorporates its own passive quenching circuit fabricated with silicon CMOS processing techniques. The outputs from the individual pixels are summed together to form the output for the detector array. This integration allows the single Geiger-mode pixels to sense when an individual photon has been detected. Each pixel, then converts the photon into charge which is then summed at the output of the array. The SiPM provides an analog output which has a varying current level for varying photon fluxes. This provides a large area, very sensitive detector which is ideal for many applications where a large, sensitive detector is required.

We will show the results of full characterisation of devices from single pixel (10-20um) to larger format arrays up to 4x4 mm. Leakage current, breakdown voltage, quantum efficiency, and pulsed laser stimulation measurements will be presented. The effect of different passive quench resistor values and readout methods will be discussed and compared with conventional Geiger-mode detectors, with current state-of-art PMT detectors and with full device and system level simulation.

6119-11, Session 3

Novel black silicon PIN photodiodes

A. M. Moloney, Dublin Institute of Technology (Ireland); L. Wall, A. Mathewson, G. Healy, J. C. Jackson, SensL Technologies Ltd. (Ireland)

The many advantages of silicon such as low cost, abundancy and a level of maturity that allows for very large scale integration, means that silicon is the most commonly used semiconductor in microelectronics and optoelectronic devices. Silicon, however, has one disadvantage, this being that it is unable to absorb light greater than 1100nm. The two primary telecommunications wavelengths, 1300nm and 1550nm, can therefore not be detected. An interesting method used to extend silicon's wavelength range is the formation of black silicon on the silicon surface. Black silicon is formed when gases that are passed over the silicon react and etch the silicon surface, forming a dark spiky pattern. This paper presents novel black silicon PIN photodiodes of various sizes (25mm2, 4mm2 and 1mm2). The diodes have been extensively characterized at wafer level, with threshold voltage, breakdown voltage, ideality factor, saturation current, dark current, shunt resistance and junction capacitance measurements being made. Further measurements of spectral responsivity and bandwidth will be made when the devices are packaged. These results together with the existing results and a detailed comparison with similar standard silicon PIN diodes will be presented in the final paper.

6119-12, Session 3

Noise performance and temperature coefficients studies for the back-illuminated, thin silicon pin photodiode arrays

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

Noise characteristics of the backlit, pin photodiode arrays having different vertical structures were studied. We showed that in many cases, the non-optical crosstalk between adjacent elements determines the noise performance and detectivity of the array pixels. For the arrays with the structure described in our recent works (see e.g. US Patent No. 6,672,4735 B1, Goushcha et al., Jul 13, 2004), the crosstalk always remained well below 0.01%, which allowed to reach the minimum noise level of ~10E-15 A/(sq.rt_Hz) determined by the thermal noise. In contrast, for the arrays built applying conventional structures the crosstalk was two orders of magnitude higher, which noticeably decreased the sensitivity of the pixels increasing their noise and switching their operation towards background-limited performance. The background signal originated from the non-optical crosstalk and produced a noise level significantly higher that the thermal noise. We also compared the temperature coefficients for different arrays. For the structures described in the cited above reference, the measured value of the shunt resistance temperature coefficient

was typically below 8 %/C and the responsivity temperature coefficient value did not exceed +0.02%/C within the spectral range from 450 through 800 nm. The advantages and drawbacks of application of the reported in this work photodiode arrays in high quality imaging systems are discussed.

6119-13, Session 3

CID25- radiation hardened color video camera

D. A. Baiko, Thermo Electron, CIDTEC and Rochester Institute of Technology and Ioffe Physical Technical Institute (Russia); S. K. Bhaskaran, S. W. Czebiniak, Thermo Electron, CIDTEC

Charge injection device, CID25, is presented. CID25 is a color video imager. The imager is compliant with NTSC interlaced TV standard. It has 484 by 710 displayable pixels and is capable of producing 30 frames-per-second color video. CID25 is equipped with preamplifier-per-pixel and parallel row processing for high conversion gain and low noise bandwidth operation. An on-chip correlated double sampling circuitry serves to reduce the low frequency noise component. CID25 is operated by a camera system consisting of two parts, the head and the camera control unit (CCU). The head and the CCU can be separated by up to 150 m long cable. The CID25 imager and the head portion of the camera are radiation hardened. They can produce color video with insignificant S/N degradation out to at least 2.5 Mrad of total dose of Cobalt 60 radiation. This represents the first in industry radiation hardened color video system, based on a semiconductor photodetector, that has an adequate sensitivity for room light operation.

6119-14, Session 3

Development of a 300,000-pixel ultrahigh-speed, high-sensitivity CCD

H. Ohtake, T. Hayashida, K. Kitamura, T. Arai, J. Yonai, K. Tanioka, H. Maruyama, Japan Broadcasting Corp. (Japan); T. G. Etoh, Kinki Univ. (Japan); D. Poggemann, A. Ruckelshausen, Univ. of Applied Sciences Osnabrück (Germany); H. van Kuijk, J. Bosiers, DALSA BV. (Netherlands)

Our goal is to develop an ultrahigh-speed, high-sensitivity broadcast camera that is capable of capturing clear, smooth slow-motion videos even in cases where lighting is limited, such as at professional baseball games played at night. In 2003, we developed an ultrahigh-speed, high-sensitivity triple CCD color camera using an 80,000-pixel ultrahigh-speed, high-sensitivity CCD. This color camera had about 10 times the sensitivity of standard high-speed cameras, and enabled an entirely new style of presentation for sports broadcasts and science programs. In order to develop an ultrahigh-speed camera with higher image quality for use in broadcasting, we have developed a first 300,000-pixel ultrahigh-speed, high sensitivity CCD that is capable of 1,000,000 frames per second.

The ultrahigh-speed, high-sensitivity CCD has a special configuration with large area photodiodes for each pixel, and a CCD memory that is directly connected to those photodiodes. We developed a new ultrahigh-speed, high sensitivity CCD with the following unique features:

In order to increase the capture time during ultrahigh-speed capturing, the CCD memory cell has been reduced in size and the number of frames increased, enabling an image recording capacity of 144 images, an increase of about 1.4 times.

We split up the horizontal CCD to achieve eight parallel outputs, so that in the case of speeds up to 1,000 frames per second, a external memory can be used for extended continuous capturing.

In the future, we will develop a four-CCD color camera compliant with the HDTV resolution by using the pixel offset method.

6119-15, Session 3

The photoelectric characteristics semiconductor nanostructures on a basis c-Si and GaAs

R. S. Udovitska, O. V. Vakulenko, S. V. Kondratenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

During experiment some spectra of different photo diodes on basis Si and GaAs have been measured the purpose - to compare their properties. It is determined, that the structure nanodimension Ge\c-Si and Al0.2Ga0.8As/In0.1Ga0.9As/GaAs is sensitive in infrared area. The sample has been made by a method molecular-beam epitaxy. And also the analysis of measurements of relief surfaces on AFM has been carried out. Experiment was carried out on installation IκS-12. Analysis of received results have shown that the spectrum Al0.2Ga0.8As/In0.1Ga0.9As/GaAs differs from standard GaAs photodiode by wider spectral sensitivity range owing to creation of nanodimensional layers Al0.2Ga0.8As/In0.1Ga0.9As on the GaAs substrate. It gives the possibility to detect optical irradiation. That results in an opportunity to use a sample for manufacturing photodetectors with the improved characteristics. They have sensitivity in IR-area (1-5mkn) in the room temperature. The same measurements were also made for the structures Ge\c-Si with further comparison of received results to standard Si photodiode.

Spectral dependence of photoconductivity having measured at the room temperature. Have determined, that the form of spectra has the similar form. Hence our sample can be used for manufacturing photodetectors. Under the schedule we can assume, that the structure is sensitive in infrared area. To determine in what range sensitive. A sample cooled up to temperature 77κ-100K.We had 6 samples with good sensitivity in IR-area.

The photoconductivity spectrum of nanodimensional Ge/c-S i structure was received at room temperature. At measurements of photoconductivity of structure. It is necessary to note that photoconductive signal was 3 orders less, than at inverse displacement. It specifies presence heterotransitions between Ge and *-S i layer. The photosensitivity of a standard silicon photodiode was investigated for comparison of such assumption.

The value of photosensitivity of a researched sample was compared with the standard photodiode. Is established, that both these values are of the same order. It is possible to explain it by presence of a potential barrier between Ge and Si.

It is known that longwave border of photoconductivity is defined by width of the forbidden zone of the semiconductor. The increase of photoconductivity is caused by increase of absorption at rising of quantums energy of the exited radiation (at reduction of wavelength). The form of a photoconductivity spectrum of the photodiode FD-142κ and absence of a hole in the spectrum in short-wave area (1,5-2,1 mkn) specifies that the speed of a surface recombination is equal to zero. For the structure nanodimensional Ge/ c-S i, otherwise, significant hole in this area was observed at the room temperature. So, samples had the large speed of surface recombination.

To observe the contribution of nonequilibrium charge carriers to the photoconductivity of structure nanodimensional Ge/c-S i it is necessary to cool down to T < 100 K. The intersubband transitions can occur in nanodimensional Ge at such temperatures. So, it is necessary to expect observation of a photosensitivity in the infrared, which corresponds energy of these transitions. It is possible to explain photosensitivity of nanostructures by existence of interzoned transitions in nanodimension Ge. The spectral dependence of photosensitivity of structure nanodimension Ge/c-S i in IR- of area is received (1-4mkn).

6119-16, Session 3

Characterization of the high speed CMOS image sensor

D. Raghu, J. D. Rogers, T. S. Tkaczyk, E. L. Dereniak, M. R. Descour, College of Optical Sciences/The Univ. of Arizona; T. Erickson, Black Forest Engineering

No abstract available

6119-17, Session 4

Progress in development on CdZnTe x-ray detector

Y. Zhou, MicroPho Corp.; Y. Chen, Optics Innovation LC; J. Wang, A. Wan, MicroPho Corp.

X-ray detector has been playing very important role in space observation, homeland security and medical application etc. Semiconductor has been very successful in visible light and Infrared radiation detections. For high-energy photon detection, such as X-ray, semiconductor detector is still in developing.

Semiconductor detectors will offer much better spatial and energy resolutions over traditional X-ray detectors. Cadmium zinc telluride (CdZnTe or 'CZT' is current the material that has emerged to be the best candidate function as X-ray detector. Scientists are still work on pushing the energy resolution of CdZnTe X-ray detector to even higher recorder, even a prototype CZT gamma camera has been demonstrated that achieve 3-4% FWHM resolution, which already much better than traditional techniques.

For CdZnTe X-ray detection, material growth technique is under developing. A real single CdZnTe ingot is currently still a dream. Material quality may be the bottleneck for the energy resolution of detector. But device process techniques are also waiting for improving. Surface polishing, ohm contact and surface passivation are all very important for the final device performance, which are still not well developed.

Another thing, which is suffering CdZnTe detector, is polarization. This is very harmful especially for the application of medical application, such as computer tomography (CT). People are still not very sure what is the mechanism of polarization. It could be the dislocation or impurity inside the CdZnTe single crystal or located in the surface or interfaces of semiconductor and metal.

In order to achieve high spatial resolution, electrode patterning to make pixel arrays with small pixels must be developed on top of clean and fresh CdZnTe surface. Shadow mask is still used for current application of CdZnTe Detector fabrication. For higher resolution, photolithograph technique must be developed on CdZnTe device process.

In this paper, well-developed surface polishing technique is used for CdZnTe surface preparation. The final surface of CdZnTe crystal was observed by X-ray Photoelectron Spectroscope (XPS), which proves the CdZnTe surface is free of Te precipitate.

2-dimensional electrode pixel arrays, 3x3 to 32x32, were fabricated by using photolithograph technique. 10μm guard rings also achieved for each metal pixel. The special surface passivation technique was developed for the final CdZnTe detector.

Device test results prove that by the application of new device process techniques, device polarization has been significantly suppress. Detail will be presented.

6119-18, Session 4

Room temperature narrow band photodetectors for the midinfrared

M. Boeberl, Johannes Kepler Univ. Linz (Austria); T. Schwarzl, J. Roither, T. Fromherz, G. Springholz, W. Heiss, Johannes Kepler Univ. Linz

Absorption line strengths are much stronger in the midinfrared spectral range than in the nearinfrared region. Thus, for sensitive gas analysis and atmospheric pollution monitoring highly efficient optoelectronic devices for the midinfrared are required. For portable gas detection systems, infrared spectrometers and other applications, one obvious requirement is to avoid the need for cryogenic cooling of the system components, including also the detectors.

After demonstrating the first resonant-cavity enhanced lead-salt detector for the midinfrared with a Dl/l of 2% and operation temperatures up to 140 K, here, we present epitaxial integrable lead salt photodetectors for room temperature operation. The midinfrared detectors can be directly grown on epitaxial devices like Bragg mirrors, filters and laser structures. We demonstrate photoconductive structures consisting of PbTe layers grown on l/4 EuTe antireflection layers optimized for 3.3 mm. The antireflection coating doubles the responsivity of the detectors at the designed wavelength.

Further, we present detector structures integrated on Fabry-Perot filters. The small-bandwidth filter designed for 3.6 mm consists of two Pb0.94Eu0.06Te/PbTe Bragg mirrors with a l/2 thick Pb0.94Eu0.06Te layer placed in between. On top of the filter the photosensitive PbTe layer was grown. The room temperature photovoltage spectrum shows a narrow peak at 3.55 mm with a linewidth of 156 nm, corresponding to a Dl/l of 4.5%.

These results give future prospects of monolithically integrated detectors that are sensitive only at a narrow spectral region for the use in gas spectroscopy systems.

6119-19, Session 4

Birefringence of yttrium vanadate single crystals in the middle wavelength infrared

H. Luo, T. Tomasz, E. L. Dereniak, The Univ. of Arizona; R. E. Sampson, I Technology Applications

The birefringence of the yttrium vanadate (YVO4) and rutile (TiO2) crystals have been measured for the first time in the middle wavelength infrared (MWIR), i.e., 3-5μm. A Fourier transform spectrometer has been used in the channel spectra technique to achieve a high spectra resolution and a quick measurement. Large birefringence over 0.2 has been observed in both of the YVO4 and TiO2 crystals, which illustrate good potential of these materials in the MWIR applications. Dispersion versus wavelength can be approximated as an exponential-increasing curve for these materials. The transmissions over 2.5-17μm of the YVO4 (0.7mm thick) and TiO2 (0.5mm thick) samples have been measured. Both of the materials show high transmission over 0.6 in the MWIR.

6119-20, Session 4

Room temperature solid state photomultiplier

K. R. Linga, E. E. Godik, J. Krutov, Amplification Technologies, Inc.

We describe an emerging photodetector technology that has the potential to replace vacuum Photomultiplier Tube (PMT) and Avalanche Photodiode (APD) in many applications. First, the key performance parameters of a room-temperature solid-state photomultiplier will be presented. Then, the technology used for realizing such parameters will be described. Next, one of the designs of a room-temperature solid-state photomultiplier will be presented. Finally, some applications areas for this emerging novel detector technology will be discussed.

We focus on the new family of photodetectors with Internal Discrete Amplification (IDA) mechanism that is used for creating room-temperature solid-state photomultipliers for the visible and near infrared photodetection in applications including free space optical communications, LIDAR, medical diagnostics, and chemical and biological sensing. These photodetectors can operate in linear detection mode with gain-bandwidth product up to 10^15, and in photon counting mode with count rates up to 10^9 counts/sec. The key performance characteristics exceed those of Photomultiplier tube (PMT) and Avalanche Photodiode (APD) devices in many applications. The measured parameters of these detectors have a gain \> 200,000, excess noise factor as low as 1.02, dark current < 10^4 cps at room temperature, rise/fall time < 300 ps.

The key benefits of this technology compared to conventional avalanche photodetectors are ultra low excess noise factor and very high gain. Particular emphasis will be on the creation of monolithic photodetector arrays.

6119-21, Session 4

Metamorphic InGaP buffered In0.53Ga0.47As p-i-n photodetector grown on GaAs substrate for 10Gbit/s and beyond

G. Lin, Y. Liao, H. Kuo, National Chiao Tung Univ. (Taiwan); M. Feng, Univ. of Illinois at Urbana-Champaign

The low-leakage In0.53Ga0.47As p-i-n photodetector fabricated on GaAs substrate with linearly graded metamorphic InxGa1-xP (MM-PINPD) buffer layer has been demonstrated in this work. The dc, the radio frequency, and the communication performance of the photodetectors are characterized. At a bias of -5 V, the MM-PINPD exhibits a dark current of only 13 pA. A 40-GHz probe was employed to negatively bias the p-type contact on the MM-PINPD. There are two 80-μm bond-pads in the both sides of the active area with diameter of 60 μm, and the coplanar waveguide structure is designed for high speed probe to enhance the frequency response. The dynamic characteristic of injecting a 200-fs pulse-train generated by semiconductor optical amplifier fiber laser (SOAFL) of at a repetition rate of 1 GHz has been analyzed. The temporal response of the MM-PINPD was measured with a digital sampling oscilloscope with bandwidth of > 63GHz. The switching responses of the MM-PINPD corresponding to 1310-, and 1550-nm pulses, respectively, are also measured in this work. The rising time of the MM-PINPD illuminated at 1310 nm and 1550 nm are 15.4 ps and 18.5 ps, respectively. A Fourier transform of the pulsed response implied that the operational bandwidth of the MM-PINPD can be up to 12 GHz even without any impedance matching circuitry. The opened eye pattern at 10-Gbps NRZ signal and the sensitivity of the MM-PINPD are also reported in this work. The demonstrated metamorphic epitaxy is particularly suitable for mass-production of such devices on GaAs substrates and is also suitable for commercial TO-can based OC-192 PIN-TIA receiver.

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6120-01, Session 1

A novel scheme for THz detection at room temperature

Y. J. Ding, Lehigh Univ.

We will summarize our most recent results on the development of a new scheme for detecting monochromatic THz pulses based on upconversion at room temperature, i.e. by mixing a THz pulse with an infrared laser pulse, we observed the upconverted signal at the wavelength just slightly longer than that of the infrared laser. The detectable energy per pulse for the THz input is only an order of magnitude higher than that for a typical Si bolometer. This scheme allows us to measure the pulse energy, wavelength, linewidth, and temporal profile of a THz pulse at room temperature. We will also describe several applications that can be realized by combining a widely-tunable monochromatic THz source with our new detection scheme. For example, one can directly measure the rotational spectra of chemical vapors with an ultrahigh spectral resolution. In addition, only this combination makes it possible to implement a relatively compact system for navigation and long-distance surveillance through THz imaging within the narrow atmospheric windows. Moreover, it is conceivable to implement a system for investigating the dynamics of THz interactions in the ns time scale.

6120-02, Session 1

Generation of intense short pulses of THz radiation via coherent scattering in atomic and molecular gases

N. G. Kalugin, Y. V. Rostovtsev, Texas A&M Univ.; M. O. Scully, Princeton Univ. and Texas A&M Univ.

We have studied of a Lambda-Ladder scheme that has potentially high efficiency to generate controllable short pulses of THz radiation. The method is based on excitation of maximal coherence in atomic or molecular gases (f.e. Rb, methanol, ethanol, and others) at room temperature by applying optical pulses and following coherent scattering of infrared radiation, and can produce pulses of THz radiaiton with pulse energies ranging from several nJ to mJ and pulse durations from several fs to ns. Our evaluations, obtained for the parameters of methanol, show that, using intensive enough optical pumping beams, one can generate short THz pulses with intensities, already comparable with intensities of synchrotron or free-electronlaser-based THz sources. The proposed method potentially provides up to 100% transformation efficiency of energy of IR drive beam into THz radiation. The duration of THz pulse can be tuned by durations of both pumping and drive beams.

Historically, the molecular gas lasers (f.e., the methanol laser), were the first laser THz sources created at 1970s. Our work opens a new way of use of molecular gas sources for highly efficient generation of short intensive THz pulses. Applications of the obtained results have broad range: from molecular spectroscopy to imaging, monitoring of environment and diagnostics of liquid and solid materials.

6120-03, Session 1

Generation of multi-cycle THz pulses via optical rectification in periodically inverted GaAs

Y. Lee, Oregon State Univ.; K. L. Vodopyanov, Stanford Univ.; W. C. Hurlbut, J. R. Danielson, Oregon State Univ.; V. G. Kozlov, Microtech Instruments, Inc.; D. F. Bliss, Air Force Research Lab.; M. M. Fejer, Stanford Univ.

We demonstrate an efficient room temperature source of narrow-bandwidth terahertz radiation using femtosecond pump pulses and periodic GaAs structure as a nonlinear material. In the past, several THz generation schemes exploited optical rectification in nonlinear crystals using femtosecond laser technology. Most of them generated single-cycle THz pulses with broad bandwidth, using nonlinear crystals shorter than the phase-matching coherence length. Recently a novel technique to generate multi-cycle THz pulses in the pre-engineered domain structure of periodically-poled lithium niobate (PPLN) crystals has been demonstrated. Quasi-phase matching (QPM) structures such as PPLN consist of a periodic system of domains of inverted crystal orientation. The sign of second order nonlinear polarization generated by femtosecond pulses is inverted at domain boundaries. If domain length is comparable with coherence length, QPM between THz wave and non-linear polarization extends the interaction length between THz and optical pulses. In the present work, using periodic GaAs structures we have achieved exceptionally high photon as well as energy conversion efficiency: 10% and 0.1% respectively. We have examined two different types of periodic QPM GaAs samples: diffusion-bonded GaAs wafers and all-epitaxially-grown orientation-pattered GaAs crystals with 3-10 mm thicknesses. The incident optical pulse energy was in the micro-Joule range and pulse duration was ~100 fsec. We measured spectral properties of THz radiation using Michelson interferometer and a bolometer. Narrow-bandwidth (~100GHz) THz output, tunable between 1 and 3 THz, was achieved. THz frequency was tuned either by tuning the light source wavelength between 2 and 4.4 microns, or by selecting GaAs samples with different domain-inversion periods. Our theoretical analysis, based on known GaAs dispersion properties, shows good agreement between the measured and predicted THz frequencies.

6120-04, Session 1

Photonic band gap structures for millimeter-wave TWTs

A. G. Bailey, E. Smirnova, L. M. Earley, B. E. Carlsten, J. L. Maxwell, Los Alamos National Lab.

We propose to use photonic band gap (PBG) structures for constructing a traveling wave tube (TWT) at 100 GHz, a completely novel approach. Using PBG crystals allows us to construct an all-dielectric slow-wave structure with very large band width and low losses in the mm-wave regime, compared to metal structures which are also under investigation. Additional capabilities such as mode selectivity are also achievable. We designed two PBG structures using Ansoft's HFSS, 3D electromagnetic simulation software for high frequency applications. We are currently investigating the possibilities for fabrication. The first design is a periodic array of dielectric rods in a vacuum matrix, surrounding a thick hollow dielectric tube that accommodates the electron beam. We are currently fabricating it out of silicon by means of high-pressure laser chemical vapor deposition (HP-LCVD), a versatile approach to synthesize fibers from the gas phase. The second design is a periodic array of vacuum rods in a dielectric matrix surrounding a smaller, defect vacuum rod. A fiber drawing procedure has been chosen to ultimately construct this design. Material selection is in progress. A 10 GHz cold test made from alumina rods is also being produced for design confirmation purposes. The 10 GHz structure will be tested with an HP8720C vector network analyzer upon its completion.

6120-07, Session 2

Electro-optic detection of THz in polymers

C. A. Leininger, Air Force Research Lab.

Development of THz sources for imaging and spectroscopy has received

considerable interest in the last decade. As output powers continue to increase, new detection methods need to be examined in order to design more compact and efficient THz systems. Current detection schemes rely on bolometers or Schottky diodes. Here we investigate the detection of THz radiation using the electro-optic effect in nonlinear optical polymer materials. Advantages of using electro-optic polymers include ease, flexibility, and cost of fabrication, as well as room temperature detection. Antenna coupling of the THz signal was used to achieve detectable signal levels within thin spin-cast polymer films. Experimental results were obtained using difference frequency mixing in GaSe from a pulsed THz source with a tuning range from 58-3500 microns and a peak power or 209 W at 196 microns.

6120-08, Session 2

Amplitude and phase recovery using holographic imaging of antenna feeds

R. J. Mahon, W. P. Lanigan, J. A. Murphy, National Univ. of Ireland/Maynooth (Ireland)

It is possible to use wave-front reconstruction for imaging at millimeter wavelengths employing off-axis holography (a frequently used technique at visible wavelengths).

We report on how the technique can also be used for imaging the phase centre of non-standard feed antennas at millimetre wavelengths such as planar lens antennas for example.

Holography provides a method for recording a lens-less image of an object reducing loss of spatial frequency information important for maximum resolution.

An experimental arrangement at 100 GHz based on a simple form of near-field off-axis holography was developed, with the object and reference beams derived from two radiating horn antennas fed by a single coherent source via a 3dB cross-guide coupler.

The reference beam derived from a well understood and characterised horn was collimated using a large off-axis mirror, while the object beam was derived directly from the horn antenna whose pattern is to be measured.

The hologram (or intensity pattern) resulting from the interference of the two beams was recorded over an area of 150x150 mm with a spatial resolution of 1 mm by a scanning detector and the object wave-front recovered by simulating the reconstruction through near-field diffraction of the reference beam.

It is possible to model the propagation of the recovered object beam back towards the horn and recover the object horn fields in the vicinity of the waist (the effective phase centre of the horn).

This is a useful inexpensive experimental method for recovering the phase centre position of non-standard feeds.

6120-09, Session 2

Tunable THz detector based on a grating gated field-effect transistor

M. C. Wanke, E. A. Shaner, M. Lee, A. Grine, J. L. Reno, Sandia National Labs.; S. J. Allen, Jr., Univ. of California/Santa Barbara

We have previously demonstrated that double quantum well field-effect transistors with grating gates can operate as direct THz detectors. For moderate gate biases the device has a tunable resonant response arising from plasmon excitation. Typical 2DEG densities from 1010 to 1012 cm-2 yield plasmon frequencies in the 100 GHz to 1 THz range, making plasmon devices attractive for millimeter wave and THz applications. The plasma resonance can be tuned by electrically tuning the 2DEG charge density with the gate bias, enabling use as a spectrometer-on-a-chip as a direct detector with a spectral resolution near the atmospheric pressure broadening limit. Higher resolution spectroscopy is possible using the measured 10 GHz bandwidth when used as a heterodyne detector.

We have recently observed similar behavior in single quantum well devices. In addition we have recently increased the direct detection responsivity by three orders of magnitude by altering the gate design and still maintaining tunability. We also have observed a photovoltaic response as compared to our earlier measurements which exhibited a mostly photoconductive response. This significantly improves the practicality of using the detectors in array formats. Measurements of the response versus pixel size are also encouraging for integration into arrays. This talk will describe the current state of the improved detector performance and our efforts into making hyperspectral arrays.

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6120-10, Session 2

Electro-optic modulator optimization for optically-based passive millimeter-wave detection

C. A. Schuetz, C. Huang, R. Shireen, T. H. Hwang, G. J. Schneider, J. A. Murakowski, D. W. Prather, Univ. of Delaware

Recent efforts in our group towards the fabrication of sensors capable of detecting passive levels of millimeter-wave radiation have led to the development of an optically-based detector with sub-picowatt noise equivalent powers. This sensor is based on upconverting the received radiation into sidebands on an optical carrier using electro-optic modulation techniques and, subsequently, suppressing the remaining carrier energy. The noise equivalent power of such detectors is critically dependent on the ability of the electro-optic modulator to efficiently convert frequencies up to and exceeding 95 GHz onto the optical carrier while suppressing potential noise sources.

In this session, we discuss the specific device requirements generated by this unique potential application of high frequency optical modulators. The effects of various modulator properties such as half-wave voltage, frequency response, and maximum optical power density will be discussed in the context of millimeter-wave detection capability. In addition, we will present experimental efforts to date towards fabricating a passive millimeter-wave detector based on this approach, including efforts to develop a suitable optical modulator technology.

6120-11, Session 2

Phase-matched optical-to-terahertz conversion via excitation of a surface plasmon polariton

M. I. Bakunov, Nizhny Novgorod State Univ. (Russia); A. V. Maslov, NASA Ames Research Ctr.; S. B. Bodrov, Nizhny Novgorod State Univ.

The ultrafast current creation and optical rectification are proven techniques for generating terahertz (THz) radiation from semiconductor surfaces using short optical pulses. In both cases the resultant THz pulse propagates from the optical spot as free-space radiation with broad spectrum. We propose to use the surface of a doped semiconductor to excite surface-plasmon polaritons, rather than free-space radiation, at frequencies in the THz range[1].

The excitation scheme can work in the following way. We illuminate a semiconductor surface by a weakly focused femtosecond laser pulse with tilted intensity front[2]. If the tilt angle exceeds 45 degrees, the strip-like spot of nonlinear polarization created on the surface by the pulse via optical rectification moves with subluminous velocity and the phase-matched generation of a surface plasmon-polariton can be realized. The frequency of the excited surface wave can be tuned by varying the doping concentration and tilt angle. Due to phase-matching, the excitation is shown to be rather efficient. For a 90 fs optical pulse with a peak intensity of a 2 GW/cm2, we estimate the energy conversion coefficient to be 10-7 at the surface of GaAs. The direct excitation of surface waves can be particularly attractive for THz spectroscopy of semiconductor surfaces.

References:

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2 J. Hebling, G. Almasi, I. Kozma, and J. Kuhl, Opt. Express 10, 1161 (2002).

6120-12, Session 2

THz semiconductor hot electron bolometer

V. N. Dobrovolsky, F. F. Sizov, Institute of Semiconductor Physics (Ukraine)

This communication aim is to consider a broad frequency range, moderately cooled (T = 77 K) semiconductor fast space-saving THz detector with principle of operation differed to those used in antennas, and quantum semiconductor detectors.

It was considered the model of Hot Electron Bolometer (HEB), in which, in contradistinction to known thermal bloomers, radiation heats only electrons in bipolar semiconductor without inertial lattice heating. In conditions proposed this heating changes generation and recombination processes, that leads to the electron and hole concentration decrease and resistance rise. This rise creates the output signal. The HEB response time is about the electron lifetime in semiconductor and sizes of its active region are order of the electron diffusion length or electron energy relaxation length.

Semiconductors with high conductivity and also high mobility, and energy relaxation time are important for the HEB manufacturing. These properties ensure high radiation absorption by electrons and their efficient heating. Narrow-gap semiconductors (e.g., mercury-cadmium-telluride-MCT) have these properties, and they were considered.

Estimations for the MCT HEB have shown: bolometer with active region 10x10 micron^2 at 77K in radiation frequency range (0.1-2) THz can have response time approximately (10^- 8 - 10^ -9) s, noise equivalent power (10^-11-10^-10) W and detectivity (10^7-10^8) cmxHz^1/2/W.

6120-13, Session 3

THz reflection spectroscopy of composition C-4 and its detection through interferometric imaging

A. Sengupta, A. Bandyopadhyay, R. B. Barat, D. E. Gary, J. F. Federici, New Jersey Institute of Technology

Previous reports using THz transmission spectroscopy and FTIR spectroscopy have suggested that C-4 explosives (~90% RDX mixed with plastic composites) have an intrinsic absorption peak around 0.8 THz using which efforts have been made to predict the reflection spectra of C-4 in THz frequencies. However, in applications like security screening and non-invasive inspection, reflection geometry plays a major role and the lack of any experimental work on the same limits the scope of such applications. In this study we report a direct measurement of reflection spectra of composition C-4 using THz time domain spectroscopic techniques. The experimental spectra are diffuse in nature as the surface of the sample was not optically flat in THz frequencies and a contrast of around 8% was observed between the neighboring frequencies of 0.7 THz and 0.9 THz. The spectral data have been used to create realistic synthetic images for use in simulations of interferometric detection in a stand-off THz imaging system. The results of the same show the effective contrast needed for positive classification of lethal agents using an interferometric array of few detectors in near field mode.

6120-14, Session 3

Characterization of hollow polycarbonated metal waveguides using Terahertz time domain spectroscopy

A. Bandyopadhyay, A. Sengupta, J. F. Federici, New Jersey Institute of Technology; V. S. Johnson, J. A. Harrington, Rutgers Univ.

In recent times, terahertz or the far-infrared region of the electromagnetic spectrum has gained critical significance in various technical applications and fundamental research problems, including nondestructive evaluation of material parameters, bio-medical imaging, chemical sensing, remote sensing and security screening. However, in some of these applications for which THz needs to be transmitted over a long distance without atmospheric absorption, a flexible waveguide could have potential application simplifying the propagation and detection of THz in remote locations. Different structures, such as, rigid hollow metallic waveguides, solid wires, or short lengths of solid-core transparent dielectrics such as sapphire and plastic have already been explored for THz guiding to characterize their individual loss and dispersion profile. Recently, it has been reported that Cu coated flexible, hollow polycarbonate waveguide has a low loss of less than 4 dB/m with single mode operation, at 1.89 THz. In the present study, using a broadband THz source of photoconductive antennae, we characterize the loss and dispersion profile of Cu and Ag coated flexible, hollow polycarbonate waveguide. We also study the coupling and propagation consideration of such waveguide structure in the frequency range of 0.2 to 1.2 THz.

6120-15, Session 3

A tunable THz source for spectroscopy and imaging applications

M. Mross, T. Lowell, M. F. Kimmitt, R. Durant, Vermont Photonics, Inc.

A tunable Terahertz source (TTS) based on a Smith-Purcell emitter will be described.[1] The tunable THz source is analogous to low frequency electron beam devices such as magnetrons, backward wave oscillators and traveling wave tubes. The device offers continuous tunability, compactness, and robust operation. Examples of THz spectroscopy and imaging will be given.

1 Urata et al. Phys. Rev. Lett. 80, 516 (1998)

6120-16, Session 3

Teraherz generalized Mueller-matrix ellipsometry

T. Hofmann, Univ. of Nebraska-Lincoln; U. Schade, BESSY GmbH (Germany); C. M. Herzinger, J. A. Woollam Co., Inc.; M. M. Schubert, Univ. of Nebraska-Lincoln

In this contribution we report on the first successful generalized Mueller-matrix ellipsometry measurements in the THz-frequency domain using the high-brilliance THz synchrotron radiation source IRIS at the electron storage ring BESSY, Germany. Generalized Ellipsometry, which is known as a powerful tool for measurement of optical constants including anisotropy and which was previously used in the FIR to VUV spectral range, is now employed for the first time to investigate condensed matter samples in the frequency range from 0.9 to 8 THz. Exemplarily, results obtained from bound and unbound charge -carrier investigations in low-dimensional semi- and superconducting systems are presented. Future applications of this technique for investigation of charge-carrier dynamics in magnetic fields are envisioned.

6120-17, Session 3

Candidate THz sources: the history and future (?) of velocity-modulated devices

T. H. Lee, Stanford Univ.

Scaling limitations for conventional semiconductors pose serious challenges for producing useful power output much beyond ~1 THz. Similar scaling problems in the GHz range motivated vacuum-tube engineers in the 1930s to invent a class of devices based on velocity modulation.

Examples include the klystron and magnetron, which generate kilowatt power levels at gigahertz frequencies. Because the study of these devices has been de-emphasized in, or even eliminated from, modern engineering curricula, this talk will provide a review of their history.

The talk will conclude with a consideration of how the "terahertz gap" can be bridged by reconceiving velocity-modulation devices to enable milliwatt power levels at terahertz frequencies.

6120-18, Session 4

Analysis of standing waves in submillimeter-wave optics

N. A. Trappe, T. J. Finn, A. Murphy, National Univ. of Ireland/Maynooth (Ireland); W. Jellema, SRON Nationaal Instituut voor Ruimteonderzoek (Netherlands); S. Withington, Univ. of Cambridge (United Kingdom)

In this paper, we report on a theoretical framework 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. In previous papers we reported on the underlining theory and described some important examples including reflections between a feed horn and telescope secondary mirror and also reflections between two coupled corrugated horns. This technique can in addition be applied to reflections between components such as lenses and apertures[1, 2].

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 including a Singular Value Decomposition (SVD) analysis, which gives new insight into optical cavity phenomena. We compare the classical example of Fabry Perot etalon transmission properties to the low level standing waves, often present in submillimeter optics.

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6120-19, Session 4

Modeling of the optical performance of the QUaD telescope in MODAL

M. L. Gradziel, C. M. O'Sullivan, 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 targetting the millimetre and submillimetre region of the electromagnetic spectrum. It is being being developed at NUI Maynooth with an aim of combining advances in modelling techniques and the availability of computing power 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 an aim 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 can be understood in terms of likely changes in the optical configuration before any adjustments are made during the Summer season.

In this paper we present the 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.

6120-20, Session 4

Grain size dependent scattering studies of common materials using THz time domain techniques

A. Bandyopadhyay, A. Sengupta, R. B. Barat, D. E. Gary, J. F. Federici, New Jersey Institute of Technology

The sensitivity of THz radiation to polar substances like water and other biologically interesting molecules and its insensitivity to non-polar substances like dust, plastic and even clothing materials, make it a very suitable non-contact, non-invasive means of spectroscopy and imaging. However, for solids having grain sizes comparable to THz wavelengths, the extinction spectra are greatly influenced by scattering losses which partially obscure the characteristic phonon resonances leading to complications in the quantitative analysis. The present work investigates the scattering effects on the absorption spectra of common materials like sugar, salt and chalks having different grain sizes in the THz region between 0.2 and 1.2 THz. We have shown that, using Mie scattering theory, one can estimate the material extinction for powdered solids accounting for the grain size dependent scattering contribution as also the intrinsic material absorption. A generic curve based on Mie theory has also been obtained which predicts the total extinction coefficient for different materials with a range of values of size parameter to account for any variation of their size and/or wavelength. This work would not only help in better identification of solids under THz study, but would also provide general understanding of the impact of scattering on absorption characteristics of solids.

6120-22, Session 5

Novel applications of Gaussian beam mode analysis

C. M. O'Sullivan, J. A. Murphy, G. A. Cahill, R. May, National Univ. of Ireland/Maynooth (Ireland); S. Withington, Univ. of Cambridge (United Kingdom)

In the presentation we report on novel applications of Gaussian Beam Mode (GBM) Analysis, including in image deconvolution and Fourier grating design.

GBMs are the natural modes with which to describe propagation of quasi-collimated long wavelength beams, with only a small number of modes required to reach adequate accuracy for many practical applications. GBMs provide a more efficient and natural basis set with which to describe propagation than for example plane wave decomposition, especially because of the limited spatial frequency content (only a few degrees of freedom are necessary to describe such beams and the degrees

of freedom can be associated with component GBMs).

We discuss how GBM analysis provides a useful alternative scheme to FFT approaches for performing deconvolutions and image retrieval in long wavelength quasi-collimated systems. The convolving beam is usually described very efficiently in terms of beam modes and an SVD approach can be used to extract the mode coefficients of the deconvolved image. We discuss in particular the novel application to mapping in astronomical telescope observations.

Another useful area of application is in the design of Fourier phase gratings. Fourier gratings can be used for beam multiplexing of local oscillator power in array imaging systems. In this case phase retrieval is often driven by an iterative approach to the solution based on FFTs and thus by implication plane waves. A GBM approach leads to a more efficient and physically more meaningful approach, especially again because of the limited spatial frequencies possible in long-wavelength systems.

6120-23, Session 5

Can fundamental gain limitations of nanostructure THz lasers be overcome?

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

We argue that nanostructure based THz lasers of standard design have a principal limitations of gain value. These limitations rise from the obvious necessity to engineer both THz gap and population inversion simultaneously. Typical approach to the gap engineering inherited from midIR lasers utilizes intersubband transitions. However, contrary to midIR range, for THz lasing selective depopulation is problematic. The problem is that the selectivity of both depopulation mechanisms, LO phonon emission and electron-electron scattering, in THz region is substantially weaker than in midIR region. We suggest to use InAs/GaSb coupled quantum wells as a way to overcome this fundamental limitation. This is the only heterostructure where THz lasing can be based not on intersubband but on interband transitions. A proper design of this structure leads to a hybridization gap coming from anti-crossing of the GaSb valence band and InAs conduction band naturally appearing in the THz range. Two more advantages of this design are (i) a large value of the interband dipole matrix element and (ii) W-shaped spectrum leading to a singular density of states. These advantages lead to a gain much higher than for intersubband THz lasing. We acknowledge the support of the Israel Science Foundation and The Israeli Center for Academic Relations with the CIS and Baltic States.

6120-24, Session 5

Determination of water content in petroleum products via terahertz transmission spectroscopy

S. Gorenflo, I. Hinkov, U. Tauer, A. Lambrecht, Fraunhofer-Institut für Physikalische Messtechnik (Germany); B. Fischer, H. Helm, Albert-Ludwigs-Univ. Freiburg (Germany)

In the Terahertz (THz) spectral range water has its strongest absorption bands. Thus very sensitive humidity measurements are possible.

Terahertz time-domain spectroscopy was used to determine the water content in different commercial petroleum products. The absorption spectrum of a number of oils with different water contents was measured in the spectral range of 0.1-2.5 THz. The experimental data was compared with well established methods. The Terahertz measurement set up was optimized. For this purpose a special sample cell was constructed. Electro-optic detection was used to measure the THz signal. The feasibility of Terahertz time-domain spectroscopy for water content analysis in different oils was investigated.

6120-25, Session 5

Analysis of Drugs-of-Abuse and Explosives Using Terahertz Time-Domain and Raman Spectroscopy

A. Burnett, W. Fan, J. Cunningham, P. Upadhya, A. G. Davies, E. H. Linfield, R. Miles, Univ. of Leeds (United Kingdom); H. Edwards, T. Munshi, A. O'Neil, Univ. of Bradford (United Kingdom)

We demonstrate that broadband terahertz (THz) time-domain spectroscopy can be used to measure far-infrared vibrational modes of a range of illegal drugs and high explosives that are of interest to the forensic and security services. We demonstrate that terahertz radiation, generated by excitation of a photoconductive switch with sub-20 femtosecond infrared laser pulses, can be used in a low water environment to observe and detect vibrational mode in the range 0.3-8 THz using coherent measurement of the transmitted terahertz electric fields. These results show that these absorption features are highly sensitive to structure and spatial arrangement of the molecules. Terahertz frequency spectra will then be compared with high resolution low frequency Raman spectra to allow further understanding of the low frequency inter- and intra-molecular vibrational modes of the molecules studied.

6120-26, Session 5

High power superlattice quantum cascade laser emitting at 2 THz

C. Worrall, Univ. of Cambridge (United Kingdom); J. Alton, TeraView Ltd (United Kingdom); M. Houghton, O. Marshall, Univ. of Cambridge (United Kingdom); C. Sirtori, Univ. of Paris 7 (France); S. Barbieri, TeraView Ltd (United Kingdom); H. E. Beere, D. A. Ritchie, Univ. of Cambridge (United Kingdom)

We demonstrate a quantum cascade laser with a photon energy of 8 meV (f = 2 THz), the lowest reported to date for these unipolar semiconductor devices in the absence of an external magnetic field. The active region consists of a GaAs/AlGaAs heterostructure with 10% Al concentration, and is based on a superlattice design yielding a high injection efficiency into the upper state. Lasing takes place on the second order mode of a double-metallic, 200 microns thick waveguide. At T = 4K, we find a maximum peak power of 50 mW when the laser is driven in pulsed, and of 25 mW in continuous wave. For the two operating modes maximum temperatures are of 77K and 47K respectively.

6120-27, Session 5

Practical applications of terahertz imaging

D. D. Arnone, TeraView Ltd. (United Kingdom)

No abstract available

6120-28, Session 5

Guided-wave THz devices for sensing the properties of overlaid dielectric films

J. Cunningham, Leeds Univ. (United Kingdom); C. Wood, C. K. Tiang, E. H. Linfield, I. C. Hunter, A. G. Davies, Univ. of Leeds (United Kingdom)

Measurement of the dielectric properties of thin films is important for several emerging applications of THz technology. We review the state-of-the-art in the field, and show calibrated measurements where a dielectric film has been overlaid onto a THz microtrip circuit which incorporates a passive filter. Measurements of the frequency shift induced in the filter by the film allow extraction of the effective permittivity or film thickness.

6120-29, Session 5

Detecting the full polarisation state of terahertz transients

M. B. Johnston, E. Castro-Camus, J. Lloyd-Hughes, Univ. of Oxford (United Kingdom); M. D. Fraser, L. Fu, H. H. Tan, C. Jagadish, The Australian National Univ. (Australia)

Terahertz time domain spectroscopy (THz-TDS) is now an established technique for performing linear spectroscopy in the far infrared region of the spectrum. The technique has become popular because of its unmatched sensitivity over a wide spectral band between 100GHz and 10THz. In general THz-TDS is performed using emitters and detectors of linearly polarised radiation. However, in order to study birefringent and optically active materials properly it is necessary to record the full polarisation state of this radiation. Chiral biomolecules such as proteins have optically active vibronic modes at THz frequencies. Thus polarisation sensitive THz-TDS would offer exciting possibilities for determination of protein structure and function.

We have developed a detector which records the full polarisation state of a THz pulse. The three-electrode photoconductive receiver simultaneously records the electric field of an electromagnetic pulse in two orthogonal directions as a function of time. A prototype device fabricated on Fe+ ion implanted InP exhibited a cross polarized extinction ratio better than 100:1. In this talk the design and optimisation of this device will be discussed along with its significance for the development of new forms of polarization sensitive time-domain spectroscopy, including THz circular dichrosim spectroscopy.

6120-30, Session 5

Terahertz scattering: comparison of a novel theoretical approach with experiment

G. P. Swift, J. R. Fletcher, J. A. Levitt, D. Dai, A. J. Gallant, D. M. Beggs, R. A. Abram, M. A. Kaliteevski, J. M. Chamberlain, Univ. of Durham (United Kingdom)

The interaction of Terahertz (THz) radiation with random structures is, at the present time, not well understood. On the one hand, scattering has adverse effects: it may produce false signatures in spectra when interference takes place within a scattering structure (e.g. fibres in clothing or granules of powder), or diminish and scramble the return signal from a suspect item secreted below garments. On the other hand, it might be used to advantage to determine the characteristic size, texture and location of an object concealed within a matrix of other material. Scattering effects are particularly relevant in this spectral regime, where the wavelength, and the size and separation of scattering centres, are often commensurable.

Here, we report theoretical and experimental studies of THz radiation scattering that are being carried out concurrently, to develop an understanding of both the attenuation and scattering of this radiation from a wide variety of random media e.g. clothing and powders. Previous work undertaken (by e.g. Mittleman et al,) has shown that the statistics of scattering events provide a means to identify individual scattering events. We have developed a new theoretical approach, the Phase Distribution Model, to describe the propagation of Terahertz Radiation through inhomogeneous media. The model is developed by splitting the scattering medium into a number of slices perpendicular to the direction of the Terahertz beam propagation, which are simultaneously thick enough to remove the average correlations between scattering centres, but thin enough to simplify the transmission calculation through the slice. A so called Phase Distribution Function is used to describe the affect of the non-absorbing scatterers within the media and several approximations exist for its calculation. The model is easily extended to cover situations involving multiple scattering events. Experimental measurements undertaken using published results and data obtained from both specially constructed phantoms and everyday textiles have been compared with the theory. These experimental results encompass both cylindrical and spherical scattering situations. The model has been compared with exact calculations using the Pendry Code.

6120-31, Session 5

TeraNova: a European integrated project on 'Novel terahertz sensing and imaging systems'

E. H. Linfield, A. G. Davies, J. M. Chamberlain, Univ. of Leeds (United Kingdom)

TeraNova is an enterprising, 5 million, 48-month European Integrated Project (IST-511415), funded under the EU Framework VI Information Science & Technologies activity. This programme will exploit terahertz radiation, lying between the microwave and infra-red regions of the spectrum, driving forward fundamental research and applications in areas including healthcare, security, bioanalytics, and process engineering, inter alia. TeraNova is a collaboration between eighteen industrial and academic partners throughout Europe, building on recent significant European technological developments.

We will discuss progress and results from the first year of the programme (www.teranova-ist.org), and overview future research directions.

6120-32, Session 5

Terahertz pulsed imaging of breast tumors

V. P. Wallace, A. J. Fitzgerald, E. Pickwell, TeraView Ltd. (United Kingdom); S. E. Pinder, A. Purushotham, Addenbrooke's Hospital (United Kingdom)

We have developed a portable terahertz pulsed imaging system (TPIscan) for use in a clinical environment. The system uses photoconduction to generate and detect terahertz radiation with frequency content from 0.1-4 THz. Here, we report on a study using TPI for imaging breast tumours ex vivo. Several breast samples were imaged and parameters from the time domain impulse functions were used to provide contrast. The size and shape of tumor regions in the terahertz images were compared with the corresponding histology section. Good correlation was found for area and shape of tumor in the THz images compared to that of histology. In addition, we have also performed spectroscopy study comparing the terahertz properties (absorption coefficient and refractive index) of excised normal breast skin and breast tumor. Both the absorption coefficient and refractive index were higher for normal tissue that contained tumor. These changes are consistent with higher water content and structural changes, like increased cell and protein density. This study demonstrates the potential of TPI to image both invasive breast carcinomas and ductal carcinoma in situ using THz and encourages further studies.

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6121-01, Session 2

Effects of growth interruption time on InGaN/GaN quantum dots size grown by metal organic chemical vapor deposition

H. H. Yao, G. S. Huang, T. C. Lu, H. Kuo, S. C. Wang, National Chiao Tung Univ. (Taiwan)

Wide-bandgap gallium nitride (GaN) and other group III-nitride based semiconductors have been successfully employed to realize short-wavelength light emitting diodes and laser diodes (LDs). Additionally, quantum dot (QD) structure is attractive because it is a 0-D confinement structure and has many unique physical characteristics. We have successfully grown self-assembled InGaN QDs structure without using any anti-surfactant by metal organic chemical vapor deposition. A high quality GaN/Sapphire template with flat surface and the suitable growth condition which include low growth temperature and low V/III ratio were used to grow InGaN QDs structure. The density of InGaN QDs is about 4.5 *10E10 cm-2 with an average lateral size of 11.5 nm and an average height of 1.6 nm. The effect of the interruption growth for InGaN QDs structure was systematic studied with the growth temperature of 660oC. The surface morphology and optical property was measured by atom forced microscopy and various temperature PL, respectively. The results indicated that as increasing interruption time from 30s to 120s, QDs area occupied on the surface above the wetting layer increases from 5.2% to 7.2%, and the In composition decreases from 25% to 21%. The results were discussed by considering the influences of ad-atom desorption and diffusion effect between wetting layer and InGaN QDs structure. Our results suggest that the interruption growth during an optimum time can modify the size of InGaN QDs and extend the emission wavelength to short wavelength, and at the same time improving the QD optical quality. Using this technique, indeed, it was feasible for formation of multi layer InGaN QDs structures and applicable for the fabrication of GaN-based light emitting devices.

6121-02, Session 2

Growth of GaN on patterned GaN/sapphire substrates with various metallic masks by high pressure solution method

M. S. Bockowski, Instytut Wysokich Cisnien (Poland)

Recently we explored the high pressure GaN growth on stripe-patterned GaN/sapphire substrates, expecting that in the laterally overgrown material the dislocation density should decrease significantly. The initial stripes increased their width from 20 mm to 60 mm and the dislocation density in the laterally overgrown material decreased more than two orders of magnitude, from 108 cm-2 to 5.105 cm-2. However, if the GaN stripes were fully merged or coupled to the GaN template, the dislocation density increased to 5.107 cm-2 [1].

The coalescence between stripes can be avoided by optimization of the growth conditions (mainly the crystallization time). In order to avoid the direct coupling of laterally overgrown material to the underlying template, a mask between GaN stripes should be used. The GaN must not react with the mask and not nucleate on it. It seems that high refractory metal films like molybdenum, tungsten and titanium might be very useful for GaN/sapphire substrate masking.

In this paper the growth in lateral direction on patterned GaN/sapphire substrates with various metallic masks like Mo, W, Ti is examined, discussed and analyzed. The newly deposited material is characterized by means of optical microscopy, scanning electron microscopy, transmission electron microscopy, X-ray diffraction and defect-selective etching. The results are compared with the existing data [1] on the growth on patterned GaN/sapphire templates without any mask.

1 M. Boćkowski et al., J. Crystal Growth 281 (2005) 11

6121-03, Session 2

Investigation the strain distribution of GaN/AlN Wurtzite crystal structure material self-organized truncated pyramid shaped quantum dot

Y. Liu, Z. Yu, Beijing Univ. of Posts and Telecommunications (China)

Based on the three-dimension finite element approach, we Investigated the strain field distribution of GaN/AlN self-organized quantum dot. The truncated hexagonal pyramid shaped quantum dots that have been found in experiment was adopted as the physical model in our simulation. The material elastic constants parameters used in this paper are wurtzite structure and there are five independent elastic constants. In dealing with the lattice mismatch, we employed a three-dimension anisotropic pseudo thermal expansion. We compared the calculated results with that calculated by Greenís function theory, which lots of assumption is adopted, and proved the corrections of our results. The strain distribution of the equal strain surface three-dimension contour plots of the six strain components are given. In the final, the anisotropic characteristics of the GaN/AlN quantum dot material is discussed, the results proved that the position of the elastic strain energy density minimum is just above the buried quantum dot and have no influence on the thickness of the capping layer. So the anisotropy has no influence on the vertical alignment of post-growth of the next layer quantum dots. Our model did not adopt the assumptions used in the Greenís function approach, so better reliability and precision results are expected to obtain

6121-04, Session 2

Quantum-structure dependent excitonic carrier dynamics of In<SUB\>x</SUB\>Ga<SUB\>1-x</SUB\>N/GaN multiquantum-wells

S. Hong, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea) and Pohang Univ. of Science and Technology (South Korea); Y. S. Kim, J. W. Kim, G. H. Lee, Y. J. Yoon, D. Kim, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea); T. Joo, Pohang Univ. of Science and Technology (South Korea)

Excitonic carrier dynamics taking place in In<SUB\>x</SUB\>Ga<SUB\>1-x</SUB\>N/GaN multi-quantum-well systems have been studied by low temperature picosecond time resolved photoluminescence (LT-TRPL), HR-TEM, XPS, and computational methods. Both time-integrated and time-resolved photoluminescence spectra of In<SUB\>x</SUB\>Ga<SUB\>1-x</SUB\>N/GaN multi-quantum-wells with different well thickness and Indium composition were measured at 10 K. We assigned the natural radiative lifetime of each sample from the time resolved PL. We observed that the natural radiative lifetime of In In<SUB\>x</SUB\>Ga<SUB\>1-x</SUB\>N/GaN multi-quantum-wells depends strongly on the well thickness and Indium composition. To support the measured natural radiative lifetimes, excitonic oscillator strengths of the In<SUB\>x</SUB\>Ga<SUB\>1-x</SUB\>N/GaN multi-quantum-wells were calculated by using a 2-D particle-in-a-box model as functions of well thickness and Indium composition. Values of the well thickness and Indium compositions from the HR-TEM and XPS compositional depth profiling were used to achieve more realistic computational results and to corroborate the measured natural radiative lifetimes of In<SUB\>x</SUB\>Ga<SUB\>1-x</SUB\>N/GaN multi-quantum wells.

6121-05, Session 2

Microscopic emission properties of nonpolar a-plane GaN grown by HVPE: effect of different buffers

T. Paskova, Univ. Bremen (Germany); P. P. Paskov, B. Monemar, Linköpings Univ. (Sweden); S. Figge, D. Hommel, Univ. Bremen (Germany)

Nonpolar a-plane GaN material is attracting considerable research interest during last few years due to its ability to overcome one of the essential problems in wurtzite nitride-based device structures, namely built-in electrostatic field. However, the in-plane anisotropic mismatch of the lattice constants and thermal expansion coefficients between the GaN and sapphire in this particular geometry leads to higher density of structural defects like dislocations, stacking faults, pits and cracks, strongly influencing the emission properties of the material.

In this work, different buffers separately deposited like reactively sputtered AlN, MOCVD grown GaN (layers and ELOG structures) were employed in order to improve the coalescence and morphology of the a-plane HVPE-GaN. We investigated the impact of different nucleation basis on the microscopic optical and structural GaN properties by highly spatially and spectrally resolved cathodoluminescence imaging and spectroscopy. The exciton related emission at about 3.472 eV, typical for c-plane GaN and indicative of high optical quality of the material, in the emission spectra of a-plane GaN is accompanied and even dominated by defect related emissions. They appear at 3.42, 3.34, 3.29 eV, as well as at 2.1 eV with different intensities, depending on the buffer used. Microscopic CL maps revealed specific intensity distributions of the emissions in the vicinity of different structural defects. Temperature and power dependence measurements of the luminescence bands, as well as HRXRD and TEM structural characterizations were performed, aiming to derive the underlying emission mechanisms in connection to the specific structural defects favoured by the different templates.

6121-07, Session 2

Crystallization of GaN by HVPE on pressure grown seeds

I. Grzegory, Instytut Wysokich Cisnien (Poland)

Growth of GaN under pressure from solution in gallium results in almost dislocation free plate-like crystals but with size limited to app. 1 cm (lateral) and 100 mm (thickness). Extremely low rate (about 1 mm/h) of stable growth in c-direction is typical for spontaneous crystallization being about 100 times faster in non-polar directions. The pressure grown GaN crystals are highly n-type if grown without an intentional doping or highly resistive if magnesium is added to the growth solution to compensate native donors.

Deposition of GaN by HVPE on the pressure grown substrates allows stable crystallization (in terms of flatness of the crystallization front and uniformity of the new grown material) with rates of a few hundreds mm/h. Morphology of the HVPE grown crystals improves with a decrease in the growth rate becoming perfect at a rate of 100-200 mm/h. The crystals with a thickness of a few mm are grown in this way. However, in these thick GaN crystals grown on almost dislocation free substrates quite a high number of dislocations appears if the crystal thickness exceeds certain critical value. The most probable reason for this effect is a small lattice mismatch between GaN grown by HVPE and the heavily doped pressure grown substrates Since the critical thickness for defect generation is of the order of 100 mm, almost dislocation free layers (density below 104 cm-2) thinner than 100 mm can be grown. The most obvious further step is removing the substrate and continue the HVPE deposition on the free standing low dislocation density layer of sub-critical thickness. The pressure grown substrates were removed by mechanical polishing, surface polarity sensitive chemical etching or conductivity sensitive electrochemical etching (for strongly n-type substrates). Then the HVPE low dislocation density GaN platelets were used as substrates for the growth of a few mm thick bulk GaN crystals. The crystals were characterized by defect selective etching of both polar (0001) and non-polar (11‘20) surfaces to check presence and distribution of structural defects. The X-ray measurements performed at every stage of the process allowed to conclude about value and character of strain in high pressure GaN-HVPE GaN system.

Some initial tests of epitaxy on low dislocation density substrates obtained by slicing of the HVPE grown bulk crystals are planned to be included in this report.

6121-08, Session 2

Non-polar GaN substrates and GaN/AlGaN quantum structures

S. A. Porowski, Instytut Wysokich Cisnien (Poland)

It is expected that the epitaxial growth of GaN-based quantum structures with non-polar orientations will result in a significant increase in the efficiency of radiative processes since the built-in piezoelectric fields could be avoided.

In this work, the non-polar GaN bulk substrates obtained by slicing of thick GaN crystals (over 3 mm) grown previously by HVPE on both sapphire and low defect density pressure grown seeds have been used. The substrates were characterized by X-ray diffraction and defect selective etching methods. The preparation of the substrates for epitaxy and their physical properties will be shortly reported.

The GaN/AlGaN multiquantum wells were grown by the plasma assisted molecular beam epitaxy. Both (0001) oriented and (11‘20) oriented substrates have been used simultaneously in order to compare the properties of structures with different polarities.

According to the expectations, the much stronger (about 100 times) UV emission was obtained from the ìnon-polarî, (11‘20) oriented multiquantum wells at room temperature. The character of the low temperature photoluminescence spectra confirmed high structural quality of these samples. The multiquantum wells of different thickness and of both polar and non-polar orientations were analyzed to determine the influence of the electric fields on the band structure and optical properties of the epitaxial GaN/AlGaN structures.

6121-09, Session 3

Growth and characterization of AlInN/GaInN quantum wells for high-speed intersubband devices at telecommunication wavelengths

C. Skierbiszewski, Instytut Wysokich Cisnien (Poland) and TopGaN Ltd. (Poland); G. Cywinski, Instytut Wysokich Cisnien (Poland); M. Siekacz, A. Feduniewicz, TopGaN Ltd. (Poland); L. Nevou, L. Doyennette, F. H. Julien, Univ. Paris-Sud II (France); M. Krysko, TopGaN Ltd. (Poland); I. Grzegory, J. Z. Domagala, Instytut Wysokich Cisnien (Poland); J. Smalc, Politechnika Warszawska (Poland); T. Remmele, M. Albrecht, Institut für Kristallz¸chtung (Germany); S. A. Porowski, Instytut Wysokich Cisnien (Poland)

AlN/GaN based multiquantum wells (MQWs), due to the high conduction band discontinuity between the well and barrier material, are attractive system for high speed intersubband (IS) devices at telecommunication wavelengths (1.3-1.55 um). It was already shown that it is possible to achieve intersubband absorption at 1.55 um in GaN/AlN thin quantum wells. However large lattice mismatch between GaN and AlN (or high Al content AlGaN) may lead to layer cracking rendering the structure useless for device applications. This is why, finding a lattice-matched system able to provide a platform for 1.55 um IS absorption is so important. One interesting candidate for this system is GaN/AlInN heterostructure, because the latter compound is latticed match to GaN for the Al content equal to 83%. However, the band offset for such system is too small to reach 1.55 um IS absorption.

In this paper we report on the growth of AlInN/GaInN MQWs with high Al

content (93%-96%) by Plasma Assisted Molecular Beam Epitaxy (PAMBE) on GaN/sapphire templates or on bulk GaN crystals. Growth of InGaN quantum wells allowed us to achieve better strain engineering of AlInN/GaInN superlattices. A series of samples with barrier thickness of 3 nm and with different well thickness 1.1 nm-3 nm were grown. The wells were doped with Si at a concentration of 5◊1E19 cm-3. Structures grown on GaN/sapphire templates and bulk GaN crystals are crack free, as demonstrated by Nomarski contrast and scanning electron microscopic measurements. The preformed XRD mapping of 'a' and 'c' lattice constants show that AlInN/GaInN MQWs are fully strained-i.e. lattice constant ëaí of MQWs is equal to lattice constant 'a' of GaN substrate. We demonstrate IS absorption at room temperatures on these structures in the range 2.45 um-1.52 um. We will discus results from XRD and TEM and compare measured IS absorption energy as a function of the well thickness with theoretical predictions. The AlInN/GaInN strain compensated MQW structures grown by PAMBE on GaN substrates, thanks to the crackless growth and good optical quality, are very attractive for telecommunication applications at 1.5 um wavelengths like electro-optical modulators or all-optical switches. Due to the low value of the refractive index, AlInN/GaInN superlattices can also replace AlGaN/GaN in thick cladding layers in nitride optoelectronic devices e. g. in blue-violet laser diodes.

This work was partially supported by the 6th European Framework Program within the STREP project NITWAVE (contract reference 004170).

6121-10, Session 3

Cathodoluminescence study of GaN and GaN:Si on sapphire

N. Pauc, D. Drouin, V. Aimez, Univ. de Sherbrooke (Canada); M. R. Phillips, Univ. of Technology/Sydney (Australia)

Thanks to the high energy of incident excitation electrons, cathodoluminescence is a particularly suitable tool for the study of wide band gap semiconductors such as GaN. We present here spectroscopic data acquired on GaN and GaN:Si samples grown on sapphire as a function of temperature and electronic density of the excitation beam. High resolution images of GaN and GaN:Si samples have been performed with a resolution better than 60 nm in the panchromatic (integration over all the emitted photons) and the monochromatic modes for each spectral component that we have identified in the previous spectroscopic analyses. It is shown that for low acceleration voltages dislocations near the sample surface can be observed. A particular attention is paid to the influence of the donor-acceptor pair (DAP) relaxation time on the image resolution when temperature varies.

6121-11, Session 3

Characterization of GaN epitaxial films grown on SiN and TiN porous network templates

J. Xie, Y. Fu, U. Ozgur, Y. Moon, F. Yun, H. Morkoc, Virginia Commonwealth Univ.; H. O. Everitt, Duke Univ.; A. Sagar, R. M. Feenstra, Carnegie Mellon Univ.; T. Kuan, C. K. Inoki, SUNY/Univ. at Albany; L. Zhou, D. J. Smith, Arizona State Univ.

Advances in GaN-based device development using conventional heteroepitaxial growth techniques is hindered due to the high density of threading dislocations (TDs) (10^9-10^10 cm^-2) and associated point defects that result from lattice mismatch between the film and the most commonly used sapphire and SiC substrates. These imperfections affect both the optical and electrical performance and act as non-radiative recombination centers.

In this study, we report on the structural, electrical, and optical characterization of GaN epitaxial layers grown by metalorganic chemical vapor deposition (MOCVD) on SiN and TiN porous templates in order to reduce the density of extended defects. The TiN network templates were prepared by in situ annealing of 10 nm-thick Ti layers deposited on GaN films grown on both sapphire and SiC substrates. For the SiN porous templates, a thin porous SiN layer was deposited directly on the GaN or AlN buffer layers grown on either sapphire or SiC substrates by interrupting the Ga source flow and flowing diluted silane gas in the presence of ammonia. Partial coverage of the buffer layer achieved by short deposition times formed the porous SiN structure. The effect of an additional SiN layer after the deposition of 2 μm of GaN on the first SiN layer was also investigated.

Observations by transmission electron microscopy (TEM) indicate an order of magnitude reduction in the dislocation density in GaN layers grown on TiN and SiN networks (down to ~10^8 cm^-2) compared with the control GaN layers. Both SiN and TiN porous network structures are found to be effective in blocking the threading dislocation from penetrating into the upper layer. Supporting these findings are the results from X-Ray diffraction and low temperature photoluminescence (PL) measurements. The linewidth of the asymmetric X-Ray diffraction (XRD) peak decreases considerably for the layers grown with the use of SiN and TiN layers, which generally suggests the reduction of edge and mixed threading dislocations. In general, further improvement is observed with the addition of a second SiN layer. The room temperature decay times obtained from biexponential fits to time-resolved photoluminescence (TRPL) data are increased with the inclusion of SiN and TiN layers. TRPL results suggest that primarily point-defect and impurity-related nonradiative centers are responsible for reducing the lifetime. The carrier lifetime of 1.86 ns measured for a TiN network sample is slightly longer than that for a 200 μm-thick high quality freestanding GaN.

6121-12, Session 3

Optical and structural characterization of wurtzite Al0.8In0.2N grown by low temperature magnetron sputter epitaxy

T. Seppänen, J. Birch, L. Hultman, Linköpings Univ. (Sweden)

The ternary III-V nitride alloy Al(1-x)InxN has a wide band-gap range from 0.7 eV for pure InN to 6.2 eV for AlN, which opens possibilities to engineer opto-electronic devices operating at from infra-red to deep ultra-violet wavelengths. Al(1-x)InxN with the alloy composition x~0.2 can also be used as a lattice-matched confinement layer for GaN based electronic devices. However, the ternary Al(1-x)InxN system exhibits a miscibility gap for compositions in the range 0.1<x<0.9 where a stable alloy can not be grown under thermodynamic equilibrium conditions.

In this work, single-crystal ternary wurtzite Al0.8In0.2N thin films were grown epitaxially onto lattice-matched (111)-oriented Ti0.2Zr0.8N seedlayers. The epilayers were grown onto single-crystal MgO (111) substrates by magnetron sputter epitaxy (MSE) using reactive direct current magnetron sputtering under ultra-high-vacuum conditions. The growth temperature ranged from 20 to 400° C. Low-energy ion-assisted growth conditions, enhancing the epitaxy, were achieved by applying a negative substrate potential of 15-60 V. Film compositions and lattice parameters were determined using Rutherford Backscattering Spectroscopy and High-Resolution X-ray diffraction (XRD), respectively. Cross-sectional High-Resolution Electron Microscopy of the interface regions verified the epitaxy and the crystallinity of the films. XRD w-rocking scans of the Al0.8In0.2N 0002-peak showed full-width-at-half-maximum values of ~1000 arcs, indicating a high structural quality of the films. Opto-electronical properties were studied by cathodoluminescence at temperatures between 5 and 293 K. Luminescence was observed at wavelengths as low as 248 nm, corresponding to an energy of 5.0 eV. These results point on the feasibility of metastable Al0.8In0.2N solid solutions as an active luminous material in opto-electronics. It also shows that MSE-grown Al0.8In0.2N can be an excellent choice for lattice-matched GaN heterostructures, with a resulting band-offset enabling strong charge carrier confinement.

6121-13, Session 3

Growth and characterization of algan/GaN epitaxial layers by MOCVD on 6H-SIC substrates for RF device applications

A. K. Sood, Y. R. Puri, Magnolia Optical Technologies, Inc.; F.

W. Clarke, U.S. Army Space and Missile Defense Command; O. Laboutin, R. Wesler, P. DeLuca, Kopin Corp.; J. C. Hwang, Lehigh Univ.

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 various commercial and military RF applications. These include, HEMT (High Electron Mobility Transistor) (1,2), HFET (Hetero-structure Field Effect Transistor) and MOSHFET (Metal Oxide Hetero-structure Field Effect Transistor) (3).

This paper will present experimental results from GaN/AlGaN epitaxial structures grown on 6H-semi-insulating SiC substrates using MOCVD. A close-coupled showerhead reactor operating at low pressure is employed for the growth experiments. The growth temperature and growth rate are monitored in-situ by a LayTec EpiTT tool mounted on the reactor optical view port. The growth conditions are optimized to attain the state-of-the-art composition and thickness uniformity along with sharp interfaces and smooth surface morphology. Sheet resistance, high-resolution X-ray diffraction, atomic force microscope, and white light reflectance measurements are carried out to characterize the epitaxial structures.

Details of the structural, optical and electrical characteristics of the layers will be presented. The characterization results show excellent growth uniformity across the wafer and excellent electrical properties. Results on the fabricated HEMT test devices will also be presented with a correlation with material properties.

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6121-14, Session 3

Impact of spontaneous polarization on surface spatial profiles of defects in GaN

D. K. Johnstone, SEMETROL; S. Akarca Biyikli, F. Yun, Y. Fu, H. Morkoc, Virginia Commonwealth Univ.

Point defects in GaN can reduce the efficiency of light emitting diodes and laser diodes, and cause degraded performance of field effect transistors by influencing the channel conductance, depending on the charge state of the defects, their location, and density. The equilibrium density of various point defects depends exponentially on the formation energy. GaN is typically n-type for most growth methods, and is expected to have the Fermi level near the conduction band even at the growth temperature, since the intrinsic carrier concentration is significantly lower than the typical background carrier concentration. The position of the Fermi level should therefore favor formation of defects such as the gallium vacancy. However, the spontaneous polarization also has a very strong influence on the Fermi level at the growth front. Considering the differences in formation energy, the equilibrium concentration of defects should be significantly different at the surface, compared to defects in the bulk. This work presents measurements of the deep level surface profiles using deep level transient spectroscopy, for various deep levels in GaN.

6121-15, Session 3

Synthesis of nanoporous GaN crystalline particles by chemical vapor deposition

J. Carvajal, N. Gomez, J. Bai, M. Dudley, J. C. Rojo, Stony Brook Univ.

The unique properties that porous semiconductor materials exhibit compared to their bulk counterparts have propelled their utilization in the fabrication of enhanced devices for advanced microelectronics, sensors, interfacial structures, and catalysis. The actual application of these materials does, however, critically hinge on the development of processing methods able to precisely control the optical and electrical properties of the resulting porous materials.

Despite of the great potential for technologies based on nanoporous GaN, very little work has been devoted to the development of approaches to produce this material. While corrosion methods, such as electrolytic etching and anodization processes, have been commonly utilized for the fabrication of nanoporous GaN, the pore size achieved with these techniques is limited to about 300 nm. Synthetic procedures which allow for high specific surface area and well defined nanopore size are still lacking.

Using a chemical vapour deposition approach based on direct reaction of Ga with NH3, nanoporous GaN particles with a pore size of less than 100 nm have been synthesized. Compared to other reported approaches, this process is unique in that it results in the formation of nanoporous structures during the growth process without requiring post-growth treatments. SEM analysis of the nanoporous GaN crystalline micron-size particles reveals a regular array of nanopores closely aligned. The morphology of these nanoporous particles seems to be strongly controlled by the growth conditions, mainly temperature flow rate, and the time of growth. The role of the substrate choice as a decisive way to control the formation of the nanostructures will also be discussed along with detailed characterization of these structures by microscopic techniques.

6121-16, Session 3

Polarization management techniques for enhanced vertical and lateral transport in III-Nitride superlattices

M. Z. Kauser, Univ. of Minnesota; A. Osinsky, B. Hertog, A. M. Dabiran, P. P. Chow, SVT Associates, Inc.

For improved performance of HBTs, Laser Diodes, large area LEDs and LED arrays highly conductive p-type and n-type layers are needed. Modulation doped AlGaN/GaN or GaN/InGaN superlattice (SL) structures have been demonstrated to enhance the lateral free hole conductivity (SigL). N-type heterostructure SLs can be used in LEDs for enhanced current spreading. However, the drawback to these structures is poor vertical conductance (SigV).

In this work we investigate various techniques for optimizing transport properties in p- and n-type AlGaN/GaN and GaN/InGaN SLs. As we show a highly conductive heterostructures can be obtained by inserting a graded doped layer, which reduces the barrier height while maintaining high sheet carrier density. In this work 1-D Schr ̂dinger and Poisson solver together with drift-diffusion and thermionic emission models were used.

For optimized p-type AlGaN/GaN SL, an 8 fold reduction of the barrier height and a 1.5 times increase in sheet hole density is obtained compared to typical SL. The optimized structure yields 13 orders of magnitude improvement in SigV compared to typical SL, and 35 times improvement in SigL compared to bulk p-GaN. For optimized p-type InGaN/GaN SL, an improvement of more than 11 orders of magnitude in SigV compared to typical SL is obtained with SigL better than that of bulk p-InGaN.

We also investigate n-type SLs as current spreading layers. A significant improvement in current distribution is obtained for the optimized SLs. Our approach shows considerable promise for reducing series resistance, and improving the thermal management in advanced III-Nitride vertical transport devices.

6121-17, Session 3

Synthesis of erbium doped gallium nitride crystals by the ammonothermal technique

B. T. Adekore, North Carolina State Univ.; K. Rakes, Air Force Research Lab.; B. Wang, Solid State Scientific Corp.; M. J. Callahan, Air Force Research Lab.; Z. Sitar, North Carolina State Univ.

Single crystalline gallium nitride (GaN) doped with erbium was synthesized using the ammonothermal process on hydride vapor phase epitaxy (HVPE) GaN seeds. The crystallization was conducted in alkaline solutions of supercritical ammonia and potassium azide (KN3) at temperatures between 525oC and 550oC for fifteen days. Scanning electron microscopy revealed a growth thickness exceeding 900μm and 200μm on the nitrogen and gallium terminations respectively. Simultaneous growth on six HVPE seeds was achieved with growth rates of greater than 70μm per day. Photoluminescence spectra obtained at 2K showed a strong band edge luminescence at 3.50eV, a blue and infrared band approximately centered at 2.90eV and 0.81eV respectively, and a significant attenuation of the defect related yellow band approximately centered at 2.0eV.

6121-18, Session 3

Studies of electron trapping in III-nitride semiconductors

L. Chernyak, O. Lopatiuk, Univ. of Central Florida; A. Osinsky, SVT Associates, Inc.

It has been recently discovered that electron injection into (Al)GaN doped with Magnesium, Manganese, Carbon, and Iron using either electron beam of a Scanning Electron Microscope or a forward bias application to p-n junction or Schottky barrier, leads to a multiple-fold increase of minority carrier diffusion length and lifetime. It has also been demonstrated that forward biasing a GaN-based photovoltaic detector results in a several-fold responsivity enhancement due to a longer minority carrier diffusion length in the detectorís Mg-doped p-region as a result of electron injection. The observed electron injection effects were attributed to the charging of the meta-stable centers associated with the above-referenced impurities.

The systematic optical and electrical studies including the Electron Beam Induced Current (EBIC) and cathodoluminescence (CL) measurements in-situ in Scanning Electron Microscope were carried out on the representative range of GaN and AlGaN samples to determine the activation energy for the effects of electron injection. For (Al)GaN doped with Mg, the activation energy is close to the thermal ionization energy of the Mg-acceptor and increases consistent with increasing Al content in the lattice. In the case of Mn-doped GaN, electron-beam induced excitation from the Mn3+ neutral acceptor state was demonstrated to thermalize with activation energy of 360 meV. The activation energy of the electron injection effects for GaN doped with Carbon and Iron are also consistent with the previously reported defect states in the band gap.

6121-19, Session 3

Direction-dependent homo-epitaxial growth of GaN nanowires

M. K. Sunkara, H. Li, Univ. of Louisville

Wurtzite GaN is a technologically important material and its 1-D structures have attracted much interest for electronic and optoelectronic applications. Due to its anisotropic and polar nature, GaN exhibits direction dependent properties. So, the growth direction control for GaN nanowires is important towards practical applications. The graduated structures of nanowires from micron scale to nanometer scale will allow easier integration of nanowires for both optical and electrical coupling. Here, we report a direct nitridation scheme for controllable synthesis of GaN nanowires in two distinct directions (<0001\>, c-direction and <10-10\>, a-direction) using amorphous substrates and describe a simple procedure based on homo-epitaxy to determine the growth directions of the resulting nanowires. Homo-epitaxy onto c-direction wires resulted in the hexagonal micro-prismatic island growth specifically at the ends which could be used for optical and electrical coupling. Homo-epitaxy onto a-direction wires led to uniform growth over entire length of the wires and formation of thin, 2-D microbelts. The morphological features observed with homo-epitaxy onto c-direction wires suggest ìballisticî or 1-D transport mechanism compared to traditional or ìslowî diffusion of adatoms on a-direction wires surfaces.

6121-20, Session 3

AFM and C-AFM studies of MBE GaN films

K. A. Cooper, J. Xie, Y. Moon, A. A. Baski, 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 n-type GaN films. Several MBE-grown GaN films were prepared on MOCVD templates using primarily Ga-rich conditions. The most common type of surface morphology consisted of undulating ìhillocksî with interspersed holes. These holes had typical diameters of ~150 nm, depths of ~350 nm, and densities on the order of 1◊10^6 cm-2. Samples grown under less Ga-rich conditions showed a higher density of such holes (5◊10^6 cm-2). For C-AFM measurements, a Pt-coated AFM tip was brought into contact with the GaN surface to form a microscopic Schottky contact. The sample itself was connected to the voltage source via an ohmic Ti/Al/Ti/Au contact. Although most of the samples had a common Ga-rich morphology, their local conduction behaviors were not all similar. The highest quality samples with low leakage were usually grown at moderate temperatures (~650 ∞C). For such samples, localized leakage only occurred at small pits located at the centers of ~30% of the surface hillocks, which are the surface termination of screw dislocations. Local current-voltage measurements indicate a field emission or Frenkel-Poole mechanism for forward conduction on defective regions. The lower quality samples were typically grown at higher temperatures (\>700 ∞) and demonstrated either high leakage or unexpected p-type behavior. This study confirms that it is not possible to predict the conduction properties of GaN films based on their surface morphologies alone. Subtle differences in growth conditions can result in films with similar hillock morphologies that demonstrate large differences in their conduction behaviors.

6121-21, Session 4

Development of very low dislocation density AlN substrates for device applications

L. J. Schowalter, K. Morgan, W. Liu, Crystal IS, Inc.

Native aluminum nitride (AlN) is a promising substrate material for emerging wide-bandgap electronic and opto-electronic devices. Although AlN crystal growth and substrate preparation technology is less mature than for sapphire and silicon carbide, substantial progress has recently been made using a sublimation-recondensation approach. Crystal IS currently has 25mm diameter substrate capability and is developing 50mm diameter substrates. These native nitride substrates have very low average densities of dislocations (~1000 per sq. cm). Advantages include the same crystal structure as GaN, close lattice match to high Al-content nitride alloys, and a thermal conductivity exceeding 3 W/cm-K at room temperature. In addition, AlN and GaN have closely matched thermal expansions over typical growth temperatures. The AlN has a band-gap energy of 6 eV with an index of refraction of 2.2, which is attractive for the extraction of UV light. The AlN substrates are also highly insulating which is attractive for many high frequency devices. Oxygen is the primary contaminant in our AlN and we have consistently demonstrated oxygen levels at or below low 1E18 per cubic cm range as measured with SIMS. Our partners have demonstrated superior performance on our native AlN substrates for mid-UV light emitting applications (250 to 340 nm). Performance mod-

eling by other groups suggests that AlN substrates may ultimately surpass silicon carbide for high power, high frequency RF devices.

6121-22, Session 4

Exploration of the growth and suitability of nitride-base semiconductors for ferromagnetic semiconductor spintronics

M. H. Kane, W. E. Fenwick, M. Strassburg, A. Asghar, N. Li, I. T. Ferguson, Georgia Institute of Technology

Wide bandgap nitrides and oxides have been heralded as a possible platform for future semiconductor spintronics applications based on the inherent compatibility of these materials with existing semiconductors as well as theoretical predictions of room temperature ferromagnetism. Reports of room temperature ferromagnetism in these materials are complicated by disparate crystalline quality and phase purity in these materials, as well as conflicting theoretical predictions as to the nature of ferromagnetic behavior in this system. A complete understanding of these materials, and ultimately intelligent design of spintronic devices, will require an exploration of the relationship between the processing techniques, resulting transition metal atom configuration, defects, and electronic compensation as related to the structure, magnetic, and magneto-optical properties of this material.

This work explores the growth and properties of Ga1-xMnxN films by metalorganic chemical vapor deposition on c-plane sapphire substrates with varying thickness, Mn concentration, and alloying elements. Homogenous Mn incorporation throughout the films was verified with Secondary Ion Mass Spectrometry, and no macroscopic second phases were detected. SQUID and vibrating sample magnetometry measurements showed an apparent room temperature ferromagnetic hysteresis, whose strength can be altered considerably through annealing and introduction of either Si or Mg during the growth process. Three sets of Raman modes appeared to be sensitive to Mn incorporation; the most prominent additional mode is attributed to nitrogen vacancy-related local vibrational modes of the GaN host lattice. The formation of a Mn-related midgap impurity band is observed via optical transmission measurement in Ga1-xMnxN with strong magnetic signatures. Magneto-optical studies have been performed to study the spin sensitivity of this band.

Initial studies on light emitting diodes (LEDs) containing a Mn-doped active region have also been produced. Devices were fabricated with different Mn-doped active layer thicknesses, and I-V characteristics show that the devices become highly resistive as thickness of the Mn-doped active layer increases. The electroluminescence of these devices is dominated by a high suppressed band-edge recombination and a midgap defect-related emission, leading to an orange-colored but weakly emitting LED. These results suggest that traditional theoretical and device approaches akin to those realized in Ga1 xMnxAs may be difficult to realize in Ga1 xMnxN, and exploitation of these materials will require further novel device approaches taking into account the nature of this material.

6121-23, Session 4

TEM studies of laterally overgrown GaN layers grown in polar and non-polar directions

Z. Liliental-Weber, D. Zakharov, Lawrence Berkeley National Lab.

In GaN -based devices with the active layers grown along c-axis spontaneous and piezoelectric polarization within the active layers results in redshifting of the photoluminescence peak and decreasing the peak intensity. One of the possible solutions to eliminate these undesirable effects is to grow GaN-based epilayers in nonpolar orientations.

However, a high density of structural defects has been observed for growth in both polar and non-polar orientations; this is undesirable from the point of view of laser diode applications. A promising method to decrease the defect density is lateral overgrowth.

Conventional and high resolution electron microscopy has been applied for studying lattice defects in GaN overgrown layers grown on nonpolar a-plane and polar c-plane. It appears that defects in the GaN layers grown in two different crystallographic directions are different. For the growth in the polar direction there are mainly threading dislocations which propagate along the growth direction, but in case of growth in the non-polar direction the c-plane is along the growth direction and stacking faults are formed on these planes. Therefore, lateral overgrowth of the layers is substantially different. For the growth in the polar direction, bending of the dislocations is observed and wing areas close to the sample surface have a very small dislocation density. However, for the growth in the non-polar direction, basal and prismatic stacking faults together with Frank and Shockley partial dislocations were found to be the main defects in the GaN layers and these stacking faults propagate to the sample surface. The growth rate of the two wings is also different since one wing grows with Ga polarity and other with N polarity.

6121-24, Session 5

Hydrostatic pressure-a unique tool in studies of quantum structures and light emitting devices based on group-III nitrides

T. Suski, Instytut Wysokich Cisnien (Poland)

Two effects have to be taken into account in consideration of light emission in GaN-InGaN-AlGaN based devices. i) in the hexagonal wurtzite nitride structures a large built-in electric fields caused by spontaneous and piezoelectric polarizations dominate their physical properties. In particular, a strong red shift of the emitted light energy and spatial separation of electron and hole wave functions causes a drastic reduction of the intensity of the emitted light. ii) it is also known that in hexagonal as well as in cubic nitrides (ternary and quaternary nitride alloys), In-distribution fluctuations lead to the strong Stark effect. Both i) and ii) cause anomalously large Stokes shifts between light emission and absorption which can reach a value of 0.5-1.0 eV.

We will show how dramatic drop of the pressure coefficient of the emitted light energy, dEE/dP, is caused by the effect of built-in electric fields, Fint, in wurtzite structures of (Al,Ga,In)N. In this context we will discuss results obtained in quantum-well and quantum-dot structures. In contrast, our results suggest that In-content fluctuations are of secondary importance with respect to modification of dEE/dP. Thus, it becomes clear that hydrostatic pressure studies of light emission in nitrides can be used for determination of Fint in blue laser and light emitting diodes based on InGaN/GaN structures. We demonstrate additionally that screening of electric fields either by doping or injection of carriers can be monitored by pressure studies enabling to optimize structures of blue laser diodes

6121-25, Session 5

Etched facet technology for GaN and blue lasers

A. Behfar, A. J. Morrow, A. Schremer, C. Stagarescu, BinOptics Corp.

Several years ago, a new technology was pioneered at Cornell University in which the laser facets were formed using a process based on chemically assisted ion beam etching (CAIBE). BinOptics has developed InP-based lasers using this proprietary Etched Facet Technology (EFT). The devices are characterized by precisely located mirrors with quality and reflectivity equivalent to those obtained by cleaving. The use of EFT also eliminates losses that result from mechanical facet cleaving, allows wafer-scale testing and coating, and enables monolithic integration. BinOptics has now developed a modified version of its EFT for GaN materials and blue lasers where mechanical cleaving losses can be even more problematic. The relatively high defect density of currently available GaN materials is expected to create an additional yield advantage for EFT: it allows the formation of shorter cavity devices with fewer defects per device. The GaN EFT process recently developed produces high quality facets with excellent surface roughness and verticality, high etch rate, and acceptable mask-to-substrate selectivity. The first GaN devices to be fabricated are Fabry-Perot type ridge waveguide lasers emitting at

405nm for optical storage applications. Results of this work will be reported.

6121-26, Session 5

Recovery of GaN surface after reactive ion etching

Q. Fan, S. Chevtchenko, X. Ni, S. Cho, H. Morko, Virginia Commonwealth Univ.

Surface potential and surface states change barrier height and reverse leakage current, and therefore, are important factors affecting the performance of Schottky diodes. In this study, we investigated the surface properties of GaN after BCl_3 reactive ion etching (RIE) by surface potential electric force microscopy (SP-EFM). The unintentionally doped n-type 2-um-thick GaN samples were grown on c-plane sapphire substrates by metal-organic chemical vapor deposition (MOCVD). The EFM measurements were performed utilizing Au-coated cantilevers and the data were precisely calibrated with a gold plate for initial potential value. The surface potential for the as-grown samples was 0.6±0.1V, and an almost linear decrease was observed with increasing RIE power. After etching at a power of 300 W the surface potential decreased to 0.2±0.1V. Additionally, after etching the intensity of the near band-edge photoluminescence reduced and as induced from Hall measurement the free carrier density increased. These results suggest that this kind of change in surface potential originates from formation of nitrogen vacancies. To recover the surface different kind of post-etching treatments such as N_2 plasma, rapid thermal annealing (RTA), and KOH wet etching were performed. For each of these methods, the surface potential was found to increase by 0.1~0.3 V which means a partial or complete recovery from the plasma-induced damage. The etched samples treated by the above three methods and two reference samples were then used to fabricate planar Schottky diodes with Ni/Au Schottky and Ti/Al/Ti/Au Ohmic contacts. The fabrication involved the thermal annealing for Ohmic contacts. The samples treated by RTA and N_2 plasma prior to diode fabrication showed no noticeable difference on the I-V characteristics compared to the reference sample. However, the second reference sample which was KOH-treated right after Ohmic contact annealing (before Schottky contact deposition) showed significant improvement in the rectifying characteristics with the leakage current reduced by one order of magnitude compared to the reference sample. Possible reasons for such behavior will be discussed. Similar studies were also performed on non-polar GaN epilayers grown on a-plane sapphire substrates.

6121-27, Session 5

Solar-blind AlGaN 256x256 p-i-n detectors and focal plane arrays

M. B. Reine, BAE Systems

We have developed 256x256 solar-blind UV Focal Plane Arrays (FPAs). These hybrid UV FPAs consist of a 256x256 back-illuminated Al(x)Ga(1-x)N p-i-n photodiode array that is bump-mounted to a matching 256x256 silicon CMOS readout integrated circuit (ROIC) chip.

The first layer in the back-illuminated AlGaN p-i-n photodiode is a silicon-doped n-type AlGaN window layer that serves as the common n-side contact to all elements in the 256x256 array. The alloy composition of this layer determines the cuton wavelength. The next layer is an unintentionally-doped n-type AlGaN absorber layer, with a smaller band gap than the window layer, that forms an isotype heterojunction with the window layer. The alloy composition of the absorber layer determines the cutoff wavelength. The final layers include a Mg-doped AlGaN p-type layer that forms a p-n homojunction with the n-type absorber layer, and a Mg-doped GaN layer that facilitates the p-side contact.

The x-values for the Al(x)Ga(1-x)N window and absorber layer in these solar-blind arrays are set at x=0.60 and 0.47 to provide cuton wavelengths of 260 nm and cutoff wavelengths of 280 nm. The solar-blind spectral region is generally defined as wavelengths less than approximately 280 nm. At these wavelengths, atmospheric ozone strongly absorbs solar radiation, preventing it from reaching the earthís surface.

The back-illuminated AlGaN p-i-n photodiode operating at zero bias voltage has a number of advantages. Because it operates at zero bias voltage, 1/f noise is not an issue. Because the device is designed so that the absorber layer is fully depleted at zero bias voltage, quantum efficiencies are high; photocarrier collection does not depend on carrier diffusion, which is an important consideration for a material such as AlGaN in which the reported diffusion lengths are quite short (<0.1 μm).

Our back-illuminated AlGaN p-i-n mesa photodiode arrays were fabricated from multilayer heterostructure AlGaN films grown by MOCVD onto 2 inch dia. c-plane double-side-polished sapphire substrates. Mesas were etched by the Inductively Coupled Plasma (ICP) process to assure minimal damage at the mesa surface.

This paper summarizes the results achieved in this three-year program.

We have improved MOCVD growth conditions and designs for high-x AlGaN films grown on sapphire in multi-wafer (3-6 films per run) reactors to achieve:

• Spectral response in the 260-280 nm band;

• High conductivity in silicon-doped n-type AlGaN (x up to 0.60): n=4e18 cm-3 and μH=25 cm2/V-s for x=0.60;

• High quantum efficiency and high R0A products in back-illuminated p-i-n AlGaN photodiodes: QE(external) up to 51.5% at 272 nm for zero bias voltage (no A/R coating),and R0A products \>3e10 ohm-cm≤.

We have implemented 2" dia. full-wafer processing, with excellent uniformity and control of ICP dry etch depth. We use probe features to measure I(V) and QE versus wavelength for wafer mapping and array screening. We have formulated analytical and numerical (Silvaco) models to fit data for QE versus wavelength and bias voltage. We have designed and implemented a new low-noise input circuit in 256x256 CMOS readout chips that has achieved 9 noise electrons rms measured at 12 Hz frame rate.

We have demonstrated high-operability solar-blind AlGaN UV FPAs. These are data for one of our recent FPAs: Format: 256x256 with 30x30 μm≤ unit cells; Spectral band: cuton=262 nm, cutoff=278 nm; QE(external) at V=0: 4.5 % at 270 nm (no A/R coating);

Response uniformity: 6 %; Response operability: 99.8 %; R0 (median): 4.3e15 ohm; and R0A product (median): 3.1e10 ohm-cm≤.

This paper will discuss these results, and will present performance data for 256x256 UV FPAs formed by hybridizing recently fabricated, solar-blind back-illuminated AlGaN p-n-N arrays to our new low-noise 256x256 silicon CMOS ROIC chips. We will include AlGaN UV FPAs, all hybridized at BAE Systems onto ROIC chips, with AlGaN solar-blind arrays coming from four different sources. AlGaN p-i-n films (2" dia.) were grown at Emcore and at the University of Texas, and were processed at BAE Systems into 256x256 arrays. AlGaN films were grown and partially processed at Cree and at the University of Texas with a BAE Systems mask set, and processing was completed at BAE Systems.

6121-28, Session 5

Ferroelectric PZT/AlGaN/GaN field effect transistors

Y. Kang, H. Morkoc, Virginia Commonwealth Univ.

The most widely used memory cell structure is 1 transistor/1 capacitor-type cell, in which a ferroelectric capacitor is combined with a metal oxide semiconductor FET (MOSFET). On the other hand, in the metal ferroelectric semiconductor field effect transistor (MFSFET)-type cell, a ferroelectric capacitor is replaced with a ferroelectric-gate FET (FFFT). Recently great progress has been made in the wide bandgap semiconductor-based FFET: MFS-type diodes using PbTiO3 and 4H n-type SiC substrates have been fabricated. The capacitance-voltage characteristics of the diodes showed memory effects;also it has been demonstrated that the channel conductance of 4H n-type SiC-based FFET can be controlled with a maintained memory state set by ferroelectric PZT under gate.

One of potential candidates for FFET is GaN; since they have such high breakdown field, high chemical and mechanical stability, and high thermal conductivity, GaN-based FFET would pave the way for the realization of nonvolatile ferroelectric random access memory (NvFRAM), desirable for the operation in high power, high temperature, and/or high frequency conditions.

In this work, we demonstrate ferroelectric field effect transistors (FFETs) with hysteresis to be used in a NvFRAM. The FFETs are fabricated in an AlGaN/GaN modulation doped FET (MODFET) platform with ferroelectric PZT under gate. The pinch-off voltage was 6 V in both MODFET and FFET. Counterclockwise hysteresis appears in transfer characteristic curve of a FFET with a drain current shift of about 5 mA when gate-to-source voltage is zero. Comparison with the transfer characteristic curve of a MODFET suggests that the key factor contributing to the counterclockwise hysteresis of the FFET is the ferroelectric switching effect of PZT gate.

6121-29, Session 5

Deep UV AlGaN light emitting diodes grown by gas source molecular beam epitaxy on sapphire and AlGaN/sapphire substrates.

S. Nikishin, B. Borisov, V. Kuryatkov, Texas Tech Univ.; A. S. Usikov, V. A. Dmitriev, Technologies and Devices International, Inc.; M. Holtz, Texas Tech Univ.

We report the electrical and optical properties of deep ultraviolet light emitting diodes (LEDs) based on digital alloy structures (DAS) of AlN/Al0.08Ga0.92N grown by gas source molecular beam epitaxy with ammonia on sapphire and AlGaN/sapphire substrates. AlGaN/sapphire substrates were grown by recently developed stress controlled hydride vapor phase epitaxy (HVPE). For DASs with effective bandgap of 5.1 eV we obtain room temperature electron concentrations up to 1x1019 cm-3 and hole concentrations of 1x1018 cm-3. Based on these results we prepared double heterostructure (DH) LEDs operating in the range of 250 to 290 nm. The emission wavelengths were controlled through the effective bandgap of the active region. We will discuss the possible ways for increase of LEDís efficiency and compare the electrical and optical properties of LEDs grown on different substrates. We will show that the addition of undoped, 10 nm thick, AlN barriers on each side of the active layer, results in significant improvement (by a factor of 10) in the emission efficiency. The introduction of AlN barriers also results in the elimination of the parasitic emission at 320 nm, even under very low excitation current density of 40 A/cm2. We will discuss a significant improvement in the room temperature luminescence efficiency (by factor of 100) of AlGaN quantum wells when the 3D growth mode is induced by reduced flux of ammonia. Preliminary experiments show that DASs grown on AlGaN/sapphire substrates have higher luminescence efficiency than DASs grown on sapphire. This work is supported by DARPA, NSF (ECS-0323640 and ECS-0304224), and the J. F Maddox Foundation.

6121-30, Poster Session

Investigation of band gaps and bowing parameters for zincblende III-nitride ternary alloys

B. Liou, Hsiuping Institute of Technology (Taiwan); S. H. Yen, Y. K. Kuo, National Changhua Univ. of Education (Taiwan)

III-nitride semiconductor materials have comprehensively applied in light emitting diodes and laser diodes, due mainly to their relatively wide range band gap tuned from the infrared, the visible across the ultraviolet spectral range and high emission performance. III-nitride semiconductor with wurtzite structure always has a direct band gap, but the zincblende structure still possesses distinct advantages. For example, the zincblende structure is provided with larger optical gain and lower threshold current density because of its smaller effective mass, and has mirror facets compatible with substrates such as GaAs. The optical characteristics of zincblende InxGa1-xN, AlxGa1-xN, and AlxIn1-xN alloys from first-principles calculations by means of a supercell with plane-wave pseudopotential-based density functional theory (DFT) in the local density approximation (LDA) will be investigated in this study. Assuming that the lattice constants of ternary compounds can be expressed as a linear combination of the lattice constants of the two forming binary compounds, the physical properties of the ternary nitride compounds are usually investigated based on the Vegard's law. First, the deviation of lattice constants from the Vegard's law will be investigated. Second, the Vegardís law deviation in physical properties and optical characteristics including direct band gap, indirect band gap, width of valence band, bowing parameter of direct band gap, and bowing parameter of indirect band gap will be discussed. Moreover, the direct-indirect crossover point for AlxGa1-xN and AlxIn1-xN alloys will be decided. Finally, for better reference, the band gap and the corresponding wavelength are shown as a function of lattice constant.

6121-31, Poster Session

Studies of spin polarized carrier injection into GaN-based heterostructures

V. Avrutin, Ü. Özgür, J. Xie, S. Cho, Y. Fu, H. Morko, Virginia Commonwealth Univ.; V. Litvinov, Waveband Corp.

Spin-based devices, such as spin field-effect transistors (FETs), require spin injection from a ferromagnetic material into a paramagnetic material across an interface. Spin injection from a ferromagnetic metal into paramagnetic metal can readily occur, but spin injection from a ferromagnetic metal into a paramagnetic semiconductor is much more difficult. The fundamental obstacle is the large difference in the conductivity of the metal and the semiconductor[1]. Therefore, the best prospect for electrical spin injection into semiconductors is direct injection from a ferromagnetic dilute magnetic semiconductor into a paramagnetic semiconductor.

Dilute magnetic semiconductors that are ferromagnetic usually have Curie temperatures well below room temperature (GaMnAs, for example, has a Curie temperature of 110 K). Therefore, at present, room temperature injection still requires using a metallic ferromagnetic injector. Fortunately, it has been shown theoretically, that interposing a tunnel barrier between a metallic ferromagnet and a semiconducting paramagnet can improve spin injection efficiency[2].

We propose the use of NiFe contacts for injecting spin polarized electrons into AlGaN/GaN FET structures with two-dimensional electron gas. In the spin-FET, the source and drain act as spin ìpolarizersî and ìanalyzersî respectively. Thus the source contact and also the drain contact of the spin-FET is a NiFe layer. The NiFe contact can provide spin polarization of about 30% under the best of circumstances. Application of an additional tunneling barrier (AlOx, SiN, MgO etc.) improves the contact performance increasing the spin injection efficiency. Device structures with separation between source and drain varying from 70 to 350 nm were fabricated using e-beam lithography. Initial magnetoresistance measurements were done for the structure containing no gate contact.

In order to inject spin polarized carriers, GaN-based DMS layers are also promising. For this purpose, motivated by the recent reports of room temperature ferromagnetism in GaN:Gd layers[3,4], with Gd concentrations as low as 7x1015 cm-3, magnetic and magnetooptical properties of Gd-implanted GaN layers were investigated. Clear room temperature ferromagnetism was observed with upto 1000 Bohr magneton saturation magnetization per Gd atom. The influence of low dimensionality on ferromagnetism was also studied by employing nano-imprint lithography. Gd-implanted and Mn-diffused GaN nanopillar samples were investigated. To identify the source of ferromagnetism magnetic circular dichroism spectroscopy was applied.

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6121-32, Poster Session

High-reflectivity and thermal-stability Cr-base reflectors and n-type Ohmic contact for GaN-based flip-chip light-emitting diodes

K. Hsueh, K. Chiang, National Central Univ. (Taiwan); C. J. Wang, LEDARTS OPTO Corp. (Taiwan); Y. Hsin, National Central Univ.

Realization of high brightness and high power GaN-based light-emitting diodes (LEDs) are of great technological importance for solid-state lighting applications, which require high extraction efficiency in LED structures. It was shown that flip-chip LEDs (FCLEDs) configuration is very effective in enhancing light extraction and thermal dissipation. We have investigated three composite metals to study the reflectivity and thermal-stability for using as the reflector and bonding layer in FCLEDs. In addition, these metals were simultaneously deposited on n-type GaN without alloy to form Ohmic contact and simplify the process. The investigated composite metals were Ti(30nm)/Al(500nm)/Ti(30nm)/Au(300nm), Cr(30nm)/Al(500nm)/Cr(30nm)/Au(300nm) and Cr(500nm)/Ti(30nm)/Au(300nm), respectively. The specific contact resistivity of Ti/Al/Ti/Au, Cr/Al/Cr/Au and Cr/Ti/Au on the n-type GaN ohmic contact were decreased from 5.4E-4, 6.6E-4 and 7.7E-4 ohm-cm2 to 5.3E-4, 4.5E-4 and 1.3E-4 ohm-cm2 respectively after 500 hours thermal stress at 150C in the air. However, the forward I-V characteristics measured up to 3.5V showed the decreased series resistance only from the diode using Cr/Ti/Au metals after thermal stress. This is due to the degradation in the p-type ohmic contact using Al metal in the Ti/Al/Ti/Au and Cr/Al/Cr/Au metals. After thermal stress, the root-mean-square (RMS) surface roughness of Ti/Al/Ti/Au, Cr/Al/Cr/Au and Cr/Ti/Au were evaluated by AFM and demonstrated the increase from 3.65, 7.17 and 3.67nm to 4.23, 17.24 and 3.76nm respectively. The luminous intensity at 20 mA of the FCLEDs in these three structures (Ti/Al/Ti/Au, Cr/Al/Cr/Au and Cr/Ti/Au) were improved about 66%, 68% and 113% compared with the normal LED without flip-chip process. Considered the wafer uniformity (7 mcd), the improvement of using Cr/Ti/Au is still significant. After 96 hours of thermal stress, the luminous intensities at 20 mA of these three structures were decreased 6.2%, 11.1% and 1.4%, respectively. Therefore, in addition to the good n-type ohmic contact, the Cr/Ti/Au composite metal demonstrated good reflectivity and thermal stability for the flip-chip reflector and bonding metal.

6121-33, Poster Session

Temperature dependent cross-relaxation of blue emission from Tm doped AlN epilayers

W. M. Jadwisienczak, H. J. Lozykowski, Ohio Univ.; A. Anders, Lawrence Berkeley National Lab.

We report on the temperature dependent cross-relaxation process of Tm implanted in AlN. Investigated AlN samples were grown on sapphire by molecular beam epitaxy, doped by implantation with Tm ions with 150 keV maximum implantation energy with a dose of 1x10^16 At/cm^2 (the peak concentration of Tm^3+ ions was 3.4x10^21 At/cm^3). Samples were thermally annealed at 1050 C in ammonia at atmospheric pressure to remove implantation induced defects. The low temperature (12 K) ëblueí part (460-489 nm) of CL spectrum of Tm-doped AlN shows multiple transition lines originating from 3P, 1I, 1D and 1G manifolds. It was observed that the shape of the CL spectrum changes radically when temperature increases leaving dominant two groups of lines centered at 463 nm (1D2->3F4) and 466 nm (3P1->3F3,2) at 300 K. These changes resulted in one order of magnitude increase of ëblueí emission intensity with respect to low temperature emission. The experimental data are analyzed using the thermally dependent cross-relaxations processes between 1I6, 1G4 and 1D2, 3P1 terms.

6121-34, Poster Session

Applications of transparent Al-doped ZnO contact on GaN-based power LED

C. Tun, National Central Univ. (Taiwan); J. Sheu, National Cheng Kung Univ. (Taiwan); B. Pong, National Central Univ. (Taiwan); M. Lee, National Cheng Kung Univ. (Taiwan); M. Lee, C. Hsieh, C. Hu, G. Chi, National Central Univ. (Taiwan)

In this study, ZnO:Al(AZO), Ni/AZO, and NiOx/AZO films were deposited on p-type GaN films followed by thermal annealing to form Ohmic contacts. After 800 degree C thermal annealing, the resistivities reduced from 5.0E-3 to 4.4E-4Ω-cm, 1.3E-3Ω-cm, and 1.1E-3Ω-cm for AZO, Ni/AZO, and NiOx/AZO films, respectively. The as-deposited AZO contacts showed a non-Ohmic characteristic, even after thermal annealing. The Ohmic characteristic could be highly improved after inserting Ni and NiOx between AZO and p-GaN. Both the Ni/AZO and NiOx/AZO contacts exhibit Ohmic characteristic after annealed at 800 degree C in N2 ambient. The light transmittance of Ni/AZO and NiOx/AZO films were higher than 80% in the range of 380-700nm after the 800 degree C -annealed treatments. In addition, we fabricated InGaN/GaN MQW LEDs with a dimension of 1x1mm^2 using the transparent Ni/AZO and NiOx/AZO Ohmic contact as a current spreading layer for p-GaN in order to increase the light extrication efficiency. For the LED with Ni/AZO contact, the light output approached to saturation when the injection current was about 400mA. However, the saturation point was as high as 500mA for the LED with NiOx/AZO contact. This could be due to that the resistivity of Ni/AZO films was higher than that of NiOx/AZO films leading to a severe current crowding effect. The increased resistivity of the Ni/AZO films could be attributable to the interdiffusion between Ni and AZO. Comparing to the GaN LED with Ni/Au Ohmic contacts, the light output intensity of the LEDs with Ni/AZO and NiOx/AZO contacts were increased by 41% and 60% at 350mA, respectively.

6121-35, Poster Session

Increase of output power and lifetime by improving the heat dissipation of GaN-based laser diodes

J. Chae, H. Ryu, K. Kim, K. Ha, SAMSUNG Advanced Institute of Technology (South Korea)

The enhanced output power with improved lifetime is required for the GaN-based blue-violet laser diode (LD) as a light source for Blu-ray Disc or Advanced Optical Disc. In this paper, the output power levels and aging behaviors in GaN-based LDs grown on sapphire substrates are compared in epi-up and epi-down bonding. At low current level, the epi-up and the epi-down bonding show little differences in L-I characteristics. At high current level, however, the epi-up bonding shows rapid decrease of slope efficiency in L-I characteristics, and usually roll-over occurs with increasing current injection. On the contrary, the slope efficiency in epi-down bonding is not so much decreased as current increases compared with that in epi-up bonding. The differences in junction temperature (Tj) between epi-up and epi-down bonding are large at higher current levels. The Tj of epi-up bonding is about two times higher than that of epi-down bonding. To investigate the thermal transient response, pulsed current is injected and change of bias voltage is monitored. The voltage is exponentially decreased within the pulse duration due to temperature increase. The thermal response time of epi-down bonding is about two times shorter than that of epi-up bonding, implying efficient heat dissipation in epi-down bonding. At aging test, the epi-down bonding has lower aging slope than that of epi-up bonding. The degradation rate is accelerated by poor heat dissipation in epi-up bonding. Thus for the higher power and longer lifetime, it is necessary to employ efficient heat dissipation structures such as epi-down bonding for the GaN-based LD on sapphire substrate.

6121-36, Poster Session

Gallium Nitride (GaN) based MODFET Devices for Power Electronics

H. F. Huq, The Univ. of Tennessee

The objective of this paper is to investigate the feasibility and explore the potential of GaN-based devices for applications of power electronics. The major tasks of this paper include: 1) Development of GaN-based AlGaN/GaN MODFET with high reverse breakdown voltages and low turn-on voltages, 2) AlGaN/GaN metal oxide semiconductor heterojunction field effect transistors (MOS-HFETs) with high current operation, fast switching speed and reverse recovery time, low on-state resistance, and high breakdown voltage; 3) Establishment of the compact models of these devices including the thermal effects; 4) device scalability, device reliability, and high temperature device packaging will be investigated.

So far, extensive investigations have been conducted on the potential of AlGaN/GaN MODFETs for microwave power applications. State-of-the-art results of AlGaN/GaN MODFETs include a microwave power density of over 30 W/mm at 10 GHz which is about 30 times higher than that of GaAs devices and over 50 times of Si-based devices.

Conference 6122: Zinc Oxide Materials and Devices

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6122-01, Session 1

On the identifications of impurities and point defects in ZnO

D. C. Look, B. Claflin, G. C. Farlow, Wright State Univ.

At present, there is much debate over the identifications of various donors, acceptors, and traps in ZnO. For example, up until the year 2000, most workers assigned the usual n-type nature of ZnO to native-defect donors, either the O vacancy VO or the Zn interstitial ZnI. Then Kohan et al. pointed out that these defects have high formation energies, and thus are not likely to exist in large concentrations. Also in 2000, Van de Walle suggested that the omnipresent impurity H is a much better choice as the dominant donor in ZnO, and indeed it turns out that H is a common residual donor in some ZnO samples. Furthermore, there is evidence that the Group III elements, Al, Ga, and In, can be strong background donors in ZnO. In an attempt to resolve some of these problems, we have subjected high-quality, bulk ZnO to annealing and electron-irradiation treatments, and have examined the results with temperature-dependent Hall-effect (T-Hall) and 4-K photoluminescence (PL) measurements. Contrary to present thought, we show that a particular point defect, ZnI, does indeed contribute to n-type conductivity, but as a complex, not as an isolated entity. This complex, ZnI-NO, can be formed in our material because of a high N background, and density functional theory finds that it has a shallow donor character as well as a relatively low formation energy. The T-Hall measurements show that this complex has a donor level at 30 meV below the conduction band, and the PL data find a new, sharp, donor-bound exciton (D0X) line at 3.36070 eV, and two-electron satellite (TES) lines at 3.33711, 3.33793, and 3.33840 eV, consistent with a 30-meV, hydrogenic-type donor. Since the as-grown material also clearly contains a 30-meV Hall-effect donor, as well as two of the three PL TES lines, we suggest that ZnI-related donors can be important in as-grown ZnO. With regard to acceptor-type defects, previous studies have shown that the Zn vacancy is the dominant acceptor in bulk ZnO. Thus, we conclude that native point defects are important both as donors and acceptors in bulk, n-type ZnO. Impurity donors, such as H, Al, Ga, and In, are also present in this material, and their T-Hall and PL fingerprints will be discussed.

6122-09, Session 2

Effect of Al diffusion and thermal annealing on the electrical properties of ZnO Films grown on sapphire substrate

J. Mimmila-Arroyo, J. Rommeluère, F. Jomard, Y. Marfaing, P. Galtier, Univ. de Versailles Saint-Quentin-en Yvelines (France)

We present first a study of the growth of ZnO films deposited by CSVT on C and R sapphire substrates. H2 and N2 were used as transport agent. The deposition on R oriented sapphire substrates give rise to a-(11-20) oriented ZnO films. Under optimised conditions, flat surfaces can be achieved and rocking curves with full half width below 500 arsec can be achieved.

Then we report on the electrical activity of ZnO films grown on sapphire substrate. The n type conductivity of the epitaxialy deposited films has been studied for thicknesses ranging from 0.1 to 60 microns. The carrier concentration, measured by Hall effect, is found to decrease linearly with the film thickness. This result is explained by the dominant contribution of an interface layer to the measured conductivity in relation with Al diffusion from the substrate as demonstrated by Secondary Ion Mass Spectrometry (SIMS). We show that this strong interface conductivity can be compensated on thin films using thermal annealing under oxygen atmosphere at 850∞C. Under these conditions, n-carrier concentration in the 10E14cm-3 range can be achieved. Furthermore, the effect of this annealing under oxygen is found to be completely reversible after a further thermal annealing under argon atmosphere at the same temperature. The results are interpreted by the successive adsorption (under oxygen anneal) and desorption (under Ar anneal) of oxygen at extended defects (grain boundaries or dislocations). In this situation, oxygen leads to a trap for electron and compensates the n carriers present in the layer.

6122-11, Session 2

Optical properties of phosphor ion implanted ZnO

B. Pong, B. Chou, C. Pan, G. Chi, National Central Univ. (Taiwan)

Red emission and green emission are observed from phosphor ion implanted ZnO. Red emission at ~680 nm (1.82 eV) is associated with the donor-acceptor pair (DAP) transition, where the corresponding donor and acceptor are interstitial zinc (Zni) and interstitial oxygen (Oi), respectively. Green emission at ~ 510 nm (2.43 eV) is associated with the transition between the conduction band and antisite oxygen (OZn). Green emission can also be found in the 800 oC-annealed ZnO sample under ambient oxygen.

6122-12, Session 2

Growth and scintillation properties of ZnO and In:ZnO single crystals as ultrafast semiconducting scintillators

A. Yoshikawa, Y. Kagamitani, D. Ehrentraut, Tohoku Univ. (Japan); M. Nikl, Instytut Fizyki (Czech Republic); T. Fukuda, Tohoku Univ. (Japan)

Scintillators are functional materials that absorb the energy of ionizing radiation in order to immediately emit photons. They are used for radiation measurements in the field of nondestructive scanning, medical imaging system (X-ray CT and PET / SPECT), high energy particle physics and so on.

Recently, due to the development of surrounding devices, the concept of Time-of-flight (TOF) device is reconsidered. Consequently, luminescence with less than 1ns decay time is strongly required. So far, BaF2 was considered as candidate, however, the existence of longer decay component as well as its low density and low light yield hinders from application. Therefore, crystalline materials with improved properties is required.

As excitonic luminescence of ZnO is of the order of sub-nano second decay, it can be used for this purpose. However, due to its self absorption, the output luminescence intensity with short decay time is rather weak. Therefore, in this study, we have grown In doped ZnO (In: ZnO) single crystals by hydrothermal method using Pt inner container. This In doping is to shift the luminescence wavelength in order to avoid self absorption.

As grown In: ZnO has slightly bluish color. Compared to non-doped ZnO, the absorption edge of In: ZnO was shifted towards shorter wavelength. From the result of X-ray radioluminescence, it proved that the excitonic luminescence peak top was shifted towards longer wavelength from around 380nm to around 400nm combined with increasing of luminescence intensity.

6122-19, Session 3

Light emission and charge transport studies on ZnO heterostructures

H. C. Ong, W. H. Nei, J. An, R. Wang, J. B. Xu, J. Y. Dai, The Chinese Univ. of Hong Kong (Hong Kong China)

Although metal/semiconductor and oxide/semiconductor junctions have long been studied in the areas of microelectronics, new phenomena and interests arise from time to time. In particular, in the realm of nanotechnology where materials are shrunk at a length scale of nanometers, the role of heterojunctions in controlling the overall characteristics of the system will become more and more important. In this presentation, we will show our recent results on the light emission and charge transport properties of metal/ZnO and oxide/ZnO system at different dimensionalities. On one hand, it is found that by capping metal on ZnO, it is possible to excite the surface plasmon polaritorn at the metal/ZnO interface and resonantly couple it with the spontaneous recombination of ZnO. This results in a significant enhancement of emission efficiency of ZnO. On the other hand, providing an oxidic overlayer is present on ZnO, a focused electron beam can be used to locally modify optical and electrical properties of ZnO. Under electron bombardment, we find the emission profile of ZnO gradually changes from green-yellow emitting into ultra-violet emitting while the conductivity decreases by more than two orders of magnitude at the same time. Well-defined sub-micron patterns with tunable optical and electrical properties can be fabricated on 2-D ZnO films and 1-D nanoribbons by carefully controlling the dose and energy density of the electron beam. Since ZnO is a versatile material, we believe our studies will shed light on the further use of ZnO in frontier technologies such as gas sensing, display technology, catalysis, spintronics, etc.

6122-20, Session 3

ZnO photonic crystal lasers

X. Wu, A. Yamilov, X. Liu, S. Li, V. P. Dravid, R. P. H. Chang, H. Cao, Northwestern Univ.

We realized ultraviolet (UV) photonic crystal lasers with ZnO. Over the past decades tremendous progress has been made in the fabrication of photonic crystal lasers with III-V semiconductors that operate in infra-red (IR) spectrum range. To realize UV photonic crystal laser, the feature size has to be reduced roughly by a factor of four. Because of technical difficulties in fabricating fine structures with chemical etching of ZnO, we developed a physical etching procedure based on focused ion beam (FIB) technique. We fabricated triangle lattices of air cylinders in ZnO thin films with high spatial resolution and aspect ratio. A post thermal annealing process was developed to remove structural defects caused by FIB etching. UV lasing was achieved in these structures under optical pump at room temperature. The radius of air cylinders is about 30nm, whereas the lattice constant is varied from 100nm to 150nm. By changing the distance between the ion gun and sample, we were able to control the feature size down to 3nm. This allowed us to tune the photonic band gap across the ZnO gain spectrum. As a result, the lasing wavelength can be tuned from 380nm to 406nm. A three-dimensional plane wave expansion method was used to calculate the band structure of the ZnO photonic crystal slabs. The calculation result confirms a complete photonic band gap exists and its spectral position coincides with the measured lasing frequency. From their spatial profiles, we believe the lasing modes are defect states that originate from the structural disorder unintentionally introduced during the fabrication process.

6122-21, Session 3

ZnO nanorods for electronic device applications

G. Yi, National CRI Center for Semiconductor Nanorods and Department of Materials Science and Engineering, (South Korea)

One-dimensional semiconductor nanorods are potentially ideal functional components for nanometer-scale electronics and optoelectronics, due to both well-controlled composition modulation and their high aspect ratio offering easy fabrication of nanodevices. Among numerous semiconductor nanomaterials, ZnO semiconductor nanowires and nanorods are attractive components for nanometer scale electronic and photonic device applications. Recently, a wide variety of nanodevices including ultraviolet photodetectors, Schottky diodes, and light emitting device arrays have been fabricated utilizing ZnO nanorods (nanowires). In particular, a field-effect transistor (FET), one of the most fundamental and important electronic components, has been fabricated using ZnO nanobelts, nanowires, and nanorods. However, most of the ZnO nano-FETs have exhibited poor transistor characteristics. The poor ZnO nano-transistor characteristics may result from a high concentration of impurities in the nanomaterials, large contact resistance, or surface-mediated effects including chemisorption and carrier scattering or trap processes by surface states. However, high performance FETs can be fabricated both using single crystalline oxide nanostructures with low impurity concentrations and coating a polymer on surfaces of ZnO nanorods as we have already reported. The ZnO nanorod metal-oxide semiconductor FET (MOSFET) exhibited field effect electron mobility as high as 1000 cm^2/Vs. In addition, metal oxide semiconductors exhibit an air-stable surface without formation of an insulating native oxide layer, which can realize clean and abrupt metal/semiconductor (M/SC) interfaces without any specific oxide etching process. Further control of the metal/oxide junction characteristics to either good ohmic or Schottky contacts on oxide nanomaterials would readily enable creation of many other oxide-based electronic nanodevices. Here we report on fabrications of high performance metal oxide nanodevices including high performance Schottky diodes, MOSFETs, metal-semiconductor field-effect transistors (MESFETs) and logic gate devices. These sophisticated ZnO electronic nanodevices would greatly increase the versatility and power of the building blocks for fabrication of numerous nanodevices based on metal oxides.

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6122-22, Session 3

Innovative optical gas sensor based on photoluminescence quenching of ZnO nanowires

C. Baratto, M. Picinelli, E. Comini, G. Faglia, G. Sberveglieri, C.N.R. - INFM & Univ. degli Studi di Brescia (Italy)

We synthesized zinc oxide nanowires by thermal evaporation of metal powders under controlled conditions and studied the effect of pollutant gas species on photoluminescence (PL) intensity in the temperature range (273K-500K).

In the literature many studies are devoted to the optical properties of ZnO nanostructures, an high gap metal oxide semiconductor in which oxygen vacancies are deemed responsible of doping. Recently much attention has been paid to the PL response in the visible -green- range. Still there is no consensus on the positions of the peaks in the PL spectrum of ZnO nanostructures and thin film and their origin. The green emission has been assigned to the transition between the photoexcited holes and single ionized oxygen vacancy[1], attributed to antisite oxygen[2] and donor-acceptor complexes[3-4]. Surface states have also been identified as a possible cause of the visible emission in ZnO nanowires[5]. Beside it was determined that the ratio of UV to visible emission is dependent on the fabrication conditions[6].

A very interesting result is the progressive increase of the green light emission intensity determined as the wires diameter decreases [7]. This suggest the possibility that reduced dimensionality of the system could play a role in the onset of visible PL spectra of high gap metal oxides, both due to quantum size effects or by the increase of the surface, rich in oxygen vacancies, to volume ratio.

PL spectrum of synthesized ZnO nanowires was acquired at different temperatures when excited with an He-Cd laser line at 325 nm.

We report for the first time that the visible PL of zinc oxide nanowires is quenched by nitrogen dioxide at ppm level in a fast and reversible way, even at room temperature. The response time is less than 30 s at room

temperature. Very small interference from other gases like humidity, NH3, ethanol and CO has been observed. The results foresee the development of a new class of selective metal oxide gas sensors working at room temperature.

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6122-23, Session 3

Fabrication, characterization and growth mechanism of ZnO nanostructures synthesized by thermal oxidation reaction

J. Delaunay, N. Kakoiyama, I. Yamada, The Univ. of Tokyo (Japan)

We fabricated ZnO nanostructures via a thermal oxidation reaction in air from Zn pellets placed in an open quartz tube heated in a furnace. The reaction started at a temperature of 900° C and consumed very rapidly the Zn pellets. The texture of the obtained product resembles that of cotton. The fabrication process does not rely on metal catalysts.

The material crystallographic structure obtained from X-ray diffraction data was found to match that of the hexagonal wurtzide structure of ZnO. No other phase could be detected in the diffraction pattern. The relative intensities of the diffraction peaks were in good agreement with those tabulated in standard powder diffraction data, suggesting a good crystallinity of our sample. X-ray fluorescence analysis shows no trace of metallic contamination, which confirms that our material was synthesized without metal catalysts. Transmission Electron Microscope (TEM) observations reveal needle-like nanostructures with a high yield for nanostructures having 4 legs assembled in a tetrapod-like shape. Diameter of the needles/legs varied in the 50-500 nm range while their lengths varied in the 1-10 μm range. Most of the needles were in the form of a monocrystal.

Our material exhibits a sharp photoluminescence peak having its maximum at 380 nm, which is attributed to radiative annihilation of excitons. Green photoluminescence around 500 nm believed to originate in crystalline defects such as vacancies and interstitials was not observed. The sharpness of the photoluminescence peak and the lack of green photoluminescence is evidence for good crystalline quality of our material.

The growth mechanism of the nanostructures is discussed in light of detailed TEM observations. Our observations point to a mechanism involving a liquid phase in the formation of the tetrapod-like nanostructures.

The high surface to volume ratio of the ZnO nanostructures makes it a good candidate for applications in catalysis such as photocatalytic oxidation of volatile organic compounds (VOCs) and in gas sensing of VOCs. Design and results of first tests of a gas sensing device based on the ZnO nanostructured material will be reported.

6122-13, Session 4

Zinc oxide based materials for Spintronics

S. Ramachandran, J. Narayan, North Carolina State Univ.

With the advances in thin film epitaxy of II-V compound semiconductors, ZnO based materials have gained significant importance. A wide variety of devices utilizing transparent semiconductors, UV LEDs, Solid state lighting and a variety of sensors, are being explored with considerable fervor in the recent years. There is a multitude of advantages of using ZnO over similar optoelectronic semiconducting materials like GaN. It is a widebandgap material with Eg=3.3eV which can be tuned both ways by cation substitutions with Cd or Mg. It has a large exciton binding energy of 60meV (only ~25meV for GaN) promising better luminescence efficiency. Also, it can be grown epitaxially on commercially available substrates like Sapphire and Si(111) by domain matching epitaxy where integral multiples of planes of the substrate and the thin film match across the interface. In this work we will discuss the present status of the field as well as the future possibilities.

In the new and emerging field of Spintronics (or spin electronics), the so-called Diluted magnetic semiconductor (DMS) materials based on ZnO, are being studied extensively for potential applications Specifically, for applications in spintronic devices where both charge and spin of the carriers are combined to introduce novel functionality, the possibility of room temperature ferromagnetism being mediated by electrons is very exciting, as the spin coherence times for electrons are more than that for holes in a semiconductor. ZnO occurring naturally as an n-type semicondcutor fits the bill perfectly. This provides opportunities to develop novel spintronics devices like high performance read-heads, on chip memories and ultra-low power consumption devices. Recently, we have grown such DMS materials based on ZnCoO(1), ZnMnO and ZnVO(2) by pulsed laser deposition technique and characterized them fully for magnetic, electronic and nanostructural properties. It is now established after elaborate studies that ZnCoO and ZnMnO materials exhibit room temperature ferromagnetism, which can aid in realizing such practical applications. Thus, if fully harnessed ZnO based materials could herald a new generation of novel functional devices.

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6122-14, Session 4

Optical and magneto-optical studies of ZnO doped with transition metals

V. Avrutin, Ü. Özgür, H. Lee, B. Xiao, C. Liu, H. Morkoc, Virginia Commonwealth Univ.; A. El-Shaer, A. Che Mofor, A. S. Bakin, A. Waag, Technische Univ. Braunschweig (Germany); N. Izyumskaya, W. Schoch, Univ. Ulm (Germany); S. Sorokin, S. V. Ivanov, A.F. Ioffe Physico-Technical Institute (Russia)

In the last two decades, diluted magnetic semiconductors (DMS) have attracted a great deal of attention as possible candidates for spintronics applications. General approach to the fabrication of DMS is the substitution of cations of host semiconductors with 3d transition-metal (TM) ions bearing a net magnetic moment. Among other material systems (II-VI DMS, GaMnAs, InMnAs, III-nitrides), ZnO-based DMSs show a great promise for applications exploiting spin manipulation. The particular interest in these materials has been triggered by theoretical predictions of ferromagnetism with Curie temperatures above 300 K [1]. However, the extensive studies of TM-doped ZnO give contradictory results. In this work we investigate the optical and magneto-optical properties of Zn(Mn)O and Zn(Cr)O layers grown by molecular beam epitaxy and radio-frequency magnetron sputtering.

The electronic properties of Mn-doped ZnO are of interest regardless, because the effect of Mn incorporation on the band gap allows one to

increase the functionality of structures by combining magnetoelectronics and band gap engineering. The layers containing up to 50% of Mn were characterized by high-resolution x-ray diffraction, photoluminescence (PL), and optical absorption. A blue shift of the band edge revealed from optical absorption measurements points to the incorporation of at least a part of Mn atoms on lattice sites. A linear increase in the Zn(Mn)O band gap and an enhancement of the broad below band gap absorption associated with Mn ions were observed with increasing Mn composition. PL of ZnO moderately doped with Mn shows several emission lines (the strongest ones are located at 3.34 and 3.36 eV). Surprisingly, no shift in the near-band-edge emission (3.36 eV) was detected in the PL data. PL excitation studies revealed that the near-band-edge peak and the peak centered around 3.34 eV have different origin. Most probably, the second line is due to Mn intracenter transitions. Similar measurements were done for Cr-doped samples. In order to give detailed insight into magnetic properties of TM-doped ZnO, magnetic circular dichroism measurements were also performed.

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6122-33, Session 4

To be announced

M. Lorenz, Univ. Leipzig (Germany)

No abstract available

6122-16, Session 5

Advances in ZnO Etching

K. J. Nordheden, The Univ. of Kansas

The author will review latest advances on ZnO etching.

6122-17, Session 5

Green-light emission of ZnO nanoparticles spontaneously precipitated in fluorinated polyimide films

A. Somwangthanaroj, Chulalongkorn Univ. (Thailand); A. Matsumura, S. Ando, Tokyo Institute of Technology (Japan)

The light emitting property of zinc oxide (ZnO) nanoparticles, which were spontaneously precipitated and dispersed in fluorinated polyimide films has been studied because this hybrid material exhibits interesting properties and could be widely applied in optoelectronics and photonics. Polyimides (PI) provide high thermal and chemical stability and outstanding electrical properties. In addition, ZnO presents excellent optical properties due to wide band gap (3.37 eV) at room temperature and large exciton bonding energy (60 meV), which can be used in light-emitting diodes, transparent electrodes, and piezoelectric devices.

By adding small amount of Zinc compounds (5 mol %), either Zinc hexafluoroacetylacetonate dihydrate or Zinc nitrate hexahydrate, to precursor solutions of polyimides followed by thermal curing at 350~390∫C, the green light emission at ca. 520 nm of polyimides has been significantly enhanced by 10 to 15 times respectively.

When zinc concentration excesses the saturation level, light emission decreases and emission peak was shifted to higher wavelengths due to the aggregation of ZnO. This can be explained by the quantum confinement mechanism and the interaction between the oxygen of ZnO and PI functional groups. The effects of zinc compounds and curing temperature and atmosphere on the light emitting behavior will be discussed in detail.

6122-32, Session 5

Defects in zinc oxide

N. Ohashi, T. Ishigaki, National Institute for Materials Science (Japan); T. Ohgaki, Tokyo Univ. of Science (Japan); S. Isao, T. Sekiguchi, H. Haneda, National Institute for Materials Science (Japan)

Zinc oxide (ZnO) is a promissing material for opto-electronic applications. For examples, excitonic emission of ZnO can be observed at room temperature, high electric conductivity with transparency can be obtained. Moreover, a lot of study has been done to realize ZnO baed light emitting diode and magnetic semiconductors.

To achieve high performance of ZnO related materials and structures, contorolling of charge compensation is the most important issue. For example, formation of charge compensating defects causes reduction of electric conductivity in spite of doping.

In this paper, we will present several topics regarding defects in ZnO.

1) non-equilibrium defects

Due to high vapor pressure of zinc, zinc oxide crystals are prpeared at relatively low temperatue. This low temperature processing is a cause of the formation of non-equilibrium defects. We will discuss about effect of non-equilibrium defects on material performance degradation.

2) passivation of defects

To obtain high performance of ZnO, we have to manage formation of defects for charge compensation. We will introduce several possible techniques for passivation of active deep levels in ZnO.

3) Interfacial issues

Structure at ZnO/GaN interface will be discussed in terms of the controlling of polarity of wurtzite-type crystals.

6122-02, Session 6

Progress of ZnO devices

Y. Ryu, T. S. Lee, J. A. Lubguban, MOXtronics, Inc.; H. W. White, Univ. of Missouri/Columbia; Y. Park, Seoul National Univ. (South Korea); C. J. Yoon, Chonbuk National Univ. (South Korea)

ZnO has been attracted for photonic and electronic applications. For these ZnO-based devices, p-type ZnO should be available. There are several reports claiming that p-type ZnO films were fabricated by using single dopant such as nitrogen (N) and phosphorus (P), two dopants (called co-doping) of III-V elements such as gallium (Ga)-N or P, and aluminum (Al)-N or P. Their results are still in controversy. In this talk, we will present how to make p-type ZnO by using arsenic (As), and demonstrate some devices made with As-doped p-type ZnO. They are strong evidences that As is a good acceptor for ZnO, and that variable ZnO-based devices can be fabricated with As-doped p-type ZnO.

6122-03, Session 6

P-type ZnO by Sb doping for PN-junction photodetectors

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

Reliable p-type doping of ZnO is important, although challenging to allow this material system to have tremendous potentials in optoelectronics and spintronics. Elements such as N, P, As, etc have been used for p-type doping. In this presentation, we report our work on Sb-doped ZnO films and their pn-junction photodetectors. Reproducible Sb-doped p-type ZnO films were grown on n-Si (100) by plasma-assisted molecular beam epitaxy. Hall effect measurements show p-type conductivity of these films. One sample exhibits a low resistivity of 0.2 ohm-cm, high hole concentration of 1.7´1018 cm-3 and high mobility of 20 cm2/Vs at room tem-

perature. Low temperature photoluminescence results show an acceptor-bound exciton emission at 3.358 eV and the acceptor level is estimated to be 0.2 eV above the valence band edge. Then, Ga-doped ZnO/Sb-doped ZnO and Sb-doped/n-type Si substrate were prepared followed by conventional lithography to form homo- and hetero-ZnO pn-junction photodetectors with Al/Ti Ohmic contacts. Rectifying I-V characteristics are observed for both homo- and hetero-ZnO diodes. Photocurrent measurements show photoresponse in UV region for all phtodetectors. The response increases as the biased voltage increases. The quantum efficiency and responsivity for all diodes were estimated. This study suggests that Sb-doping should be an excellent candidate for p-type ZnO and UV optoelectronic applications.

6122-04, Session 6

Optical and electrical properties of n- and p-type doped ZnO thin films

T. Makino, Univ. of Hyogo (Japan)

Optical properties of ZnO are currently the subject of numerous investigations, in response to the industrial demand for short-wavelength optoelectronics devices. Production of high-quality doped ZnO films is indispensable for the device application. 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. It is found that the N-related acceptor ionization energy depends on the nitrogen concentration and ranges from 165 to 348 meV.

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. As far as this case concerned, the theoretical value is in good agreement with the experimental value.

6122-28, Session 6

ZnO light-emitting diode using phosphorus doped p-type ZnO

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

p-Type ZnO films were grown by using phosphorus oxide as a p-type dopant source by RF sputtering and a subsequent post annealing processes. Photoluminescence spectra of p-type ZnO:P thin films showed an acceptor bound excitonic and phosphorus related peaks. We will report on the fabrication and characteristics of heterojunction ZnO light-emitting diode (LED) which consists of p-type ZnO:P and n-type GaN:Si layers. The current-voltage (I-V) and electroluminescence measurements of ZnO LED showed a threshold voltage of 5.4 V and a band-edge emission of 409 nm at room temperature. We also fabricated a p-n homojunction LED with a structure of p-ZnO:P/n-ZnO:Ga and it showed an emission peak at 380 nm corresponding to the near band gap of ZnO for the first time. The I-V characteristics of ZnO LED showed a low threshold voltage of 3.2V and an ideality factor of 2.5 were very similar to those of GaN LED

6122-05, Session 7

ZnCdO/AlGaN heterostructures for application as UV and visible light emitters

A. Osinsky, J. Dong, J. Xie, B. Hertog, M. Z. Kauser, A. M. Dabiran, P. P. Chow, SVT Associates, Inc.; W. V. Schoenfeld, L. Chernyak, College of Optics and Photonics/Univ. of Central Florida; S. J. Pearton, Univ. of Florida; D. C. Look, Wright State Univ.; M. D. Gerhold, U.S. Army Research Office

In this paper we review recent developments in hybride ZnO/AlGaN heterostructures for applications as LEDs. Simulation results incorporating the strong piezoelectric and spontaneous polarization fields in ZnCdO and AlGaN-based materials are discussed. The calculated electrical and optical emission characteristics of n-ZnO/p-AlGaN heterostructures are presented. The simulated emission intensity from the heterostructures is shown to depend strongly on the doping and layer thicknesses.

ZnO/AlGaN/GaN triple-heterostructure (THS) p-n junction LEDs have been fabricated and characterized. I-V characteristics show a strong rectifying behavior with a turn on voltage of ~3.2-3.5V. Optical emission with a peak intensity at ~ 390nm was observed from these structures. This is attributed to optical transitions near ZnO/AlGaN interface possibly due to the presence of excitons. The photovoltaic current measurements suggest that the transitions are excitonic in nature at this wavelength.

High quality ZnCdO layers and CdZnO/ZnO heterostructures were grown epitaxially on both GaN/Sapphire and ZnO substrates as confirmed by crystallographic, optical, and electrical measurements. A summary of high resolution X-ray diffraction, SIMS, RBS, optical transmission, photoluminescence, and cathodoluminescence mapping for CdxZn1-xO layers with Cd mole fraction up to x=0.78 is given. Strong optical emission ranging from UV to yellow has been observed for mole fractions od Cd 0-0.78. The dependence of the fundamental optical band gap on the composition of CdxZn1-xO alloys as well as gap bowing parameters are also discussed.

The reported results demonstrate the great potential of ZnO-based LEDs for use as a light emitter and, in particular, for solid state lighting.

6122-06, Session 7

ZnO LED

M. Kawasaki, Tohoku Univ. (Japan)

We present current status of our research for p-type doping and light emitting diode based on ZnO. Hole concentration of mid-10^16cm^-3 and ZnO pn-junction emitting at 440nm are demonstrated. For making p-type doping, point defect management based on high temperature annealed buffer (HITAB) and successful incorporation of activated nitrogen by repeated temperature modulation method (RTM) are the key technologies.

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6122-07, Session 7

ZnO based light emitting diodes growth and fabrication

M. Pan, R. Rondon, J. Cloud, V. Rengarajan, W. Nemeth, A. Valencia, J. Gomez, J. Nause, Cermet, Inc.

Zinc oxide is receiving more and more attention for its application to UV or blue light-emitters because of a direct band gap of 3.37eV and an exciton binding energy of 60meV. In this paper, we report our newest results of ZnO p-n junction growth and LED fabrication. A vertical, disk rotating reactor MOCVD tool with specially designed plasma system was employed for ZnO epitaxial growth, which enables a high efficiency incorporation of p-type dopant into the ZnO film. DEZn and O2 are used as

precursors for Zn and O, respectively. NH3 Plasma was used for nitrogen dopant source. N-doped ZnO films were successfully grown on both ZnO substrate and sapphire substrate. The p-type ZnO films were characterized by different techniques, including X-ray diffraction (XRD), secondary ion mass spectroscopy (SIMS), photoluminescence (PL), and atomic force microscopy (AFM). I-V characteristics of ohmic contacts to n-type ZnO substrate and p-type ZnO epilayer were measured to investigate the electrical property of the materials. It has been found that annealing process plays important role for ohmic contact formation and demonstration of p-type behavior. ZnO light emitting diodes was fabricated based on the achievement of p-type ZnO film. Two different LED structures were investigated, one is formed by MOCVD grown p-n junction on sapphire substrate, the other is p-type ZnO film grown directly on n-type ZnO substrate. Strong electroluminescence of 380nm wavelength from ZnO p-n junction was obtained at room temperature. To the best of our knowledge, this is the first EL emission peak obtained from pure ZnO based LED structure.

6122-08, Session 7

Development of UV LEDs based on epitaxial ZnO grown by pulsed laser deposition

D. Rogers, Nanovation (France) and Univ. Technologique de Tryes (France); F. Hosseini Teherani, Nanovation (France); K. Mayes, R. P. McClintock, A. Yasan, P. Kung, M. Razeghi, Northwestern Univ.

At present, GaN (bandgap energy Eg = 3.39eV) is the only wide band-gap material which has been developed and commercialized on an industrial scale for use in blue/UV Light Emitting Diodes (LEDs) and Laser Diodes (LD). Sustaining the current rapid development of GaN-based device performance could prove difficult, however, because of a number of complicating factors including GaN's resistance to chemical etching, the lack of a widely-available, device-grade native substrate at a reasonable cost level and a strong drop-off in device brightness and lifetime with increasing dislocation density and operating temperature.

ZnO (Eg = 3.37eV) is considered a promising material for the next generation of UV opto-emitters because it is not hampered by any of these problems. In particular, the very large exciton binding energy in ZnO (~60 meV) gives it a potential for ultra-high LED brightness, low threshold current LDs, better performance at high temperature and an extremely high radiation resistance.

For the moment, however, reproducible and stable p-type ZnO material with good conductivity and high carrier concentration is still in a development phase, and homostructural ZnO LEDs and LDs are not commercially available.

In an alternative approach, there have been numerous attempts to develop p-n heterojunction LEDs with ZnO as the n-type layer. These attempts have employed a wide range of p-type materials deposited using a large variety of thin film growth tools. To date, however, there have been few publications reporting electroluminescence (EL) and even fewer with a dominant UV emission.

In this work, we report on the development of both heterojunction and homojunction LEDs. In a first instance, high quality epitaxial growth of ZnO thin films was obtained on various substrates using Pulsed Laser Deposition. Several potential dopants were then tested.

Optoelectronic devices were then developed based on this combined know-how including:

- UV n-ZnO/pGaN:Mg/c-Al2O3 heterojunction LEDs with EL at 375 nm
- p-n ZnO homojunctions on c-Al2O3 substrates

6122-30, Session 7

Two different features of ZnO: transparent ZnO:Ga electrodes for InGaN-LEDs and homoepitaxial ZnO films for UV-LEDs

K. Nakahara, K. Tamura, H. Yuji, S. Akasaka, ROHM Co., Ltd. (Japan); S. Niki, National Institute of Advanced Industrial Science and Technology (Japan); A. Tsukasaki, A. Ohtomo, M. Kawasaki, Tohoku Univ. (Japan)

6122-15, Poster Session

Room temperature ferromagnetism in MOCVD grown ZnO thin films

V. Rengarajan, Cermet, Inc; M. H. Kane, N. Li, Georgia Institute of Technology; M. Pan, Cermet, Inc.; I. T. Ferguson, Georgia Institute of Technology; J. Nause, Cermet, Inc

Dilute Magnetic semiconductors (DMS) are solids with magnetic atoms occupying some of their lattice with potential utility in electronic and photonic applications. DMS materials with room temperature ferromagnetism are potential alternative in achieving high spin injection efficiency in semiconductor devices as ferromagnetic metals face severe conductivity mismatch. These DMS materials have intriguing applications in spintronics devices such as spin-valve transistors, spin light emitting diodes, memory devices, logic devices, optical isolators, sensors and optical switches. Theoretical predictions suggest room temperature ferromagnetism should be possible in ZnO doped with transition metals. In this present investigation, epitaxial growth transition metal doped ZnO thin films were grown by MOCVD with various dopant concentrations. The growth parameters were optimized to yield high quality films. The structure and quality of the grown films were characterized by X-ray diffraction. Optical studies indicate linear shift in the absorption edge for the doped films. Magnetic measurements indicate room temperature ferromagnetism in transition metal doped ZnO thin films. The results of structural, optical, electrical and magnetic properties will be presented and discussed in detail.

6122-18, Poster Session

Physical vapor transport crystal growth of ZnO

J. C. Rojo, S. Taraphdar, G. Dhanaraj, H. Chen, J. Bai, M. Dudley, Stony Brook Univ.

ZnO is increasingly attracting much attention as one of the most promising materials for the fabrication of high-brightness blue/near-UV emitters. With the recent demonstration of p-type ZnO the development of a competing short-wave technology based on this material has become practical. To make ZnO an attractive choice for device fabrication, however, it will be also necessary to demonstrate a reliable and cost-efficient crystal growth technology that ensures the availability of high-quality, large-diameter substrates. Using chemically-assisted sublimation and hydrothermal techniques 2" diameter crystals have been successfully grown. Nevertheless, the growth rates achieved using those approaches are very low (<0.1 mm/h and ~0.2mm/day, respectively).

Numerical predictions carried out by the authors indicate that growth rates exceeding 0.5mm/h could be theoretically achieved at over 1,600oC under by using a physical vapor transport (PVT) approach similar to those used for other wide-bandgap semiconductors such as AlN or SiC. The potential feasibility of this growth technology has been encouraged by recent experimental observations revealing the growth of wurzite ZnO crystals at temperatures exceeding 1,600 oC. Those preliminary experimental results and the numerical analysis of the PVT growth of ZnO, including growth rate predictions and operational conditions, will be presented.

6122-24, Poster Session

Synthesis and characterization of (Zn,Mg)O:P/ZnO heterostructures for light emitting applications

Y. Li, H. Yang, J. G. M. Erie, H. Kim, S. J. Pearton, D. P. Norton, F. Ren, Univ. of Florida

Currently, ZnO is attracting much attention for its applications in optoelectronic devices due to its wide direct band gap of 3.3 eV and a strong excitonic binding energy of 60 meV. Moreover, the band gap of ZnO can be tuned in the range of 3.0 eV - 4.0 eV via alloying with CdO and MgO, which open opportunities for band gap engineering. However, the development of ZnO-based optoelectronic devices has been hindered by achieving low resistivity, high carrier density p-type ZnO. Recent efforts have focused on ZnO p-type doping with N, P or As. In this study, p-type conductivity in phosphorus-doped (Zn,Mg)O films were achieved by adjusting the oxygen partial pressure during the deposition. A hole concentration of 2.7 x 10e16 cm^-3 and mobility of 8.2 cm^2/Vs were determined from van der Pauw Hall measurements for p-type (Zn,Mg)O:P films. However, the p-type behavior was highly dependent on the growth process and annealing conditions. The systematic study of the relationship of doping concentrations, growth conditions with the transport and optical properties will be discussed. The p-(Zn,Mg)O:P/n-ZnO heterostructures were fabricated on commercial single crystal ZnO via pulsed laser deposition. The metal contacts in top-to-bottom p-n junctions were made with Ni/Au as the p-ohmic and Ti/Au as the backside n-ohmic contact. Previous device results show the linearity of the p-contacts improved after annealing process. Rectifying characteristics were shown in the vertical structure, confirming the presence of a p-n junction. In order to reduce the effect of hydroxide layer on the performance of the diode, an undoped ZnO layer was deposited on single crystal ZnO first, followed by a p-type phosphorus-doped (Zn,Mg)O film. Hall measurement, room temperature photoluminescence (PL), X-ray diffraction (XRD) and Atomic Force Microscopy (AFM) were utilized to characterize the films properties. The device characteristics were achieved by performing I-V and electroluminescence (EL) measurements. This work was supported by the National Science Foundation, Air Force Office of Scientific Research, the Department of Energy, and the Army Research Office. The authors would also like to acknowledge the Major Analytical Instrumentation Center, Dept. of Materials Science and Engineering, University of Florida.

6122-25, Poster Session

Strong green luminescence in P+-implanted ZnMnO thin films

S. Lee, H. S. Lee, S. J. Hwang, D. N. Kim, Dongguk Univ. (South Korea); D. Y. Kim, Dongguk Univ.

The high dose P+ ions were implanted into the ZnMnO thin films, which had been grown on Al2O3 (0001) substrates by an r.f. magnetron sputtering deposition method, in order to find a p-type conduction in ZnMnO thin films. The dose of P+ ions and the acceleration energy were 1*10^16 cm^-2 and 70 KeV, respectively. After the implantation, the films were annealed at 1000°C for 60 sec in N2 atmosphere in order to recover the implantation damages and activate the implanted ions. For measurements of luminescence properties, the green emission was observed for the post-growth-annealed ZnMnO thin films while the as-grown ZnMnO thin films showed only UV emission without emissions from native defects. After P+ ion implantation, the green emission was slightly decreased. However, the intensity of green emission was dramatically increased after post-implantation-annealing. In order to clarify the origin of the strong green luminescence, the micro-cathodoluminescence properties were characterized systematically. It was confirmed that the green luminescence is originated from the nano-sized pores in the post-implantation-annealed ZnMnO thin films. With regard to the green luminescence property for Mn-doped ZnO thin films, it is normally explained by the emission from oxygen vacancies and the intraband transition from Mn2+ ions. It is considered that the green emission for P+-implanted ZnMnO thin films used in this study might be attributed to the effect of band-filling in native deep traps resulting from the formation of nano-sized pores, because the deep level of oxygen vacancies might be concentrated in the unstably-terminated edge area around nano-sized pores formed by the thermomigration of Mn components. The formation mechanism of thermally generated nano-pores and the effect of oxygen vacancies and Mn2+ ions on luminescence properties are to be discussed in details. In addition, the electrical and the magnetic properties are also to be discussed.

6122-26, Poster Session

Rare Earth doped bulk ZnO

W. Nemeth, J. Nause, J. Cloud, N. Spencer, Cermet, Inc.

Zinc oxide is a wide band gap semiconductor with great potential for a variety of commercial applications. A patented pressurized melt growth approach to growing single crystal ZnO is employed at Cermet, Inc. This approach utilizes induction melting a ZnO precursor in a water cooled crucible. The crucible prevents the outer crust of ZnO from melting thereby encapsulating the resulting melt, making inadvertent impurity incorporation highly unlikely. By directionally solidifying the melt, single crystals of high quality are grown. This entire melting and containment process is carried out in a controlled gas atmosphere ranging from 1 atmosphere to over 100 atmospheres, which prevents the evolution of volatile components, as well as the decomposition of some compounds into atomic species. The process, which is ultimately scalable to large dimensions, has been used to melt 5.5 inch diameter, kilogram dimensioned ingots of ZnO. From these large ingots, high quality, high purity, ZnO crystals have been crystallized, oriented and shaped into round or square boules, and eventually processed into epitaxial-ready substrates.

Rare earth ions when doped into host crystals are unique in that they will produce characteristic peaks when excited, regardless of the host crystal. Cermet possesses the technology to dope rare earth materials into single crystal ZnO in situ, resulting in a relatively uniform distribution of dopant throughout the grown crystal without the cost and damage encumbered by implantation. Various rare earth elements have been doped into single crystal ZnO, and characterization of these substrates will be discussed.

6122-27, Poster Session

Metal organic chemical vapor deposition of zinc oxide

W. E. Fenwick, Georgia Institute of Technology; M. Pan, Cermet, Inc.; J. Song, N. Li, S. Gupta, H. Kang, A. Asghar, M. Strassburg, Georgia Institute of Technology; N. Dietz, Georgia State Univ.; I. T. Ferguson, Georgia Institute of Technology

This work presents results obtained from a comprehensive study of the factors affecting ZnO thin film growth by metal organic chemical vapor deposition. Structural, optical, and electrical properties of the films are used to discuss the effect of growth parameters on growth kinetics and rotating disk reactor dynamics. The reactor geometry was used to calculate a growth window in which gas flow is stable and in the laminar flow regime. Growth parameters were systematically varied within this window to determine the optimal ZnO growth conditions. Growth temperature was varied from 300°C to 650°C. Growth pressure, disk rotation speed, and VI/II ratio were also investigated within the calculated growth window. Films were investigated using X-ray diffraction (XRD), atomic force microscopy (AFM), Hall Effect measurements, and Photoluminescence (PL). XRD showed asymmetrical ZnO peaks in θ-2θ, suggesting formation of second phases or incorporation of excess Zn into the crystal. Hall Effect measurements characterized the as-grown films as n-type with carrier concentrations between 1016 and 1017cm-3. This is most likely

due to surface states, as carrier concentration scaled roughly with RMS surface roughness. Room temperature PL data revealed a dominant near bandgap emission at 376nm and a luminescence band peaking at 504nm. A more detailed study of these bands will be provided by temperature-dependent PL investigations. The doping incorporation and carrier concentration will be studied by Raman spectroscopy. The effects of growth parameters on film properties will be used to discuss the kinetics of ZnO growth and dynamics of the rotating disk reactor system.

6122-29, Poster Session

Optical modes in ZnO nanoresonators

T. Nobis, A. Rahm, M. Lorenz, M. Grundmann, Univ. Leipzig (Germany)

We investigate and simulate the optical resonant behavior of ZnO nanostructures. Such systems are candidates for future nanophotonic components such as nanolasers. Their hexagonal cross section creates a two-dimensional dielectric cavity on nanoscopic scale. The green luminescence band of ZnO allows for a spectrally broad excitation of the nanocavities via catholuminescence (CL) spectroscopy and polarization-resolved micro-photoluminescence spectroscopy[1]. The dominant modes are found to be whispering gallery modes (WGMs) with low radial quantum number.

Numerical calculations of hexagonal WGMs using a boundary element algorithm[2] yield mode energies, line widths and near-field intensity patterns. Taking into account the spectral dispersion of the refractive index of ZnO we are able to simulate the experimental resonance spectra in very good agreement with our theoretical results. The spectral line widths are close to the theoretical limit proving the structural quality of the resonators. A comparison of theory and experiment for TM and TE polarized modes furthermore yields the birefringence of a single ZnO nanocavity. Modes of higher radial order, e.g. TM5,3, are preferentially excited by CL. The influence of the particular resonator shape is demonstrated analyzing structures with dodecagonal cross section.

1 Thomas Nobis, Evgeni M. Kaidashev, Andreas Rahm, Michael Lorenz, Marius Grundmann, PRL 93, 103903 (2004)

2 J. Wiersig, J. Opt. A 5, 53-60 (2003)

6122-31, Poster Session

Exchange polarization coupling in wurtzite-perovskite

M. M. Schubert, Univ. of Nebraska-Lincoln; N. Ashkenov, H. Wenkstern, H. Hochmuth, M. Lorenz, M. Grundmann, Univ. Leipzig (Germany)

We investigate the interaction between the lattice-fixed ionic wurtzite interface charges of ZnO and the switchable ferroelectric interface charges of BaTiO3, which gives rise to ferroelectric polarization exchange coupling phenomena. We report on structural, optical, electrical and electro-optical properties of ZnO/BaTiO3 and ZnO/BaTiO3/ZnO heterostructures grown by pulsed laser deposition on Pt-coated (001)Si wafer-substrates. Structural properties are investigated by XRD, TEM, Spectroscopic Ellipsometry and Raman-Scattering techniques. Temperature-dependent optical, electro-optical, and electric polarisation, current-voltage (I-V) and capacitance-voltage (C-V) studies reveal the interplay between spontaneous non-switchable wurtzite and switchable ferroelectric polarization. Observed results suggest that the polarization exchange coupling between ZnO and BaTiO3 can be used in future transparent nano-optoelectronic device structures.

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6123-01, Session 1

Patterned UV-curable high refractive index coatings

R. V. Morford, C. Planje, D. Holmes, W. Shih, J. Dachsteiner, K. Marler, Brewer Science, Inc.

The development of optoelectronic devices has seen rapid advancements on several fronts in recent years. Advances in materials, along with novel processing techniques, have enabled new and important devices. Recently, the development of high-value materials coupled with a low-cost and high-throughput method of fabricating structures in photonic components and devices has become a necessity to drive the implementation of optoelectronic devices in the near term.

We have developed high-value materials with several useful properties. This paper will discuss the properties of the materials, including transparency, refractive index, viscosity, cure, and thermal stability. In addition, we will also discuss our efforts to produce structures in films of these materials. Our patterning technology utilizes press patterning and photolithographic techniques. The coupling of material development and process development will allow for greater flexibility in component and device design and manufacture.

6123-03, Session 1

Elaboration of polymer-based materials and waveguides doped with erbium complexes for amplification at 1.55 μm: a multifunctional approach

A. Q. Le Quang, I. N. Ledoux-Rak, J. Zyss, École Normale Supèrieure de Cachan (France); E. Besson, C. Reye, R. Corriu, Univ. Montpellier II (France)

A key parameter for the choice of an erbium-doped material suitable for efficient amplification around 1.55 μm is its ability to isolate Er ions from each other in order to increase the quenching concentration and henceforth to improve pumping efficiency. Encapsulation of Er ions by organic ligands results in quenching concentrations exceeding a few % in a polymer matrix and may therefore induce high gain values at 1.55 μm.

In this communication, we report on the elaboration and optical characterization of Erbium complex-doped PMMA thin films and waveguides with different concentrations by spin-coating technique. Refractive index of these thin films and etching conditions for waveguide fabrication are carefully investigated. Strong gain coefficient values (up to 9 cm-1) measured by Amplified Spontaneous Emission are reported at 1.55 μm under 980 nm cw pumping of an erbium-complex-doped PMMA film. A multifunctional polymer material containing an erbium complex together with an electric-field oriented nonlinear optical (NLO) chromophore is shown to simultaneously display good IR gain properties and quadratic NLO response, then qualifying this approach for in-situ amplification of active electro-optic devices for optical signal processing.

Rib waveguides made of erbium-doped PMMA have been elaborated using standard lithographic and reactive ionic etching techniques, based on a systematic optimization procedure of etching conditions for various concentrations of erbium complexes. Gain and loss measurements of these waveguides are characterized for single mode propagation of signal (1.55 μm) and pump (980 nm) waves, and compared to predictions from beam propagation method modelization

6123-04, Session 1

Novel nonlinear electro-optic composite materials

B. Birchfield, Univ. of Dayton; R. L. Nelson, Air Force Research Lab.; J. W. Haus, Univ. of Dayton

Compact electro-optic modulators are an essential element in the developmen of integrated optical circuits. Current Mach-Zehnder modulators are on the order of centimeter lengths which makes reduction in size desirable. Key to the progress of such modulators is continuing advancements in the nonlinear materials used to construct them, such as the latest generation of nonlinear optical polymers. A novel nonlinear optical material system which is comprised of an embedded electrode inside an electro-optic (EO) polymer is presented here. This nonlinear optical composite has interesting and useful optical properties. Comparisons of theoretical bulk material performance to predictions of effective medium theory (EMT) and the experimental results in a waveguide geometry are given with discussion of implementation in practical device applications.

6123-05, Session 1

Fast amplitude and delay measurement for characterization of integrated optic devices

C. K. Madsen, M. Thompson, W. Rivera, H. Zhu, M. Solmaz, D. Adams, Texas A&M Univ.

Integrated optic devices such as multi-stage reconfigurable filters with many input/output ports and coupled interferometric stages, each containing tunable elements, are becoming more commonplace. To keep up with this advancement in integration scale as well as device complexity, improvements are needed in our ability to quickly and fully characterize such devices. For applications with high bitrates, accurate measurement of dispersion is critical in addition to the easily obtainable amplitude response. So, phase sensitive measurements of the device response are required which adds complexity to the measurement setup. In addition, the polarization dependence is also critical for typical integrated optic devices. Thus, a complete characterization of the device operation is challenging because of polarization dependence, the potential for a large number of degrees of freedom and coupling between stages and/or tuning elements. Fast measurements are critical from both the perspective of cost and measurement accuracy, which may be impacted by drifts in waveguide coupling or temperature in the latter case. We present a measurement technique that is non-interferometric but allows the frequency-dependent delay and amplitude responses to be measured in a very small amount of time relative to currently available techniques. Typical approaches use the modulation phase-shift technique or an interferometric technique. Our approach builds on the modulation phase-shift technique but the phase sensitive detection is much faster than typical lock-in amplifiers for audio frequencies, so we can accommodate a sweep of the modulation frequency in addition to sweeping the tunable laser source. A high-resolution measurement over several GHz is limited by the 10 millisecond sweep rate of our RF source generator. For a single amplitude and relative phase measurement at a fixed optical wavelength, the measurement time is on the order of a microsecond. The measurement speed can be used in a variety of ways including multiplexing multiple wavelengths, polarization, tunable elements, or tracking swept-wavelength sources.

6123-06, Session 1

Polymeric integrated nonlinear optical devices

R. L. Nelson, Air Force Research Lab.; J. W. Haus, B. Birchfield, Univ. of Dayton

Active and passive polymers offer some advantages for integrated optic devices of certain types. Here we discuss the use of electro-optic polymers for a few different device concepts and present fabrication and experimental results where available. Emphasis is on micromodulators but some attention is also given to waveguides, plasmonic interactions, silicon-polymer devices, photonic crystals, and nanostructured electrodes. Some useful and interesting results are obtained in planar waveguide geometries utilizing these active polymers which may make them amenable to opto-electronic integration. Second order active chromophores are typically used but discussion of possible application to third order electro-optic materials is included.

6123-07, Session 2

Emerging Trends in Photonics Modeling

J. F. Pond, Lumerical Solutions, Inc (Canada); T. Kleckner, P. Paddon, A. Reid, Lumerical Solutions, Inc. (Canada)

Continued improvements in computational resources bring new opportunities and challenges for photonics modeling. In particular, widely available computer clusters are making a dramatic impact by allowing larger simulation volumes to be computed faster. We demonstrate how this opportunity can be exploited in the area of photonic integration to rigorously simulate three-dimensional devices by FDTD previously thought to be intractable. For example, larger multi-component or hybrid devices composed of both dielectrics and metals can now be simulated.

Moreover, there is an increasing need for performance optimization of robust devices that are resistant to imperfections introduced by commercially-viable manufacturing technologies and that function reliably in demanding operating environments. We show how actual manufactured devices can be modeled including imperfections and demonstrate a variety of design optimization capabilities.

Advances in waveguide-based integrated optics technology require mode solving and simulation of complex materials and geometries, such as surface plasmon waveguides and micro-structured optical fibers. We show how to efficiently solve for modes of arbitrary waveguide geometries. We also demonstrate how optical designers can bridge the gap between micro-scale and macro-scale optical devices by interfacing rigorous FDTD models of photonic systems with ray-tracing descriptions of optical delivery and collections systems.

6123-08, Session 2

Plasmon-enhanced absorption and transmission in spherical Bragg resonators

M. Deutsch, K. Hasegawa, C. Rohde, Univ. of Oregon

We present a theoretical study of the plasmonic dispersive properties of mesoscopic metal/dielectric/metal (MDM) spheres. These are spherically symmetric Bragg resonators comprising thin, alternating layers of dielectric and metal shells around spherical metal cores. We solve Maxwellís equations in spherical coordinates and obtain the dispersion of such MDM spheres. Using a Mie scattering multipole expansion for plane-wave scattering in the visible/NIR we also obtain the extinction efficiencies.

In particular we address absorption and scattering cross-sections for MDM particles consisting of metal cores comparable in size to optical wavelengths, surrounded by a single unit cell comprising one dielectric/metal shell sequence. We find two separate and independent resonance regimes:

We show that when the dielectric shell thickness satisfies a resonance condition, the MDM sphere sustains a band of eigenmodes whose frequencies depend weakly on angular momentum. This results in flat-dispersion modes and hence a narrow, intense plasmonic absorption resonance. Consequently, the calculated absorption cross-section is several-fold greater than that of uncoated metal spheres, as well as standard metal/dielectric core-shell particles of comparable size. We attribute this to simultaneous excitation of the flat-dispersion modes, which provides an efficient channel for focusing and concentrating the incident electromagnetic field to the metal-dielectric shell interfaces.

In a separate regime of shell ratios we find a plasmon-enhanced narrow transmission resonance, which is tunable both in height and spectral position. This resonance corresponds to multi-mode cancellation of the scattering due to a difference in sign of the polarization between the metallic and dielectric components of the MDM particle.

6123-09, Session 2

Subwavelength plasmonic waveguide structures based on slots in thin metal films

G. Veronis, S. Fan, Stanford Univ.

Waveguide structures which support highly-confined optical modes are important for achieving compact integrated photonic devices. In particular, plasmonic waveguides have shown the potential to guide subwavelength optical modes. Several different plasmonic waveguiding structures have been proposed, such as metallic nanowires and metallic nanoparticle arrays. However, these structures support a highly-confined mode only near the surface plasmon frequency. In this regime, the optical mode typically has low group velocity and short propagation length.

In this paper, we demonstrate the existence of a bound optical mode supported by an air slot in a thin metallic film deposited on a substrate, with slot dimensions much smaller than the wavelength. The modal size is almost completely dominated by the near field of the slot. Consequently, the size is very small compared with the wavelength, even when the dispersion relation of the mode approaches the light line of the surrounding media. In addition, the group velocity of this mode is close to the speed of light in the substrate, and its propagation length is tens of microns at the optical communication wavelength. Thus, such a waveguide could be potentially important in providing an interface between conventional optics and subwavelength electronic and optoelectronic devices.

We also investigate the performance of bends and power splitters in plasmonic slot waveguides. We show that, even though the waveguides are lossy, bends and splitters with no additional loss can be designed over a wavelength range that extends from DC to near-infrared, when the bend and splitter dimensions are much smaller than the propagation length of the optical mode. We account for this effect with an effective characteristic impedance model based upon the real dispersion relation of the plasmonic waveguide structures.

6123-10, Session 2

Resonant leaky mode silicon-on-insulator photonic devices

R. Magnusson, Univ. of Connecticut

With focus on the silicon-on-insulator materials system, this paper provides computed results elucidating the nature of resonant leaky modes associated with periodic refractive-index lattices such as gratings and photonic crystals. Single-layer subwavelength periodic leaky-mode waveguide films with binary profiles can be applied to fashion optical elements that provide a remarkably broad variety of tailored spectral characteristics. These sparse elements even with one-dimensional periodicity can function as new types of narrow-line bandpass filters, polarized wideband reflectors, polarizers, polarization-independent elements, wideband antireflectors, and sensors. The key physical properties are explained in terms of the photonic band structure and its relation to the structural symmetry of the elements. The interaction dynamics of the leaky modes at resonance contribute to sculpting the diverse spectral bands observed by numerical simulations. The leaky-mode spectral placement, their spectral density, and their levels of interaction are shown to be fundamentally important in understanding device operation. These results demonstrate potentially new dimensions in optical device design.

6123-11, Session 2

The modeling of MMI devices

L. W. Cahill, La Trobe Univ. (Australia)

Multimode interference (MMI) devices now figure in a wide variety of applications. Originally thought of as a simple optical waveguide coupler or combiner, the MMI structure is now used in waveguide-division multiplexers/demultiplexers, switches, optical code-division multiplexing encoder-decoders, two-dimensional couplers, optical power monitors and optical wavelength monitors.

Devices based on the multimode interference effect generally have the advantages of robustness, reliability, reasonable bandwidth, fairly low polarization sensitivity, good power balance when required, ease of fabrication, and compatibility of fabrication processes with other photonic integrated circuits.

There are a number of approaches that can be employed in the design of MMI devices. The simplest analytic approach is to assume that the multimode waveguide section of the device consists of an ideal optical waveguide bounded by perfectly reflecting walls. This approach yields formulas that are easy and quick to use, but neglect the penetration of the lateral modes into the cladding. This latter effect can be approximately taken into account by using a one-dimensional slab waveguide model. The effect of excitation and collection can be included by using overlap integrals. The two-dimensional cross-section can be partly taken into account if a two-dimensional effective index model is used.

To more completely model these MMI devices, numerical techniques such as those based of various forms of beam propagation methods, mode matching methods, finite difference and finite element methods can be used. The telling advantage of these numerical techniques is that they can solve the full vectorial problem to high accuracy.

In this paper, however, we shall concentrate on analytical and semi-analytical approaches to the first order design of MMI devices. The key idea is that for planar devices, there is only one vertical mode and many horizontal modes. This can simplify the problem significantly and lead to comparatively simple design formulas as well as supply more insight into the operation of these devices than do entirely numerical techniques.

6123-12, Session 3

Bimetallic silver-gold film waveguide surface plasmon resonance sensor

B. H. Ong, X. Yuan, S. C. Tjin, Nanyang Technological Univ. (Singapore)

A waveguide surface plasmon resonance (SPR) optical sensor based on wavelength modulation is presented. Embedded strip waveguides were fabricated using MicroChemís SU-8 photoresist via UV lithography. Next, a silver-gold film is deposited on the waveguides for exciting surface plasmon resonance. The underlying silver yields better evanescent field enhancement of the waveguide SPR sensor, while the overlying gold ensures that the stability of the sensing surface is not compromised. Experiments were conducted using various glucose concentrations as the analyte, and the normalized transmission output of the waveguide shows good SPR curves for all the samples. With a better evanescent field extension, the proposed waveguide SPR configuration extends the use of SPR, especially in bio-sensing, as longer ligands can be immobilized and bigger analytes can be monitored. The waveguide SPR sensor, being compact, rugged and low-cost, has great potential to be implemented in point-of-care bioassay applications.

6123-13, Session 3

Some new trends on LINBO3 modulators

N. Courjal, M. Bernal, Univ. de Franche-Comtè (France); H. Porte, Photline Technologies (France)

Amongst the optical materials, LiNbO3 is an excellent candidate for the fabrication of modulators because of its large refractive index, high electro-optic coefficient and low optical losses at 1.55um. If the device is integrated on an X-cut substrate, it can also benefit from a low chirp, which is a key property for long haul high bit rate telecommunication systems. But unless they are locally thinned down, X-cut modulators exhibit a large halfwave voltage (~6V at 40Gbit/s). In addition, modulators would be more attractive with a reduced size.

We will present two recent developments devoted to improve these performances. The first development is based on the use of ferro-electric domain inversion to reach a low chirp, while preserving a low half-wave voltage. The half-wave voltage is linked to the use of a Z-cut substrate, and the low chirp is obtained with the association of a poled section with phase reversal electrodes. With this innovative structure, we have demonstrated the first Z-cut LiNbO3 modulator with low chirp for 10Gb/s applications. We will show the electro-optical characterization and eye diagrams, and demonstrate that the use of several poled section can improve the control of the frequency chirping.

Another trend that will be outlined is the development of LiNbO3 photonic crystals to get components with micrometric size. Our team has been the first in demonstrating the feasibility of photonic bandgap structures in LiNbO3 substrates. By focused ion beam (FIB) milling, we have performed the fabrication of triangular arrays of holes with a periodicity of 500nm or less, and a depth larger than 1mm. The transmission response has been measured with a supercontinuum source for several structures, confirming a gap for the TE polarization, with an extinction ration lower than -12dB. A near field characterization has also confirmed the possibility of guiding the light in photonic waveguides with one or three line of defects. We will show how these structures can be used for the fabrication of micrometric LiNbO3 modulators. First, we will detail the numerical simulations by FDTD (Finite Domain Time Difference) method, and then we will describe the process of fabrication. Finally the electro-optical characterization will be presented.

6123-14, Session 3

Novel optical-waveguide sensing platform based on grating coupler

S. Grego, S. Naskar, A. M. Patel, B. R. Stoner, RTI International

Optical waveguide-based sensors can respond to minute changes of a medium index of refraction or to adsorption of molecules by exploiting the high sensitivity of the coupling condition into the waveguide by means of a grating [1]. The most convenient way to exploit this phenomenon consists of an input grating that couples a laser into a slab waveguide, in a configuration known as Optical Waveguide Lightmode Spectroscopy. We will present a sensor platform based on an OWLS-type configuration, including novel approaches to achieve a highly integrated and potentially compact microfabricated device.

Our sensor platform uses PECVD deposited Silicon Oxynitride (SiOxNy) slab waveguides. One of the features of SiOxNy is the tunability of refractive index by variation of the film composition. The index of refraction, growth rate and stress developed in our PECVD deposited films have been systematically measured and the transmission loss has been characterized and interpreted through a detailed material analysis [2].

High quality gratings are generally obtained by embossing; we found that a low-cost, easy-to-implement method to fabricate a grating coupler on a SiOxNy slab waveguide is a self-assembled ordered array of polystyrene microspheres. Although the coupling is not highly efficient and the array is not defect-free, coupling of a He-Ne laser beam into the slab waveguide was demonstrated. The effects due to two-dimensional nature of the coupling grating and different suspension media have been investigated [3]. The use of infrared laser will also be presented because relatively low-cost, highly tunable lasers are available in the telecom wavelength region.

1 Tiefenthaler, Adv. Biosensors (1992) vol.2, 261

2 Naskar et al, MRS proceedings, Spring 2005 A20.3

3 Zhao et al, Appl. Phys. Lett. (1999) vo. 75, 3596

6123-15, Session 3

Novel integrated polarization analyzer sensor made by ion-exchange in glass

K. Djerroud, Institut National Polytechnique de Grenoble (France); P. Lemaitre-Auger, École Supérieure d'Ingénieurs en Systèmes Industriels Avancès Rhùme-Alpes (France); P. Benech, P. Benech, École Nationale Supérieure d'Electronique et de Radioélectricité de Grenoble (France)

Optical polarization analyzers are nowadays a well-known investigation tool commonly used in many industries and laboratories. They are very useful in the investigation of some surfaces state and for the measurement of polarization transmission properties of optical components and systems. Commercial polarization analyzers are made of bulk optic components and because of that, may suffer from mechanical instabilities.

In this paper, we propose a novel integrated polarization analyzer sensor (IPAS) made by ion exchange on a glass substrate. It is capable to determine the polarization state of a light beam: elliptical, circular or linear. Furthermore, in the first case, the sensor measures the ellipseís eccentricity and the angle between its major axis and the x-axis of the IPAS (parallel to the glassí top surface). Also, for linear polarization, the angle between polarization direction and the x-axis of the IPAS is measured. Finally, for elliptical and circular polarizations, the rotation direction is measured by the proposed IPAS.

The exchange chosen is a silver-sodium one realized in a special glass. The waveguide structure of the IPAS is very simple: a Y-junction, a piezoelectric modulator and two linear polarizers. Light to be analyzed is first coupled into a monomode isotropic waveguide. It then undergoes phase modulation thanks to an acoustic stationary wave. Light is split in the Y-junction and finally crosses the two polarizers placed at both output waveguides of the component. The transmission axis of the latter are respectively +45∞ and -45∞. Proper signal processing is required to give the results.

Results obtained for different polarizations will be given at the conference and compared to expected ones.

6123-16, Session 4

Novel glass-based devices for photonic integrated circuits

D. Zhang, W. Pan, Y. Zhang, The Univ. of Nottingham (United Kingdom); A. Loni, The Univ. of Nottingham (United Kingdom) and pSiMedica (United Kingdom); P. Sewell, T. M. Benson, C. A. Miller, D. Furniss, A. B. Seddon, The Univ. of Nottingham (United Kingdom)

New optical waveguide structures have been developed with a view to the realization of complex photonic integrated circuits. Based on inorganic glass compositions, in both planar and fibre forms, we combine low-temperature thermal bonding with mechanical compression to produce ëfibre-oníglassí (FOG) components.

Our inorganic glass compounds are chosen for optical functionality over a wide wavelength range, and combine high optical non-linearity with the ability to incorporate active dopants. The range of glass compositions facilitates design and process flexibility. Heavy metal fluorides, chalcogenides, and fluoro-tellurites have been to experimentally validate a variety of structures, designed using an in-house Finite Difference (FD) mode solver and the FD Beam Propagation Method (FD-BPM).

Waveguide fabrication has been achieved with a commercially-available thermo-mechanical analyzer. Pre-prepared fibres are pressed, by mechanical loading, onto a polished planar glass substrate (of dissimilar composition and lower refractive index) above the glass transition temperature (Tg). On cooling, a strong thermal bond between fibre and substrate results in a hybrid glass component. The technique has been further developed as a hot embossing process, in which a groove is formed in a glass substrate by embossing above Tg with a suitable mould, the embossed substrate acting as a low index cladding. A fibre is then pressed into the groove to form the core of an inverted rib-type waveguide. Large cross-section single-mode waveguides with lateral dimensions up to 30μm, and other compact designs of a few microns, have been investigated and waveguiding demonstrated. Such discrete hybrid components show potential for integration with other optoelectronic platforms and are well-suited to current ëpick-and-placeí manufacturing techniques.

With a view to minimization of fibre manipulation and facilitation of volume production, we have applied the hot embossing methodology to a dual-layer planar structure, in which the higher refractive index (top) layer is embossed into the lower index layer, forming a rib waveguide structure. In this situation, the glasses are deposited on single-crystal silicon substrates and, as such, show potential for integration at the wafer and chip-scale levels.

6123-17, Session 4

UV imprinting of waveguides on active silica-germania sputtered thin film

S. Sebastiani, S. Berneschi, M. Brenci, Istituto di Fisica Applicata Nello Carrara (Italy); A. Chiasera, M. Ferrari, Institute of Photonics and Nanotechnologies (Italy); G. Nunzi-Conti, S. Pelli, Istituto di Fisica Applicata Nello Carrara (Italy); C. Tosello, Univ. of Trento (Italy); G. C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy)

Direct imprinting of refractive index structures can be achieved by UV exposure of a photo-refractive layer through an intensity mask. This simple technology is an attractive route for the fabrication of integrated optical components since it avoids time consuming and expensive fabrication steps such as lithography and chemical or physical etching.

We report on direct UV photo-imprinting and characterization of channel waveguides fabricated on radio frequency (RF) sputtered silica-germania thin films codoped with erbium and ytterbium. Sputtering deposition of the films was performed by using a silica target on which pieces of germania, metallic ytterbium, and metallic erbium were placed. Low loss slab waveguides were obtained after annealing at 600∞C, with a single mode at 1550 nm. A 75SiO2-25GeO2 layer was then irradiated through a metallic mask with openings of different widths by using a KrF excimer laser source at l = 248 nm. The maximum induced index change value (about 3∑10-3) is high enough to laterally confine the light. Single mode channel waveguides were indeed fabricated with no additional losses compared to the slab ones. Waveguides spectroscopic properties of the 4I13/2 <==> 4I15/2 transition of the Er3+ ion, including lifetime and emission bandwidth, were also examined in order to fabricate an integrated laser source around 1550 nm.

6123-18, Session 4

Thick hybrid silica-zirconia sol-gel film for single-step fabrication of channel waveguide

M. He, J. Bu, X. Yuan, Nanyang Technological Univ. (Singapore)

A novel hybrid silica-zirconia sol-gel material, which can generate ten-μm-thick film by only one layer of spin-coating, has been successfully developed and employed in single-step fabrication of channel waveguide on silicon substrate with a layer of silica film. The hybrid silica-zirconia sol-gel material was prepared by uniform hydrolysis and subsequent co-polymerization of [3-(methacryloxy) propyl] trimethoxysilane and zirconium propoxide. It was easy to form a thick film with a thickness of 10 μm by coating only one layer for our hybrid silica-zirconia sol-gel material so that the sol-gel film had good internal homogeneity and surface uniformity, compared with the sol-gel materials reported before. In the proposed single-step fabrication process, the hybrid silica-zirconia sol-gel film was exposed to UV through a binary mask and directly patterned into a channel waveguide on silicon substrate with a silica layer, which could be used as an end product with no further etching steps. The sol-gel film had a refractive index of 1.52, larger than that of the silica layer on the silicon substrate. The root-mean-square value of the surface roughness of the channel waveguide was measured as 1.32 nm, comparable to a

measured roughness value of 1.10 nm on a silicon substrate. In the 1.55 μm telecommunication window, the channel waveguide had a acceptable loss of 0.4 dB/cm. In addition, the fabricated channel waveguide had steep ridge wall, good optical confinement and high robustness. The results indicate that the hybrid silica-zirconia sol-gel material is promising for fabrication of micro-waveguide.

6123-19, Session 4

Polymer photonic integrated circuits by DUV-induced modification

D. G. Rabus, Forschungszentrum Karlsruhe (Germany) and Univ. of California/Santa Cruz; P. Henzi, M. Bruendel, H. Hein, Y. Ichihashi, T. Rogge, A. Welle, Forschungszentrum Karlsruhe (Germany)

Polymer optical waveguide devices will play a key role in several rapidly developing areas such as optical networks, biophotonic and fluidic applications. We have developed a technology which enables the increase of the refractive index of methylmethacrylate based polymers by deep ultra violet (DUV) radiation. The modification of the dielectric properties of polymers by DUV is a useful technique for the realization of photonic integrated optical circuits. The technique presented here has several advantages with respect to common methods because only a single polymer layer is used, which serves as the substrate and waveguide as well and no further etching or development step is required. This method can not only be applied to planar polymer substrates but also to pre embossed substrates. This enables the fabrication of ridge waveguide based devices by hot embossing. Nickel stampers with feature heights of about 15-20 micrometers and aspect ratios usually between 2:1 and 3:1 can be utilised for replication without major effort. Nickel stampers are not only used to replicate optical waveguides, but are also used to realize fluidic channels in the range of several microns. Finally UV modification of methylmethacrylate polymers leads to a new surface chemistry affecting the selective absorption of proteins and the adhesion of living cells in vitro. The bi-functionality of the modified polymer chips supporting waveguides and cell anchorage capabilities at the same time provides the opportunity to monitor protein adsorption, cell attachment and spreading processes by evanescent-field techniques. Highlights of fabricated devices will be given.

6123-20, Session 4

Highly stable and low loss electro-optic polymer waveguides for high speed modulators using photodefinition technique

M. Balakrishnan, M. Diemeer, A. Driessen, M. Faccini, W. Verboom, D. Reinhoudt, Univ. of Twente (Netherlands); A. Leinse, LioniX, BV (Netherlands)

Polymers with optically active nonlinear chromophores have been shown to have a promising future in low cost and high speed electro-optic (EO) device applications. However, a main question of concern is the photochemical stability and the thermal stability of the polar order of the chromophores for long term application. The chromophore tricyanovinylidenediphenylaminobenzene (TCVDPA) with a single benzene bridge between a tricyanovinyl acceptor and an amino donor has been reported to have high photochemical stability combined with high electro-optic activity. In the current work TCVDPA is incorporated as side chain in the high glass transition temperature (Tg) polymer, polycarbonate (PC). The high Tg (~190∞C) of this polymer is suitable for high thermal stability of the electro-optic modulators. The glass transition temperature, which drastically reduces when TCVDPA is incorporated as guest in PC host (because of the plasticizing effect of the chromophore) is prevented by attaching the chromophore as side chain to PC. The intermolecular interaction between the chromophores during the poling process (which aligns the chromophores in the direction of the applied electric field and gives a net EO effect) has been studied. The EO coefficient (r33) of TCVDPA incorporated as guest in polysulfone was measured at different concentrations of TCVDPA. A maximum r33 of 12.5 pm/V at 830 nm was measured. A deviation from linearity was observed above 15 wt% of TCVDPA because of intermolecular interaction which causes anti-parallel clustering of the chromophores. The possibility of reduction of this intermolecular interaction by attaching bulky side groups to TCVDPA and thereby preventing their close approach has been shown. The material system PC-TCVDPA is being proposed for high speed EO modulator using microring resonator. Inverted structures for port waveguides and the adjacent microring resonator are defined in a cladding material by photodefinition. These inverted structures are then filled in with the active polymer (TCVDPA-PC) by spin coating. This method of defining inverted ridges offers the possibility of fabricating waveguide structures with reduced side wall roughness which is difficult to realize using reactive ion etching technique.

6123-21, Session 5

InP-based 1.55 μm waveguide-integrated photodetectors for high-speed applications

A. Beling, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz Institut (Germany)

In the past years the demand for speed and capacity of telecommunication systems has been increasing due to the massive growth in internet usage. Optical fiber networks and fiber-based microwave links will be required to provide a high capacity of data transmission. Ultra-high-speed photodetectors with high opto-electronic (O/E) conversion efficiency and high power handling capability are key components in these upcoming optical fiber networks, fiber-based microwave links and leading edge O/E measurement equipment. To achieve a high bandwidth-efficiency-product side-illuminated photodiodes show distinct advantages as compared to surface-illuminated detector structures. Waveguide-integrated photodetectors utilizing evanescent coupling circumvent the trade-off between high quantum efficiency and short transit time and offer an excellent high power capability. These devices are well suited for the monolithic integration with further components, such as spot-size transformers for effective fiber-chip coupling, waveguides and power splitters for advanced detector structures. This concept exhibits advantages in functionality and stability, and maintains bandwidth, high power handling capability and high responsivity at the same time.

In detail, we present a highly efficient miniaturized waveguide-integrated photodetector with spot-size converter. In order to maintain a high quantum efficiency, an optical matching layer exploiting mode beating effects is employed. Its optimization leads to a twofold enhanced external responsivity of 0.5 A/W at 1.55 μm wavelength in accordance with simulation. The reduced p-n junction capacitance enables 3 dB bandwidths up to 120 GHz mainly limited due to carrier transit time effects.

In contrast to the lumped photodetector, the traveling wave photodetector is a fully distributed structure. The characteristic impedance of this device can be matched to that of the external circuit by distributing the RC elements on a transmission line. Hence, the bandwidth is not limited by an RC constant and the inherent trade-off between maximized RC-limited and carrier-transit-time-limited bandwidth can be overcome. In the paper we report on monolithically integrated traveling wave photodetectors employing discrete miniaturized photodiodes with serial and parallel optical feeding.

6123-22, Session 5

Infrared single-mode hollow conductive waveguides for stellar interferometry

P. R. Labeye, CEA-LETI (France); J. Broquin, IMEP (France); L. Labadie, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); P. Noel, CEA-LETI (France); P. Saguet, IMEP (France); P. Y. Kern, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); C. Ruilier, Alcatel Alenia Space (France)

This paper reports the design, realisation, and characterisation of singlemode hollow conductive waveguides for stellar interferometry. These

waveguides are developed in the frame of technological developments for the ESA DARWIN mission, which aims at direct detection of exoplanets, and possible biomarkers on them (proof of life), using nulling interferometry in the ~6-20μm spectral range. The use of singlemode waveguides is mandatory in order to meet DARWIN required performance, and achieve modal filtering (re10-6). While there is ongoing developments of infrared dielectric fibers or integrated waveguides, both using chalcogenide glasses or silver halide compounds, this paper presents the first realisation and characterisation of singlemode hollow conductive waveguides in the DARWIN spectral range, made using standard microelectronic and wafer bonding technologies.

6123-23, Session 5

Manipulation of microparticles with integrated optics

O. G. Hellesø, K. Grujic, Univ. of Tromsø (Norway); J. P. Hole, Univ. of Southampton (United Kingdom); H. Jaising, Univ. of Tromsø (Norway); J. Wilkinson, Univ. of Southampton (United Kingdom)

In a dielectric waveguide, the optical power is confined mostly in the core of the waveguide, where the refractive index is highest. Outside of the core the field is evanescent, i.e., the field strength decreases exponentially with the distance from the core. This evanescent field can be used to manipulate microparticles. For a particle with index of refraction higher than that of the surrounding medium (water), the optical forces due to the evanescent field act to guide the particle along the waveguide. The use of waveguides to trap particles combines the possibilities of conventional optical tweezers with the techniques employed in integrated optics, and it has the added advantage of integration of several functions on a single chip.

We have experimentally observed size-dependent trapping and propulsion at velocities up to 33μm/s of polystyrene spheres, of diameters between 3 and 15μm, and in propulsion of 0.25μm diameter gold spheres at velocities up to 200μm/s. A Y-junction with a multimode input waveguide has been used to sort particles. By moving the input fibre relative to the input waveguide, the light goes into one of the two output branches. We have shown that this principle can be used to sort polystyrene microbeads. Recently we have used counter-propagating waves to move particles in both directions and also to stop a particle at a precise location. Experimental results and simulations for polystyrene microbeads, yeast cells and gold particles will be presented. An overview of related work will also be given.

6123-24, Session 5

Enhanced second-harmonic generation in a lithium niobate photonic crystal waveguide

C. Deng, J. W. Haus, A. M. Sarangan, A. Mahfoud, Univ. of Dayton; M. Scalora, U.S. Army Aviation and Missile Command; C. Sibilia, Univ. degli Studi di Roma/La Sapienza (Italy); A. Zheltikov, M.V. Lomonosov Moscow State Univ. (Russia)

Enhanced second harmonic generation (SHG) conversion efficiency was theoretically predicted in waveguide geometry with coupling to a one-dimensional grating photonic band gap (PBG). Here we compare the theory with experiments. Our samples were made using lithium niobate with a waveguide fabricated near the surface by using the proton exchange technique. We investigated Cerenkov second-harmonic generation (CSHG) in the substrate under the condition of a PBG resonance in the waveguides. The SHG inside planar waveguides was also experimentally investigated. In this experiment, the second mode in the waveguide was tuned to a band edge resonance to confine and enhance the guided electromagnetic field and enhance the nonlinear optical efficiency. The highest conversion efficiency of CSHG with PBG was enhanced case around 50 times above the CSHG signal without a PBG.

6123-25, Session 6

Cascaded planar reflective gratings

S. Bidnyk, M. R. Pearson, A. Balakrishnan, M. Gao, Enablence Inc. (Canada)

Recent progress in the development of planar reflective gratings has resulted in the demonstration of multiplexers, comb filters, interleavers, power monitors, and receivers for long-haul and metro-area networks. Until recently, all of these devices were based on a single-grating architecture. We have now successfully designed, fabricated, and tested optical chips that are composed of cascaded planar reflective gratings. The chips have been realized in both additive and subtractive dispersion configurations. The versatility of cascaded gratings was utilized to produce a variety of optical responses, including single-mode transmission of wide bands (> 100 nm) with simultaneous demultiplexing of narrow optical channels with Gaussian and box-like responses. We have further demonstrated that cascaded gratings can be used to suppress optical noise and improve isolation. The devices were fabricated using a standard silica-on-silicon process with a refractive index contrast of 0.82% and have a remarkably small footprint of less than 0.3 sq. cm. We discuss the potential for tailoring of cascaded planar reflective gratings for applications in biophotonics, spectroscopy, and telecommunications.

6123-26, Session 6

Multilayer integrated nano-optical devices

J. J. Wang, X. Deng, P. Sciortino, Jr., X. Liu, NanoOpto Corp.

Nano-optic retarders and polarizers based on dielectric and metal nano-gratings were fabricated by UV-nanoimprint lithography. Different from conventional nanostructure-based optical devices, atomic layer deposition, a highly uniform and conformal deposition process, were utilized to fill trenches of the both dielectric and metal nano-gratings.

The nano-trench-filling process described in this work simultaneously functions as a planarization process, which allows us to build multi-layer vertically integrated devices. The resulted immersion nano-grating design opens a path for innovative nano-grating based optical devices and integrated optical devices. An examples, two two-layer integrated nano-optic devices were developed. The first one is a high retardation optical retarder based on stacking of an all-dielectric immersion nano-grating retarder layer. The multilayer vertical integration of such nano-grating retarder potentially leads us to artificial birefringent optical crystals. The second one is a monolithically integrated circular polarizer based on stacking a nano-optic quarter wave plate onto an immersion aluminum nanowire-grid polarizer. The ability to integrate multiple nanostructure-based optical layers opens a path for innovative integrated optical devices and materials as well as a new strategy for driving both miniature and cost.

6123-27, Session 6

Integration of encoder/decoder for avionic OCDMA by holographic Bragg reflectors

Y. Huang, V. Baby, I. Glesk, P. R. Prucnal, Princeton Univ.; C. M. Greiner, D. Iazikov, T. W. Mossberg, LightSmyth Technologies, Inc.

With the merits of protocol independence and similar optical routing capabilities as DWDM, optical code division multiple access (OCDMA) could potentially provide the bandwidth needed for avionic platforms with significantly higher spectrum utilization and expandability. We applied wavelength-hopping time-spreading (WHTS) OCDMA to avionic topologies by introducing tunable en/decoders with capability to swap code assignments for enhanced channel isolation. To achieve low-cost, low-footprint solutions for the implementation of WHTS codes, we will study the suitability of holographic Bragg reflector (HBR) technology.

HBRs are two-dimensional holographic refractive index structures written into slab waveguides by deep ultra-violet projection photolithogra-

phy. They can interact with specific signal beams and provide signal routing and wave-front transformations with powerful spectral control. To manipulate the WHTS codes, the en/decoder must have the ability to distribute/distinguish the wavelength and time coordinates of different optical pulses, which can be granted by HBRs. A typical signature swapping node in an OCDMA testbed can be built by interleaving two HBRs so that the two generated codes can be selected by a fast electro-optic switch.

For demonstration, an encoder has been fabricated with two heavily-interleaved HBRs with sixteen ~1.2 mm-long grating segments. The input is connected to two output ports with port-specific temporal and spectral transfer functions. When a 1.5-ps-wide supercontinuum optical pulse (spectral width ~80 nm, centered at ~1550nm) is injected, the two generated WHTS codes will each consist of 8 distinct frequency components with 1-nm spectral width. These spectral components will spread in time according to the different grating locations, providing 16 time chips spaced by ~ 11ps. HBR-based en/decoders provide both spectral slicing and temporal delay simultaneously, enabling a very small footprint comparing to those based on AWGs and TFFs. Its spatially distinct input-output mapping greatly simplify signal routing, making it a promising candidate for avionic OCDMA platforms.

6123-28, Session 6

Compact coding devices using the novel anti-symmetric gratings

J. M. Castro, D. F. Geraghty, S. Honkanen, The Univ. of Arizona; C. M. Greiner, D. Iazikov, T. W. Mossberg, LightSmyth Technologies, Inc.

With the ever increasing bandwidth of optical communications systems, it is critical to allow multiple users to access the available bandwidth. CDMA is especially attractive in local area networks due to the large number of subscribers possible, the security and the simple architecture. Optical encoding and decoding has already been demonstrated using bulk elements such as fiber Bragg gratings and circulators. Integrated optic null coupler devices, using tilted Bragg gratings (TBG) and asymmetric y-branches can be used to produce compact devices since they do not need circulators to separate incoming from outgoing signals. However, TBGs produce multiple reflections peaks which produce noise and crosstalk. We have recently demonstrated the novel anti-symmetric grating which outperforms TBGs since only one reflection peak is produced. This novel grating can provide the separation between the incoming signal (information bits) and the outgoing signal (encoded sequence) without adding noise. We will present the designs of compact encoders using coding schemes such as prime codes as well as balance incomplete block designs (BIBD) codes. The feasibility of novel non-binary coding schemes using the anti-symmetric grating will be analyzed. The devices are fabricated by LightSmyth Technologies, Inc using silica on silicon technologies.

6123-29, Session 6

Annular Bragg resonators (ABR)-the ideal tool for biochemical sensing, nonlinear optics and cavity QED

J. Scheuer, California Institute of Technology

Circular resonators are fundamentally interesting elements that are essential for research involving highly confined fields and strong photon-atom interactions such as cavity QED, as well as for practical applications in optical communication systems as and biochemical sensing. The important characteristics of a ring resonator are the Q-factor, the free spectral range (FSR) and the modal volume, where the last two are primarily determined by the resonator dimensions. The Total-Internal-Reflection (TIR) mechanism employed in ìconventionalî resonators couples between these characteristics and limits the ability to realize compact devices with large FSR, small modal volume and high Q.

Recently, we proposed and analyzed a new class of a resonator in an annular geometry that is based on a single defect surrounded by radial Bragg reflectors on both sides. The radial Bragg confinement breaks the link between the characteristics of the mode and paves a new way for the realization of compact and low loss resonators. Such properties as well as the unique mode profile of the ABRs make this class of devices an excellent tool for ultra-sensitive biochemical detection as well as for studies in nonlinear optics and cavity QED.

6123-30, Session 7

Study of a pump/signal multiplexer based on a segmented asymmetric Y junction by Silver/Sodium ion exchange on glass

D. Bucci, J. Grelin, E. Ghibaudo, J. Broquin, Ecole Nationale Superieure d'Electronique et de Radioélectricité de Grenoble (France)

Broadband wavelength (de)multiplexers play an important role in different fields of integrated optic. In particular, the development of Erbium Doped Waveguide Amplifiers (EDWA) requires efficient integrated pump/signal multiplexers.

In this article, the design of a 980nm/1550nm wavelength multiplexer based on a segmented asymmetric Y junction made by silver/sodium ion exchange on glass is discussed. The asymmetric Y junction is particularly interesting for its properties of wideband operation and small footprint.

We first present the index averaging principle of a segmented waveguide, as well as its application for the design of a branch. Then, the modeling of an asymmetric Y junction is presented, in order to describe its behavior as a wavelength (de)multiplexer.

BPM simulations validating the design have shown crosstalks of 35dB at 980nm and 23dB at 1550nm with excess losses of 1.3dB at 980nm and 0.5dB at 1550nm. The broadband operation is only limited by the characteristics of the waveguides composing the junction and can reach 200nm at 1550nm.

In a second time, we present the realization of this component using a Silver/Sodium ion-exchange on glass. It is shown how the isotropic diffusion of ion-exchange must be taken into account very early in the device design, to achieve good performances.

Finally, results obtained on fabricated devices will be presented.

6123-31, Session 7

Femtosecond micromachining of waveguides in a Faraday material

T. Shih, R. R. Gattass, E. Mazur, Harvard Univ.

The use of femtosecond lasers for micromachining purposes has grown significantly over the past decade. Femtosecond micromachining of photonic devices has been demonstrated using only a few nanojoules of energy from a laser oscillator. This oscillator-only technique has recently become increasingly valuable as a micromachining tool.

Faraday isolators have not yet been realized using this ultrafast micromachining technique. A Faraday isolator is an important device because it functions as an optical diode, allowing signals to propagate only in one direction. It is particularly useful in circulators, where the signal selected by a Bragg grating is dropped to an alternate path. When a Faraday material is exposed to a magnetic field, a non-reciprocal index change linear with respect to the applied magnetic field is induced on the material. A Faraday isolator can be constructed by adding polarizers at the entrance and exit of the Faraday material.

We used an extended-cavity laser oscillator delivering pulses with an energy 20 nJ and a pulse duration of 55 fs at a 25-MHz repetition rate to micromachine waveguides into a Faraday glass sample. The laser is focused into the sample with a 1.4-NA oil-immersion objective and the sample is translated at a speed of 10 mm/s. The sample has a Verdet constant of -4300 degrees/T-m at 632.8 nm. The waveguides are single-

mode at 632.8 nm and 1550 nm. We are studying the feasibility of integrating these microstructures into small Faraday isolators.

6123-32, Session 7

Active and passive integrated optical devices written in glasses with femtosecond laser systems

R. Osellame, N. Chiodo, G. Della Valle, S. Taccheo, G. Cerullo, R. Ramponi, P. Laporta, Politecnico di Milano (Italy); A. W. Killi, TRUMPF Laser GmbH & Co. KG (Germany); U. Morgner, Univ. of Hannover (Germany)

Direct writing of integrated optical devices by femtosecond laser pulses has attracted much attention in recent years. Many experiments have used amplified Ti:Sapphire lasers at low repetition rate (<250 kHz). While these systems are very useful in studying the physical mechanism underlying the refractive index modifications they show some drawbacks in the production of photonic devices, i.e. slow processing time and asymmetric cross section of the fabricated waveguides. Regarding this last aspect, writing with astigmatic laser beams has proved to be a solution, while to overcome the slow processing time, several groups developed stretched cavity laser oscillators with high repetition rates (5-25 MHz). The main limitation of these lasers is the small number of glasses that can be processed with good results. More recently, a new family of Yb-based femtosecond lasers have been introduced in this field providing repetition rates up to 2 MHz with energies in the microjoule range, thus intermediate with respect to the two previous systems and optimal for this application.

In this work, the results obtained with these three femtosecond laser systems are compared. Waveguides, written on different types of glass, are characterized in terms of refractive index profiles and guided modes. Some passive devices as 1x2 and 1x4 splitters, fabricated exploiting the unique 3D capabilities of this technique, will be shown. Active devices, as erbium doped waveguide amplifiers and waveguide lasers for telecom applications, will also be presented and their performances discussed.

6123-33, Session 7

Fabrication of multifunctional optical waveguides by capillary-electrophoresis doping technique

T. Yano, J. Taguchi, H. Segawa, S. Shibata, Tokyo Institute of Technology (Japan)

Electric-field assisted doping of optically functional molecules or ions were conducted into the organic/inorganic hybrid waveguides in order to obtain the integrated optical device with multi-functions. Capillary electrophoresis technique was modified to transport and dope the optically active chemicals into the hybrid waveguides. This CED (capillary electrophoresis doping) technique enables the multi-doping on the same waveguide or the waveguides on the same device.

After an Au electrode was coated on the glass substrate by sputtering, the organic/inorganic hybrid film with about 5 micrometer thickness was formed on the electrode. SiO2 glass capillary (O.D.=370 micrometer, I.D.=75 micrometer and length=30 cm) was used as the transport device of optically functional chemicals, and filled with the organic dye n-hexanol/ethanol solution (organic dye=rhodamine6G and cresyl violet). A capillary bridge was made between the hybrid film and the solution bath and DC voltage was applied between them. When the tip of the capillary touched with the surface of the hybrid materials, the doping started, and the proceedings were monitored and controlled electrically via the electrometer.

Doped dyes were found to reach the interface between the electrode and the hybrid material, and the luminescence from the hybrid materials increased with increasing charge conducting through the capillary. Doped area had the same shape and dimension as those of the capillary cross section.

Various types of the doping were performed on the hybrid waveguide by CED technique, and the multi-functions were introduced into the same substrate. It was found that CED technique has much potential to realize the integration of the optical functions in the optical devices.

6123-34, Session 7

All optical broadband steering by phase angle controlled stationary element (PACSE) mirrors

D. V. Tsu, R. O. Miller, Energy Conversion Devices, Inc.

Controlling steering of broad band light beams is typically accomplished by MEMS mirror rotation, with limits of milli-second switching speeds. Mirror rotation introduces a linear phase angle shift. Also, because the mirrors are continuous, higher order diffraction is suppressed and all energy is directed into the 0th order diffracted beam. Combination of linear phase shift and 0th order diffraction explains specular steering. We have developed a method of introducing the desired phase angle shift at optical wavelengths without any need for physical rotation. In our PACSE mirror device, active elements are positioned across its surface in a 2D sub-wavelength diffraction array. Each active element can be controlled to effect a change in the local value of the phase angle, and therefore provides for specular beam steering.

This ìphased arrayî beam steering is widely used in Radar applications, and here we describe its implementation for optical NIR 1550 nm wavelengths. The active component is a Chalcogenide layer having a refractive index change of nearly 2X between its amorphous and crystalline states. Device steering involves locally changing the atomic structure of the active layer state by focused optical energy (650 nm laser). Thus the PACSE system is all optical. Similar Chalcogenides are used in rewritable optical recording media, where high speed and reliability is demonstrated. Ultimate steering speed is governed by material switching speeds (sub 50 ns). We will describe the materials as well as initial experiments demonstrating the steering capability of the PACSE device to be better than ± 10∞.

6123-35, Session 8

Photonic crystal waveguide-based dispersion compensators

M. Kamp, J. Zimmermann, A. W. Forchel, Univ. Würzburg (Germany); S. Anand, Kungliga Tekniska Högskolan (Sweden); R. März, Infineon Technologies AG (Germany)

Tunable dispersion compensators are among the key devices for the dynamic dispersion management in high-bit-rate long-distance optical communication networks. Photonic crystals (PhCs) have very unique dispersive properties and possible dispersion coefficients several orders of magnitude larger than those of standard optical fibers. PhC based devices are therefore attractive for the realization of compact dispersion compensators.

We have investigated the dispersion properties of photonic crystal waveguides and waveguide resonators. A passive InGaAsP/InP slab waveguide structure was used for the fabrication of the samples. The PhC waveguide resonators were defined by the omission of several rows of holes along the M direction of the triangular lattice. In addition, mirrors with a thickness of 2 to 5 rows of holes were inserted into the waveguide. An optimized dry etch process was used to etch the patterns to a depth of 3.5 μm through the waveguide layer. The group delay of the PhC devices was measured using the phase shift technique. The signal of a tunable laser was modulated at 3 GHz using a LiNbO3 Mach-Zehnder modulator and detected with a high-frequency lightwave receiver. A phase sensitive detection with a network analyer measured the phase shift of the transmitted signal, which is proportional to the group delay. Close to the center of the resonances, the chromatic dispersion reaches values of -250 ps/nm and 250 ps/nm. This corresponds to the chromatic dispersion of 15 km standard fiber.

6123-36, Session 8

The fabrication and study of in-plane multiquantum well microring lasers

B. Miao, J. A. Murakowski, D. W. Prather, Univ. of Delaware

In this paper, we present the fabrication of ridge-waveguide microring lasers with GaAs/AlGaAs multiple quantum wells (MQWs). The microring laser structure consists of a 1mm diameter ring and a lateral coupling waveguide. The fabricated laser is an electrical pumping laser. The excited beam in the ring resonator is coupled to the lateral waveguide and emits from it. The microring laser was patterned on the wafer using e-beam lithography, and then the pattern was transferred to semiconductor layers using inductive coupled plasma (ICP) etching. After that, a SiO2 layer was deposited on the sample surface using lift-off method, where the etching mask also worked as the lift-off mask. The SiO2 layer covered the entire surface except the laser structure area and functioned as an insulation layer, which confined the electrical current that only passed through the active layer under the ring structure. Finally, metal electrodes were formed using UV lithography and lift-off processes. To analyze the emitting light from the in-plane coupling waveguide, an optical spectrum analyzer (OSA) was employed. And less than 0.04nm line width of emitting peaks was observed. The wavelength of the emitting light was at 884nm, and the threshold current was 130mA at room temperature. In order to optimize the lasing performance, the width of the microring will be adjusted around 2um, and the microring lasers with different etching steps will also be study. And the electrical characteristics and lasing performance will be present in this paper.

6123-37, Session 8

Nonlinear optical nanostructures for filtering and switching light

A. Scherer, M. Hochberg, T. Baehr-Jones, G. Wang, California Institute of Technology; R. Lawson, Y. Liao, P. A. Sullivan, L. R. Dalton, A. K. Jen, Univ. of Washington

A new generation of photonic devices has recently emerged that rely on the geometry of sub-wavelength microstructures with a high enough refractive index contrast to confine and manipulate light within small volumes. Very high optical field densities can be obtained within such structures, and these in turn can amplify optical nonlinearities. Moreover, many of these structures, as for example photonic crystals and slotted waveguides, can be engineered for the efficient localization of light within the low-index regions of high index contrast microstructures. When such structures are back-filled nonlinear polymers or liquids, devices can be tuned and novel phenomena can be observed. In particular, such devices are very interesting when constructed from silicon on insulator (SOI) material in which the optical waveguide also serves as a transparent electrical contact. Here we show examples of the design, fabrication and testing of optical microstructures in which the electro-optic (2) and photo-refractive (3) nonlinearities are used for electro-optic tuning, frequency mixing, optical rectification, and high-speed switching of light.

6123-38, Session 8

Net gain demonstration with glass hybrid optical amplifier made by ion-exchange and wafer bonding

F. Gardillou, J. Broquin, École Nationale Supérieure d'Electronique et de Radioélectricité de Grenoble (France)

Integrated optics circuits made by ion-exchange on glass substrate have proven to be really efficient when dealing with passive devices, sensors, amplifiers and lasers. However, one of the major issue of this field is now to integrate both active and passive functions on a same substrate. For this reason, a wafer bonding technique has been implemented in order to report an Erbium/Ytterbium co-doped phosphate glass thin film on a ion-exchanged silicate glass. A proper design and choice of the glasses refractive indices allow obtaining an hybrid amplifying waveguide in which the vertical confinement is provided by the doped layer while the ion-exchange stripe ensures the lateral one.

In this paper we present the design, realization and characterization of such devices with different configurations based on either a Thallium/Potassium or a Silver/sodium ion-exchange. A linear gain of more than 3 dB/cm has been measured with the first implemented solution whereas a net gain of 1 dB has been demonstrated with the second one.

Current works are focused on laser operation and adiabatic transition development between passive ion-exchanged waveguides and the hybrid amplifiers.

6123-39, Session 8

Design, fabrication, and characterization of 3D photonic crystals constructed from low-index polymers

D. W. Prather, Univ. of Delaware and EM Photonics, Inc.; A. S. Sharkawy, P. Yao, S. Shi, E. Kelmelis, EM Photonics, Inc.

Applications relying on the dispersive properties of photonic crystal (PhC) structures have recently attracted significant attention within the photonic crystal community. This stems from their ability to provide similar functionality to that offered by devices that operate in a PhCís stop band or bandgap but without the need for high fabrication tolerances, strict alignment, or high index contrast with the material used to construct the PhC lattice. Recent experimental studies have shown that the dispersion properties in PhC structures can be engineered to implement various optical devices. While most initial interest has been in examining the dispersion properties of PhCs in high-index materials, we explore the possibility of implementing similar functionality using low-index materials, specifically polymers, thus allowing for a new set of possible applications. In this paper, we present a novel fabrication procedure to create three-dimensional PhC structures in low-index polymers. Our procedure provides the ability to introduce completely arbitrary, non-regular patterns into the PhC lattice. The PhC structures we fabricated were initially analyzed numerically using the plane wave expansion method to extract the dispersion properties of the structures. We present various examples of periodic structures fabricated in low-index polymers including simple cubic, woodpile, and a two-layer planar diamond lattice. We compared the operation characteristics, mechanical stability, and suitability for device creation of these different lattice structures. We also present a discussion of key issues in the fabrication procedure including the ëkeystoningí effect and study its impact on the spectral response of the pre-designed 3D PhCs for low-index materials.

6123-41, Session 9

Integration of plastic waveguide lasers on film and its application

Y. Oki, H. Watanabe, Kyushu Univ. (Japan); M. Maeda, Kurume National College of Technology (Japan)

An integrated and disposable tunable laser system was proposed and remonstrated. Waveguide DFB plastic dye lasers were made of polymethylmethacrylate:hydroxyethylmethacrylate(pMMA:HEMA) doped with laser dyes. The dye doped polymer is spin-coated on PMMA substrate and stripped waveguides were fabricated by deep UV lithography technique. The distributed feedback structure was fabricated using exposure by two interfered UV beams.

The size of the laser waveguide is 100micron (width) x 3-5micron (thickness) x 10mm (length). Very small laser threshold of less than 1 micro Joule was obtained, and a SHG of passively Q-switch microchip Cr:Nd:YAG laser was used as a pumping source. The spectral coverage of the DFB dye laser is over 560 - 1100 nm by exchanging the 14 kinds of laser dyes. The repetition rate of 100-1000 pps was available, and the spectral bandwidth is less than 0.1nm. Since the pumping energy can be suppressed less than 1 micro Joule, the waveguide laser showed good

durability as long as 6 million shots.

Subsequently, two novel techniques specified to the waveguide DFB lasers were proposed and developed. Quasi-mode coupled (QMC) pumping scheme using dual-core-layered waveguiding is as first technique. No phase matching is needed and effective absorption length can be varied by controlling the refractive indices and thicknesses of the core layers. The end firing scheme based on QMC as a fiber-top alignment was demonstrated. The effective absorption length was as long as in the range of 0.1-10mm even though the absorption length was 10-100 micron in the dye-doped plastics. The variable effective absorption length can optimize the slope efficiencies of the several doping concentrations. The numerical simulation said that the effective absorption length can be varied 10 times by varying the refractive index of 0.02.

Furthermore, a laser operation control based on a thermo-optical (TO) effect was demonstrated. Aluminum electrode was introduced into the fabrication process, and pulsed resistance heating was applied to change the refractive index of the waveguide. The output wavelength of a DFB plastic laser can be tuned over 10nm using the rapid pulsed-heating. The alternative wavelength switching with a wavelength split of 5nm was also demonstrated. Subsequently, a TO pump-switching using Y-branched waveguide for pumping beam delivery was designed and demonstrated.

Finally, as applications using integrated DFB plastic dye laser, novel scheme of a spatial transformed absorption spectroscopy was proposed and demonstrated. Multiple-wavelength DFB laser array that covers around 590nm was used and an absorption spectrum of sodium vapor was observed as a example. The application of micro-flowcytometry was also proposed as a future plan.

6123-42, Session 9

From magic to technology: materials integration by wafer bonding

V. Dragoi, EV Group E. Thallner GmbH (Austria)

The need for dissimilar materials integration appeared since semiconductor devices early history. After numerous years of development work on seemingly incompatible materials systems it is now possible to combine very dissimilar materials and devices into integrated systems. New technologies as wafer bonding are responsible for this important progress.

Wafer bonding is a technique used to join two flat mirror polished surfaces having a high degree of cleanliness.

Despite the fact most of wafer bonding applications are based on silicon, wafer bonding technology is by no means restricted to silicon wafers. Appropriate polishing methods and control of the surface chemistry makes possible bonding of a large variety of solids independently on their structure (amorphous, polycrystalline, single crystals), crystallographic orientation and lattice constant. Wafer bonding allows materials combinations which were not possible by the conventional approach of epitaxial growth.

During last decade wafer bonding became a key technology in various fields. Different wafer bonding processes are used nowadays for applications in the field of microelectronics, Micro-Electro-Mechanical Systems (MEMS), micro-opto-electromechanical systems (MOEMS) and advanced wafer level packaging.

In theory any two materials can be joined together by using the right wafer bonding procedure (the concept ìAnything-on-Anythingî). The choice of the proper bonding method depends on the initial substrates and the desired final application.

This paper aims to present a review of the most used wafer bonding techniques, illustrated by typical examples of applications. A special attention will be focused on optical and optoelectronic applications of wafer bonding.

6123-43, Session 9

Integrated high-q reflective cavities

T. W. Mossberg, C. M. Greiner, D. Iazikov, LightSmyth Technologies, Inc.

Integrated photonic circuits have relied heavily on channel-waveguide-based transmissive elements because of their ability to guide in low index contrast environments and relatively low loss. On the other hand, reflective device elements lend important design flexibility to the integrated optical environment and approaches to their implementation are valuable. We report on the fabrication and test of a 4-mm-long, laser-cavity-like, integrated resonator employing a pair of curved 2D mirrors in a silica-on-silicon dual-core slab waveguide. The cavity mirrors comprise first-order distributed reflectors patterned via DUV photolithography. The cavity exhibits a Q-value approaching 1,000,000 indicating very high slab waveguide homogeneity providing wavefront stability and extremely low loss from the volume-holographic lithographically scribed mirrors. Pathways to the implementation of high-reflectivity and low loss distributed reflectors promise new directions in photonic integration with applications in sensing, filtering, and signal transport.

6123-44, Session 9

Wafer bonding between InP and Ce:YIG(CeY2Fe5O12) using O2 plasma surface activation for an integrated optical waveguide isolator

J. W. Roh, Yonsei Univ. (South Korea) and Korea Institute of Science and Technology (South Korea); J. S. Yang, W. Y. Lee, Yonsei Univ. (South Korea); S. H. Ok, D. H. Woo, Y. T. Byun, Y. M. Jhon, Korea Institute of Science and Technology (South Korea); T. Mizumoto, Tokyo Institute of Technology (Japan); S. Lee, Korea Institute of Science and Technology (South Korea)

In optical communication systems, the importance of the optical isolators has been increased in order to protect active devices from unwanted reflected light and stabilize oscillation of a semiconductor laser diode. An integrated optical waveguide isolator has been essential to realize photonic integrated circuits. For the purpose of monolithic integration, the low temperature wafer bonding between semiconductor guiding layer and magneto-optic cladding layer is indispensable by reason of the large lattice mismatch and the difference of thermal expansion coefficient between semiconductor and magneto-optic material. Prior to bonding between InP and Ce:YIG, the surface roughness of Ce:YIG after chemical surface activation by H3PO4 and plasma surface activation by O2 plasma was investigated by AFM(Atomic Force Microscopy), respectively. The RMS of surface roughness of Ce:YIG substrate after O2 plasma surface activation was much smaller than that of Ce:YIG after chemical surface activation. It is reasonable that surface activation using O2 plasma is more effective for wafer bonding than chemical surface activation. And wafer bonding between InP and Ce:YIG substrate was demonstrated using O2 plasma surface activation. The wafer bonding was found to be successfully performed without an air gap between bonded layers from the cross sectional SEM(Scanning electron Microscope) image of the bonded wafer between the InP and Ce:YIG.. And we successfully adopted the same bonding process to fabricate an integrated waveguide optical isolator with multimode interference section. The isolation ratio of optical isolator fabricated by wafer bonding using O2 plasma was 2.9 dB.

6123-45, Poster Session

Theoretical and experimental study of non-adjacent channel crosstalk of AWG devices induced by random phase errors

W. Li, Huazhong Univ. of Science and Technology (China); W. Ma, Accelink Technologies Co., Ltd (China); D. Liu, D. Huang, Huazhong Univ. of Science and Technology (China)

Crosstalk of AWG based DWDM components is one of the most important parameters for its application in DWDM optical communication systems. Comparing with the thin film filter based DWDM devices, adjacent and non-adjacent channel crosstalk of AWG devices between its output waveguides is the most disadvantages. The channel crosstalk is mainly

caused by the mode coupling between output waveguides, and it can be reduced through waveguide structure optimization and fabrication processing improvement. In order to lower the crosstalk level, it needs considerable design treatment and strict processing control. In this paper, non-adjacent channel crosstalk of AWG devices induced by random phase errors is studied theoretically and experimentally. The origin of random phase errors is analyzed by considering the random errors of waveguide structure and refractive index distribution uniformity, etc. Several analytical formulas for crosstalk level estimation of AWG devices are given. These formulas can be used to optimize the crosstalk level of AWG based DWDM components in a very simple way, and the corresponding fabrication processing parametersí requirement can be obtained at the same time. Using these formulas, a typical 40 channel AWG demultiplexer was designed and fabricated with the non-adjacent crosstalk below -40dB. The experimental result shows that the crosstalk level between non-adjacent channels is as low as -45dB, with the random change in waveguide geometric structure is less than 0.5micron, the average refractive index deviation of core layer and cladding layer is less than 2*10-4 and 6*10-4, respectively.

6123-47, Poster Session

Long-term stability of polymeric integrated optical components

W. Kwong, Consultant

Traditionally, glass has been a suitable waveguide material and passive integrated optical circuits in glass substrates are widely used as passive components. Long-term tests of optical glass flats with a high level of internal stress revealed gradual systematic-change with time to produce inconsistent results. Since long-term stability has been the primary concern for users of specific applications, investigations of instabilities in various optical materials have been carried out via measurements and tests. From the development of the integrated optical systems' point-of-view, polymers are promising candidates that possess excellent compatibility with all other materials and their associated processes. Polymeric materials offer large refractive-index contrasts, relatively high values of thermo-optic coefficients, high performance, environmental stability, simple low-cost fabrication and may be processed by unconventional forming techniques. Polymer technologies can be designed to form stress-free films, so that stress-induced losses can be eliminated. Optical polymers may also be tailored to meet specific requirements for optical waveguide devices and can be highly transparent in such a way that they are not a limiting factor in components' lifetime. In this paper, tests results and characteristics of polymeric materials shall be reviewed; different types of polymer are detail-studied and a brief analysis shall be presented. Examples of polymeric integrated optical passive components are single-mode splitters, couplers, switches (e.g. thermo-optic switches), attenuators (e.g. variable optical attenuators) and tunable filters (e.g. tunable Bragg-grating-based filters), which may find applications in the optical communication and the telecom industries.

6123-48, Poster Session

Proton exchanged waveguides in LiNbO3: characterization and design methodology

J. M. M. M. de Almeida, Univ. de Trás-os-Montes (Portugal); A. M. P. P. Leite, Univ. of Porto (Portugal)

The purpose of this work was to develop a design methodology for the fabrication of proton exchanged channel waveguides in LiNbO3 operating in the singlemode regime at several wavelengths, with specific characteristics required to optimize integrated devices. To achieve this, it is necessary to obtain the relations between the optical characteristics of the waveguides and their respective fabrication conditions, and to introduce models of the waveguide formation process. The relations between fabrication conditions and optical characteristics of planar waveguides realized by proton exchange in benzoic acid are documented extensively in the literature. However, reports on the characterization of waveguide fabrication processes, performed in a systematic way, could not be found, resulting in the need to combine information from several sources. Discrepancies among results from different researches are evident, resulting from different experimental methodologies and calibration of equipment. Therefore, aiming at extracting a consistent data set, optical characterization techniques of the refractive index profile were employed to study series of samples.

6123-49, Poster Session

Microdisplacement measurements with moire patterns of fresnel zone plates films

M. Pérez-Cortés, Univ. Autónoma de Yucatón (Mexico); M. Ortíz-Gutiérrez, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); J. C. Ibarra, Tratamientos Geotecnicos, S. A. de C. V. (Mexico); A. Olivares Pérez II, Insituto Nacional de Astrofísica, Optica y Electrónica (Mexico); J. Becerra-Macìas, Digital Optical Quantum Electronics Devices (Mexico)

In this work we propose a technique to measure micro displacements using moire 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.

6123-50, Poster Session

Metal clad optical waveguide with high index buffer layer

K. N. Tripathi, Univ. of Delhi (India)

Metal clad optical waveguide with high index buffer layer possess a unique property arising from periodic coupling effect between the lossless modes of a dielectric waveguide and the lossy mode supported by the high index buffer claded with metal. In the present work, the eigenvalue equations for multilayer structure has been solved numerically using Mullerís iteration method. It is observe that both TE and TM pass polarizers can be produce using this structure. High extinction ratio polarizers for a high index dielectric buffer layer and a metallic overlayer for ion exchanged planar optical waveguides for *=633 nm have been designed and fabricated. An oscillatory behavior similar to the semiconductor waveguide is observed for both TE and TM mode losses. Results are presented for ZnO as a buffer layer and metals (Al, Ag and Au) as claddings. Effects of buffer thickness and index on guided modes are also presented. The theoretical results show good agreement with experimental results.

6123-51, Poster Session

Super slim optical pickup for mobile data storage device applications

S. Suh, E. Cho, SAMSUNG Advanced Institute of Technology (South Korea); Y. Jin, SAMSUNG Electro-Mechanics Co., Ltd. (South Korea); H. Kim, Y. Nam, J. Sohn, M. Lee, SAMSUNG Advanced Institute of Technology (South Korea)

As portable devices, such as cell phones, digital cameras, camcorders, MP3 players and notebook PCs are widely spreading, the demand of the portable storage devices is increasing. This paper addresses the design, fabrication and packaging issues of super slim optical pickup module using blu-ray technology. By using blu-ray technology, which uses a 405nm LD (Laser Diode) and an objective lens having NA (Numerical Aperture) 0.85, storage devices become miniaturized but have a high capacity.

The developed prototype uses the integrated structure of an upper SiOB (Silicon Optical Bench) and a Silicon Substrate. The upper SiOB should be processed in order that a thin film PD(Photodiode) and interconnections, LD, Lens, QWP(Quarter Wave Plate) and HOE can be placed, and on the Silicon Substrate should Micromachined Silicon Mirror be formed.

The upper SiOB is aligned and bonded with the wafer on which Silicon

Mirror was formed. Then, it is diced. Because it is fabricated through this order, the super slim optical pickup can be fabricated by using wafer-level process. As a final step LD on the upper SiOB and HOE are assembled and bonded using an active alignment.

The proposed super slim optical pickup was prototyped and characterized by measuring wavefront error and detecting static focusing and tracking error signal.

6123-52, Poster Session

Designing WDM filter on planar holographic Bragg reflectors with iterative layer-peeling algorithm

Y. Ouyang, Chinese Military Academy (Taiwan)

Combining the advantages of spectrally filtering and spatially routing optical signal, the WDM (wavelength divisions multiplexing) filters based on the planar holographic Bragg reflector have attracted more and more interests in recent years. In this paper, we have developed the design method for planar holographic Bragg reflector by iterative layer-peeling algorithm. Layer-peeling algorithm is known as an efficient tool for synthesizing fiber Bragg grating which is one-dimension grating without absorption. By taking account of attenuation and angle of incident wave, we have modified the layer-peeling algorithm that can synthesize planar holographic Bragg reflector. In order to solve the difficulty of fabricating the negative parts of apodized planar holographic Bragg reflector, we use iterative layer-peeling algorithm with fabrication constraints. The designed planar holographic Bragg reflector with 1 lob is 5.7 mm long, containing no phase shift. The stopband isolation is -30 dB. The BWU is 68%. The dispersion is 91 ps/nm in the 0.54 nm passband at -1 dB. The GDR is below 0.6 ps

6123-53, Poster Session

Low loss optical interconnect to silicon waveguides

A. Donval, R. Oron, M. Oron, KiloLambda Technologies, Ltd. (Israel); A. N. M. M. Choudhury, T. R. Stanczyk, D. Richardson, Molex Fiber Optics

Waveguides fabricated in high-index-contrast material systems offer very strong light confinement in smaller dimensions compared to that achieved in low-index-contrast material systems. A core layer of silicon (refractive index ~ 3.5) surrounded by silica cladding (refractive index ~ 1.5) on a silicon-on-insulator (SOI) substrate is an example of a high-index-contrast material system. This enables miniaturization of functional optical components and enhances dense integration of devices on waveguide chips.

A large mismatch between the common optical fiber dimension and that of the high-index-contrast waveguide makes it difficult to couple light in and out of the chip. A number of techniques have been utilized for this purpose, including prism couplers, grating couplers, tapered fibers and micro-lens mode transformers[1,2]. A better option to effectively couple light in this situation is by incorporating a waveguide section that is tapered vertically, as well as laterally between the fiber and the waveguide. This tapered section acts as a classic adiabatic modal transformer [3,4,5,6] that transforms the input fundamental mode shape to that of the waveguide mode.

In this paper, theoretical predictions of coupling loss between optical fibers and rib-loaded SOI waveguides with lateral only (1-D) and combination of lateral and vertical (2-D) tapers are presented. The fabrication process of rib-loaded SOI waveguides down to 0.75μm size with the tapers is discussed and the measured coupling losses are compared to those predicted by theory. Measured coupling loss values for waveguides with 2-D tapers show significant improvement (~1.8dB) over those for waveguides with 1-D tapers (~4dB) or no tapers (~8dB). There is excellent agreement between measured and calculated coupling loss values.

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6124-01, Session 1

Optical components and subsystems: opportunities and challenges

J. Hong, Oplink Communications, Inc.

The current trend in optical components and subsystems will be briefly reviewed. The opportunties and chanllenges will be discussed.

6124-02, Session 1

Semicustom OEIC implementation in an optical networking DWDM system

C. M. Look, J. J. Maki, A. P. Aitken, Intellambda Systems, Inc.

Optical communication systems have evolved from simple point-to-point transmission systems in the late '70's to today's multi-channel DWDM systems integrated with optical switching. These advanced DWDM systems have very stringent optical performance, system reliability, and cost requirements. As a result, deployment of these systems has been limited to date. This situtation has started to change recently and a lot of industry interest is now focused on deploying advanced optical systems in high performance telecommunication environments. Integrating optical functions in a single Optoelectronic Integrated Circuit (OEIC) has the potential to accelerate this deployment by reducing manufactured costs, reducing physical card size, and increasing reliability.

This talk will describe a specific instance of a DWDM transport and optical switching system, and its functional decomposition into individual cards. The requirements that are then imposed on the optical components placed on these cards are described. We will show the function of advanced switching and optical monitoring. Initial validation of a system card was made using off-the-shelf discrete optical components and then replaced with an OEIC implementation. Results of the integration experience will be presented.

6124-03, Session 1

Integrated Optoelectronic Materials, Devices, and Systems

D. V. Plant, McGill Univ. (Canada)

By utilizing a heterogeneous materials approach, we propose to develop enabling technologies required to support integrated photonic/electronic devices that use dielectrics and SOI for waveguiding (on-chip optical wiring) and III-V compound semiconductors for light generation, amplification, and switching. Further, we propose to integrate these waveguide/III-V structures onto CMOS electronics thereby creating a generic platform capable of meeting a vast assortment of applications needs.

6124-04, Session 1

Nanophotonics for integrated information systems

Y. Fainman, U. Levy, Univ. of California/San Diego

Optical technology plays an increasingly important role in numerous information system applications, including optical communications, storage, signal processing, biology, medicine, and sensing. As optical technology develops, there is a growing need to develop scalable and reliable photonic integration technologies. These include the development of passive and active optical components that can be integrated into functional optical circuits and systems, including filters, electrically or optically controlled switching fabrics, optical sources, detectors, amplifiers, etc. We explore the unique capabilities and advantages of nanotechnology in developing next generation integrated photonic information systems. Our approach includes design, modeling and simulations of selected components and devices, their nanofabrication, followed by validation via characterization and testing of the fabricated devices. The latter exploits our recently constructed near field complex amplitude imaging tool. The understanding of near field interactions in nanophotonic devices and systems is a crucial step as these interactions provide a variety of functionalities useful for optical systems integration. Furthermore, near-field optical devices facilitate miniaturization, and simultaneously enhance multifunctionality, greatly increasing the functional complexity per unit volume of the photonic system. Since the optical properties of near-field materials are controlled by the geometry, there is flexibility in the choice of constituent materials, facilitating the implementation of a wide range of devices using compatible materials for ease of fabrication and integration.

6124-05, Session 2

Microphotonics: hardware for the information age

L. A. Eldada, DuPont Photonics Technologies

We present the findings of a 5-year industry consortium at MIT studying OEICs. One of the main outcomes of this program is a 25-year communications technology roadmap focusing on optoelectronic integration. We describe the roadmap and present recommendations to the industry.

6124-06, Session 2

Challenges and opportunities for integrated optics in computing systems

M. A. Taubenblatt III, IBM Thomas J. Watson Research Ctr.

The confluence of highly integrated computation chips, huge off-chip interconnectivity requirements, increasingly high channel speeds, and the large spatially extended systems being considered for future high end servers together with the looming issues of thermal and power management offer an opportunity for optical interconnects to become the preferred solution for many interconnect domains. To achieve this status for link distances less than one meter will require increasingly integrated optical interconnect solutions, which presents many challenges as well as opportunities. This talk will present some of the key challenges and metrics for optics to meet in this short distance regime along with solutions which IBM is pursuing.

The incumbent technology, PCB based electrical interconnects, have continued to offer a cheaper and more mature solution through continued advances in electrical signaling rates, utilizing ever cheaper and higher performance chip technology and improved packaging technology. The optical equivalent, an optical waveguide based PCB, is a potential challenger. Recent results on IBMís Terabus program [DARPA funded] will be presented, which has the goals of achieving up to 20Gbps data rates with under 5mW/Gbps power consumption in an ultra-dense on card optical wiring format (62.5um pitch).

OEICís present an opportunity to extend this paradigm even further by aggregating optical functionality onto single low cost chips, and including new capabilities such as optical switching, but only if they can further the advantages of optics relative to the electrical competition. Some examples of metrics and challenges for these OEICís will also be discussed.

6124-07, Session 2

Waveguide and packaging technology for optical backplanes and hybrid electrical-optical circuit boards

H. Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

The need for optical interconnects is increasing and asking for new technological solutions. For future generations of data- and tele-communication this development is strongly driven by the permanent growing demand for higher data rates and increasing performance but also for higher interconnection density and low thermal budgets. Some international roadmaps were surveyed and most important technologies were reviewed to give an outlook to the technology crossover.

Glass and polymer optical waveguides can be packaged with opto-electronic components on the packaging level of modules, PCB and backplane. Polymer waveguides are for example made by hot embossing or photolithography and glass waveguides in thin glass foils by ion exchange. Such concepts, which are based on a hybrid electrical and optical carriers containing both electrical and optical interconnects will be presented as well as experimental results. The key element is an additional optical layer with multimode waveguide structures. This layer is handled by standard PCB technology. In the resulting board, the waveguides are completely incorporated into the circuit board.

To achieve this it is necessary that materials and processes are compatible with each other. Because multimode structures for the waveguides are used the assembly tolerances can be handled. An important aspect is the interface to common SMD technology. That is to say, that the concept can merge with current methods of manufacturing commercial equipment. For that concept special coupling components have been designed and will be presented.

6124-08, Session 3

Fabrication and integration of micro/nano-scale optical waveguides and photonic devices for application specific planar optical integrated circuit board

E. Lee, Inha Univ. (South Korea)

(Submitted to be considered as an invited talk.) We present, in the form of review and overview, new results and progresses of our work on the design, fabrication and integration of micro/nano-scale optical waveguides and photonic devices for planar optical printed circuit board (O-PCB) and VLSI micro/nano-photonic applications. The O-PCBs are to perform the functions of sensing, transporting, switching, routing and distributing optical signals on flat modular boards in a manner similar to the electrical printed circuit boards (E-PCBs). They are to offer new functions and merits of high speed, compactness, light-weight, energy saving, and portability that can overcome the limitations of E-PCBs. For waveguides we use polymers. Photonic devices that are optically integrated on O-PCB include vertical cavity surface emitting lasers (VCSELs), sensors, couplers, power splitters, wavelength splitters, wavelength filters, arrayed waveguide grating devices, multimode interference devices, micro-ring/racetrack resonator devices, photonic crystal devices, and plasmonic devices in micro-scale and nano-scale. We describe the fabrication and integration processes of these devices and the O-PCBs in detail and report on their performance characteristics. We also discuss scientific and technological issues of using the integrated optical micro-circuits and boards for VLSI micro/nano-photonic applications, computers, telecommunications, transportation systems, and for avionic and satellite systems.

6124-09, Session 3

Chalcogenide glass waveguide devices for high-speed all-optical signal processing

D. J. Moss, The Univ. of Sydney (Australia)

We present an overview of the research program at CUDOS on integrated ultrahigh speed nonlinear optical signal processing devices based in chalcogenide glass waveguides. This includes work based on integrated waveguides and waveguide Bragg gratings, as well as chalcogenide glass based photonic crystal waveguide devices.

6124-10, Session 3

An extended long-range surface-plasmon-polariton waveguides

S. Song, H. Won, K. Kim, Hanyang Univ. (South Korea)

Rapid developing of the information technology demands highly integrated optical circuits. Miniaturization of optical components is one way to increase the density of optical integrated circuits by adopting photonic crystal structures, high refractive-index dielectrics, metal-dielectric hybrid waveguides, and purely metal wires embedded in dielectric. In particular, the metal wires which support long-ranging surface plasmon polaritons(LR-SPP) are intensively studied because such metal waveguides can also carry electrical signals modulating the LR-SPP mode. Propagation loss of about 3 dB/cm has been demonstrated at telecomm wavelength by using a 20 nm thick, LR-SPP metal waveguide embedded in a silica substrate.

In order to reduce the propagation loss down to further less than 1.0 dB/cm, we propose an extended LR-SPP scheme composed of vertically coupled, two metal waveguides. By adjusting gap distance and dielectric constant of the layer between the two waveguides, we can improve propagation distance of SPP waveguides at least one order of magnitude longer than that of a single LR-SPP metal waveguide. It should be noted that mode size of the extended LR-SPP waveguides is still comparable with the single-mode fiber, therefore, butt-coupling loss to fiber remains very small.

We present some results of evaluation in theory and experiment on mode profiles and dispersion relations of extended LR-SPP modes supported by two vertically coupled metal waveguides, based on gold as the metal strips and photopolymers as the dielectric materials. The extended LR-SPP waveguides proposed here may be one of promising approaches to be able to implement low-loss metal waveguides for optoelectronic integrated circuits and optical PCBs.

6124-11, Session 3

Photonic crystal nanosecond wavelength switches

R. O. Miller, D. V. Tsu, Energy Conversion Devices, Inc.; J. A. Reed, Science Applications International Corp.

We present our design and fabrication methodology of planar photonic crystal wavelength switches and the optical micro-bench surrounding them. The core device is a channel add-drop multiplexer (CADM) whose pass/transfer element can be turned off and on in tens of nanoseconds. The photonic crystal consists of a regular triangular array of SiO2 -filled holes in an amorphous Ge3Si film. The film is sandwiched between two SiO2 cladding layers. The pass and transfer buses consist of linear extended defects in the crystal, with the pass bus and each drop bus separated by a cavity resonator defect tuned to each wavelength. There is a small region where an ECD-designed chalcogenide alloy is incorporated into each resonator. Switching is accomplished by changing the structure of the chalcogenide between amorphous and crystalline, using a short wavelength diode laser. The optical bench consists of photonic wire waveguides formed in the Ge3Si film and deep trenches in an underlying thick SOI film to accommodate bonded access fibers, both features be-

ing photolithographically co-aligned to the photonic crystal array. This, along with our impedance-matching interface designs, assures that there is low input-output power loss. The local reconfigurability in effect elevates the CADM to an all-optical router. Sub-100 nanosecond latency enables packet-level discernment. The large difference in optical constants of the two chalcogenide phases provides high on-off contrast (low crosstalk). The stability of the two phases gives complete latching nonvolatility. Our current progress in building and testing prototypes of our switches is also presented.

6124-12, Session 4

Design optimization of high-speed optical modulators

A. B. M. Rahman, City Univ. (United Kingdom); S. Haxha, Univ. of Kent (United Kingdom); V. Haxha, K. T. V. Grattan, City Univ. (United Kingdom)

Optical modulators are key components for todayís optical communications systems. High-speed modulators predominantly exploit fast electro-optic effects and are mostly constructed using GaAs, InP, or LiNbO3 crystal materials and more recently polymer materials have also been considered. In the development of low-voltage modulators, the key design parameter is the product of the half-wave voltage and the device length, VpL. To reduce this parameter, the highest electro-optic coeffeicents, rij, need to be exploited by using the correct crystal orientation and by enhancing the overlap between the optical and modulating fields.

The bandwidth of a high-speed optical modulator with a travelling-wave electrode is primarily limited by the velocity mismatch between the optical carrier wave and the modulating microwave signal. For high-speed modulators, when phase velocity matching is achieved, the next limiting factor is the overall microwave propagation loss. At lower operating frequencies, the electrode conduction loss, ac, dominates; however, as the operating frequency is extended beyond 40GHz, increasingly dielectric loss, ad, is expected to play an important role in the bandwidth of the devices. In practical applications, if the characteristic impedance of the electrode, Zc, is not matched to the external source impedance, the performance of a high-speed modulator will also be affected. Finite element-based numerical methods have been developed to analyse both microwave[1] and optical wave[2] propagation characteristics and to calculate the key design parameters such as the VpL and the bandwidth of the optical modulators.

In the development of a high-speed modulator, directional coupler-based designs[3] can be used, but Mach-Zehnder-based [1] devices are more efficient. In the Mach-Zehnder-based design, the optical power spliiter can be implemented by using a half-length directional coupler or a Y-branch splitter; however, more recently a more compact design based on the MMI principle is increasingly being considered. The design of compact bends to reduce the overall chip size or the incorporation of a spot-size converter to reduce the insersion loss are also key issues for modulator systems. Rigorous numerical methods are required to design both the optical and micorwave properties of such guides, besides the design of compact bends, power splitters and spot-size converters.

The powerful, versatile, accurate and numerically efficient finite element based computer programs have been developed[2,1] to study the effects of various fabrication parameters, such as the waveguide height, waveguide width, buffer thickness, metal electrode thickness, electrode width and the separation between the guides, on the optical parameters, such as VpL and the optical bandwidth. These are presented for deep-etched GaAs[4], etched LiNbO3[1] and rib-type polymer electro-optic modulators.

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6124-13, Session 4

Extraction of orthogonal incident state of polarization spectra using Mueller matrix approach

É. Desfonds, K. Pimenov, MetroPhotonics Inc. (Canada); M. Crawford, dBm Optics, Inc.

Many challenges not typically seen in the testing of discrete components must be tackled to fully characterize integrated optics components. For example, DWDM optical power monitors require accurate calibration of the absolute responsivity spectrum of each of its channels across large wavelength spans. This can be a challenge for integrated optics, merging the demultiplexing and detection functionalities into a single device.

Extremes of responsivity at each wavelength step, obtained using a fixed-states method for polarization dependent loss (or responsivity) measurement and extracted Mueller matrix terms, are useful to ensure accurate calibration and screening of device performance.

Yet, for design and manufacturing purposes, the extraction of the spectra of said DUT under excitation from orthogonal incident TE and TM states of polarization is more appropriate. Novel algorithms based upon these Mueller matrix terms and associated Mueller calculus are presented herein which allow the recovery of the spectra for incident TE and TM orthogonal states of polarization. These, in turn, yield polarization-dependent frequency shifts and other polarization-dependent parameters for the overall response of the DUT.

These Mueller matrix-based techniques and algorithms are shown to be more efficient and accurate than PM-fiber rotation and other polarization scrambling-based techniques and still allow for the evaluation of the DUT performance and corresponding spectrum at any fully polarized incident state. They greatly help the root-cause analysis efforts of component designers as well as allow monitoring of any impact from manufacturing steps throughout the production lifetime of an integrated optic device.

Computationally intensive PoincarÈ sphere sampling algorithms, based on the evaluation of different performance parameters and extraction of extremes of said parameters, are compared to a novel eigenvalue-solving algorithm aimed to maximize the spectral difference between known orthogonal incident states of polarization. These resulting spectra are considered analogous to the spectra of eigenmodes obtained through Jones matrix based instrumentation, without the required knowledge of the incident and output states of polarization, nor the expense of two polarimeters. This further allows the use of said algorithms with optical-in-electrical-out integrated optical devices alongside Mueller-matrix based equipment.

This elegant patent-pending solution, based on eigenvectors and eigenvalues, involves little computational efforts and has significantly improved the testing capacity and capabilities of the Test and Measurement group of MetroPhotonics Inc. They have been used for other types of planar-lightwave circuitry for enhanced characterization of individual integrated optics building blocks or overall response of the DUT, which exhibits orthogonal dependence to the incident polarization, in a TE/TM-like fashion.

6124-14, Session 4

Stydy on the group velocity anomaly in the photonic band gap crystals and it's applications

H. Noh, B. O, S. Lee, K. H. Kim, E. Lee, Inha Univ. (South Korea)

Photonic crystals have drawn much attention owing to their ability of pho-

ton control. Especially, the existence of the photonic band gap opens various application areas . Another example is the group velocity anomaly that is realized in all 2D and 3D crystals. The small group velocity implies that the interaction time between the radiational mode and the matter system is long. This leads to a large effective coupling between them, and various optical processes are enhanced. In this paper, we investigate the time delay on light propagation caused by the group velocity anomaly in the various type photonic band gap crystals and suggest their applications to optoelectronic devices.

6124-15, Session 4

Analysis on planar-type long-period gratings for wavelength tuning filters

K. H. Kim, D. Lee, E. Lee, Inha Univ. (South Korea)

This paper reports a numerical analysis on temperature dependent performances of planar-type long period gratings (LPGs) for a thermally tunable wavelength filter. The optimum waveguide parameters as well as the grating parameters for thermally tunable filters of a four-layer geometry have been evaluated. The polarization dependent properties depending on the refractive index variation and the thermal expansion coefficient of the waveguide materials have been also analyzed.

6124-16, Session 4

Broadband InAs/InGaAlAs dot-in-well superluminescent diode

C. E. Dimas, H. Susanto Djie, B. Ooi, Lehigh Univ.

The optical characterization of an integrated multiple-electrode broadband superluminescent diode (SLD) fabricated on an InAs/InGaAlAs dot-in-well structure will be presented. The dot-in-well structure consists of four layers of InAs quantum dots embedded in InGaAlAs quantum wells grown on an InP substrate using a molecular beam epitaxy (MBE) system. The device consists of two sections of 4 micron rib waveguide emitters butt-coupled with a 50 micron wide broad area photon absorber for oscillation suppression. A spectral bandwidth as broad as \>100 nm, centered at 1620nm, has been measured from non-facet coated devices at 15 degrees Celcius with the emitter section at 30 mA operating in continuous wave. Under these measurement conditions, the SLDs yield a spectral modulation of ~0.04 dB. The spectral bandwidth is comparable with other quantum-dot based SLDs. However, a substantially lower ripple modulation has been observed in our case, resulting from a more efficient feedback oscillation design. The electroluminescence bandwidth of the SLD is expected to increase substantially by spatially modifying the bandgap of the front emitter section using selective quantum-dot intermixing technique. Such compact, robust, low coherent light sources have important applications in optical sensors, metrology, and instrumentations.

6124-58, Session 4

Experiment and modeling of tilted mirror MEMS variable optical attenuator

C. He, Alliance Fiber Optic Products Inc.

No abstract available

6124-17, Session 5

WDM package enabling high-bandwidth optical intrasystem interconnects for high-performance computer systems

J. Schrage, Siemens AG; Y. Soenmez, Cooperative Computing & Communication Lab.

From long haul, metro access and intersystem links the trend goes to applying optical interconnection technology at increasingly shorter distances. Intrasystem interconnects such as data busses between microprocessors and memory blocks are still based on copper interconnects today. This causes a bottleneck in computer systems since the achievable bandwidth of electrical interconnects is limited through the underlying physical properties. Approaches to solve this problem by embedding optical multimode polymer waveguides into the board (EOCB technology) have been reported earlier. And the principle feasibility of optical interconnection technology in chip-to-chip applications has been validated in a number of projects. For reasons of cost considerations waveguides with large cross sections are used in order to relax alignment requirements and to allow automatic placement and assembly. On the other hand the bandwidth of these highly multimodal waveguides is restricted due to mode dispersion.

However, the advancement of WDM technology towards intrasystem applications will enable sufficiently high bandwidth required for future high-performance computer systems: Assuming for example 8 wavelength with 10Gbps each, optical on-board interconnects with data rates a magnitude higher than the data rates of electrical interconnects for distances typically found at computer boards can be realized.

In this paper we present an approach for an advanced hybrid integrated optoelectronic WDM package that will be used to apply WDM technology to Electro-Optical Circuit Boards (EOCB).

6124-18, Session 5

Challenges for the introduction of board-level optical interconnect technology into product development roadmaps

C. Berger, IBM Corp. (Switzerland)

Optical interconnects have gradually replaced electrical interconnects in the long-distance telecom, local-area, and rack-to-rack link classes. We believe that this transition will also have to happen in the card-backplane-card datacom link class in the near- to mid-term future, both for bandwidth*length reasons and for density reasons (especially at bottlenecks such as the card-backplane interface).

In analogy to the transition from individually wired boards to integrated printed circuit boards, we believe that early optical card-backplane-card solutions will use technologies based on individual fibers (as already available on the market), but that eventually board-level optical interconnects will be based on an integrated technology such as board-embedded waveguides.

In order to bring optical waveguide technology into mainstream product development plans, however, numerous challenges on many levels have to be met. Problems to be tackled span from the base level of materials (stability, processability) and devices (reliability, lifetime), over the subsystem level of packages (concepts, cost-efficient assembly and alignment) all the way up to the system level (link architecture, system packaging, heat management). A sustainable solution can only be reached if the development of all individual technology components is done with the whole system in mind. Important figures of merit are the cost per gigabit per second, the power per gigabit per second, and the reliability of the technology.

We will give an overview of our optical interconnect activity, with respect to these challenges. We will discuss our approaches, explain some of our technology decisions and present experimental results of our multi-disciplinary activity.

6124-19, Session 5

Speeding up multiprocessor machines with reconfigurable optical interconnects

W. Heirman, Univ. Gent (Belgium); I. Artundo, L. Desmet, Vrije Univ. Brussel (Belgium); J. Dambre, Univ. Gent (Belgium); C. Debaes, H. Thienpont, Vrije Univ. Brussel (Belgium); J. M. Van Campenhout, Univ. Gent (Belgium)

Electrical interconnection networks connecting the different processors and memory modules in modern large-scale multiprocessor machines are running into several physical limitations. In shared-memory machines, where the network is part of the memory hierarchy, high network latencies cause a significant performance bottleneck.

Parallel optical interconnection technologies can alleviate this bottleneck by providing fast and high-bandwidth links. Moreover, new devices like tunable lasers and detectors or MEMS mirror arrays allow us to reconfigure the network at runtime in a data transparent way. This allows for extra connections between distant node pairs that communicate intensively, achieving a high virtual network connectivity by providing only a limited number of physical links at each point in time.

In this paper, we introduce available low cost components that will enable us to build such a reconfigurable network and identify the limitations they impose on network performance. We show, through detailed simulation of benchmark executions, that the proposed network can provide a significant speedup for shared-memory machines, even with the described limitations.

6124-20, Session 6

2D parallel optical interconnects between CMOS ICs

O. Rits III, K. Naessens, R. Bockstaele, R. Baets, Univ. Gent (Belgium)

As data rates inside digital electronic systems increase, the bandwidth of electrical inter-chip interconnects increasingly suffers from signal distortion, cross-talk and limited pin-out capacity. Optical interconnects are considered as viable alternatives for these copper wires. The standard approach for implementing such optical inter-chip links is to place dedicated electro-optical conversion chips next to each corresponding CMOS chip. This approach however still requires the difficult routing of a high number of high-speed electrical interconnects from one chip to another over some kind of substrate trhough a limited area. To meet the demand for increasing number of high-speed inter-chip channels, we believe it is better to bring the optical interconnects all the way down to the CMOS chip itself. In this paper we present an optical interconnect demonstrator in which parallel 2-D arrays of fibers directly interconnect digital CMOS ICs, with flip-chip mounted VCSEL and detector arrays and with the analog driver and receiver circuits integrated in the digital design. We will also present novel approaches for the optical interface to the CMOS package, where the optical alignment of the different arrays of optical components is critical. Finally we will demonstrate the implemented 2-D parallel optical interconnects with direct on-chip optical access.

6124-21, Session 6

High-density parallel optical interconnection for 10Tbps interconnection in high-speed memory test systems

T. Okayasu, D. Watanabe, A. Ono, Y. Hayase, Advantest Corp. (Japan); H. Mori, T. Nomura, The Furukawa Electric Co., Ltd. (Japan)

With rapid evolution of the semiconductor process, the operating frequency and capacity of memory devices improve every year. Specifically, high-speed memory devices such as DDR-SDRAM, SGRAM, and Rambus DRAM have I/O speeds of several Gbps. For high-speed memory test systems to test these high-speed memory devices, a higher test rate and more test channels are demanded.

The total amount of data to be processed in a memory test system is proportional to the product of the test rate and the number of channels. Because the total amount of data tends to increase rapidly, required data transfer throughput inside memory test system will exceed a range of Tbps. The physical limit of the cable quantity, the number of connector pins or the number of LSI used in the test system will be reached making the transmission bottleneck a serious problem.

To solve this transmission bottleneck, we developed a protocol-free parallel optical interconnecting module capable of transmitting from DC to 34.1 Gbps (4.267 Gbps x 8 ch) with ultra-thin multi-fiber optical connectors and a high-density flexible optical fiber cable suited for high-density optical interconnection in high-speed memory test systems. Random jitter of the whole transmission system < 3ps (RMS) is achieved. The module size is the 11.0 mm (Width) x 23.0 mm (Length) x 4.6 mm (Height). Data transmission throughput density per unit volume of 19 Gbps/cc is achieved.

And also, we will describe the manufacturing process, the module testing, and self-diagnosis for optical transmission system.

6124-22, Session 6

A scaleable optical interconnect for low-latency cell switching in high-performance computing systems

M. Sauer, B. R. Hemenway, R. R. Grzybowski, Corning Inc.

The ever growing demand for high-performance computing (HPC) enabled by massively parallel systems requires large-scale, high-bandwidth, and low-latency interconnection networks. An optically cell-switch based solution for interconnecting massive-parallel nodes offers the potential for reduction in size, power consumption and cost of such switches. We designed an architecture based on a broadcast and select approach that is highly flexible in terms of supported ports and can easily scale from a 16x16 to a 2048x2048 switch by exploiting both wavelength multiplexing and fiber multiplexing[1]. For increasing the node number to very high counts, a fat tree architecture can be applied. A key design feature is low latency even under high load and in a high port count solution (N \> 1024), which for our design is under 1 μs in a very large switch. The optical system is designed for 40 Gb/s operation, but full 160 Gb/s switching can be supported by the architecture for future systems with very high data rate demands.

At the core of the switch is an array of semiconductor optical amplifiers (SOAs), which provide fast switching (~1ns), high extinction ratio (\>40 dB) for cross-talk reduction, and optical gain (15 dB typical) to overcome optical component losses. They additionally offer excellent integration potential for ultra-dense packaged solutions integrated with other optical functionalities like wavelength multiplexing. The full optical switch consists of a 2-stage broadcast and select design for (i) fiber select and (ii) color select. By this way, a bufferless low-latency crossbar cell switch could be implemented. The optical switching is steered by a fast arbiter with an efficient control path design that focuses on efficient and fast contention resolution to support the low-latency requirement for the overall switch [2].

A switch system demonstrator with 8 full optical paths has been implemented and used for performance characterization. Based on 40 Gb/s EAM laser-integrated modules as transmitters and taking a worst case design into consideration (i.e. PDL of components, gain flatness, loss uniformity, etc.), the required optical dynamic range was determined to be 5 dB. A fast 40 Gb/s packet receiver was developed which was proven to support at least this dynamic range (up to 9 dB measured). Since the data cells are 2048 bits long (51.2 ns including switching time, pre-amble, header information, and payload), a very fast switching time with error-free detection of the data payload (~5 ns between critical data bits) is important and was a key requirement for component choices and overall design. Due to the nature of the system with massively parallel transmission, a very high bit error ratio (BER) requirement of significantly better than 10-17 is important. This is enabled by a specially designed forward-error correction (FEC) algorithm for very short data packets. Single bit errors can be fully corrected, which requires a raw bit error ratio of ~10-10. The system demonstration measurements have shown that a raw BER of 10-15 is achievable due to the relatively high OSNR of better than 33 dB and low distortion due to other system components. The cell switching experiments have shown that optical cross-talk is negligible and does not degrade the system performance.

Overall, an excellent optical performance with error-free transmission under full switching could be demonstrated. A large-scale 64x64 40 Gb/s switch

is currently being built and will be operational shortly. Measurements with this system will include full arbitration and results will be given in the full paper and presented at the conference. The system design and verification experiments demonstrate that a scaleable 40 Gb/s switch for massively parallel systems is feasible and offers the potential for significant size, power consumption, and cost reduction by applying the scalability of an optical solution to a HPC system.

1 R. Hemenway, R. Luijten, R. Grzybowski, C. Minkenberg, M. Sauer: "A scaleable optically switched interconnect for high performance digital systems", IEEE/LEOS 16th Annual Workshop on Interconnections, Santa Fe, NM, May 2005

2 C. Minkenberg, . Abel, P. M¸ller, R. Krishnamurthy, M. Gusat: "Control Path Implementation for a Low-Latency Optical HPC Switch", 13th Annual IEEE Symposium on High Performance Interconnects, Stanford university, CA, August 2005

6124-23, Session 7

Scaling VCSEL performance up to 250Terabits/s of system bandwidth

J. E. Cunningham, A. V. Krishnamoorthy, Sun Microsystems

There continues to be strong interest in scaling servers as High Productivity Computers in order to meet the growing computation demand generated within industry and military segments. Such HPC systems require sophisticated architectures for optimizing an increased number of processor-memory units, lower latency signaling between chips, and larger system bisection bandwidths for communication. Currently, the top ten HPC systems have bisection bandwidths between 1 and 10Tbps and next-generation systems are looking for 100X improvements in bandwidth. To meet next-generation applications a significant increase in optical interconnection capacity would be required. However, this would necessitate vast numbers of optical modules and fiber optic cables. In the present work we report our investigations that evaluate VCSEL based interconnects for meeting the challenge of providing 250Tbps of bandwidth.

We present results for VCSEL based links operating Pulse Amplitude Modulation PAM-4 signaling using a commercial 0.13μm CMOS technology. Multilevel signaling as a means for increasing data rates in electrical backplanes has been widely explored to overcome frequency dependent media losses. Likewise, mitigation of ISI penalties for dispersive fiber for optical links would be one advantage. We perform a complete link analysis of the Bit Error Rate, Q factor, random and deterministic jitter and sensitivity by measuring waterfall curves versus margins in time and amplitude. We demonstrate that VCSEL based PAM -4 can match or even improve performance over binary signaling under conditions of bandwidth limited link conditions at 5Gbps. This enables the first complete comparison between PAM-4 and binary optical signaling. Our goal is to determine the optimal signaling method for a given optical link that takes into account the optical medium, the timing margins, link bandwidth, and the optical device reliability.

We also evaluate VCSEL reliability for next-generation High Productivity Computers in which several hundreds of terabits of bandwidth are envisioned. An empirical relationship for VCSEL scaling versus bit rate and aperture is presented in order to explore reliability of VCSEL-based links. Reliability is found to degrade with aperture with a fourth order power law dependence. VSCEL sparing, water-cooling and redundancy though percentage of link failures are analyzed.

6124-24, Session 7

High-speed integrated transceivers development for short reach communications

S. M. Deliwala, B. Omara, M. K. Emsley, J. Yasaitis, C. Roberts, E. Gleason, J. Steigerwald, B. Scharf, Analog Devices, Inc.

In the near future, optical communication links are likely to be found at many distance scales-from hundreds of km to hundreds of microns. At Analog Devices Inc. we are focused on bringing the advantages of the optoelectronic integration for high speed communication in the distance range of 1 meter to 1 km. Analogís approach to the integration challenge will be discussed with emphasis on the compatibility of active and passive integrated optoelectronic devices that work with both single mode and multimode fibers.

6124-25, Session 7

Highly Reliable High Power Optical Amplifiers at 1.55 um

T. H. Wood, Lucent Technologies/Bell Labs.

A variety of new applications require High Power Optical Amplifiers (HPOAs) that operate with very high reliability over periods on the order of 10 years. We will discuss our multistage designs based on cladding-pumped Er/Yb co-doped fibers. Truly single-mode output at \>10 W optical power levels are achieved. Both Polarization-Maintaining (PM) and non-PM HPOAs have been demonstrated.

6124-26, Session 7

Hybrid integration of a CMOS active quench and reset circuit and a geiger-mode avalanche photodiode

D. Cronin, A. P. Morrison, K. McCarthy, National Univ. of Ireland/Cork (Ireland)

An active quench and reset circuit (AQRC) is an essential control circuit for ensuring high-speed photon counting with geiger-mode avalanche photodiodes (GMAPs). It turns off the detector when an avalanche event occurs, increments a counter and then resets the device to its quiescent voltage after a preset interval, to enable detection and counting of further avalanche events. This paper presents the design, operation and testing of a novel AQRC-IC fabricated on Austria-Microsystems' 3.3 V 0.35μm CMOS process through Europractice's ASIC Service - the most advanced technology used to date for integrated AQRCs. The design achieves a high-speed compact CMOS AQRC for hybrid integration with GMAPs previously developed. This includes a ballast resistor for the external GMAP, a novel comparator sensing-stage, an active quench and an active reset. The hold-off time is determined using external silicon delay lines and an FPGA but a future fabrication will incorporate these elements in a full AQRC design.

The prototype is implemented using a ceramic DIP for the GMAP and the ASIC, leading to a saturated count-rate of 5 Mcounts/sec, an active quench of 35 ns, an active reset of 18 ns and selectable hold-off increments between 50 ns and 500 ns. As the ASIC is suitable for flip-chip or wirebonding, further improvements on these results are expected with implementation of such packaging technologies to significantly reduce parasitic effects between the GMAP and the ASIC and hence minimise the main detriment to the maximum achievable count-rate of the current AQRC prototype.

6124-27, Session 7

Integrated photon counting gain and bias control system

D. O'Connell, A. P. Morrison, National Univ. of Ireland/Cork (Ireland); J. C. Jackson, SensL Technologies Ltd. (Ireland)

This paper describes the integration of an automatic gain and bias control circuit for avalanche photodiodes into the Sensl PCMPLusX photon counting module. The combination is a self contained module with integrated sensor, power supply, cooling and full microprocessor control system. The sensors can be configured remotely via a PC enabling the user to optimise the sensor performance for a particular application. The system has four channels which can configured either in photon counting mode or gain control mode. With the photon counting module the user can optimise detector characteristics such as quantum efficiency, dark

count, amplification and operating temperature for specific applications. With the gain control module the gain of the photodiode can be set to a desired value by setting the reverse bias voltage of the device to the correct level. A feedback system is used to monitor the gain of the photodiode and the bias voltage can be adjusted intermittently to take into account variations in reverse high bias voltage supply. The gain control module can incorporate a number of photodiodes and is not limited to the PCMPLusX integrated photodiode technology. This solution allows the user to program the sensor to a desired multiplication gain factor and for the circuit to automatically adjust for fluctuations in supply voltage.

6124-28, Session 8

Increased functionality in Si-wire photonics

R. M. Osgood, Jr., Columbia Univ.

Increased Functionality in Si-Wire Photonics

This talk will describe our project to develop new functionality in Si wire photonics waveguides.

6124-29, Session 8

3D integration of sub-surface photonics with CMOS

B. Jalali, T. Indukuri, P. Koonath, Univ. of California/Los Angeles

The integration of photonics and electronics on a single silicon substrate requires technologies that can add optical functionalities without significantly sacrificing valuable wafer area. To this end, we have developed an innovative fabrication process, called SIMOX 3-D Sculpting[1], that enables monolithic optoelectronic integration in a manner that does not compromise the economics of CMOS manufacturing. In this technique, photonic devices are realized in sub-surface silicon layers that are separated from the surface silicon layer by an intervening SiO2 layer (Fig.1). The surface silicon layer may then be utilized for electronic circuitry. SIMOX 3-D sculpting involves (1) the implantation of oxygen ions into a patterned silicon substrate followed by (2) high temperature anneal to create buried waveguide-based photonic devices. This process has produced subterranean microresonators with unloaded quality factors of 8000 and extinction ratios \>20dB[2]. On the surface silicon layers, MOS transistor structures have been fabricated (Fig. 2). The small cross-sectional area of the waveguides lends itself to the realization of nonlinear optical devices. We have previously demonstrated spectral broadening and continuum generation in silicon waveguides utilizing Kerr optical nonlinearity [3]. This may be combined with microresonator filters for on-chip supercontiuum generation and spectral carving, as shown in Fig.3. The monolithic integration of CMOS circuits and optical modulators with such multi-wavelength sources represent an exciting objective for silicon photonics.

6124-30, Session 8

Photonic crystals and silicon photonics

C. Wong, Columbia Univ.

Recent important advances in subwavelength nanostructures offer extraordinary control over the properties of light. We can now manipulate the propagation, storage, and generation of light, as well as practically prescribe its matter interaction properties based on first-principles. Photonic crystals, in particular, offer the unique ability to achieve ultrahigh Q/V nanocavities, and the arbitrary control of dispersion characteristics to increase photon-matter interaction times. In addition, silicon photonics offer the unique opportunity towards the convergence of electronics and photonics in a monolithic silicon platform for unprecedented information processing capacity. In this talk, we will review critical advances in these arenas, as well as present our developments in fundamental and applied studies of optics in subwavelength nanostructures.

6124-31, Session 8

Laser direct molding of good-quality silicon nanostructure for photonic integration

E. Liang, Z. Huang, C. Kuan, C. F. Lin, National Taiwan Univ. (Taiwan)

Laser direct molding is a convenient tool to fabricate nanostructures on silicon. In addition to the advantage of simple process steps, we demonstrate that it has low-damage to the molded silicon nanostructures. This prevents optical devices from efficiency degradation since crystal quality is preserved. Therefore it is promising to simultaneously integrate silicon-based light-emitter, photonic crystal components, detectors, sensors, and other photonic components onto one substrate by the same fabrication technique.

Here we present laser direct molding to fabricate good-quality silicon nanostructures. In the first place, a quartz pattern has to be carefully fabricated. A tri-layer process of electron-beam-lithography is used to circumvent charging problem and to reduce dosage interference due to high the resistivity of quartz. A conductive polymer, e-beam resist, and Si underlayer is used. Spot patterns down to 25nm feature size with 50nm pitch are produced.

Three factors are important in the laser direct molding experiments. First, laser intensity around 0.8~2J/cm2 is critical to ensure silicon single-crystalline recrystallization. Second, quartz and silicon has to be mechanically pressed by 10~100 g/cm2 force to overcome the viscosity of molten silicon. Third, the process chamber ambient is pumped to base ambient pressure of 10-6 torr to prevent from oxidation. Using KrF excimer laser with 25ns duration, high vacuum prevent oxidation of silicon and reduces Si-O-complex defect diffusion. This results in small change of surface recombination velocity in molded Si nanostructures down to 56cm/s. Compared with SRV change of 1500cm/s after dry etch, it does preserve good crystal quality of Si.

6124-32, Session 9

Organics in optoelectronics: advances and roadmap

L. A. Eldada, DuPont Photonics Technologies

Optoelectronic components based on organic materials have met the highest performance requirements and reliability standards in the photonics industry. We describe advances in organic optoelectronic integrated circuits, and present a two-decade roadmap for this field.

6124-33, Session 9

The optical performance of perfluorocyclobutyl based fluoropolymers and waveguides

J. M. Ballato, D. W. Smith, Jr., Clemson Univ.

The proliferation of optical systems has manifested the need for materials that possess a unique combination of physical, chemical, and optical properties as well as being easily fabricated into low loss waveguide structures. This talk will focus on the optical properties and waveguide performance of perfluorocyclobutyl-based (PFCB) polymers and copolymers. Topics will include their experimental and theoretical optical performance, fiber and planar waveguide structures and devices, and novel light emissive composites with quantum dots and inorganic lanthanide nanoparticles.

6124-34, Session 9

Integrated polymer optoelectronic time delay device for an X-band phased array antenna system

B. Howley, R. T. Chen, The Univ. of Texas at Austin

A novel 4-bit optoelectronic polymer true time delay device is demonstrated. The device is composed of monolithically integrated low loss passive polymer waveguide delay lines and 2x2 polymer thermo-optic switches. Waveguide junction offsets and air trenches simultaneously reduce the bending loss and device area. Simulations and measurements are used to optimize the trench and offset structures for fabrication. The 16 time delays generated by the device are measured along with switching speeds and insertion losses for each delay state. The fabricated 4-bit delay devices are inserted into an X-band phased array antenna system to demonstrate optical control of the antenna steering angles.

6124-57, Session 9

Silicon and polymer based nano photonic crystal waveguide devices

R. T. Chen, The Univ. of Texas at Austin

No abstract available

6124-36, Session 10

Advanced arrayed-waveguide gratings and integrated optical devices

B. Fondeur, B. Brainard, S. M. Thekdi, D. K. Nakamoto, D. Dougherty, J. K. Bhardwaj, JDS Uniphase Corp.

Advanced arrayed-waveguide gratings and integrated optical devices

6124-37, Session 10

Integrated bidirectional transceivers for Access applications based on a cost-effective PLC hybridised platform

H. Imam, Ignis Photonyx A/S (Denmark); J. P. Rasmussen, ignis Photonyx A/S (Denmark); M. R. Pearson, Enablence Inc. (Canada)

The demand for high data rate bandwidth to the consumer is now greater than ever. Applications such as HDTV, video-on-demand and on-line gaming are only a few of the applications that drive the need for a wider broadband connection. This has led to the increased focus especially by telcos in the Far East and the RBOCs in the US to deploy Fibre-to-the-Home or Premise (FTTH/P).

An important component in FTTH/P deployments is the bidirectional transceiver, which is responsible for filtering/detecting incoming data and video wavelengths transmitting the upstream wavelength at the premise. The major cost for the transceiver lie in the optical head. Today, transceivers are based on bulk-optic solutions, which require a deal of manual assembly. Labour costs and associated manufacturing yield limit the cost reduction path for devices in volume. As the transceiver can be up to 30% of the ONT cost, there is a demand for a more cost-effective solution at high volume.

In this talk, we will describe the realization of a bidirectional transceiver device based on PLC (Planar Lightwave Circuit) Technology. By manufacturing the optical filter as a waveguide circuit and hybridizing the PIN detectors and Fabry-Perot laser, a low-cost optical head can be realized as a self-contained integrated optical chip. Automated manufacturing tools reduce manpower and maintain high yields, which provides for a cost-effective integrated optical device.

We will present the techniques developed to realize the integrated optical chip for the bidirectional transceiver, together with results from fabricated prototypes, targetting xPON standards.

6124-38, Session 10

Integrated PLCs based on high-index contrast microring resonator

Y. J. Chen, Industrial Technology Research Institute (Taiwan) and Univ. of Maryland/Baltimore County; S. Chang, Y. Huang, Y. Chu, Industrial Technology Research Institute (Taiwan); Z. Wang, Univ. of Maryland/Baltimore County

A growing number of current and future photonics applications in optical communications/networking, interconnects, sensors, and other optics related subjects call for large scale integrated optics/optoelectronics technology and built-in intelligence. Two of the key elements for large scale integrated planar Lightwave circuits (PLC) are high index contrast waveguide material and efficient device platform. To implement system level intelligence in an integrated photonic circuit, integration of electronic circuits and PLCs are essential. This is the direction of the next generation OEIC.

Although optics boasts advantages of many more independent properties: amplitude, phase, polarization and wavelength over electronics, these advantages also introduce tremendous challenges for large scale integration. As a case of point: it takes a quarter of wavelength phase change to switch the state in a Mach-Zhender interferometer. That translates into a demanding nonlinear, electro-optic or thermo-optic waveguide property in the waveguide and/or a large device size. This is true for most optical devices based on interference principle. Micro-ring device, on the other hand, is operating under resonance principle. For a high-Q resonant device, only a small change of resonance frequency (phase) is sufficient to produce the desired switching state. The large dispersion property associated with ring devices has also been considered for dispersion compensation applications. Thus micro-ring structure has been touted as a promising PLC building block.

In this talk we will review a number of PLC devices based micro-ring resonator using the ultra-high index contrast waveguide materials by Little Optics. We will visit the challenges in material properties, fabrication, testing and control of micro-ring devices.

6124-39, Session 10

Highly integrated photonic modules

J. Shmulovich, S. Frolov, A. Paunescu, D. C. Lee, Y. DeHazan, A. A. Hanjani, A. Bruce, Inplane Photonics, Inc.

Inplane Photonics technical vision is a versatile and comprehensive photonic integration platform based on PLC technology. I will review our significant progress toward this goal. Such enabling elements, as waveguide amplifiers, mux/demuxes, switches, splitters, monitors, receivers, and pump lasers are integrated simultaneously on one chip.

6124-40, Session 11

Photonic integration for high-denisty and multifunctionality in the InP-material system

H. Jaeckel, F. Robin, D. Erni, E. Gini, J. Holzman, H. Lohe, K. Rauscher, R. Scollo, P. Strasser, W. Vogt, R. Wueest, ETH Zürich (Switzerland)

Progress in photonics by monolithic integration for higher functional density, performance and reduced cost faces challenging hurdles due to technological and functional heterogeneities of optoelectronic technology. Advanced local material growth techniques and the emerging photonic crystal (PhC) technology are enabling concepts towards high-density photonic integration, unprecedented performance and multi-functionality allowing ultimately for optical systems-on-a-chip.

We first present our work on a multi-section monolithically integrated mode-locked InP/InGaAsP-laser as a case study in photonic integration for future Tb/s OTDM-systems. To generate stable sub-ps optical pulses

\@ l=1.55mm directly from the laser an ultrafast uni-travelling carrier (UTC) absorber has been integrated by multiple MOCVD-regrowth into an actively mode-locked laser with an MQW-InGaAsP/InP optical amplifier and passive waveguides. The structure demonstrated in a preliminary experiment optical pulses below 600fs.

Second we discuss our results on InP-based PhC-technology suitable for the integration of passive and active PhC-based devices and the related fabrication challenges. We perforate a vertically weakly guiding InP/InGaAsP/InP-waveguide with deeply etched air holes (4micrometer deep for a <300nm diameter) using ICP-based dry-etching subsequently to highly accurate proximity effect correction and e-beam lithography. End-fire characterization or novel SNOM-measurements of PhC-devices such as waveguide transitions, splitters and a novel standing-wavemeter will be presented. Due to the substantial out-of-plane scattering losses of low-contrast 2D-PhCs we developed 2D simulation tools including synthetic losses for fast prototyping/optimization that are calibrated against 3D-PDTD-simulations and measurements.

The potential of PhC-technology is not limited to its own specific functionalities and revolutionizing size-reduction for OICs, but also leads to performance, size and functional enhancement of conventional devices. Manipulation of dispersion, filtering and strong nonlinearities caused by the high photon density opens up possibilities for high performance lasers, modulators, detectors and all-optical switches and are reviewed by addressing the state-of-the-art in these emerging fields.

6124-41, Session 11

Waveguide devices for polarization control

X. Guo, T. Zaman, R. J. Ram, Massachusetts Institute of Technology

High-index contrast waveguide devices in InP that are capable of manipulating the polarization state of light are presented. The paper will review our recent work on reciprocal and non-reciprocal waveguide devices.

6124-42, Session 11

Field modulated wavelength conversion

J. S. Barton, A. Tauke-Pedretti, M. Dummer, M. N. Sysak, J. W. Raring, L. A. Coldren, Univ. of California/Santa Barbara

In this talk we will outline some of our latest results on monolithic wavelength converter design. Using a flexible epitaxial growth platform, high performance tunable lasers, modulators, detectors, and passive waveguides can all be integrated on a single chip. This can enable monolithic wavelength converters or “transceiver on a chip” architectures which are seen as important to the lowering of costs and increase of flexibility in future optical networks.

6124-43, Session 11

InP-based monolithically integrated optical gain-competition inverter

A. Y. Hsu, G. A. Vawter, E. J. Skogen, G. M. Peake, K. C. Baucom, R. J. Shul, W. W. Chow, Sandia National Labs.; C. R. Alford, B. Salters, L&M Technologies, Inc.; F. Cajas, Jobs Plus

Next-generation high-bandwidth optical data links exceeding 100 Gb/s demand challenging solutions where optical-electrical-optical conversion is not suitable. Technical approaches combining both high modulation bandwidth capability as well as high levels of device integration are essential. One particular example of this is in the area of high-speed all-optical logic where multiple-input optical logic gates are combined to form photonic circuits for applications such as encryption. One promising approach for this technical challenge is the use of the gain competition to produce an inverter function in cascaded edge-emitting lasers. Simulation results indicate that optical modulation in this manner can enable much higher modulation bandwidths compared with current modulation. Other advantages of this approach include scalability to monolithic-integrated logic gates and circuits.

An integrated InP-based optical inverter operating at 1.55 microns using a gain-competition effect has been demonstrated. The optical inverter consists of an etched-facet laser which actuates inversion via a decrease in gain and output power through optical side-injection. This is an important demonstration of a fundamental building block for higher-level cascaded optical logic gates and circuits at 1.55 microns.

The demonstration device consists of an etched-facet slave laser which is side-injected with a monolithically integrated etched-facet master laser and semiconductor optical amplifier (SOA) which are oriented on an axis perpendicular to the slave laser. The lasers and SOA employ a ridge waveguide, and the SOA is flared into the slave laser to increase overlap with the slave laser and improve inversion efficiency as shown by simulation results. The device wafer consists of InGaAsP/InP epitaxy grown by metal-organic chemical vapor deposition. A p-i-n diode structure is used, and the active region consists of compressively-strained quantum wells. The etched facets and waveguides were fabricated by HBr-based high-density inductively-coupled plasma etching. Si3N4 was deposited and etched to define contact regions and Ti/Au p-ohmic contacts were evaporated and plated. The wafer backside was lapped and evaporated with n-ohmic contact metal. Individual laser, laser-SOA devices and inverter devices were cleaved and soldered on to copper submounts which provide mechanical stability and heat sinking.

Experimental results for cleaved-facet laser, etched-facet laser, and integrated laser-SOA devices will be presented including power, threshold current and SOA amplification efficiency. Optical inverter performance under pulsed current injection will also be evaluated for different inverter designs which have different laser cavity lengths, injection region dimensions and SOA flare widths and lengths. Experimental data will include output power and the contrast ratio between inversion and non-inversion states under different operating conditions for the slave laser, master laser and SOA. A comparison between different types of inverter devices will also be presented. Issues that affect device performance including side-injection efficiency, onset of lasing in the SOA and inverter cascadability will be discussed.

6124-44, Session 11

Ultrafast InP optical integrated circuits

E. A. Bente, M. K. Smit, Technische Univ. Eindhoven (Netherlands)

In this paper we first present a brief overview of our work on InP integrated optical circuits. Integrated circuits can be produced that contain active components such as optical amplifiers and passive component such as waveguides, arrayed waveguide gartings and phase modulators. With this set of components complete laser systems can be designed and realised on a chip. Then we will present in what way our integration technology can be used to generate and utilise ultrafast optical pulses. Issues concerning the realisation, operation and future developments will be discussed.

6124-35, Poster Session

Fabrication of an optical-electrical printed circuit board (OE-PCB) by double-side lamination of an embedded polymer waveguide board between two electrical printed circuit boards

H. Lee, S. An, S. Lee, B. O, E. Lee, Inha Univ. (South Korea)

We report on the design and fabrication of a novel optical-electrical printed circuit board, which we call OE-PCB, by laminating a board of embedded polymer waveguide arrays between two electrical printed circuit boards. We first fabricated embedded polymer waveguide array on a polycarbonate film substrate with several hundred micron thickness. The fabrication procedures of the embedded waveguide arrays are as follows. First, an

under-cladding polymer layer is embossed by integrated silicon molds onto a polycarbonate substrate. And then, the upper-cladding polymer is spin-coated over the waveguide layer. Waveguides are formed with cross-sectional width of 100 micron, the height of 100 micron and the length of 10cm. Finally, the layer of polycarbonate film is placed over the waveguide arrays. This thin substrate board carrying embedded waveguide array is then placed between two electrical printed circuit boards in the form of a sandwich and a pressure is applied to laminate the entire E-PCB/O-PCB/E-PCB boards to produce the OE-PCBs. Polycarbonate film substrate has a good adhesion property to electrical PCB material such as FR-4. The polymer waveguide arrays are molded by embossing technique using a specially designed silicon mold, which can form the optical waveguide arrays and the 45 degree mirrors concurrently. The integrated silicon molds are fabricated by dry etching or wet etching. The layers of the waveguide arrays are sandwiched and laminated between the upper and the lower electrical PCBs to form the OE-PCBs. The transmission data rates of the waveguide array at 850nm wavelength are measured to be 2.5Gbps and 10Gbps per channel.

6124-45, Poster Session

Investigating the effects of package capacitance on the frequency response of shallow junction avalanche photodiodes

G. J. Cleary, National Univ. of Ireland/Cork (Ireland); A. M. Moloney, Dublin Institute of Technology (Ireland); A. P. Morrison, National Univ. of Ireland/Cork (Ireland)

Shallow junction silicon avalanche photodiodes developed for photon-counting applications, when operated in Geiger-mode, exhibit a multiplication gain of several hundred when operated near breakdown. The small size and relatively large gain of these devices identifies them as potential candidates for short-haul optical networking at 650nm. Of importance is the frequency response of these devices and in particular the limitations on achievable bandwidth placed by the packaging of the diodes. This work investigates the effect package capacitance has on the frequency response of Geiger Mode Avalanche Photodiodes (GMAP) when compared to micro-stripline mounted devices. Impulse response measurements are made of the diode using a pulsed laser diode at a wavelength of 650nm which provides pulses with full-width at half maximum (FWHM) of 70ps typical and 200ps maximum. A Fast Fourier Transform (FFT) is applied to the measured pulse to convert it to the frequency domain and de-embed the response of the test fixture and cable assembly. The electrical parameters of the packaged and micro-stripline mounted devices are compared in the frequency domain to see the effect of the package capacitance on the frequency response. Different device geometries are explored to identify suitable candidates for short-haul plastic optical fibre communications.

6124-46, Poster Session

Photon-assisted conducting polymer polymerization process development for storage information and microelectronic device applications

W. M. de Azevedo, E. F. da Silva, Jr., R. A. de Barros, Univ. Federal de Pernambuco (Brazil)

In this work we present a new polymerization process to prepare conducting polymer image (ROM device) and conducting polymer pattern. This method uses photons and transition metals instead of conventional oxidants to promote polymerization of conducting polymer monomer. For the image storage process, polyvinyl alcohol is used as a solid support doped with conducting polymer monomer and transition metals. For the patterns, the process consist to replace the conventional ink used in any DeskJet printer, for a solution of transition metal that will be used to print the desired pattern on a substrates such as, plastic, transparence sheet, glossy paper, or in any substrates material found in standard working office previously soaked in an aqueous solution of conducting polymer monomer. Soon after the patterns are written a UV light is used to develop the printed characters. This contribution describes the use of a fast and low-cost technology to produce conducting polymer structured materials for optical and microelectronic devices applications.

6124-47, Poster Session

Hybrid CMOS compatible active/passive quenching module

F. Lin, Tyndall National Institute (Ireland); J. C. Jackson, SensL Technologies Ltd. (Ireland); M. MacSweeney, M. M. Sheehan, Tyndall National Institute (Ireland)

This paper demonstrates the experimental results of combining new state-of-the-art Geiger mode avalanche photodiodes with an integrated hybrid active/passive quenching circuit. This creates an ultra-compact form factor for a low-light level detection module. Both devices, the photodiode and the quenching circuit, are fabricated using conventional CMOS process technology and wafer substrates. The photodiodes operate at low voltage levels (30 V to 40 V). Detector active areas are of various dimensions (10 μm to 50 μm) and shapes (circular or square). The integrated active/passive quenching circuit is included on a 2.5 mm ◊ 2.5 mm die, which has the functionalities of bias conditioning, passive/active quench, output signal generation and active recharge. The prototypes are hybrid packaged onto a PCB substrate. The module is characterised for detecting very low level optical signals such as the single photon activities. Parameters such as dark count, timing jitter, and responsivity will be shown for the compact detection module. A customized graphical user interface is programmed to control the photon-counting operation with flexible bias level, hold-off time and temperature settings. Our findings show that the proposed avalanche photodiode operation is considerably faster than the conventional discrete systems and the module size is greatly reduced

6124-48, Poster Session

Synthesis and characterization of fluorinated methacrylates-based copolymers containing cross-linkable pendant groups for optical waveguides

H. J. Kim, K. Kim, I. Chin, Inha Univ. (South Korea)

Polymers have been widely used for waveguides in optical components because of flexibility, controllability of optical properties, and low-cost fabrication process. However, most polymers show a substantial transmission loss in the near-IR region due to the vibrational overtone absorption of C-H bonds. To overcome the shortcomings fluorinated polymers have been utilized, mainly because of their low optical loss. In general, acrylic polymers are common materials for optical polymers. In this study, we prepared copolymers of octafluoropentyl methacrylate and hydroxyethyl methacrylate having pendant groups which can be crosslinked thermally or by UV irradiation. Chemical structure and thermal stability of the copolymers were investigated and the UV-induced crosslinking process was also monitored.

6124-49, Poster Session

The analysis of optical signal transmission characteristics in laser diodes

D. Kim, Y. Yun, K. Kim, J. Lee, Y. Choi, Chung-Ang Univ. (South Korea)

The optical interconnection is a recent issue for high-speed data transmission and the laser diodes (LD) are the best candidates. The optical signals are modulated by LD, which are affected by the dynamics characteristics of photons and carriers. In order to understand temporal behavior of the LD, the rate equation for photons and carriers must be ana-

lyzed.

In this paper, we analyze the rate equation using finite differential method (FDM). For analysis of the modulated optical signals, the injected current term in the rate equation is altered to the appropriated signals for instant digital or analog signals. So, output optical signals have the dynamics characteristics of photons and carriers. The bandwidth, transmission characteristics, SFDR (Spurious Free Dynamic Range) and nonlinearity are analyzed for optical interconnection systems.

6124-50, Poster Session

A 2.5 Gb/s CMOS optical transmitter with 10:1 serializer using clock generation method

K. Kim, D. Kim, Y. Moon, H. Kang, Y. Choi, Chung-Ang Univ. (South Korea)

The proposed optical transmitter is composed of FF(flip flop), PLL(phase locked loop), reference clock generator, serializer and LD driver. 10 x 250 Mb/s data arrays are translated to the 2.5 Gb/s data signal by serializer. In this case, 1 data bus is allocated usually as a reference clock for synchronization. In this proposed optical transmitter, 125 MHz reference clock is generated from 10 x 250 Mb/s data arrays by reference clock generator. From this method, absent of reference clock bus is available and more data transmission becomes possible. To achieve high speed operation, the serializer circuit is designed as three stacks. For 10:1 serialization, 10 clocks that have 1/10 lambda differences is essential, so the VCO(voltage controlled oscillator) composed of 10 delay buffers is designed. PLL is for runing at 250 MHz, and dual PFD(phase frequency detector) is adopted for fast locking time. Most of circuits including LD driver is formed differential pair signals to lessen common noise. The optical transmitter is designed by using of 0.35 um CMOS technology.

6124-51, Poster Session

Replication of precise optical waveguide for an optical device

M. Y. Jeong, Pusan National Univ. (South Korea)

For a simple, precise and low-cost planar lightwave circuit (PLC) device, we describe a novel method using polymer mold. Channel waveguide made of polymer for transmitting a signal is fabricated by using the replication method. Among replication techniques, embossing technique is preferred because of its simplicity and short process time and ease of precise manufacturing. Embossing technique requires the precise mold as an embossing tool for good replication. By this time, one makes use of silicon, nickel, and quartz as a mold for embossing, but these mold is not desirable due to their high cost, complex fabrication process, short lifetime by brittleness and so on. In this study, we are to replace these mold by polymer mold for mass production. We choose epoxy resin as a mold material from the viewpoint of mechanical strength, dimensional stability, and optical transparancy, As an intermediate step, we make use of PDMS frame for good productivity. We have developed distortion-free and void-free epoxy mold, and we heat-treated this mold by sub-Tg annealing to improve the mechanical properties of mold. It is important to improve the surface quality of mold because the accuracy of fabricated structure is related to that of the mold in UV embossing. The PDMS frame has been fabricated by the replica molding technology with ultrasonic vibration to eliminate micro-air bubbles during the fabrication process. Also, this fabrication to use ultrasonic vibration promotes PDMS solution to fill into micro channel and edge parts. Using polymer mold, we report the fabrication of an optical core using UV embossing. This fabricated core is 7 μm at depth, 6 μm at width. This measured value has the difference below 1 μm as compared with the original dimension. The surface roughness of core is about 14 nm root mean square. This is satisfactory value to use low-loss optical waveguide. Our successful demonstration of polymer replication presents an alternative approach for waveguide fabrication by UV embossing.

6124-52, Poster Session

Fabrication of a compact photonic crystal wavelength demultiplexer using ultraviolet embossing process

J. Sung, B. O, S. G. Lee, S. Park, E. Lee, Inha Univ. (South Korea)

We have investigated an ultra-violet (UV) embossing technique for fabrication of submicron scale polymer photonic crystal (PC) structures that can be simply performed at room temperature by UV cross-linking with a silicon mold. The structure of this device consists of a 1-μm-thick SU-8 2000 (MicroChem Corp., refractive index n=1.561 at 1.55-μm) core layer above a 10-μm-thick PDMS (refractive index n=1.4021 at 1.55-μm) cladding layer and fused glass substrate. Core and cladding layers are patterned with a two-dimensional square lattice of holes of radius r=0.3a, where a is the lattice constant, 540-nm. The hole array has 15 columns by 23 raws. To launch the light, we truncate the crystal at a (10) surface, and place an external incident dielectric waveguide, with a width of 2-μm, which is tilted at 22.5∞. And, we attached two external output dielectric waveguides, with a width of 4-μm. The process is rather simple. We first prepared core and cladding polymers, which was then spin-coated on the fused-glass substrate. The core material, SU-8, is cross-linked by exposure to UV light after the silicon mold is pressed. In our device, the beams of two different wavelengths (1043- and 1550-μm) are separated with the difference of 15∞ degree in PC region, then they propagate to each output waveguide. We expect that this device allows for high-density integrated circuits and for low-cost mass productable PC-based devices because of its simple fabrication process as well as its compact size.

6124-53, Poster Session

Polymeric 1 x 2 switch using thermo-optic transition controlled directional coupler

C. Choi, M. W. Lee, B. O, S. Lee, S. Park, E. Lee, Inha Univ. (South Korea)

We propose a novel directional coupler (DC) type switch based on mode transfer by thermo-optic effect. In our design, the switch operates by changing the refractive index of the coupling in OFF state and the anti-coupling in ON state. The DC switch consists of only one single electrode on the opposite side of input waveguide in the coupling region and is designed to have the coupling length for perfect coupling. Polymer materials with thermo-optic effect are adopted for the change of symmetry between waveguides. As the thermo-optic coefficient of a polymer is negative, the refractive index decreases with heating. When the electrode is sufficiently powered, the incident light propagates along the input waveguide due to breaking the symmetry. For the optimized switch design, our simulating study shows the extinction ratios of -27.4 and -24.0 dB in OFF and ON states, respectively. The required variation of the refractive index for switching is only order of 0.001. This concept is expected to improve the power consumption and the extinction ratio of a DC switch.

6124-54, Poster Session

Design and fabrication of polymer AWG using UV embossing technique

J. Kim, B. O, S. Lee, S. Park, E. Lee, Inha Univ. (South Korea)

We designed and fabricated a polymer arrayed waveguide grating(AWG) using UV embossing process. The designed AWG has a center wavelength of 1550 nm and 5 wavelength channels of 0.8-nm channel spacing. To fabricate the AWG, a poly-(dimethylsiloxane) (PDMS) mold is cast against a master that has a waveguide pattern. Then the PDMS mold is filled with core material. After removing the residual of core material by scratching, the mold filled with core material is covered with a fused silica

glass substrate and is then exposed to UV irradiation. A core patterned substrate is obtained after removal of the PDMS mold. The substrate is then covered with cladding material by spin coat process. After curing the cladding layer, the AWG fabrication is complete. By reusing the PDMS mold, we can replicate a large number of AWGs which have same structure and characteristics. This easy fabrication method is very simple, cost-effective and suitable for mass production. Crosstalk and detailed experimental results will be discussed.

6124-55, Poster Session

A triplexer optical transceiver module using cascaded directional couplers

H. Bae, E. Lee, H. Lee, S. An, K. H. Kim, S. G. Lee, B. O, S. Park, Inha Univ. (South Korea)

We report on the development of a newly conceived triplexer optical transceiver module for its application for a gigabit Ethernet passive optical network (GE-PON) and for fiber-to-the-home (FTTH) network. We designed the triplexer in the form of a planar optical integrated circuit using a cascaded array of directional couplers. This is to reduce the fabrication processes and costs compared to other triplexer designs. This module is designed to split three different wavelengths: one for the upstream and the other two for downstream, very much like a triple play service (TPS). The upstream uses 1310 μm for voice and data from the optical network terminal (ONT) to the optical line terminal (OLT) on the central office (CO). The downstream uses 1490 μm for voice and data and the other downstream uses 1550 μm for video from OLT to ONU. The triplexer proposed here is designed to have a compact size, low crosstalk (lower than -30dB) and large bandwidth at the channel center wavelength (1310 μm, 1490 μm, and 1550 μm). This wide bandwidth allows sufficient tolerance to the fabrication error and to the temperature changes. We analyzed its performance characteristics by BPM method. The FTTH network based on GE-PON has been considered a good solution for broadband access networks because it can offer high information capacity like TPS and decrease the cost to maintain network. The triplexer optical module that we developed is considered highly useful for this type of application.

6124-56, Poster Session

Fabrication of a 45° microreflector ended polymer waveguide using one-step UV embossing technique

S. An, H. Lee, B. O, S. Lee, S. Park, E. Lee, Inha Univ. (South Korea)

This paper reports, for the first time, a new method of fabricating a 45°-micro-reflector-ended polymer waveguide using one-step UV embossing technique. This technique allowed us to fabricate an array twelve channel multimode polymer waveguides equipped with a 45°-micro-reflector by using a one-step UV embossing technique. For the embossing we used a 45°-ended silicon waveguide mold. The silicon waveguides mold has a 45° slope prefabricated at the end of each waveguide structure. First, a 1um-thick-SiO2 layer is grown on the (100) silicon substrate. Then, the waveguide channel is patterned. The patterned waveguide channel is tilted at 45° from (100) silicon alignment base line to use the wet etching morphology which has 90° and 45° etched slopes when exposed to KOH and isopropanol saturated KOH solutions. After that, silicon substrate is wet etched with KOH solution to form the rectangular waveguide patterns. Another thin SiO2 layer is deposited again to protect the waveguide patterns and substrate. A thin line is then patterned on the top of the waveguide structure and a thin-line shaped silicon surface of the top of the waveguide structure is opened. Then, the opened silicon surface is wet etched in KOH saturated with isopropanol solution. The other area is protected by SiO2 layer. The etched shape has a V-shape and the angle from the bottom side is 45°. After SiO2 removal and cleaning, 45°-ended silicon waveguide mold is completed. With this mold, UV embossing is performed to form undercladding structure and 45° slope simultaneously. And a metal film is coated on the surface of the 45° slope. And then, core polymer is filled and cured by UV irradiation. This method can be applicable to waveguide structures of sizes ranging from multimode to single mode.

Conference 6125: Silicon Photonics

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6125-01, Session 1

CMOS photonics technology platform

C. Gunn, Luxtera Inc.

Luxtera has completed a practical silicon photonics technology platform including optical transmitters, receivers, and filters. For the first time, the performance of these components exceeds the requirements for implementation of commercially viable optical systems directly linking two silicon die. All optical components are integrated into Freescale Semiconductor's 0.13 micron CMOS process, which is currently in production of their PowerPC(TM) line of embedded microprocessors. MZI modulators and ring modulator configurations are demonstrated at 10Gb/s, both with good extinction ratio and low jitter. Tunable optical filters such as rings and arrayed waveguide gratings, as well as numerous passive components have also demonstrated. The optics are implemented alongside the RF circuitry required to construct operationally complete transceivers. Results from several critical circuits will be presented, including the modulator driver, VCO, and TIA. Techniques for scaling to 100Gb/s in and out of a single silicon die are presented as well as the technical drivers for short range optical links. An analysis of integration of these components in larger CMOS die, such as a microprocessor will be presented.

6125-02, Session 1

Recent advances in CMOS compatible integrated photonics

L. C. Kimerling, Massachusetts Institute of Technology; A. B. Apsel, Cornell Univ.; M. Beals, Massachusetts Institute of Technology; D. Carothers, BAE Systems North America; Y. Chen, Lucent Technologies; T. Conway, BAE Systems North America; D. Gill, Lucent Technologies; M. Grove, BAE Systems North America; C. Hong, Massachusetts Institute of Technology; M. F. Lipson, Cornell Univ.; J. Liu, J. Michel, Massachusetts Institute of Technology; S. S. Patel, Lucent Technologies; A. T. Pomerene, BAE Systems North America; M. Rasras, Lucent Technologies; D. K. Sparacin, Massachusetts Institute of Technology; K. Tu, A. E. White, Lucent Technologies; C. Wong, Columbia Univ.

The optical components industry stands at the threshold of a major expansion that will restructure its business processes and sustain its profitability for the next three decades. This growth will establish a cost effective platform for the partitioning of electronic and photonic functionality to extend the processing power of integrated circuits. BAE Systems, Lucent Technologies, Massachusetts Institute of Technology, 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). As part of the development of this demonstration platform we are exploring selected functions normally associated with the front end of mixed signal receivers such as modulation, detection, and filtering. The chip will be fabricated in the BAE Systems CMOS foundry and at MITís Microphotonics Center. We will present the latest results on the performance of multi-layer deposited High Index Contrast Waveguides, CMOS compatible modulators and detectors, and optical filter slices. These advances will be discussed in the context of the Communications Technology Roadmap that was recently released by the MIT Microphotonics Center Industry Consortium.

6125-03, Session 1

Electronic photonic integrated circuits for high speed, high resolution, analog to digital conversion

F. X. Kaertner, Massachusetts Institute of Technology

Currently, progress in developing high speed ADCís occurs rather slowly - at a resolution increase of 1.8 bits per decade. This very slow progress is mostly caused by the inherent jitter in electronic sampling - currently on the order of 250 femtoseconds in the most advanced CMOS circuitry. Progress in femtosecond lasers and laser stabilization has led to the development of sources of ultrafast optical pulse trains that show jitter on the level of a few femtoseconds over the time spans of typical sampling windows and can be made even smaller. The MIT-GHOST Program funded under DARPAís Electroic Photonic Integrated Circuit (EPIC) Program is trying to harness the low noise properties of femtosecond laser sources to overcome the electronic bottleneck inherently present in pure electronic sampling systems. Within this program researchers from MIT Lincoln Laboratory and MIT Campus develop integrated optical components and optically enhanced electronic sampling circuits that enable the fabrication of electronic-photonic A/D converters that surpasses currently available technology in speed and resolution and opens up a technology development roadmap for ADCís on the order of 6-bit improved resolution per decade for many decades to come. This talk will give an overview on the planned activities within this program and its current status on some of its key devices such as wavelength-tunable filters, high-speed modulators, Si/Ge photo detectors and miniature femtosecond-pulse lasers that are compatible with standard CMOS processing.

6125-04, Session 2

Continuous-wave silicon raman laser and amplifier for opto-electronic integration

H. Rong, M. J. Paniccia, Intel Corp.

With a reverse biased p-i-n structure embedded in a silicon waveguide, we efficiently reduced the nonlinear loss due to two photon absorption induced free carrier absorption and achieved continuous-wave net gain and lasing in a silicon waveguide cavity on a single chip. We report here the recent progress on the silicon Raman laser and amplifier for optoelectronics integration.

6125-05, Session 2

High performance self-organized In(Ga)as quantum dot lasers monolithically grown on silicon

Z. Mi, J. Yang, P. K. Bhattacharya, P. K. L. Chan, K. P. Pipe, Univ. of Michigan

Inter- and intra-chip optical interconnects, essential for future high-speed digital systems, require high-performance and reliable lasers that can be integrated with Si electronics. Recent demonstrations have shown that self-organized In(Ga)As quantum dot (QD) lasers exhibit superior characteristics. It is also recognized that the strain field surrounding the QDs can effectively suppress the propagation of dislocations. In this context, we demonstrated the first room-temperature operational InGaAs QD lasers grown directly on silicon utilizing a thin (≤ 2μm) GaAs buffer layer.

The thin GaAs buffer layer grown directly on offcut Si substrates has defect densities ~ 5◊107 cm-2. A QD buffer layer was grown to further reduce the defect density. GaAs/AlGaAs separate confinement heterostructure QD lasers were then grown, and the active region consists of three sets of coupled In0.5Ga0.5As QD layers. These devices

exhibit relatively low threshold currents (Jth ~ 1100 A/cm2) and high output power (~ 150 mW) under pulsed-mode operation at room temperature. Utilizing the technique of acceptor-doping in the dots, we also demonstrated a large characteristic temperature (T0 = 244 K) and constant output slope efficiency (0.31 W/A) in the temperature range of 5 to 95 ∫C, a first for any laser on silicon.

Our work suggests that QD lasers are a viable light source for integration with CMOS chips. We are currently investigating the growth and characteristics of QD lasers on relaxed and graded GexSi1-x buffer layers with substantially reduced dislocation densities (≤ 1◊106 cm-2). The reliability of these devices and their integration with CMOS chips will also be reported.

6125-06, Session 2

Emitting 1530 nm light on Si with optical gain from light emitting layer consisting of Er2O3, P2O5, Yb2O3 nanoparticles and spin-on glass

C. F. Lin, National Taiwan Univ. (Taiwan)

Emitting 1530 nm light on Si wafer is very useful because 1530nm is an important band in optical fiber communication. We explore a new way of light emission at 1530 nm. We demonstrate a simple and non-expensive process to form light-emitting layer. It can be deposited on silicon wafers. The properties of samples can be varied through controlling the composition. A very valuable part of the process is that it can be possibly integrated with IC manufacturing process, giving promise to building electrical and optical systems together on a single Si chip.

This light-emitting layer contains the mixture of Er2O3 nanoparticles and spin-on glass. It emits 1530nm light because Er2O3 nanoparticles release Er3+ into glass at high temperature. The emission efficiency can be further improved by introducing P2O5 and Yb2O3 nanoparticles into the solution.

This emitting layer can provide optical gain around 1530 nm even though this layer is very thin. Unlike the Er-doped optical fiber which requires a quite long distance to acquire optical gain, or significant light emission from Er3+ ions, our emitting layer is able to show the signals only within several millimeters due to surface effect of nanoparticles, enabling the higher concentration of Er3+. The optical gain at 1530nm is measured using variable stripe length method. The gain coefficient can be as large as 18 cm-1. It is sufficient for microlaser operation if a resonant cavity is formed.

6125-07, Session 3

Silicon light emitters and amplifiers: state of the art

L. Pavesi, Univ. degli Studi di Trento (Italy)

Silicon the material per excellence for electronics is not used for sourcing light due to the lack of efficient light emitters and lasers. In this talk, I will discuss the physical reasons why silicon is not a laser material and some approaches to make it lasing. I will start with bulk silicon, then I will discuss silicon nanocrystals and Er3+ coupled silicon nanocrystals where significant advances have been done in the past and can be expected in the near future. I will conclude with an optimistic note on silicon lasing. A summary of this talk can be found in L. Pavesi

ìRoutes towards a silicon-based laserî Materials Today 8(1) (January 2005) pag. 18-25.

6125-08, Session 3

Raman emission in porous silicon: prospects for an amplifier

M. A. Ferrara, Univ. degli Studi Mediterranea di Reggio Calabria (Italy) and Istituto per la Microelettronica e Microsistemi (Italy); L. Sirleto, Istituto per la Microelettronica e Microsistemi (Italy); L. Moretti, Univ. degli Studi Mediterranea di Reggio Calabria (Italy) and Istituto per la Microelettronica e Microsistemi (Italy); L. Rotiroti, Istituto per la Microelettronica e Microsistemi (Italy); E. Santamato, Univ. degli Studi di Napoli Federico II (Italy); B. Jalali, Univ. of California/Los Angeles; I. Rendina, Istituto per la Microelettronica e Microsistemi (Italy)

According to Raman approach, the natural atomic vibrations of material can be used to create or amplify light. Raman effect is used in optical fibres for light generation and amplification, however several kilometers of fibre are required to make a useful device. Interestingly, the Raman effect in silicon is nearly 10,000 times larger than that in the glass fiber. Exploiting these properties, Raman emission at 1542 nm, Stimulated Raman Scattering (SRS) and Coherent Anti-Stokes Raman scattering (CARS) have been already demonstrated. However two important limits have been pointed out: the two photons absorption, which is competitive with Stimulated light scattering, and a reduced Raman bandwidth [1].

In this paper, an approach based on Raman scattering in porous silicon is discussed [2]. We claim that this approach present some advantages: first, we prove that an increase of Raman bandiwidth is obtained due to the structure of porous silicon. Then, we prove that if liquids are infiltrated in porous silicon a reversible blue-shift of Raman scattering is achieved so a tunability of Raman spectra can be obtained. In fact, the adsorption of chemical species in porous silicon can induce compressive strain in the adsorbent [3] due to the action of the molecular forces.

Finally we discuss nonlinear effects in porous silicon. Due to quantum confinement, nonlinear properties of porous silicon are enhanced with respect to silicon. Moreover the two photon absorption could be negligible choosing a suitable porosity.

1 B. Jalali, R. Claps, D. Dimitropulos V. Raghunatan, ìLight Generation, amplification and Wavelength Conversion via stimulates Raman Scattering in silicon microstructures.î

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6125-09, Session 3

New approaches to silicon-based light emitters

H. A. Atwater, R. J. Walters, J. S. Biteen, S. Kim, California Institute of Technology

Efficient light-emitting devices are key components of future Si-based optoelectronic systems. In this talk we will describe recent developments in Si CMOS compatible near-infrared sources using field effect electroluminescence, a newly-identified charge injection process for CMOS-based light emitting devices. Field-effect light emitting devices (FE-LEDs) are MOS transistors with nanocrystals embedded in the gate dielectric. Excitons are electrically programmed in FE-LEDs by sequential electron and hole injection from the MOS channel and pulsed light emission is observed upon injection of the second carrier. A device performance analysis suggests potential for these devices to enable chip-based sources for optical power at 850 nm at the 1-200 microwatt/device level. We will also describe plasmon-enhanced light emission from Si nanocrystals that can increase the radiative rate of Si nanocrystal emitters, and will discuss approaches to using Si-nanocrystal based FE-LEDs to achieve emission in the 1300-1550 nm wavelength range.

6125-10, Session 4

Recent developments in silicon photonics

M. J. Paniccia, Intel Corp.

The silicon chip has been the mainstay of the electronics industry and it may similarly someday come to dominate the photonics industry. Silicon photonics especially that based upon silicon on insulator (SOI) has re-

cently attracted a great deal of attention since it offers an opportunity for low cost opto-electronic solutions for applications ranging from telecommunications down to chip-to-chip interconnects. Recent advances in performance of silicon based photonic devices are demonstrating that silicon can be considered as a practical material onto which one can build optical devices. The presentation will provide an overview of research being done at Intel in the area of Silicon Photonics. The presentation will present some recent results and also provide a discussion on the applications and future opportunities for silicon photonics.

6125-11, Session 4

Towards the era of silicon photonics through high-efficient silicon-based light emitter

G. Y. Sung, K. Kim, N. Park, T. Kim, K. S. Cho, C. Huh, J. H. Shin, Electronics and Telecommunications Research Institute (South Korea)

Current electronic devices are strongly dominated by silicon technology. However silicon technology does not allow easy integration with optical component since silicon is a poor light emitter. The unique properties of Si nanocrystals (nc-Si) can be exploited to fabricate Si-based light source. We will introduce a quantum confinement effect in the nc-Si embedded in a silicon nitride formed by PECVD. The band gap of the nc-Si could be controlled from 1.38 to 3.02 eV by decreasing the nanocrystal size. In addition, we will demonstrate a silicon light emitter with a transparent doping layer on nc-Si embedded in silicon nitride active layer by using ITO and n-type wide bandgap semiconducting layer. This light emitter has high external quantum efficiency(EQE) of 1.6%. Finally, we will present further improvement in EQE of Si-based light emitter by increasing light extraction efficiency using rugged surface pattern. From the simulation results based on the Snell°Øs law in 1-D emission model, the detection probability of emitted light increases as height of mesa pattern increases and was closely related to the ratios of pattern size and period.

6125-12, Session 4

High-speed modulators

M. F. Lipson, Cornell Univ.

Using highly confined photonic structures we have demonstrated ultra-compact passive and active photonic components with very low loss. The highly confined photonic structures enhance the electro-optical and non-linearities properties of Silicon and enable external manipulation of light on-chip.

6125-13, Session 4

Design of a 10 GHz silicon modulator based on a 0.25 um CMOS process

D. Zheng, D. Feng, Kotura, Inc.; G. Gutierrez, Independent Consultant; T. Smith, Kotura, Inc.

We report the design of a 10 GHz non-return-to-zero (NRZ) Silicon modulator based upon 0.25-mm CMOS/BiCMOS processes. The basic optical component is a ridge waveguide slightly-doped with P and N impurities fabricated on a Silicon-on-Insulator (SOI) substrate using the shallow trench Isolation (STI) step of a CMOS process. Doped P and N impurities form a PN junction whose depletion region overlaps with the optical mode confined by the afore-mentioned ridge waveguide. The diode typically operates between reverse and zero biases, which changes the number of free carriers overlapping with the optical mode and consequently modulate the phase of the light. Since the diode works in reverse-bias, only the transit time to move carriers in and out of the ridge waveguide limits the device speed, which is sub-nano seconds under 4V of bias swing.

Due to the relatively large capacitance of a reverse (or zero) biased diode, which was about a few PF/cm, a traveling wave design was adopted to achieve high bandwidth. The transmission lines (TML) used to carry electrical drive signals were critical to achieve the phase match between the electrical and the optical signals.

Silvaco device and SPICE circuit models will be presented to elaborate various delicate points in a 10 GHz modulator design, where the waveguide doping profile and transmission line geometries are critical. The most inspiring attribute of this design lies in its true compatibility with the standard CMOS process readily available at semiconductor foundries, and CMOS drive electronics are monolithically integrated.

6125-14, Session 4

Electro-optic modulators in silicon using 2D photonic bandgap structures

M. Haurylau, S. P. Anderson, K. L. Marshall, P. M. Fauchet, Univ. of Rochester

Silicon is a poor electro optic material, which makes the development of silicon-based electro optic modulators difficult. Recently, all-silicon Mach-Zehnder interferometers capable of modulation speed well in excess of 1 GHz have been demonstrated [1,2]. However, the size and power consumption of these devices remain prohibitive. In this presentation, we investigate the use of tunable photonic bandgap (PBG) structures to minimize both size and power consumption. While tuning of the optical properties of silicon PBG devices through temperature modulation has already been demonstrated [3], tuning with an electric field has not [4]. In our work, tuning is accomplished by filling the air holes with an electro-optic material; for example, liquid crystals, polymers or semiconductor quantum dots. Electrical tuning of PBG structures requires that both the energy of the optical mode of interest and the applied electric field be present inside the electro-optic material. We present a design that meets these requirements, overcomes the challenge due to field screening by silicon, and allows for efficient modulation. Further, we demonstrate the validity of our approach using 2-D PBG membranes made of silicon infiltrated with liquid crystals, showing switching at an applied field of 1 V/μm. These results could lead to the development of active silicon-based switches, routers and filters to be used in optical interconnects.

1 A.S. Liu et al., ìA high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor,î Nature 427, 615-618 (2004).

2 L. Liao et al., ìHigh speed silicon Mach-Zehnder modulator,î Opt. Express 13, 3129-3135 (2005).

3 M. Haurylau, A.R. Shroff, P.M. Fauchet, ìOptical properties and tunability of macroporous silicon 2-D photonic bandgap structures.î Phys. Stat. Sol. A 202, 1477-1481 (2005).

4 Modulation of an optical signal using an electric field applied to a 1-D PBG made of porous silicon and liquid crystals has been demonstrated by S.M. Weiss, H. Ouyang, J. Zhang, and P.M. Fauchet, ìElectrical and thermal modulation of silicon photonic bandgap microcavities containing liquid crystals,î Opt. Express 13, 1090-1097 (2005).

6125-29, Poster Session

Silicon photodetectors at 1.55um

M. Casalino, L. Sirleto, L. Moretti, G. Coppola, S. Libertino, I. Rendina, Consiglio Nazionale delle Ricerche (Italy)

Photodetector based on internal photoemission effect have drawn much interest because of their potential for high speed optical detection and large scale integration. Traditionally the operation of photodetectors, being based on interband transition, gives an electrical signal when the incident photon energy is greater than the semiconductor band gap. Interband transition has a cutoff wavelength about 1.1 micron for Si, so the 1.3-1.55 micron wavelength range needed for optical fiber transmission is excluded. Silicon Photodetectors based on the internal emission over the metal semiconductor Sckotty barrier may offer a solution to this problem. In an internal emission detector, the photon energy has to be greater than the Sckotty barrier at the semiconductor metal interface. Therefore for a Sckotty barrier height of about 0.75 micron the detector can detect photons in the range of interest for telecommunications.

This paper is concerned with the internal photoemission of electrons from thin metal films over the Schotty barrier at the silicon interface. This photodetectors have, generally, a low efficiency due to high riflettivity of metal. A possible way to improve the efficiency is the enhancement of electric field inside the absorbing layer using a microcavity.

In this paper, quantum efficiency for a silicon detector using fabry-perot and waveguide microcavity configuration are investigated.

6125-31, Poster Session

Novel GaP-based Ga(NAsP)laser material

W. Stolz, B. Kunert, S. Reinhard, M. Lampalzer, K. Volz, Philipps-Univ. Marburg (Germany)

Monolithic integrated optoelectronic circuits on Si-substrate would open up an exciting new field of applications. In the past a lot of effort has been devoted to the growth of standard direct band gap III/V-compound semiconductors on Si-substrate, i.e. GaAs/Si or InP/Si. Due to the large lattice mismatch of these materials to Si-substrate large densities of threading dislocations are formed, preventing any long-term stable lasing operation of corresponding device structures. In this study we present the novel direct band gap Ga(NAsP)-material, which can be grown lattice-matched to GaP. Due to the similar lattice constants of GaP and Si, this novel laser material system could lead to the real monolithic integration of III/V-based optoelectrnics and Si-based micro- and nanoelectronics in the near future.

Pseudomorphically strained Ga(NAsP)/GaP-quantum well heterostructures (QWH) on GaP-substrates have been grown by low temperature metal organic vapour phase epitaxy (MOVPE) in a commercial reactor system. No dislocation formation is observed as verified by detailed studies applying high-resolution X-ray diffraction (XRD) and transmission electron microscopy (TEM). The direct band gap characteristic in this novel material system has been detected by optical spectroscopy investigations. Electrical injection layer sequences have been deposited by combining the active Ga(NAsP/GaP-QWH with (AlGa)P/GaP-based waveguide structures. Already at this early stage of material development electrical injection laser structures have been realized around 100 K for the first time. Possible ways to improve the material performance leading to room temperature lasing activity and the integration schemes of this novel material system to Si-substrate will be presented and discussed in detail.

6125-32, Poster Session

Silicon microspheres for wavelegth division multiplexing

A. Serpengüzel, Koç Univ. (Turkey)

Silicon microspheres coupled to optical fibers are used for optical channel dropping in the near-infrared communication wavelenghts of 1300 nm. The observed morphology dependent resonances have quality factors of 100000. The measured quality factors are limited by the sensitivity of the experimental setup. These optical resonances provide the necessary narrow linewidths, that are needed for high resolution wavelenght division multiplexing applications. In addition to channel dropping, detection, and switching applications of this optoelectronic system is studied experimentally and numerically. The silicon microsphere and optical fiber system shows promise as a building block for wavelenght division multiplexing applications.

6125-33, Poster Session

Characterization of high-index contrast silica guided-wave devices

A. B. M. Rahman, N. Somasiri, City Univ. (United Kingdom); T. Wongcharoen, Bangkok Univ. (Thailand); V. Rakocevic, City Univ. (United Kingdom)

Silica-based thin films are the most common materials used for the fabrication of passive elements in integrated optics, due to their compatibility with silica optical fibers, by using well-established microelectronics planar technology. Silica-based integrated optic guided-wave photonics components such as connecting waveguides, directional couplers, power splitters, ring resonators, filters, and phased-array multi/demultiplexers are essential building blocks for future optical telecommunication networks. So far mostly silica waveguides with a low index contrast between the core and cladding have been used, which match very well with the large symmetrical spot-size of typical single mode fibers and as a consequence insersion losses have been small. However, due to their low index contrast, these guides are weakly confined and the leakage loss increases rapidly with the bending radius reduction, which limits the overall OEIC size. As a result, today high-index contrast waveguides are the subject of intense research because they would allow for the construction of optical devices that exploit small bending radius and thus will increase the functionality of the OEICs.

Modes in optical waveguides with two-dimensional confinement are not strictly TE or TM, but hybrid in nature. Although practically modal hybridness may not be an issue for typical low-index contrast silica guides, however, modal hybridness increases with the index contrast, and can have a major impact in optoelectronic system designs, for waveguides with slanted side walls or when the two polarized modes degenerate. In these structures polarization conversion possible, particularly, due to random wall roughness, or slanted side walls [1], or bent sections [2]. Modal birefringence of such silica waveguide is negligible due to their nearly squared shape cross-section. However, these guides are often polarization dependent due to the thermal stress induced material birefringence. It has been shown that by using a layered core, the effective material birefringence can compensate [3] the stress-induced birefringence.

Optimizations of the waveguide designs, their single mode operation, designs of directional coupler, bending loss, modal hybridness, birefringence compensation, spot-size conversion, and design of compact MMI-based optical power splitters would be presented by using a powerful, verstile, rigorous, and full-vectorial finite element-based modal solution [4] and a beam propagation [5] approaches.

References:

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6125-34, Poster Session

The convergence of photonics and microelectronics

L. W. Cahill, La Trobe Univ. (Australia); T. V. Clapp, Dow Corning Corp. (United Kingdom) and Univ. of Cambridge (United Kingdom)

The most recent impetus for the convergence of photonics and silicon integrated circuit technology has been the looming communications bottleneck associated with on-chip high-speed data transfer. Whilst there have been significant separate improvements in the materials and technologies for both integrated optics and integrated electronics, there is now a real commercial interest in putting these pieces together to achieve functional circuits that take advantage of both technologies in integrated circuit design. It is the purpose of this paper to examine the possibilities, the

pitfalls, and the projected future of this convergence of photonics and electronics.

There are a number of enticing areas of research that promise to provide desirable functions that will aid the convergence. For example, at the present time there is considerable research being conducted into silicon emitters. Such emitters would enable on-chip light generation to be achieved without the need for flip-chip bonding of III-V sources. However, with silicon it is difficult to generate light efficiently and there is often the problem of light collection and guiding, as well as heat dissipation problems in the vicinity of the source. Lasing in silicon has been achieved by using Raman pumping, but this is not a very efficient process and still requires a pump source that would be external to the chip.

In order to transmit data across a chip, efficient modulators with high modulation depth are also needed. Photonics also offer the possibility of wavelength-division multiplexing for high transmission bandwidths and routing, but there may be a real estate penalty when on-chip multiplexing is used. Much research has already been carried out on narrow silicon waveguides which offer the promise of very small bend radii, but in practice these often are more lossy than expected and so low-loss sharp bends are difficult to realize. Polymers that are compatible with integrated circuit technology also show considerable promise as waveguides and modulators. Their high electro-optic coefficient would be a decided advantage.

Therefore, there are very good prospects that the convergence of photonics and integrated circuit technology will not only continue, but gather pace.

6125-35, Poster Session

Silicon-nanocrystal-coated silica microsphere thermooptical switch

A. Tewary, M. J. F. Digonnet, M. L. Brongersma, Stanford Univ.; J. Y. Sung, J. H. Shin, Korea Advanced Institute of Science and Technology (South Korea)

We report a novel low-switching-energy, all-optical fiber switch that consists of a silica microsphere resonator coated with an annealed silicon rich silicon oxide (SRSO) layer containing silicon nanocrystals. A signal at 1450 nm and a pump at 488 nm are multiplexed and coupled into the microsphere through a tapered fiber. When a pump pulse is launched into the sphere, it is absorbed by the nanocrystal layer, heats the sphere, and changes its refractive index. This index change is used to switch the signal by tuning the signal wavelength in and out of resonance with a Whispering Gallery Mode of the microsphere. A resonance wavelength shift of 5 pm, sufficient to fully switch the signal, was observed with a pump energy of only 85 nJ. The rise time of the switch was measured to be ~25 ms (limited by the pump peak power) and its fall time to be ~30 ms (limited by the sphere's thermal time constant), which is in good agreement with a thermal model. The product of the switching peak power (3.4 μW) and the deviceís characteristic dimension (a diameter of 150 μm) is 5.1◊10-10 Wm, one of the lowest values reported for an all-optical fiber switch. The advantages of these devices is that they are compact (~150 μm across), fiber-pigtailed, and they exhibit a very low switching energy.

6125-15, Session 5

Integration issues of a photonic layer on top of a CMOS circuit

J. Fedeli, CEA-LETI (France); R. Orobtchouk, Institut National des Sciences Appliquées de Lyon (France); C. Seassal, École Centrale de Lyon (France); L. Vivien, Univ. Paris-Sud II (France)

Photonics on CMOS is the gathering of CMOS technology with integrated optics components for either a new functionality to the electronic circuit (optical clock distribution as an example) or means to miniaturize optical functions (transceiver as an example). The integration of a photonic layer on a CMOS circuit can be seen as a specific layer embedded between top metallic layers of the CMOS circuit. A 200mm technological platform with high index contrast materials is needed. Not to disturb the behaviour of the microelectronic components, Near Infra Red (NIR) wavelength range (1.3 or 1.55μm) is selected. For waveguide layer, low temperature waveguide technology as Si3N4 (loss 2.5dB/cm) or amorphous silicon is one way. Monocristalline silicon waveguides embedded with silicon dioxide cladding either with rib (loss 0.4dB/cm) or stripe configuration (loss around 5dB/cm) requires high temperature processing. So distribution networks on a SOI substrate were successfully reported on top of a CMOS circuit by full wafer molecular bonding and by silicon substrate removal. The molecular bonding of InP dies on CMOS wafers was performed for the integration of the source. Using a microdisk, 50% coupling was achieved to a stripe silicon waveguide. A modulation-doped SiGe-Si Multiple Quantum Well modulator (MD-MQW) embedded in a reverse biased PIN junction was designed and fabricated. Optical index variation can be achieved by plasma-dispersion effect associated to carrier depletion. Germanium photodetectors were directly coupled to silicon waveguide or processed for vertical illumination from a fiber. With MSM configuration, they exhibited bandwith of 35 GHz.

6125-16, Session 5

Integrated silicon photonic circuit- monolithic 8-channel modulator, tap, vertical coupler, and flip-chip mounted photodetector array

B. T. Smith, H. Lei, C. Kung, D. Feng, J. Yin, H. Liang, Kotura, Inc.

This paper describes a silicon photonic circuit of eight parallel waveguides, each straddled by independent p- and n- junctions. The junctions form PIN diodes that pass transverse currents through the optical fields, thus modulating the optical powers in the waveguides up to 5 MHz. The modulator regions are followed by wavelength insensitive directional couplers that split the transmitted light into two waveguides: one passing 95% optical power to eight output ports at the edge of the chip and the second carries 5% power to tap ports in the body of the silicon.

Each of the eight tap ports is terminated at a vertical coupler comprising an open cavity, formed by MEMS-compatible processes, and a turning mirror. The mirror comprises aluminum metal deposited on the Si (111) facet that has been wet-etched to form the cavity at the end of the tap waveguide. Light exiting the waveguide and entering the cavity is directed upward by the mirror, to a down-looking photodetector array. The eight-element photodiode array, a commercial III-V component, is flip-chip bonded to Al pads that had been formed on the silicon surface. This paper describes the design and circuit performance in terms of insertion loss, modulation characteristics, tap properties and photodetector response and crosstalk of a packaged Si photonic circuit.

Applications of this circuit include intelligent telecommunication equipment that requires microsecond speed for rapid power balancing, optical power transient suppression, and subcarrier modulation for channel tracking and system health monitoring.

6125-17, Session 5

Monolithically integrated photodetectors for optical signal monitoring in silicon waveguides

A. P. Knights, J. Bradley, S. Gou, P. Jessop, McMaster Univ. (Canada)

The development of monolithic silicon photonic systems has been the subject of intense research over the last decade. In addition to passive waveguiding structures suitable for DWDM applications, integration of electrical and optical functionality has yielded devices with the ability to dynamically attenuate, switch and modulate optical signals. However, for silicon to dominate as the substrate of choice for the fabrication of photonic circuits, the development of a full range of monolithically integrated functionality is required including detectors capable of signal monitoring at a wavelength around 1550nm. Photodetectors integrated with silicon-on-insulator rib waveguides have been recently demonstrated. Significant response at infrared wavelengths was shown to be mediated via deliberately introduced deep band-gap levels. This presentation describes

in detail the device fabrication and the performance of the waveguide photodetectors with regard to photoresponse, bandwidth, polarization sensitivity, thermal stability and wavelength sensitivity. Currently the most efficient devices tap between 10-20% of an optical signal from an SOI waveguide and generate a photocurrent of several micro-amps. We also describe results from the operation of an integrated photonic circuit consisting of a variable optical attenuator (VOA) and a photodetector. The detector faithfully monitors the optical signal as it is modulated using the VOA. Finally, the several potential applications of this device are described.

6125-18, Session 5

Heterogenous integration of InP/InGaAsP photodetectors onto ultracompact silicon-on-insulator waveguide circuits

G. Roelkens, J. Brouckaert, D. Van Thourhout, R. Baets, Univ. Gent (Belgium)

In recent years, Silicon-On-Insulator has emerged as a promising platform for high density passive integrated optics fabricated on a wafer scale. Due to the high omnidirectional index contrast very compact wavelength scale components can be fabricated. For active opto-electronic components however III-V material remains the workhorse of telecom industry due to its superior performance. Therefore, to come to complex optical systems-on-a-chip with active and passive optical functionality, the heterogeneous integration of III-V active components and SOI passive circuitry is needed.

We present first results on the integration of InP/InGaAsP photodetectors bonded using benzocyclobutene (BCB) to an SOI waveguide circuit. To couple light from the SOI waveguide circuit into the photodetector a 10um long grating coupler is used. On top of the SOI waveguide structure an unprocessed InP/InGaAsP epi-layer stack is bonded up side down using a 3um thick BCB layer. After grinding and chemical removal of the substrate until an etch stop layer is reached, the thin epi-layer stack remains bonded to the SOI circuit. This epi-layer stack contains an InP/InGaAsP p-i-n layer structure with an InGaAsP absorbing layer. After bonding of the InP/InGaAsP film, individual photodetectors are fabricated on top of the grating couplers.

First devices with non-optimized epi-layer stack show an efficiency of 0.02A/W which is close to simulated values. Simulations show however that this efficiency can be increased by a factor of 10 by optimizing the epitaxial layer structure. Wavelength selective filters based on cascaded ring resonators with integrated photodetectors were measured and will be presented at the conference.

6125-19, Session 6

Monolithically integrated graded-index waveguide input couplers for silicon-photonics

S. Janz, A. Delage, B. Lamontagne, A. Bogdanov, D. Xu, K. P. Yap, National Research Council Canada (Canada)

We review our recent work on graded-index (GRIN) waveguide couplers for silicon-on-insulator (SOI) and silicon nitride high index contrast waveguides. Although symmetric (i.e. high index in the middle) planar GRIN lenses have been considered and demonstrated, it has not been previously recognized that a half-GRIN structure truncated at the high index layer is also an effective focusing and coupling element for waveguide optics. The half-GRIN lens design results in an enormous simplification for the monolithic integration of a coupler with a waveguide, since the half-GRIN lens may be grown directly on an underlying waveguide using PECVD deposition of a-Si or SiOxNy. The need for precise vertical alignment of the waveguide and GRIN chip, or well calibrated etching and overgrowth in the case of a monolithic coupler, is thereby eliminated. Only a modest lateral lithographic resolution of ±1 microns is necessary to fabricate these couplers on SOI waveguides.

Both symmetric GRIN and half-GRIN waveguide couplers are examples of imaging multimode interference devices. Calculations demonstrate that while near perfect coupling to sub-micron SOI waveguides can be achieved using a half-GRIN coupler with a quadratic index profile, half-GRIN structures with a few discrete layers can also be effective. We will present our most recent experimental results. For example, an amorphous-Si coupler integrated with an 0.8 micron thick SOI waveguide has been fabricated, and a optimum coupling length of 15 microns is measured. Ongoing work on developing lithographically defined optical facets to facilitate the monolithic integration of half-GRIN couplers is also described.

6125-20, Session 6

Polarization-independent directional couplers on silicon-on-insulator

G. T. Reed, B. Timotijevic, G. Z. Masanovic, W. R. Headley, Univ. of Surrey (United Kingdom); A. Liu, M. J. Paniccia, Intel Corp.

Silicon-On-Insulator (SOI) material is showing great promise in the field of optical telecommunications. Its high index of refraction allows for submicron cross-sectional waveguide dimensions. This in turn allows for large device packing densities. Also, many of the devices necessary to comprise an optical network can be realised in SOI. These advantages coupled with Ultra Large Scale Integration (ULSI) processing techniques, can make the cost of these devices economically advantageous with respect to current telecommunication devices.

One device that is particularly useful is the directional coupler. As a stand alone device it has the ability to split an optical signal into practically any number of splitting ratio combinations simply by choosing the desired length. They can also be used to greatly improve the coupling of light to and from a waveguide. For ring resonator devices they are integral in coupling the necessary amount of light to and from the ring waveguide. Typically these devices are highly polarisation dependent. Therefore one or more couplers are needed to effectively handle an input signal whose polarisation state is unknown. Herein we describe a method to create a polarisation independent directional coupler. Devices were fabricated using this method and the results are compared with the initial model. Applications of polarisation independent directional couplers are also investigated.

6125-21, Session 6

Silicon integrated optics for stellar interferometry

P. R. Labeye, CEA-LETI (France); J. Broquin, IMEP (France); J. Berger, P. Y. Kern, Lab. d'Astrophysique de l'Observatoire de Grenoble (France)

Stellar interferometry is an old technique (first successful measurement of Titan diameter by Michelson in 1890), that has recently seen great performance improvements thanks to integrated optical devices. The technique, which consists in combining coherently several beams coming from distinct telescopes allow to reconstruct images with very high resolution, typically 10 times better than diffraction limit of the biggest telescopes on Earth and about 20 times better than Hubble space telescope. During the last few years, LETI, in collaboration with IMEP(Institut de MicroElectronique et Photonique) and LAOG(Laboratoire d'Astrophysique de l'Observatoire de Grenoble) has developped several components for stellar interferometry, either using its well established silica on silicon technology, or developping a new silicon technology for mid-infrared hollow metallic waveguides for the ESA-DARWIN mission. This paper will present the latest developments made at LETI in this field, describing the silicon technologies involved, devices, laboratory and on-sky results.

6125-22, Session 7

Planar single-molecule sensors based on hollow-core ARROW waveguides

H. Schmidt, D. Yin, P. Measor, Univ. of California/Santa Cruz; J.

P. Barber, E. J. Lunt, A. R. Hawkins, Brigham Young Univ.

Optical sensing is an integral part of analyzing molecules in liquid solution and gases. Single-molecule sensitivity has previously been achieved using a variety of techniques. The requirements for femtoliter sample volumes and guiding light through non-solid, low-index media have prevented fully integrated, planar single-molecule detection on a chip. We have developed a fully planar optical sensor platform on silicon using hollow-core antiresonant reflecting optical (ARROW) waveguides. Optical sensing of tens of femtoliter volumes of liquid with single-molecule resolution is discussed. Various aspects of design and performance of ARROW waveguide sensors and sensor arrays are discussed. These include fabrication, waveguide optimization, optical detection methods (fluorescence and Raman scattering), and integration with microfluidic system components on a silicon chip.

6125-23, Session 7

Compact add and drop and wavelength filter based on microdisk on SOI substrate

A. Morand, K. Phan Huy, D. Amans, B. Martin, F. Bredillot, P. Benech, École Nationale Supérieure d'Electronique et de Radioélectricité de Grenoble (France); J. Verbert, E. Hadji, CEA Grenoble (France); J. Eedeli, CEA-LETI (France)

The increase of metallic-interconnect number becomes a real barrier for future generation of VLSI. Optical interconnects in SOI technology decrease the delays and give access to higher bandwidth. In order to perform the on-chip routing of information, basic functions like add-and-drop structures or wavelength filters based on microdisk resonator are investigated. Microdisks exhibit high quality-factor with few micrometers diameter thanks to the high refractive index contrast between silica and silicon materials.

In this paper, realization and characterization of these components are reported. The dropped-wavelength function, composed of 1.5 μm radius disk and 0.3 μm x 0.3 μm square section waveguides, is demonstrated. 20 dB extinction ratio is shown while keeping a quality factor of 1000 from spectral measurement. In this structure, the distance between the microdisk and the waveguide is discussed from experimental point of view. Indeed, the efficiency of the add and drop is strongly dependant of this parameter.

Moreover, a wavelength filter based on a 4 μm radius microdisk is also shown. Quality-factors of 100,000 were measured. These filters are more efficient than equivalent filter based on microring. A 10 dB extinction ratio of the wavelength rejected signal is measured. For some resonance wavelengths, spectral response degeneracy of the filter appears. This phenomenon is usually observed in Silica microsphere or microtorus. An explanation of this effect is given in this paper.

6125-24, Session 7

Surface waveguide technology for telecom and biochemical sensing applications

J. A. Walker, JayWalker Technical Consulting, LLC and LioniX, BV (Netherlands); R. G. Heideman, LioniX, BV (Netherlands)

SiO2-based surface waveguides have become the de-facto standard for telecom applications. Telecom requirements are dominated by a need for low optical attenuation and low polarization effects across the 1.3-1.6 micron-wavelength band. Constituent films as thick as 20 microns and minimum bend radii of tens of millimeters (due to low refractive-index contrast between core and cladding) make SiO2-waveguide optical circuits large and expensive though, and this has limited the use of SiO2 surface waveguides primarily to telecom applications.

Recent advances in high index-contrast material systems, however, have begun to create new opportunities for waveguide technology in non-telecom areas such as sensing. LioniX BV, of the Netherlands, has been at the forefront of the development of high-index waveguides based on silicon nitride (SiN) and silicon oxy-nitride (SiON) cores. These material systems offer much smaller bending radii (tens to hundreds of microns) and stronger confinement of the optical mode to the core. As a consequence, SiN-core and SiON-core waveguides can have core thicknesses that are sub-micron and cladding thicknesses of only a few microns.

Telecom and sensor devices have been demonstrated using SiN and SiON waveguides. A Mach-Zehnder Interferometer (MZI) has been developed as a platform sensor technology that has very high sensitivity. The MZI incorporates ZnO as electro-active material, and can be designed to have high TM polarization rejection, which further improves signal-to-noise ratio. In addition, multiple sensors can be monolithically-integrated to provide sensitivity to a wide-array of biological and/or chemical agents.

LioniX has recently expanded the application space for waveguide technology with a newly developed ìcompositeî waveguide structure that offers both low attenuation and independent control over polarization characteristics. This new, potentially lower-cost technology, which requires only a single etch step, comprises a nanometer-scale ìsurface treatmentî of silicon nitride on an SiO2 waveguide core. Composite waveguides have demonstrated low attenuation but also derive the advantages of high-index-contrast waveguides. In addition, the modal birefringence is easily adjustable. Waveguides with attenuation of 0.10 dB/cm and modal birefringence as low as 0.001 have already been demonstrated.

6125-25, Session 8

Integrated nanosensors

I. K. Schuller, A. C. Kummel, M. J. Sailor, W. C. Trogler, Y. Lo, B. Fruhberger, M. Montero, Univ. of California/San Diego; G. J. Brown, H. J. Haugan, F. Szmulowicz, K. Mahalingam, B. Ullrich, S. Houston, Air Force Research Lab.

The UCSD project on Integrated Nanosensors is an interdisciplinary research project which includes collaborations from chemists, bio-chemists, physicists, materials scientists and engineers. This project is dedicated to studies of issues related to the integration of diverse sensors, with local processing and wireless communications on a single chip. The key philosophical issue which drives the whole project is the understanding based development of Integrated Nanosensors. This project is motivated by the belief that the problem is complex enough that a simple Edisonian approach cannot search the vast parameter space necessary to design highly sensitive and specific devices that incorporate chemical, biological, magnetic, and imaging sensor elements.

The suite of sensors have now been refined to the following individual sensors which are at various stages of development; infrared sensors based on GaSb/InAs superlattices, many metallophtahlocyanine-based vapor phase chemical sensors and porous silicon-based liquid phase chemical and biological sensors. Phthalocyanine-based sensors capable of detecting a number of interesting analytes have been developed and advanced testing under a variety of conditions and stimulii are under way. Porous silicon based sensors have been developed mostly for liquid phase analytes and are currently being integrated into a chip-based flow cytometry system. Infrared physical sensors are being developed based on GaSb/InAs superlattices and will become part of the integrated system. A unique sensor test bed was developed which allows testing of multiple sensors under realistic and controlled conditions.

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6125-26, Session 8

Monolithic silicon optoelectronic devices for protein and DNA detection

K. Misiakos, P. Patrou, S. E. Kakabakos, M. Vlachopoulou, A. Tserepi, E. Gogolides, National Ctr. for Scientific Research Demokritos (Greece)

The present work outlines a new class of miniaturized monolithic silicon optoelectronic transducers properly functionalized as biosensors and provides bioanalytical results that demonstrate the efficiency of the device.

The devices are made on silicon wafers by employing standard silicon integrated circuit technology. Every die monolithically integrates a number of silicon optocouplers consisting of an avalanche diode, a silicon nitride waveguide, and a p-n junction detector. The avalanche diode operates in reverse bias and beyond its breakdown voltage where it emits light due to hot carrier interactions in the high field region of the heavily doped junction. Silicon dioxide surface micromachining and implantation through the nitride layer allow for very efficient optical coupling between the light emitting avalanche diode, the silicon nitride waveguide, and the detector. The implantation through the nitride film forms the avalanche junction and self-aligns it to the waveguide. As a planar waveguide biosensor, the silicon nitride fiber is functionalized by aminogroups through proper treatment and is then selectively coated by the capture molecule. The selective coating is made either by dispensing techniques or by microfluidic channels that run in parallel to the nitride waveguides. Signal transduction is based on attenuated total reflection. Here, the resonant modes interact with the capture and the binding analyte molecules through evanescent wave optics and create a drop in the photocurrent of the detector, thus allowing real time observation of the capture molecule reaction with its counterpart in the sample. To enhance sensitivity, special nanoparticle labels are employed due to their large effective extinction cross section due to absorption and scattering. Sensitivity is also enhanced due to the small waveguide thickness, 150 nm. The paper reviews such techniques as well as label free methods and provides results in protein and DNA testing and outlines packaging and microfluidics issues towards a point of care bioanalytical microsystem.

6125-27, Session 8

Porous silicon-based Bragg reflectors and Fabry-Perot interference filters for photonic applications

D. Mangaiyarkarasi, M. B. H. Breese, O. Y. Sheng, K. A. Mahabadi, D. J. Blackwood, National Univ. of Singapore (Singapore)

Visible light emission from the porous silicon(Psi) formed by anodic etching of Si in HF solution has raised great interest in view of possible applications of Si based devices in optoelectronics. In particular, multilayers consisting of the periodic repetition of two PSi layers with different refractive indices can be exploited to design interference filters for controlling the emission wavelength as well as for the spectral narrowing of the wide emission band of Psi. Fabry-Perot optical microcavities with an active layer sandwiched between two Bragg reflectors, consisting of alternating layers of high and low refractive indices are fabricated on heavily doped p-type silicon. We have investigated the optical properties of these microstructures using reflectivity and photoluminescence measurements at room temperature. Furthermore, the effect of ion irradiation, which modifies the porous formation and hence the emission wavelength, has been studied. Any slight change in the effective optical thickness induces change in the reflectivity spectra, causing a shift in the interference peaks. So the wavelength of the narrow peak could be tuned by altering the optical constants in the adjacent areas of Si wafer that offers a wide range of potential applications in flat panel display technology and photonics.

6125-28, Session 8

Electrostatically tunable infrared filter that uses etched thin Si plates

I. Yamada, K. Kimura, Ryukoku Univ. (Japan); Y. Yamagishi, HORIBA Ltd. (Japan); M. Saito, Ryukoku Univ. (Japan)

Infrared spectrometry is indispensable for chemical analyses. Spectrometers that use diffraction gratings or Michelson interferometers are being used widely, but a small and robust infrared spectrometer is required if measurement has to be conducted in hazardous environment. Silicon is a useful material for infrared spectroscopy, since it has a wide transmission range in the infrared and provides a high-reflectance cavity with its high index of refraction. In addition to these optical characteristics, silicon can be controlled electrically, and can be machined into various shapes by microfabrication processes. In a previous paper, we reported an infrared Fabry-Perot filter consisting of two silicon plates, whose spacing was controlled electrostatically [Appl. Phys. Lett., vol. 79, no. 26, p. 4283 (2001)]. In this work, we reduced a driving-voltage of the filter by etching a central portion of silicon wafers.

We used (100) silicon plates, 200 É m in thickness and 20Å~20 mm2 in size. Only the central part of the plates was etched to ~110 É m in a 8-mol/l KOH solution at 80Åé for 90 minutes. The etched plates were adhered on their edges with an epoxy adhesive containing glass spacers. Since the filter acts as an air-gap capacitor, the voltage application induces positive and negative charges on the two silicon plates. Consequently, the plates were attracted by each other, leading to the decrease in the spacing. Transmission spectra of the fabricated filter were measured by using a Fourier-transformation infrared spectrometer. When a dc voltage was applied to the fabricated filter, interference peaks shifted to shorter wavelengths; e.g., a peak shifted from 8.1 É m to 4.2 É m when a driving-voltage changed from 0 V to 50 V. This filter seems useful to construct a small and robust infrared spectrometer.

Conference 6126: Photonics Packaging and Integration VIII

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6126-01, Session 1

Ultra-high speed transmission of polymer-based Multimode Interference: devices for high-throughput Optical Interconnects

G. Chang, Y. J. Chang, Georgia Institute of Technology

No abstract available

6126-02, Session 1

Holographic optical elements for optical backplane bus targeted at high speed data transfer

J. Ellis, Advanced Communications Concepts, Inc.

No abstract available

6126-03, Session 1

Development of a fabrication technology for integrating low cost optical interconnects on a printed circuit board

G. V. Steenberge, N. Hendrickx, P. Geerinck, E. Bosman, S. Van Put, Univ. Gent/IMEC (Belgium); H. Ottevaere, H. Thienpont, Vrije Univ. Brussel (Belgium); P. Van Daele, Univ. Gent/IMEC (Belgium)

We present a fabrication technology for integrating polymer waveguides and 45∞ micromirror couplers into standard electrical printed circuit boards (PCBs). The most critical point that is being addressed is the low-cost manufacturing and the compatibility with current PCB production. The latter refers to the processes as well as material compatibility. Planar multimode waveguides are patterned by UV exposure using acrylate polymers (TruemodeTM) with 0.05dB/cm propagation loss at 850nm. Single mode waveguides using inorganic-organic hybrid polymers (OrmocerÆ) show an attenuation loss of 0.62 ± 0.08 dB/cm at 1.3μm. Out-of-plane coupling micromirrors are fabricated using excimer laser ablation, a very flexible technology that is particularly well suited for structuring of polymers because of their highly non-thermal ablation behavior. A coupling structure based on total internal reflection is enhanced by developing a process for embedding metal coated 45∞ mirrors in the optical layers. The mirrors are selectively metallized using a lift-off process. Filling up the angled via without the presence of air bubbles and providing a flat surface above the mirror is only possible by enhancing the cladding deposition process with ultrasound agitation. Surface roughness of both the mirrors and the upper cladding surface above the mirrors is investigated using a non-contact optical profiler. Loss measurements at 1.3μm show a mirror loss of 1.55dB. During most recent experiments RMS roughness has been reduced from 160nm to 20nm, which will seriously improve the mirror performance, and will allow further investigating laser ablation for the fabrication of not only the mirrors, but the entire optical interconnection, including the waveguides.

6126-04, Session 1

Bit-interleaved optical bus for high-speed secure multiboard system

H. Bi, The Univ. of Texas at Austin; X. Han, Brewer Science, Inc.; R. T. Chen, The Univ. of Texas at Austin

Optical backplane bus based on glass substrate with volume holographic gratings on top surface possesses a great ability to broadcast information. This feature is utilized to accomplish a bit-interleaved optical interconnect system. In this system, each daughter board sends only one bit per round and the bit pulses from different boards can cascade in a designed series when the transmitters are distributed in an appropriate manner. In this way, even slow electronic chips can be coordinated to generate an aggregate bandwidth up to 10Gbps, which is impossible to be achieved with a multi-drop electrical bus. Besides the benefits of high data rate and low crosstalk, such a bit-interleaved architecture provides a secure data storage method. Each daughter board only stores a quarter bits of any byte, so that no single board has the entire information.

Alignment tolerance and power budget of the proposed optical interconnect system is theoretically calculated and experimentally verified. With collimating lenses, the packing density of transceivers is more than 4/cm2, and thus the signal density can be above 40G/cm2/board. The insertion loss due to misalignment and beam divergence is measured to be approximately 4dB. The bit error rate (BER) of 10Gbps receivers with -12dBm sensitivity is estimated to be below 10-12.

6126-05, Session 2

Advanced packaging materials for optical applications: bridging the gap between nm-size structures and large-area panel processing

R. Houbertz, Fraunhofer-ISC (Germany)

During the last two decades, nano-materials have been intensively investigated due to their wide range of properties, resulting in a variety of applications. In order to serve as advanced packaging material, from an industrial point of view emphasis has also to be on cost reduction either for the materials, the processes, or for both. Materials are searched for which enable processing and integration from a nm up to a cm scale.

A particular class of low-cost nanoscale materials are inorganic-organic hybrid polymers (ORMOCERs) which are synthesized by catalytically controlled hydrolysis/ polycondensation reactions, resulting in storage-stable resins. Due to the variety of chemical and physical parameters, the material and processing properties which directly influence the resulting structure, can be varied over wide ranges. Upon synthesis, functional organic groups are introduced into the material which allows one to photochemically pattern the resins.

The materials are capable to be patterned on a nm up to a cm scale, employing a variety of different micro- and nano-patterning methods such as, UV lithography, UV replication/lithography, laser-direct writing, or two-photon polymerization, in order to generate micro- and nano-optical components. While for most of the techniques the patterning has to be repeated several times in order to achieve multi-functional layers, the latter method allows one to directly write arbitrary 3D structures into the hybrid polymer material.

The combination of chemically designed low-cost materials with tunable material parameters such as low optical absorption, tunable refractive index, good processibility, and high chemical, thermal and mechanical stability, is very attractive for (integrated) optical applications. Examples for application of the materials for microoptics as well as for optical backplanes generated by large-area processing will be given.

Conference 6126 Abstracts

6126-06, Session 2

Fiber optics structural mechanics, and nanotechnology based new generation of fiber coatings

E. Suhir, Univ. of California/Santa Cruz

The talk consists of two parts-review and extension. The review part deals with typical fiber optics structures (bare, single- and dual-coated fibers; fibers experiencing low temperature micro-bending; fibers soldered into ferrules or adhesively bonded into capillaries; role of the non-linear stress-strain relationship, etc.) subjected to thermally induced and/or mechanical loading in bending, tension, compression, or to various combinations of such loadings. The emphasis is on the state-of-the-art in the area of optical fiber coatings and the functional (optical), mechanical and environmental problems that occur in polymer-coated or metallized fibers. The solutions to the examined problems are obtained using analytical methods (predictive models) of structural mechanics. The review is based primarily on the authorís research conducted at Bell Laboratories, Murray Hill, NJ, during his eighteen years tenure with this company. The extension part addresses a new generation of optical fiber coatings and deals with the application of a newly developed (by the ERS/Siloptix Co.) nanoparticle material (NPM) that is used as an attractive substitute for the existing optical fiber coatings. This NPM-based coating has all the merits of polymer and metal coatings, but is free of their shortcomings. The developed material is an unconventional inhomogeneous ìsmartî composite material, which is equivalent to a homogeneous material with the following major properties: low Youngís modulus, immunity to corrosion, good-to-excellent adhesion to adjacent material(s), non-volatile, stable properties at temperature extremes (from -220 C to +350 C), very long (practically infinite) lifetime, ‘active’ hydrophobicity - the material provides a moisture barrier (to both water and water vapor), and, if necessary, can even ‘wick’ moisture away from the contact surface; ability for ‘self-healing’ and ‘healing’: the NPM is able to restore its own dimensions, when damaged, and is able to fill existing or developed defects (cracks and other ‘imperfections’) in contacted surfaces; very low (near unity) effective refractive index (if needed). NPM can be designed, depending on the application, to enhance those properties most important. NPM properties have been confirmed through testing. The tests have demonstrated the outstanding mechanical reliability, extraordinary environmental durability and, in particular applications, improved optical performance of the light guide.

6126-08, Session 2

Lithography-grade tungsten-copper substrates for wafer level packaging

G. I. Rudd, B. Cronk, Spectra-Mat, Inc.

Wafer level packaging of opto and opto-electronic devices can result in significant cost savings. A substrate with good thermal conductivity is required where devices dissipate significant power. Additionally, using a substrate with a coefficient of thermal expansion (CTE) similar to the device can increase reliability when temperature-induced strain is a problem.

Tungsten-copper metal-matrix composite (W/Cu) has long been used for package components and heat sinks. It has good thermal conductivity (similar to that of aluminum), but unlike aluminum or most alloys, it can be made with any of a range of CTEís to match various other device and substrate materials. W/Cu has some ductility to relieve strain and is readily machined, plated, and brazed.

In our paper, we present data on W/Cu wafers up to 150mm diameter produced to specifications suitable for wafer level packaging. We describe the properties of the material and show the result of the measurement of flatness/bow, Total Thickness Variation (TTV), and surface finish. We also discuss how processes impact these parameters. Finally, we show how micro-channel fluid cooling can be integrated into such substrates.

6126-21, Session 2

Versatile coupling of a plastic optical fibre imaging bundle to an avalanche photodiode array

D. M. O’Driscoll, A. P. Morrison, National Univ. of Ireland/Cork (Ireland)

With the increasing use of optical fibre in both the telecommunications and home networking areas, the packaging and alignment of various optoelectronic devices has never been more critical. In particular coupling of Plastic Optical Fibre (POF) to detectors has become an important area of research. Most off-the-shelf POF has a core diameter of 980μm, while a typical photodiode may have an active area diameter of 50μm. Hence without some kind of physical alignment losses may become unmanageable. This paper describes efforts to couple Plastic Optical Fibres to an avalanche photodiode (APD) array.

An imaging POF fibre-bundle is used to connect to the array in a low cost versatile manner. An array of up to ten fibres is used to form the bundle. Mechanical guide systems both on the substrate of the chip and on the package housing itself are used to align each individual fibre to a corresponding photodiode. The results from several focusing techniques are presented to overcome coupling losses encountered while focusing the beam from the POF onto the smaller detector active area. A multi fibre connector is used to connect other instruments at the opposite end of the fibre bundle. The primary application of this technology will enable the use of arrays of photon counting detectors in astronomy.

6126-09, Session 3

3D chip-scale optical interconnects and switches with self-organized wiring based on device-embedded waveguide films and molecular nanotechnologies

T. Yoshimura, Y. Suzuki, K. Asama, Tokyo Univ. of Technology (Japan)

We present three-dimensional (3-D) architectures of chip-scale optical interconnects and optical switching systems, which consist of stacked waveguide films with embedded thin-film devices, such as light modulators, optical switches, VCSELs, PDs and LSIs, and optical Z-connections for inter-film optical couplings. Related core technologies are described. Potential applications of the molecular nanotechnology to future 3-D optoelectronic (OE) LSI is also discussed.

3-D Architecture: ‘3-D stacked OE LSI’ achieves high-density/high-speed/low-loss optical interconnects, resolving the problems of cross-talk, attenuation and propagation delay of signals in next generation LSIs. OE-ADLES (OE Amplifier/Driver-Less Substrate), in which optical signals are generated by light modulators driven directly by LSI outputs using external strong light sources, is suitable for the system. ‘3-D Micro Optical Switching System (3D-MOSS)’ achieves high-speed massive optical switching by optimizing the stacked film count.

Core Technologies: ‘Waveguide film with surface-normal mirrors’ that is a platform for the 3-D architectures were duplicated using newly-proposed ‘built-in mask method,’ which enables us to construct fine-pitch mirrors with arbitrary directions. NFP/FFP measurements showed that 45-degree mirrors that reflect a propagated light beam in a waveguide to surface-normal direction were constructed. ‘Self-organized optical Z-connection,’ into which ‘SOLNET (Self-Organized Lightwave Network)’ is implemented, was found from the BPM/FDTD simulation to be effective to fabricate 3-D optical wiring with low-cost. Proof-of-concept for a resource-saving device embedding process ‘PL-Pack with SORT (Photolithographic Packaging with Selectively-Occupied Repeated Transfer)’ was demonstrated.

Potential Applications of Molecular Nanotechnologies: Self-organized growth of pai-conjugated polymer chains based on MLD (Molecular Layer Deposition) was found to be applicable to form high-performance electro-optic materials for optical switches/modulators as well as future molecular transistors.

6126-10, Session 3

Progress toward intra-chip optical interconnects

M. W. Haney, M. Iqbal, M. McFadden, D. W. Prather, T. E. Dillon, Univ. of Delaware

Microprocessor performance is now limited by the bandwidth capacity available within the on-chip global wiring layers. Although relatively few in number, the global metal wires have proven to be the primary performance limiter-effectively leading to a premature saturation of Mooreís Law scaling in future Silicon generations. This paper reviews the status of possible intra-chip optical interconnect solutions in which the Silicon chipís global metal wiring layers are replaced with a high-density guided-wave or free-space interconnection fabric. The overall goal is to provide a scalable approach that is compatible with established Silicon chip fabrication and packaging technology, and which can extend the reach of Mooreís Law for many generations to come. System-level interconnect performance analysis-based on wire-length distribution estimation and projected circuit and device characteristics-is used to predict interconnect requirements and motivate the use of potential photonic solutions. To achieve the required densities, the integrated sources are envisioned to be modulators that are optically powered by off-chip sources. Structures for coupling dense modulator arrays to optical power sources and to free-space or guide-wave optical global fabrics are analyzed. Results of proof-of-concept experiments, which demonstrate the potential benefits of ultra-high-density optical interconnection fabrics for intra-chip global communications, are presented.

6126-11, Session 3

A novel, free-space optical interconnect employing vertical-cavity surface emitting laser diodes and InGaAs metal-semiconductor-metal photodetectors for Gbit/s RF/microwave systems

G. R. Savich, Univ. of Rochester and NASA Glenn Research Ctr.; R. N. Simons, NASA Glenn Research Ctr.

Emerging technologies and continuing progress in research are making way for novel, high speed forms of optical data transfer. Vertical-cavity surface emitting laser (VCSEL) diodes operating at 1550nm have only recently become commercially available, while metal-semiconductor-metal (MSM) photodetectors are pushing the limits of contact lithography with interdigitated electrode widths reaching sub micron levels. We propose a novel, free-space optical interconnect operating up to 1Gbit/s utilizing commercially available 1550nm VCSEL diodes and newly fabricated InGaAs MSM photodetectors with functionality for both chip level and board level applications. We report on development, progress, and current work. Analyses of the divergent behavior and of the normalized frequency response of VERTILAS GmbH 1550nm VCSEL diodes for coupling to MSM photodetectors with a 50μm by 50μm active area are presented. The MSM photodetectors are fabricated on a pseudomorphic In0.9Ga0.1P-InP-InGaAs heterostructure and have gold interdigitated Shottky contacts with varying electrode width and spacing on the order of 1 to 3 microns. We discuss the calculated response of these MSM photodetectors as well as the fabrication and characterization of the devices. A report on bit error rate (BER) characteristics of the VCSEL diodes coupled to commercially available high-speed photodetectors and successively coupled to the novel MSM photodetectors integrated with commercially available transimpedance amplifiers (TIA) follows. The work accounted here will lead to the formation and characterization of a fully integrated 1Gbit/s free-space optical interconnect applying VCSEL diodes and MSM photodetectors operating at 1550nm for RF/microwave digital systems.

6126-12, Session 3

Application of parallel optical axis converting waveguide to optoelectronic-PWB

T. Tanaka, H. Nanai, H. Sakamoto, Y. Yamamoto, S. Sakaguti, Central Glass Co., Ltd. (Japan)

Optical printed wiring board (OPWB) has been attracting as a possible solution against bandwidth limitation for signal transmission in copper based PWB with increased clock speed in LSIs. Although tremendous studies have been performed for OPWD utilizing optical waveguides and active elements such as VCSELs and PDs to date, poor optical coupling efficiency between the waveguides and the elements has remained OPWB disadvantageous in manufacturing cost.Optical axis converter (AXC), which equips a vertical waveguide connected optically to a horizontal one via a corner micro-mirror, is promising to overcome such a problem. Since AXC developed so far also has electrodes on its surface, VCSELs can be surface-mounted directly via Au/Sn bumps. Such a structure improves not only optical properties such as coupling efficiency and cross talk but also manufacturing cost by using passive alignment.In this report, we describe optical properties of 4-channel AXC-U and parallel optical signal transmission capability. AXC-U developed here includes 4-channel waveguides, which have U-shaped optical path and a cross sectional dimension of 40x40 mm. The AXC-U accommodates VCSEL and PD arrays mounted on its surface at both vertical waveguides in a manner of passively alignment and flip-chip bonding.It exhibits an insertion loss as low as 1.0dB and an optical crosstalk as high as 35dB. In addition, AXC-U has successfully transmitted parallel optical signal at a speed of higher than 10Gb/s/ch.To adapt AXC makes OPWB be more practical by improving optical properties such as insertion loss and cross talk and by decreasing manufacturing cost due to avoiding cumbersome active alignment of active elements.

6126-13, Session 3

High-channel density optical interconnects using photonic crystal fibers

T. J. Shepherd, C. R. H. Bennett, D. M. Taylor, L. F. Michaille, QinetiQ Ltd. (United Kingdom)

Demanding real-time data processing applications are driving the need for high throughput programmable logic. Improvements to computing speed from reduction of processor feature sizes are predicted, but these are expected to be hampered within the next 2-5 years by the limitations of metallic interconnects between processors. Optical interconnect alternatives have been attempted, but independent optical channel densities are, at present, restricted by conventional fiber dimensions. In this paper a novel solution to this problem is presented employing a multi-core microstructured fiber. In this type of fiber - a photonic crystal fibre (PCF) - each core is a solid silica region surrounded by air holes shot through the length of the fiber. This is created by stacking capillaries and solid canes of silica (forming cores) to create a preform, with the structure preserved after drawing down; a core may be created by omitting an air hole. The criteria for the fiber design will be discussed: a bit error rate restriction leads to an upper limit for cross-coupling between cores and hence the distance (or number of air holes) between each channel. Modelling indicates a final fiber design containing 37 cores 31.25 microns apart, equivalent to a density of 1150 independent channels per millimetre squared. Details of an optical transmitting/receiving system utilising four of the channels and arrays of VCSELs as transmitters and receivers will be described. Future improvements to the system will also be discussed.

6126-16, Session 4

Efficient optical communications using multibit differential signaling

D. M. Chiarulli, S. P. Levitan, S. J. Dickerson, J. D. Bakos, J. R. Martin, Univ. of Pittsburgh

We present an alternative signaling method for multi-channel fiber ribbon based optical links. The method is based on a hybrid of differential signaling and single-ended channels. Channels are grouped into code blocks of N-bits. Each code word transmitted in the block is restricted to conform to an N choose M rule. Electrical drivers steer current between M active VCSELS with no dummy loads. A virtual reference is synthesized from the received signals and used for differential discrimination. This signaling method approaches the signal-to-noise characteristics of fully differential signaling but can be implemented with significantly lower channel overhead giving a 33% reduction in fiber count and 44% reduction in power. Further, code utilization rates on these links can be as low as 51%, leaving substantial code space available for ECC or channel management functions. We describe the signaling method and present an example system implemented in a system-in-package module based on 0.25um UTSi Silicon on Sapphire and 10GHz VCSEL sources. The design is electrically and mechanically compatible with the popular POP4-MSA transceiver standard with a net transfer rate of 40Gbs over 6 fibers.

6126-17, Session 4

Multimode fibers with integrated optical mode field adapters for 40Gbit/s optical ethernet systems

U. H. P. Fischer, T. Windel, S. Hemrungrote, Hochschule Harz (Germany)

The demand for high-speed digital communication such as data, video, and the broadband Internet increases, the required throughput of the modules in communications systems will also increase. Ethernet is well established up to 10Gbit/s in local area networks. Now the next extension up to 40 Gbit/s is in the definition phase and several development steps must be performed. As in well known SDH-long-haul optical transmission systems, fast transmitter and receiver modules are basic elements of these systems, respectively. These devices are connected with optical and electrical interfaces for the transmission of data. In the optical transmission line the coupling of the optical output of the laser diodes into the optical fiber and reverse at the end of the transmission line to the photodiode with high efficiency and low cost is until now a challenge for optical communications industry to provide high coupling efficiency in stable modules at affordable prices.

In this paper we present the fabrication of optical mode field adaptors, which act as a micro lens, for 40Gbit/s Ethernet fiber optical communications devices with newly developed type of a 50μm core graded index multimode fiber (GI-MMF), capable up to 40Gbit/s data over 1km. The mode field adaptors were used to focus the optical output field (1550nm wavelength) of the GI-MMF onto a photodiode with 10μm active region. The work was performed in cooperation with the Heinrich-Hertz-Institute in Berlin, who performed the system tests in their well known 40Gbit/s ring test bed. To characterise the output field distribution, we developed a new method for spot size measurement for multimode optical components, which is applicable in mass production. Based from the classical far field-method where the measurements are made circular, the mounting of the used rotary stages and the long measurement time are great disadvantages. The new method is working planar, which overcomes these problems and opens the possibility to characterize optical mode fields of arrayed fibers, passive waveguides or laser bars very fast. The method will be described in comparison to common far field and near field techniques.

The mode field adaptors are fabricated by drawing/melting in a fusing process. A reliable method was found to manufacture reproducible spot-size adaptors with radii from 5μm to 90 μm. A study of more than 50 devices with identical drawing parameters was performed. The average fiber end radius of 10.1μm was accomplished with a very small standard deviation of =0.16μm. The maximum detected values for the fiber lenses were 9.8μm and 10.27μm. Additionally BPM (OPTIWAVE) simulation are performed to predict the spot sizes at different fiber end diameters. To compare the results with ray tracing simulations which are more applicable with multimode fibers, a cooperation with the University of Siegen/ Germany was performed.

6126-18, Session 4

Highly integrated plastic package transceiver modules for large core fiber systems

F. H. W. Ho, B. Lui, W. Hung, F. Tong, T. Choi, S. Yau, G. Egnisaban, T. Mangenete, A. Chow, E. Wong, A. Wong, S. K. Cheng, E. Cheung, T. Wipiejewski, Hong Kong Applied Science and Technology Research Institute Co. Ltd. (Hong Kong China)

We have developed highly-integrated ultra small form factor fiber optic transceiver (FOT) modules using plastic packaging technologies for large core fiber systems (PCS or POF). The transmitter module contains a VCSEL and a driver IC. It can be operated from Mbps to Gbps. An internal control circuit stabilizes the optical output power to within 0.5dB variation over the wide ambient temperature range from -40°C to +125°C. Eye diagrams at 50Mbps are wide open over the normal operating temperature range from -40°C to +105°C. The extinction ratio is larger than 10dB and the uncorrelated jitter is less than 150ps. For 50Mbps data rate, the fiber optic receiver module consists of a Si-pin photodetector (PD) and a transimpedance amplifier (TIA). The eye diagrams at 50Mbps and -24dBm OMA input are wide open over the entire temperature range from -40°C to +105°C. The uncorrelated jitter is less than 800ps. For high data rates up to the Gb/s range, a GaAs metal-semiconductor-metal (MSM) PD is used in the receiver module. With a pair of VCSEL transmitter and MSM-PD receiver we achieve 1.25Gb/s transmission over 10m of polymer cladded silica (PCS) fiber. The leadframe style package exhibits a compact small size of 9.7mm x 6.2mm x 3.6mm. It provides loose alignment tolerances of ±100um in lateral axis for a working distance of 500um to a 200um core PCS fiber. The transmitter module is highly reliable and stable over 1000 temperature cycles from -40°C to +125°C and also over 1000 hours at 85°C/85% damp heat condition.

These transceiver modules are well suited for automotive and industrial optical links, as well as home networking solutions.

6126-07, Session 5

Recent advances in photonics packaging materials

C. H. Zweben, Advanced Packaging Materials Consultant

Thermal deformation, thermal stresses, thermal management, and for some systems, weight, are critical photonics packaging issues. Coefficient of thermal expansion (CTE) mismatch affects reliability and performance, and leads to major compromises, such as use of ìsoft,î indium-based solders which have thermal fatigue and metallurgical problems. Heat removal limits laser diode power levels. For some systems, low-CTE thermal insulators are required. In the last few years, there have been revolutionary advances in low-CTE, thermally conductive and thermally insulating packaging materials. These materials, some of which are anisotropic, fall in six categories; monolithic materials, polymer matrix composites, metal matrix composites, ceramic matrix composites, carbon/carbon composites and advanced alloys. Composite reinforcements include a variety of fibers and particles. There are now over 15 low-CTE materials with thermal conductivities between that of copper (400 w/m-K) and 4X copper (1600 W/m-K). For comparison, traditional low-CTE packaging materials like copper/tungsten have thermal conductivities that are little or no better than that of aluminum (200 W/m-K) and high densities. There are also thermal insulators with low CTEs. Some advanced materials are low cost. Most have low densities and do not outgas. They have a wide range of electrical properties that can be used to minimize electromagnetic emissions or provide EMI shielding. Several are now in commercial and aerospace applications, including laser diodes packages, plasma displays, servers, laptops, heat sinks, thermally conductive low-CTE printed circuit boards, and printed circuit board cold plates. Advanced material payoffs include: improved thermal performance, reliability, alignment and manufacturing yield; reduced thermal stresses and heating power requirements; simplified thermal design; enablement of hard solder direct attach; weight savings up to 85%; size reductions up to 65%; and lower cost. This paper discusses the large and increasing number of

advanced composite and monolithic packaging materials, including anisotropic properties, development status, applications, using composites to increase manufacturing yield, lessons learned and future directions, including nanocomposites.

6126-19, Session 5

Advanced integration schemes for high-functionality/high-performance photonic integrated circuits

J. W. Raring, M. N. Sysak, A. Tauke-Pedretti, M. Dummer, Univ. of California/Santa Barbara; E. J. Skogen, Sandia National Labs.; J. S. Barton, S. P. DenBaars, L. A. Coldren, Univ. of California/Santa Barbara

Monolithically integrated photonic circuits offer tremendous advantages in optical networks such as high functionality, improved efficiency, decreased size, and lower costs. As the functionality demands on photonic integrated circuits (PIC) continues to increase, the circuits will inevitably require higher levels of integration complexity. With this complexity, the realization of an optimally performing device becomes a far more difficult task due to the design constraints often imposed by monolithic integration.

The widely-tunable photocurrent-driven wavelength converter is one such example as it requires the integration of widely-tunable lasers with semiconductor optical amplifiers (SOA), photodetectors, and modulators. The diverse functionality of these individual components results in performance trade-offs due to the use of common waveguide architectures within the components, degrading the performance of the overall device.

Here we present recent progress in integration technology that facilitates high performance SOAs, photodiodes, and quantum well (QW) electroabsorption modulators (EAM) to be fabricated on the same chip as the widely-tunable sampled-grating DBR (SG-DBR) laser. These novel approaches are anchored in our established offset-QW and QW intermixing SG-DBR laser integration platforms, requiring only a moderate increase in processing/growth complexity. The techniques include simple waveguide flares for improved SOA/detector saturation power and the growth of dual QW stacks in the epitaxial base structure for the realization of QW EAMs in the offset QW platform. Finally, we employ MOCVD regrowth for the definition of low optical confinement QWs and uni-traveling carrier photodiode structures over intermixed QW material for the realization of high saturation power/ high-speed SOA/photodiode receivers.

6126-20, Session 5

Two-dimensional scalable optical controlled phased-array antenna system

M. Y. Chen, Omega Optics, Inc.

No abstract available

6126-22, Session 5

Edge termination effects on finite aperture polarizers for polarimetric imaging applications at mid- and long-wave IR

A. A. Cruz-Cabrera, S. A. Kemme, J. R. Wendt, R. R. Boye, Sandia National Labs.; T. R. Carter, S. Samora, L&M Technologies

Polarimetric imaging applications at the 2 to 5 microns or Mid-Wave Infrared (MWIR) and the 8 to 12 microns or Long-Wave Infrared (LWIR) ranges use large pixel-count focal plane arrays (FPA) with small pixel size. This project is centered in designing, fabricating and testing micro-polarizers that work in the two wavelength regimes and intended for that type of FPAs. The micro-polarizers will be used in conjunction with a FPA in snapshot mode and will be in the near field of the imaging device. The pixel pitches for some commercial FPAs are small enough that the finite apertures of the polarizing devices may significantly affect their performance given that their aperture size varies between 3 and 5 waves. We are interested in understanding the effect on extinction ratio and transmitted TM polarization due to variations in the edge terminations of a polarizer with a small aperture. Edge terminations are the spaces between the first or last wire with the perimeter of the aperture of the polarizer. While this parameter has negligible effects on a larger polarizer, it will be significant for apertures that are about 3 to 5 waves. We will present data that indicates significant variation in performance due to edge terminations.

6126-23, Session 6

Fabrication of a hybrid electrical-optical printed circuit board (EO-PCB) by lamination of an optical printed circuit board (O-PCB) and an electrical printed circuit board (E-PCB)

E. Lee, Inha Univ. (South Korea)

(Invited Talk) We report on the fabrication of a novel, hybrid type electrical-optical printed circuit board (EO-PCB), by laminating a board of optical printed circuit board (O-PCB) and an electrical printed circuit board (E-PCB). The O-PCB is made of embedded polymer waveguides and the E-PCB is made of electrical circuits. We first fabricated the O-PCB carrying the embedded polymer waveguide. The embedded polymer waveguides are fabricated by UV-embossing technique on a polycarbonate film substrate of several hundred micron thickness. The fabrication procedures of the embedded waveguide arrays are as follows. First, an under-cladding polymer layer is embossed by integrated silicon molds onto a polycarbonate substrate. And then, the upper-cladding polymer is spin-coated over the waveguide layer. Waveguides are formed with cross-sectional width of 100 micron, the height of 100 micron and the length of 10cm. Finally, a layer of polycarbonate film is placed over the waveguide arrays. The E-PCBs carry electrical circuits to drive the VCSEL microlasers and detectors. The O-PCB board with embedded waveguide array is then placed between two electrical printed circuit boards in the form of a sandwich and a pressure is applied to laminate the entire E-PCB/O-PCB/E-PCB boards to produce the EO-PCBs. The polymer waveguide arrays are molded by embossing technique using a specially designed silicon mold, which can form the optical waveguide arrays and the 45 degree mirrors simultaneously. The integrated silicon molds are fabricated by dry etching or wet etching. The transmission data rates of the waveguide array at 850nm wavelength are measured to be 2.5Gbps and 10Gbps per channel.

6126-24, Session 6

Low-cost plastic micro-optics for board level optical interconnections

C. Debaes, M. Vervaeke, B. Volckaerts, J. Van Erps, L. Desmet, H. Ottevaere, P. Vynck, V. Gomez, A. Hermanne, H. Thienpont, Vrije Univ. Brussel (Belgium)

One of the grand challenges to solve the interconnection bottlenecks at the Printed Circuit Board (PCB) and Multi-Chip-Module (MCM) level, is to adequately replace the PCB and intra-MCM galvanic interconnects with high-performance, low-cost, compact and reliable micro-photonic alternatives.

In our labs at the Vrije Universiteit Brussel we are therefore focusing on the continuous development of a rapid prototyping technology for micro-optical interconnect modules, which we call Deep Lithography with Protons (DLP). The special feature of this prototyping technology is that it is compatible with commercial low-cost mass replication techniques such as micro injection moulding and hot embossing. We will address more specifically in this talk the following components:1) out-of-plane couplers for optical wave-guides embedded in PCB, 2) peripheral fiber ribbons and two dimensional single- and multimode fiber connectors for high-

speed parallel optical connections, and 3) intra-MCM level optical interconnections via free-space optical modules.

We furthermore give special attention to the optical tolerancing and the opto-mechanical integration of the components. We use both a sensitivity analysis to misalignment errors and Monte Carlo simulations. It is our aim to investigate the whole component integration chain from the opto-electronic device to the micro-opto-mechanical components constituting the interconnect module. We focus our study to the tolerancing of the intra-MCM free-space optical interconnection module which includes a high density optoelectronic device array, a spacer and micro-balls for assembly and height control. Both the technological requirements to ensure a high process yield and the compliance of the specification to the DLP fabrication technology are discussed.

6126-25, Session 6

Integrated waveguide and microoptic elements for board-level optical interconnects

A. L. Glebov, M. G. Lee, S. Aoki, S. D. Zhou, K. Yokouchi, Fujitsu Labs. of America

The main building blocks of the waveguide-based board-level optical interconnects (OI) are the waveguides and embedded microelements such as 45∫ vertical mirrors enabling a variety of three dimensional routing architectures. Optical polymers proved to be the materials of choice for the large-scale OI modules with propagation dimensions exceeding 10 cm. In order to meet the loss budget available for the integrated OI modules, the polymers are expected to have optical losses less than 0.05 dB/cm. Both channel and slab waveguides can be used to transmit signals between the input and output ports. In the case of channel waveguides, the critical issues are the waveguide core shaping, propagation losses and ability to form various passive elements such as bends, crossings, splitters etc. In the case of slab waveguides, two dimensional waveguide microlenses have to be designed to collimate the light beams for propagation at larger distances with controllable beam divergences. 45∫ micromirrors can be used to couple the light signal in and out of the waveguiding layer. Although a number of micromirror fabrication solutions have been demonstrated, only a few can be fully integrated with waveguides into multilayer structures. In this work, we will present the experimental and computational results on the development of different waveguide devices and microelements for the board level OI. The OI modules integrating those elements are fabricated and signal transmission at \>10 Gbps data rates is demonstrated.

6126-26, Session 6

Hyperboloid solgel microlens array fabricated by soft-lithography for optical coupling

M. He, J. Bu, Nanyang Technological Univ. (Singapore); X. Yuan, Nanyang Technological Univ. (Singapore) and Shenzhen Univ. (China); H. Niu, X. Peng, Shenzhen Univ. (China)

It is known that the best way to correct spherical aberrations is the use of aspheric microlenses in optical systems, where a single aspheric microlens can be employed to replace a compound of spherical microlenses in a compact design. However the fabrication of aspheric microlenses is often complex because expensive high-energy beam-sensitive (HEBS) gray scale mask is needed in the fabrication process. In this paper, we reported a cost-effective fabrication method, with a combination of the sample-inverted reflow technique and the soft lithography replication method, to fabricate hyperboloid refractive microlens arrays (MLAs) in the inorganic-organic hybrid SiO2/ZrO2 sol-gel material. The fabrication procedures involved two basic steps. Firstly, a master of hyperboloid MLA was made in photoresist by the sample-inverted reflow technique. Secondly, a negative mold of the master was built by casting polydimethylsiloxane (PDMS) to a silicone elastomer against the master, and then the profile was impressed onto the sol-gel glass. As a result, the fabricated sol-gel MLAs have been obtained with excellent smooth profiles, having negligible discrepancies from the profiles of the ideal hyperboloid MLAs. The root-mean-square roughness values (Rq) of the surface of MLA were measured as 1.2 nm in the central areas and 2.1 nm in the outskirts of the lens. In an application of coupling a laser diode (LD) to a single-mode fibre (SMF), we proposed a two-MLA coupling scheme where two revolved-hyperboloid MLAs were used between the LD and the SMF. In this configuration, the coupling efficiency has achieved 83.4% (-0.79 dB).

6126-27, Session 6

Fabrication of SIL array of glass by surface-tension mold technique

T. Kishi, S. Shibata, T. Yano, Tokyo Institute of Technology (Japan)

A microlens array of the super-spherical glasses was fabricated by a combination of the photolithography and the Surface-tension Mold (StM) techniques. A super-spherical lens has been gathering much attention because of its function as a Solid Immersion Lens (SIL) with the super-resolution, which circumvents the optical diffraction limit. However, it is very difficult to obtain the desirable SILs using conventional method such as the mechanical polishing of spherical glasses because they require high precision of the dimension of the sub-micrometer order. StM technique enables the preparation of a micrometer-sized SIL (μ-SIL) with the desirable shape, and the obtained SILs realize the optical function. In order to develop the optical micro-devices composed of SILs, the combination of the micro-fabrication techniques like photolithography with StM technique is required. In the present work, a thin glass film on a substrate was cut into the aligned array structure by a photolithography process, and a subsequent heat treatment of StM technique was carried out to fabricate the μ-SIL array. Na2O-CaO-SiO2 glass film was prepared by the mold press technique using silicon carbide, and etched into glass tiles with the dimention of 10-100μm square after the formation of masks by the photolithography. Then they were heated up to 800∫C to self-organize into the super-spherical form of the glass droplets. The obtained lens array was found to be composed of the SILs with the uniform radius and thickness, having the functionality of the super-resolution of the μ-SIL.

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6127-01, Session 1

To be announced

C. K. N. Patel, Pranalytica, Inc.

No abstract available

6127-02, Session 1

Improved performance of quantum cascade lasers utilizing epi-down mounting

A. G. Tsekoun, R. Go, M. Pushkasrsky, Pranalytica, Inc.; M. Razeghi, Northwestern Univ.; C. K. N. Patel, Pranalytica, Inc. and Univ. of California/Los Angeles

We report substantially improved performance of high power quantum cascade lasers by utilizing epitaxial side down mounting that provides superior heat dissipation properties. We have obtained CW power output of 400 mW at 25∞C from mid-IR QCLs. The improved thermal management achieved with epi-side down mounting has also permitted us to carry out life time tests on the mid-IR QCLs. No degradation of power output is seen even after 500 hours of CW operation with power output well in excess of 200 mW. We believe these improvements should permit incorporation of mid-IR QCLs in reliable instrumentation.

6127-03, Session 1

High power, continuous-wave, quantum cascade lasers for MWIR and LWIR applications

S. Slivken, A. J. Evans, J. Nguyen, J. Yu, S. R. Darvish, K. Mi, M. Razeghi, Northwestern Univ.

It has been a dream for many years to have a high power, compact source of mid- and far-infrared radiation. The quantum cascade laser (QCL) is an important technology that is capable of meeting these goals. While pulsed operation and high peak output power at room temperature has been observed over a wide wavelength range (3.4-16 μm), the average output power has suffered due to low duty cycle (pulse width/pulse period) limitations to the device operation. High average power delivery is necessary for remote applications and some forms of spectroscopy (e.g. photoacoustic). For high resolution spectroscopy, the preferred operating mode is actually in continuous-wave, which avoids spectral broadening due to thermal chirp in pulsed lasers.

One of the main limitations to achieving continuous-wave operation of QCLs at room temperature has been a high threshold current density (\>2 kA/cm2). This leads to rapid heating at typical operating voltages (\>10 V), which causes the laser efficiency to drop significantly. In addition, at any power, internal heat must be efficiently dissipated into the laser submout.

Keeping these limitations in mind, lasers were designed to have a low threshold current density and a core that can operate at temperatures well above 400 K. From a development standpoint, several requirements must be met. 1) Laser active elements were designed with an increased energy budget and activation barriers to make them less sensitive to temperature. At shorter wavelengths, this involves the use of strain-balanced heterostructures, which allows for a deeper quantum well without changing the material system. 2) The laser waveguide materials, thicknesses and doping were chosen to exhibit extremely low losses due to free-carrier and surface plasmon absorption while providing a high thermal conductance surrounding for the laser waveguide core. 3) The material quality was optimized to give narrow x-ray diffraction and photoluminescence features. In addition, the doping level and distribution in the entire laser heterostructure was carefully monitored and controlled. 4) The laser geometry and packaging were theoretically analyzed and experimentally optimized for maximum performance under current technological limitations.

The systematic optimization of laser performance has allowed for demonstration of high power, continuous-wave quantum cascade lasers operating above room temperature. Since 2002, the power levels for individual devices have jumped from <20 mW to >600 mW . Expanding on this development, we have able to demonstrate continuous wave operation at many wavelengths throughout the mid- and far-infrared spectral range, and have now achieved >100 mW output in the 4.3< *<9.5 μm range.

In addition to maximizing performance for Fabry-Perot lasers, we also have investigated single-mode QCLs, which incorporate buried, first-order diffraction gratings (DFB-QCLs). This technology has also demonstrated >100 mW continuous-wave operation at room temperature and can scale to other wavelengths in a straightforward manner.

6127-04, Session 1

High-power distributed-feedback and Fabry-Perot quantum cascade lasers

J. R. Meyer, W. W. Bewley, J. R. Lindle, C. Kim, I. Vurgaftman, Naval Research Lab.; B. Gokden, A. J. Evans, J. Yu, S. R. Darvish, S. Slivken, M. Razeghi, Northwestern Univ.

Rapid progress in the development of quantum cascade lasers (QCLs) has recently led to demonstration of the first semiconductor mid-IR sources capable of emitting high cw powers at ambient temperature and above. - The cw Tmax reached 340 K, and 640 mW was produced at T = 295 K (* = 6.0 μm) with a wallplug efficiency of 4.5%. In this presentation, we report further breakthroughs in the development of quantum cascade lasers (QCLs) that emit high powers at room temperature. Strain-balanced InGaAs/InAlAs structures were grown on InP substrates by MBE at Northwestern. Stripes of width 13 μm were chemically etched and coated with SiO2 to form index-guided ridges.

Single-mode output is preferable for many applications. While numerous distributed-feedback (DFB) QCLs have been demonstrated previously, cw operation was never reported above 303 K, and no more than a few mW was generated at any temperature accessible with a thermoelectric cooler. However, we report here the fabrication and characterization of the first high-power mid-IR DFB lasers, which emit \> 100 mW cw into a single mode at room temperature. Figure 1 illustrates the L-I characteristics of a DFB QCL operating at * 4.8 μm. The power at 200 K exceeds 350 mW, and cw operation continues to 333 K. That the DFB output is single-mode is illustrated in Fig. 2, which plots the spectral intensity on a semi-log scale. At both 200 K and 298 K, the FWHM is 1 ≈ (instrument-limited) and the side-mode suppression ratio exceeds 25 dB. Robust single-mode emission was maintained for all of the currents and temperatures investigated.

Recently-studied devices have ranged in wavelength from 4.8 μm to 7.3 μm. In all cases, cw output powers exceeding 100 mW were obtained at room temperature. Far-field characterizations show that the quality of the single-lobed output beam is better than twice the diffraction limit along both axes under all operating conditions tested.

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6127-05, Session 2

Waveguides with uniaxially patterned layers

S. Luryi, A. V. Subashiev, Stony Brook Univ.

Semiconductor structures with cylindrical pores forming a 2-d periodic lattice are actively studied for photonic bandgap applications. In the long wavelength limit such a structure can be well described as an effective medium possessing the symmetry of a uniaxial crystal and the optical anisotropy that can be externally controlled. We discuss the effects of patterning the cladding or the core layer of an slab waveguide on the polarization properties of propagating radiation. These effects enable numerous optical devices that are sensitive to the shape and the polarization of the optical mode, such as polarizers, lasers, amplifiers and modulators.

The control of polarization properties of a uniaxially patterned (UAP) layer is obtained by varying its fill-factor, e.g., the density of pores. They can be further fine-tuned by changing the optical contrast between the waveguide constituents with an applied field or optical pumping. We show that the cutoff thicknesses and modal propagation constants in asymmetric waveguides with a thin core layer are sensitive to both the permittivities of the layers and their patterning. Small variations of the propagation constants will change the ratio of the modal confinement factors. In waveguides based on III-V heterostructures, the index contrast between the core and the cladding layers is weak, so that the modal competition takes place at small values of filling factor and for a thin core. The region were modes compete can be made substantially larger in asymmetric waveguides with properly chosen layer compositions.

Under high illumination the photo-induced concentration of free electrons can be large enough for a substantial change of the permittivity, effecting the polarization switch in a UAP waveguide. Using materials with a short carrier lifetime, the switching time can be made very short, thus providing an ultrafast all-optical modal control. Polarization switching can be most easily achieved with asymmetric structures with the optical excitation energy above the absorption edge of the cladding layer but below the absorption edge of the substrate layer.

UAP waveguides can also be exploited in resonant-layer devices, vertical directional couplers and filters, and leaky waveguides. UAP layers bring polarization control to such devices.

Gradual lateral variation in the density of pores in a UAP cladding layer can be used for shaping the mode field in the laser stripe. In this way one can achieve desirable properties, similar to those obtained by the parabolic stripe etching or the parabolic variation of the material index. Implementation of the proposed devices is within a reasonable range of lithographic and material parameters.

6127-06, Session 2

Recent progress is short wavelength quantum cascade lasers

C. Sirtori, Thales Research & Technology (France)

No abstract available

6127-07, Session 2

Room temperature midinfrared laser absorption spectrocopy in hollow optical waveguides

G. J. Fetzer, A. S. Pittner, W. L. Ryder, Areté Associates

A discussion of a mid infrared laser absorption spectrometer which utilizes hollow optical waveguides and a room temperature Continuous Wave Quantum Cascade laser is discussed. The device is being developed to analyze trace gases in exhaled breath. The focus of this discussion will be on characterization of the system and a presentation of the results achieved using mixtures of laboratory gases.

6127-08, Session 3

To be announced

Q. Hu, Massachusetts Institute of Technology

No abstract available

6127-09, Session 3

Optimizing short-wavelength performance and injector doping concentration of InP-based quantum cascade lasers

C. Mann, Q. Yang, W. Bronner, K. Köhler, F. Fuchs, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

The short-wavelength limit of practical InP-based quantum cascade lasers (QC lasers) as well as the dependence of their performance on the injector doping concentration is investigated. For the first purpose QC lasers based on different designs covering the 4.7 to 5.4 μm wavelength range were fabricated. The conduction band discontinuity DEc was either 510 meV for devices based on lattice-matched GaInAs/AlInAs or 710 meV for QC lasers employing strain-compensated heterostructures. Increasing DEc and/or the emission wavelength results in an increased effective barrier height, leading to an improved confinement of the electrons in the upper laser level. Thus the high-temperature performance of short-wavelength QC lasers is limited by the available conduction band discontinuity.

For applications in spectroscopic sensing employing high-resolution absorption spectroscopy of molecular species, single-mode distributed feedback (DFB) QC lasers were fabricated for the detection of carbon monoxide (CO) around 4.7 μm wavelength and of nitric oxide (NO) around 5.4 μm. Operated in pulsed mode the maximum operating temperature of these devices exceeds 400 K with a side mode suppression ratio (SMSR) > 27 dB.

Finally, the dependence of the device performance on the injector doping concentration was investigated for QC lasers emitting around 9.3 μm wavelength. For moderate sheet doping densities Ns in the 1e11 to 3e11 cm-2 range the threshold current density Jth is found to increase linearly with Ns. The maximum emitted optical power is determined by the current density Jmax that corresponds to the operating voltage at which misalignment of the conduction subbands of the QC laser structure occurs. Also Jmax is found to depend on the injector doping concentration such that the “dynamic range”, defined as Jmax-Jth, increases linearly with Ns in the investigated range. Hence there exists no optimal value of Ns per se. In fact the injector doping concentration has to be adjusted individually depending whether emphasis is placed on obtaining low threshold current densities or on high power operation.

6127-10, Session 3

Pixilated wideband achromatic waveplates fabricated for the mid-IR using subwavelength features

R. R. Boye, S. A. Kemme, J. R. Wendt, A. A. Cruz-Cabrera, Sandia National Labs.; T. R. Carter, S. Samora, L&M Technologies

Subwavelength diffractive features etched into a substrate lead to form birefringence that can be utilized to produce polarization sensitive elements such as waveplates. Using etched features allows for the development of pixilated devices to be used in conjunction with focal plane ar-

rays in polarimetric imaging systems. Typically, the main drawback from using diffractive devices is their high sensitivity to wavelength. Taking advantage of the dispersion of the form birefringence, diffractive waveplates with good achromatic characteristics can be designed.

We will report on diffractive waveplates designed for minimal phase retardation error across the 2-5 micron spectral region. The required fabrication processes of the sub-wavelength feature sizes will be discussed as well as the achromatic performance and transmission efficiency of final devices. Previous work in this area has produced good results over a subset of this wavelength band, but designing for this extended band is particularly challenging. In addition, the effect of the finite size of the apertures of the pixilated devices is of particular interest since they are designed to be used in conjunction with a detector array. The influence of small aperture sizes will also be investigated.

6127-11, Session 3

Cavity ring-down spectroscopy with pulsed distributed feedback quantum cascade laser

A. P. Lytkine, O. Sukhorukov, W. Jäger, J. Tulip, Univ. of Alberta (Canada)

A pulsed distributed feedback quantum cascade laser (QCL) operating near 10.3 μm (Alpes Lasers) was used as a source in cavity ring-down spectroscopy experiments. A ring-down cavity (RDC) was formed in open air by two concave mirrors (reflectivity 99 or 99.5 %) with radius of curvature of 1 m; the distance between the mirrors was varied in the range between 20 and 65 cm. The mirrors in standard optical mounts were fixed on an optical table and aligned with a He-Ne-laser. An aspheric lens was used to obtain a collimated QCL beam with diameter corresponding to the diameter of the TEM00 mode of the RDC. The peak power of the QCL after the collimating lens did not exceed 0.2 W. The QCL frequency was tuned at a rate of about 8*10-2 cm-1/K by changing the heat sink temperature in the range between-30 and + 30 0C. Several absorption peaks of CO2 were recorded by measuring the decay time with CO2 flowing through an open tube placed between the CRD mirrors. We demonstrated that a detection limit of ammonia of 20 ppb can be attained with the arrangement described. Basic instrumental performance and limitations to the sensitivity due to frequency chirp of pulsed QCL will be presented. Proposals for sensitivity improvement and the development of rugged and sensitive field-usable gas sensors based on a pulsed QCL coupled to an unlocked RDC will be discussed.

6127-12, Session 4

To be announced

G. A. Mourou, École Nationale Supérieure de Techniques Avancées (France)

No abstract available

6127-13, Session 4

High power vertical external cavity surface emitting lasers and their applications

M. Fallahi, College of Optical Sciences/The Univ. of Arizona

Optically pumped vertical-external-cavity surface-emitting lasers are very attractive for their high power and excellent beam quality, making them suitable for a range of commercial and defense applications. In this talk I present the development and demonstration of multi-watts high-brightness vertical-external-cavity surface-emitting lasers (VECSELs). The performances of single-well and dual-well resonant periodic gain structures are presented. Over 10 W TEM00 CW output with high efficiency is demonstrated. Tunable multi-watts VECSELs with over 20 nm tuning range and narrow linewidth is achieved. The latest developments and future directions are discussed.

6127-14, Session 4

High-performance optical modulators based on stepped quantum wells

H. Mohseni, Northwestern Univ.

High-speed and high-performance optical phase and amplitude modulators are critical components of many photonic systems. Semiconductor-based modulators are very attractive, since they can be monolithically integrated with other semiconductor devices. Unfortunately, the commonly used modulators based on square quantum wells have inherent properties that limit their modulation performance.

We will show that a new class of quantum wells called ‘stepped quantum wells’ (SQW) provides extra degrees of freedom that can be used to design much better optical modulators. We will demonstrate SQW phase modulators with nearly one order of magnitude higher efficiency than their counterparts. Also, linearized modulators based on SQW with more than two orders of magnitude higher linearity than the existing semiconductor modulators will be presented. Finally, high-performance surface-normal modulators based on SQWs with nearly two times better efficiency and 7 dB higher extinction ratio compared with the conventional devices with rectangular and coupledquantum well active layers will be demonstrated.

6127-15, Session 4

Recent advances in infrared laser diode system for paper cutting in digital printing applications

O. Acher, H. Pagès, H. Piombini, CEA Le Ripault (France)

Laser diodes have been associated to Digital Printing for laser printing and photofinishing. Laser diode systems are also more and more used for material processing applications. But up to now, laser diodes have not been used for direct processing of paper. This is mainly because conventional paper is white not only in the visible range, but also in the near infrared (NIR). As a consequence there is a very poor interaction between paper and NIR lasers. In contrast, CO2 laser have been successfully used for years in the paper conversion industry to cut paper, but there is no hope to scale down power and prices of this type of laser to adapt them to desktop mass-market environment.

We present here a significant advance that combines existing inkjet technology and solid-state NIR laser diodes to performed laser cutting and scoring of paper for desktop applications [1]. We show that using a specially formulated ink that is absorbing in the NIR, a conventional 1W laser diode can cut the paper along lines marked with this ink very efficiently and tidily. The efficiency of different types of ink is presented. Several Dyes with Near Infrared Absorbing properties are used to formulate inks that are jetted using a HP1600C Deskjet Printer. The influence of dye concentration and jetting parameters on the ability to laser-cut are discussed. Different types of laser diodes are also used, and results are compared.

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6127-16, Session 5

Ballistic electrophotonics

V. Narayanamurti, Harvard Univ.

The ballistic transport of hot electrons in semiconductors has long been a subject of interest. Over the last decade enormous progress has been made in the study of such transport by use of tunneling based hot electron (or hole) injectors.1 In this talk, I will present several exciting new results which have broad implications for the study of new semiconductor nanostructures including the transport of spin. These are:

1) Ballistic Electron Emission Luminescence2,3 (BEEL) which allows the simultaneous monitoring of electron transport and luminescence for quantum dot structures placed below the surface.

2) Demonstration of several new types of hot electron based devices involving the monitoring of spin transport. Examples include spin valve photodiodes4 and avalanche spin valve transistors.5

3) Transport and luminescence studies of semiconductor nanowires6 such as ZnON and GaN.

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6127-17, Session 5

Strain effects on the electronic properties of InAs/GaAs self-assembled quantum dots

J. Leburton, Univ. of Illinois at Urbana-Champaign

In this talk, we discussed the electronic properties of InAs/GaAs self-assembled quantum dots (SAD) with respect to their shapes, sizes and stoichiometric compositions with emphasis on the three-dimensional strain distribution and the piezoelectric potential. Distinctive shape-dependent features in the interband optical transitions of single, vertically stacked and laterally coupled SADs are presented. Particular attention is paid to the quantum Stark effect in single and vertically coupled lens-shaped and truncated-pyramidal SADs. Our analysis based on a 8-band k.p, strain and electric field-dependent Hamiltonian showed good agreement with various experiments.

*Work done in collaboration with W. Sheng and P. Moon

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6127-18, Session 5

Nanostructured semiconductors for optoelectronic applications

J. P. Reithmaier, Univ. Würzburg (Germany) and Univ. Kassel (Germany)

An overview is given about nanostructuring technologies based on self-assembly techniques during epitaxial growth as well as on high resolution lithography process technologies. As application examples, optoelectronic devices will be discussed for high power, telecom and sensor applications.

6127-19, Session 6

GaN quantum dots: nanophotonics and nanophononics

M. Dutta, D. Alexson, Univ. of Illinois at Chicago; J. Brown, P. M. Petroff, J. S. Speck, Univ. of California/Santa Barbara; M. A. Stroscio, Univ. of Illinois at Chicago and Univ. of California/Santa Barbara; T. Yamanaka, Univ. of Illinois at Chicago

Self-assembled GaN quantum dots are characterized using photoluminescence and Raman techniques. The electrical and optical properties of these GaN quantum dots are modeled in light of optoelectronic applications. Strain-induced changes in the phononic properties of these nanostructures are modeled and the strain-induced frequency shifts are compared with Raman measurements.

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6127-20, Session 6

Optical advanced spectroscopic techniques for the study of nanostructured materials

S. R. Lefrant, Univ. de Nantes (France)

Nano-materials are nowadays commonly used in various domains whenever they exhibit properties that are of interest in terms of applications. The preparation of such materials in good reproducibility requires pertinent characterization studies. To achieve this goal, new tools have been developed, besides the well-known transmission electron microscopy and near-field electrical microscopies such as AFM or STM. In particular, optical techniques are now under great progress with the use of Raman Scattering in improved confocal conditions, Surface Enhanced Raman Scattering (SERS) and near-field optical spectroscopy (SNOM). Applied successfully to individual molecules, these non-destructive techniques have also been used in the case of nano-materials and exploited in-situ to investigate in details modifications in the spectroscopic features of the studied materials embedded in host matrices.

In this presentation, we will review the most recent developments of these new optical spectroscopies and illustrate their usefulness by describing few examples, such as the different types of functionalization encountered in carbon nanotubes and carbon nanotubes/conducting polymers nano-composites.

6127-21, Session 6

Fabrication of GaN nanotubular material using MOCVD with aluminum oxide membrane

W. Jung, S. Jung, Kookmin Univ. (South Korea); P. Kung, M. Razeghi, Northwestern Univ.

GaN nanotubular material has been fabricated with aluminum oxide membrane in MOCVD. SEM, XRD, TEM and PL were employed to characterize the fabricated GaN nanotubular material. The aluminum oxide membrane having ordered nano holes was used as template. The gallium nitride was deposited inner wall of the nano holes in aluminum oxide template, and the nanotubualr material with high aspect ratio was synthesized using the precursors of TMG and ammonia gas. The optimal synthesis condition for the gallium nitride nanotubular material was obtained in the present work. The GaN nanotubular material consisted of many fine GaN particulates with size of 15 ~ 30 nm. The composition of GaN was confirmed to be stoichiometically 1:1 for Ga and N by EDS. XRD and TEM analysis indicated that grains in GaN nanotubes have crystalline structure. The diameter of GaN nanotube fabricated was approximately 200 ~ 250 nm and the wall thickness was about 40 ~ 50 nm. No blue shift was found in the PL spectrum on the GaN nanotubular material fabricated in aluminum oxide template.

6127-22, Session 7

Colloidal quantum dots as optoelectronic elements

M. A. Stroscio, D. Alexson, M. Dutta, D. Geerpuram, Univ. of Illinois at Chicago; N. A. Kotov, Univ. of Michigan; Y. Li, D. Ramadurai, P. Shi, Univ. of Illinois at Chicago; Z. Tang, Univ. of Michigan

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.

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6127-23, Session 7

InAs quantum dot infrared photodetectors on InP by MOCVD

W. Zhang, H. Lim, M. Taguchi, S. Tsao, J. Szafraniec, A. A. Quivy, B. Movaghar, M. Razeghi, Northwestern Univ.; V. Nathan, Air Force Research Lab.

Here we report our recent results of InAs quantum dots grown on InP substrate by low-pressure metalorganic chemical vapor deposition (MOCVD) for the application of quantum dot infrared photodetector (QDIP). We have previously demonstrated the first InP-based QDIP with a peak detection wavelength at 6.4 μm and a detectivity of 1010cmHz1/2/W at 77K. Here we show our recent work toward shifting the detection wavelength to the 3-5 μm MWIR range. The dependence of the quantum dot on the growth conditions is studied by atomic force microscope, photoluminescence and Fourier transform infrared spectrometer. The device results from the MWIR InAs/InP QDIP are discussed. Right now the performance of QDIPs is still far below the predicted potential, and one of the reasons is the low quantum efficiency. Resonant cavity enhancement is one possible way to increase the quantum efficiency of QDIPs. Different schemes for cavity enhancement and preliminary experimental results are reported.

6127-24, Session 7

InGaAs/InGaP quantum-dot infrared photodetector with a high detectivity

J. Szafraniec, S. Tsao, A. A. Quivy, W. Zhang, H. Lim, M. Taguchi, B. Movaghar, M. Razeghi, Northwestern Univ.; M. Z. Tidrow, Missile Defense Agency

Quantum-dot infrared photodetectors (QDIP) have recently been considered as strong candidates for numerous applications such as night vision, space communication, gas analysis and medical diagnosis involving middle and long wavelength infrared (MWIR and LWIR respectively) operation. This is due to their unique properties arising from their 3-dimensional confinement potential that provides a discrete density of states. They are expected to outperform quantum well infrared photodetectors (QWIP) as a consequence of their natural sensitivity to normal incident radiation, their higher responsivity and their higher-temperature operation. So far, most of the QDIPs reported in the literature were based on the InAs/GaAs system and were grown by molecular beam epitaxy (MBE). Here, we report on the growth of a high detectivity InGaAs/InGaP QDIP grown on a GaAs substrate using low-pressure metalorganic chemical vapor deposition (LP-MOCVD). The peak responsivity decreased with temperature and had a value of 1.2 A/W at a peak detection bias of -0.9V at 77K at 4.7μm. The noise current in was measured using a Fast Fourier Transform spectrum analyzer. A noise current of 3.3x10-14A at -0.9V bias yielded a specific detectivity of 1.2x1012 cmHz1/2/W at 77K. Peak responsivities and specific detectivities of 190.5mA/W and 8.3x1010 cmHz1/2/W were still measured at 120K and peak detection bias of -0.6V. A BLIP temperature of 200K was determined with a 45∞ field of view and a 300K background.

6127-25, Session 7

Charge carrier transport in barrier ìin-macroporous siliconî structures

L. A. Karachevtseva, V. F. Onishchenko, F. F. Sizov, A. V. Sukach, V. F. Teterkin, Institute of Semiconductor Physics (Ukraine)

Charge carrier transport mechanism in barrier ìIn-macroporous siliconî structures has been investigated. Current-voltage, capacitance-voltage, photoelectrical and noise characteristics were analysed comparatively in structures of macroporous and single-crystal silicon. There has been designed manufacture technology of ohmic and barrier contacts on macroporous silicon as well as single-crystal silicon in the same technological cycle. The contacts were found to exhibit stable characteristics during six month period of time. The saturation of the reverse current at $0.2 \le U \le 1.0$ V was observed at high temperatures. The carrier transport mechanism in the investigated structures are determined by thermal activation mechanisms at room temperature and tunneling of carriers through the transient region at temperatures $T \le 180$ K. Capacitance-voltage characteristics are similar to those observed in the metal-oxide-semiconductor structures and are included capacitance of the oxide layer and the depletion region. The presence of the transient region between metal and silicon was confitmed by the photoresponse spectra of ìIn-macroporous Siî structures contained two pronounced peaks at the wavelengths 0.56 and 1.1 μm. The long-wavelength peak was observed for In contacts on single n-Si crystal prepared by the same method.

6127-26, Session 8

Space-based infrared technology for missile defense

M. Z. Tidrow, Missile Defense Agency

Infrared Technology is very important to space based sensing systems for missile defense. Space based sensing systems perform functions of search, track, and sometimes discrimination. Space based sensing systems endure a different environment from ground and airborne platforms and therefore have different sensor features. In this presentation, we will briefly introduce some facts about the earth atmosphere, different sensor platforms, target locations and satellite orbits. We will discuss how these facts affect the infrared detector selection and sensor design consideration when the infrared sensor is looking up, or looking down. We will also discuss space infrared sensor limitations and challenges, and the state-of-the-art infrared sensor technology development for space.

6127-27, Session 8

MCT research at the Night Vision Lab

J. Pellegrino, U.S. Army Night Vision & Electronic Sensors Directorate

No abstract available

6127-28, Session 8

Infrared lasers and detectors operating in the 3-12 um range using band-gap engineered structures with type II band-gap alignment

V. S. Swaminathan, Army Research Lab.

The Type II broken band-gap alignment in semiconductor structures wherein the conduction band minimum is in one semiconductor (e.g., InAs) and the valence band maximum is in another (e.g., GaInSb) offers certain unique advantages which can be utilized to realize band-gap engineered novel quantum electro-optic devices such as lasers and detectors. The advantages of the type II structures include reduced Auger recombination, extending the effective band-gap energy of materials wherein

type I band-gap alignment would give rise to difficulties such as miscibility gap. In this talk, the author will describe the work carried out at the Army Research Laboratory on type II semiconductor quantum electro-optic devices of interest to the Army such as IR lasers and detectors operating in the 3-12 um range. The talk will specifically cover the progress made in GaSb based type II Interband Cascade IR Lasers and strained layer superlattice IR detectors. It will also cover the recent work in self-assembled quantum dots with type II band-gap alignment with the matrix material in which they are embedded.

6127-29, Session 8

Influence of IR sensor technology on the military and civil defense

L. S. R. Becker, U.S. Army Space and Missile Defense Command

Advances in basic infrared science and developments in pertinent applications technology have led to mature designs being incorporated in the military as well as in civil area defense systems. Military systems include both tactical and strategic applications and civil area defense includes homeland security. Technical challenges arise in applying infrared sensors technology for detecting and tracking targets for space and missile defense. Infrared sensors are valuable due to their passive capability, lower mass and power consumption, and usefulness throughout all phases of missile defense engagements. Nanotechnology holds significant promise in near future by offering unique material and physical properties to infrared components and is experiencing rapid development in recent years.

This presentation will cover the current IR sensor technology, its applications and future development that influence military and civil defense applications.

6127-30, Session 9

High quantum efficiency long-wave infrared photodiodes using W- structured type-II superlattices

E. H. Aifer, J. G. Tischler, J. H. Warner, Naval Research Lab.; C. L. Canedy, E. M. Jackson, Naval Research Lab. and SFA Inc.; I. Vurgaftman, J. C. Kim, J. R. Meyer, L. J. Whitman, Naval Research Lab.

Recent improvements in material quality and design have led to large improvements in the quantum efficiency (QE) of long-wave infrared (LWIR) photodiodes based on W-structured type-II superlattices (WSL), which now achieve external QE of over 25%. While single band and dual band WSLs have been demonstrated with cutoff wavelengths out to 17 μm, these devices also showed significant losses of photo-excited carriers resulting in QE levels of 10% and less. Here we describe recent results in which these losses have been dramatically reduced by modifying WSL barrier layers to increase the mini-band width, by achieving low background impurity levels, and by improvements in material structural quality as evidenced by x-ray diffraction and cross-sectional scanning tunneling microscopy. As a result, minority carrier diffusion lengths have increased to 3-5μm, allowing for much higher collection efficiency in PIN photodiodes with intrinsic regions up to 3 μm thick.

6127-31, Session 9

Performance characteristics of high-purity mid-wave and long-wave infrared type-II InAs/GaSb superlattice infrared photodiodes

A. D. Hood, E. J. Michel, F. Fuchs, M. Razeghi, Northwestern Univ.; V. Nathan, Air Force Research Lab.; E. H. Aifer, Naval Research Lab.; M. Z. Tidrow, Missile Defense Agency

The authors report on recent advances in the development of mid and long wavelength infrared (MWIR and LWIR) type-II InAs/GaSb superlattice infrared photodiodes. The residual carrier background of binary type II InAs/GaSb superlattice photodiodes cut-off wavelengths around 5 and 10 μm has been studied in the temperature range between 10 and 200 K. A four-point, capacitance voltage technique on mid wavelength and long wavelength type-II InAs/GaSb superlattice infrared photodiodes reveal residual background concentrations around 1◊1015 cm-3. Below 100 K carrier freeze-out is observed with a thermal activation energy of 4.5 meV, leading to net carrier concentrations at 77 K in the mid 1014 cm-3. Additionally, recent progress towards LWIR photodiodes for focal plane array imaging applications is presented. Single element detectors with a cut-off wavelength, *c,50%, of 10 μm demonstrated detectivities of approximately 6 1010 cmHz1/2W-1 and a quantum efficiencies of 25% at the peak responsivity wavelength of around 7.5 μm. The latest developments in this material system lend further suppSort for its use as a high-performance alternative for infrared optical systems compared to the current state-of-the-are imaging systems, especially those approaching the LWIR and very long wavelength infrared.

6127-32, Session 9

Optical performance of InAs/GaSb superlattice LWIR detectors

G. J. Sullivan, Rockwell Scientific Co., LLC

InAs/GaSb short period superlattice photodiodes are attractive candidates for LWIR and VLWIR imaging applications. Recent results have demonstrated impedances and quantum efficiencies approaching those of HgCdTe photodiodes. The optical performance of these detectors will be reviewed, and particularly their suitability for use in hybrid focal plane arrays.

6127-33, Session 9

Single- and two-color HgTe/CdTe-superlattice based infrared detectors

C. H. Grein, P. Boieriu, EPIR Technologies, Inc.; M. E. Flatte, The Univ. of Iowa

The optimal performance of HgTe/CdTe superlattice-based LWIR (8-12um cutoff wavelengths) and VLWIR (greater than 12um cutoff wavelength) photovoltaic detectors is assessed theoretically. The electronic band structures and optical absorption spectra are computed with a fourteen-band restricted-basis envelope function Hamiltonian. Auger and radiative lifetimes are computed with these accurate band structures. Vertical carrier mobilities are obtained from a Monte Carlo transport methodology. Single and two-color photon detectors are modeled by solving current continuity and Poisson's equaltions. Upper bounds to dector diffusion-limited detectivities are presented. Predictions are compared with those for HgCdTe-alloy based detectors. We also present preliminary results for MBE-grown detectors based on these designs.

6127-34, Session 10

SOI diode uncooled focal plane arrays

M. Kimata, Ritsumeikan Univ. (Japan); M. Ueno, M. Takeda, T. Seto, Mitsubishi Electric Corp. (Japan)

Uncooled infrared focal plane array (UC IRFPAs) is the infrared imager with thermal detectors. While various types of UC IRFPAs have been proposed with different temperature sensors, SOI diode UC IRFPAs discussed in this paper uses single crystal diodes to measure the temperature at freestanding pixel structures. This type of UC IRFPA offers many advantages in connection with the Si LSI technology. We have developed two pixel structures for the SOI diode UC IRFPA. One is for relatively large pixels and has a two-level structure. We have developed a 40um pixel 320x240 UC IRFPA with this structure. The other has a three-level structure with an independent infrared reflector between the base level and

top infrared absorbing structure. The latter pixel structure enables us to design smaller pixels with higher thermal isolation and higher infrared absorption. Using the latter pixel structure, we have developed a 320x240 and 640x480 UC IRFPAs with 25um pixels. This paper reviews development of SOI diode UC IRFPAs.

6127-35, Session 10

High-quantum efficiency dual band C-QWIP detectors

J. W. Devitt, D. P. Forrai, D. Endres, R. Rawe, L-3 Communications Cincinnati Electronics, Inc.; K. K. Choi, V. S. Swaminathan, Army Research Lab.; A. M. Sarangan, Univ. of Dayton

Current generation QWIP detectors, although very cost effective, have relatively narrow spectral range and low quantum efficiencies. Tactical operation is generally limited to a single spectral band. These limitations arise from the design approach and restrict applications to those that can tolerate these performance limitations.

Using recent device design improvements, a novel material, and special processing approaches, High Quantum Efficiency Dual Band C-QWIP detectors are currently being developed. These are expected to overcome traditional limitations in the QWIP design approach and deliver extremely high performance.

In the first phase of the program, single color LWIR and VLWIR C-QWIP FPAs in large (1024×1024) format will be demonstrated with targeted peak quantum efficiency of 35%, and correspondingly high BLIP operating temperatures. In the next phase of the program, the team will continue to improve QE towards 50% with conversion efficiency of 75%, and demonstrate dual band MW/LW FPAs. The detector gain will be optimized for operation in either low background or high background applications. These goals will be accomplished using highly producible/low cost materials and processes.

This work is being carried out by the Army Research Lab, L-3 Cincinnati Electronics, and the University of Dayton, under funding provided by the Missile Defense Agency.

6127-36, Session 10

Development of device fabrication process for strained layer superlattice IR detectors

D. R. Rhiger, R. E. Kvaas, M. V. Liguori, M. A. Gritz, G. Crawford, Raytheon Vision Systems; C. J. Hill, Jet Propulsion Lab.

Type-II strained layer superlattice (SLS) structures, composed of InAs/GaSb for example, have the potential to replace HgCdTe for sensitive LWIR applications. SLS applicability will depend on continuing improvements in the superlattice material itself, but the goal will be reached only after the development of a suitable device fabrication process. The latter requirement is the subject of this paper.

We report on progress in the development of a device fabrication process. Steps of the process include etching mesas, cleaning up the surface, applying a surface passivation treatment (or depositing a passivating film), forming windows in the coating, and depositing metal contacts on both the n-type and p-type regions. The surface chemistry is complicated by the presence of the four elements of the semiconductor, plus those introduced by the etching and passivation steps. Issues include establishing a benign surface, while preserving the quality of the SLS material.

6127-37, Session 11

Fancy shaped polymer based micro-billiard lasers: tailoring testbeds for wave chaos physics

M. Lebental, J. Lauret, R. Hierle, J. Zyss, École Normale Supérieure de Cachan (France)

Visible and near IR emitting micro-lasers are an important class of devices that are in demand to complement the existing passive and electro-optic waveguide technology on the way to a full fledged all-polymer based integrated optical circuitry with a wide range of applications from information technologies to biotechnologies. The use of organic polymers in this approach meets the demand for a consistent material avenue while ensuring compatibility with inorganic semiconductors at all scales, from intimate hybrid blends at the molecular scale to relatively straightforward deposition on semiconductor substrates. Along these lines, we have developed three kind of basic schemes for micro-lasers: polymer micro-rings around silica fibres, distributed feedback structures (DFBís) and planar micro-cavities sustaining whispering gallery modes (WGM). We will emphasize in this talk latest advances on WGM microlasers with special emphasis on micro- and nano-scale fabrication technologies all the way to combined experimental and theoretical considerations pertaining to mode pattern (in particular ìclosed loopî versus chaotic behaviour). The engineering of out-coupling angular features will be discussed in terms of the tailoring of the micro-cavity outer shape as well as transverse pump geometry[1-3].

A new and general scheme, based on two photon fluorescence strobe will be demonstrated so as to unveil the modal orbits traced by ìlight bulletsî triggered by repeated short pump pulses. It will be shown that whispering gallery mode features are indeed robust and surviving significant perturbations away from micro-disks such as spiral shaped micro-cavities. This will be used to propose a mechanism for the angular out-coupling features such spiral shaped micro-cavities whereby a micron size notch provides the out-coupling exit, however at a tilt angle dependant on the material index [4].

The most interesting case of stadium shaped micro-cavities will be discussed both theoretically and experimentally in view of the special destabilizing nature of this type of contours at increasing aspect ratios. In contrast with what one would expect from such unstable properties, predictable out-coupling features will be evidenced and interpreted in terms of low order bouncing closed orbits which are shown to play a key underlying role [5].

Polymer based structures can be tailored at will and entail multiple advantages as compared to semiconductors: much easier technology entailing the possibility to test new cavity design concepts ‘overnight’, much lower effective index (in the vicinity of 1.5 as compared to 3 or more for III-V’s) opening up to out-coupling a broader range of modes and finally the possibility to use polymers as host matrices for embedding a variety of embedded active units from molecules to quantum dots for near IR emission and telecom as well as biotech applications.

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6127-38, Session 11

Anisotropic magneto-thermopower in ferromagnetic structures

J. Wegrowe, H. M. Drouhin, École Polytechnique (France)

Spin injection in Normal/Ferromagnetic metal junctions is investigated,

taking into account Anisotropic Magnetoresistance (AMR) effects. It is shown that there exists an interface resistance contribution originating from anisotropic interband scattering, beyond accumulation and Giant Magnetoresistance (GMR). The expression of the related thermopower is derived. Experimental results which were obtained with electrodeposited Ni nanowires contacted with Ni, Au, and Cu are discussed. It is concluded that, while GMR effects are related to spin-flip processes, the anisotropic magneto-thermopower originates from s-d interband relaxation.

6127-39, Session 11

Fabrication and integration of micro- nano-scale photonic devices and sensors for application specific planar optical integrated circuit board

E. Lee, Inha Univ. (South Korea)

We present, in the form of review and overview, new results and progresses of our work on the design, fabrication and integration of micro/nano-scale photonic devices and sensors for planar optical printed circuit board (O-PCB) and VLSI micro/nano-photonic applications. The O-PCBs are to perform the functions of sensing, transporting, switching, routing and distributing optical signals on flat modular boards in a manner similar to the electrical printed circuit boards (E-PCBs). They are to offer new functions and merits of high speed, compactness, light-weight, energy saving, and portability that can overcome the limitations of E-PCBs. Photonic devices that are optically integrated on O-PCB include polymer waveguides, vertically coupled surface emitting lasers (VCSELs), quantum devices, sensors, couplers, power splitters, wavelength splitters, wavelength filters, arrayed waveguide grating devices, multimode interference devices, micro-ring/racetrack resonator devices, photonic crystal devices, and plasmonic devices in micro-scale and nano-scale. We describe the fabrication and integration processes of these devices and the O-PCBs and report on their performance characteristics. We also discuss scientific and technological issues of using the integrated optical micro-circuits and boards for VLSI micro/nano-photonic applications, computers, telecommunications, transportation systems, and for avionic and satellite systems.

6127-40, Session 12

Precise control of number of carbon nanotube growth by current monitoring

M. Maeda, Univ. of Tsukuba (Japan); T. Kamimura, Osaka Univ. (Japan); C. Hyon, National Institute of Advanced Industrial Science and Technology (Japan); K. Murata, Olympus Corp. (Japan); K. Matsumoto, Osaka Univ. (Japan)

We have established the new technology to control the number of the carbon nanotube (CNT)between electrodes during the growth by monitoring the current. CNT is the useful element for the future nanodevices. However the control of the position, the direction and the number of CNT is difficult. Therefore, it is indispensable to control them for the applications of electronic devices.

An n-type silicon wafer with a thermally grown oxide was used as the substrate. The layered electrodes of Ti/Pt and catalyst of Si/Mo/Fe were patterned on the substrate using the conventional photo-lithography process. The CNTs were grown between two electrodes by the thermal chemical vapor deposition using bubbeled ethanol and hydrogen. During the growth of CNT, the DC bias was applied between two electrodes and the current was monitored.

The step-like increase of the current was observed during the growth of CNT in the monitoring current. This step like increase in current is due to the increase in the number of CNTs connecting the electrodes. After the CNT growth, CNTs were cut using the electrical breakdown process and the current was monitored. In this process, the step like decrease of the current was observed in the monitoring current. The number of steps of the current in the electrical breakdown process coincided with that of the monitoring current during the growth of CNT. Therefors the number of CNT could be confirmed from the step of the monitoring current.

The result of this experiment shows that the number of CNT can be counted by monitoring current.

6127-41, Session 12

Electrical observation of 1D sub-band structure of carbon nanotube in Schottky barrier transistor

T. Kamimura, K. Matsumoto, Osaka Univ. (Japan)

We demonstrated the observation of the one dimensional (1D) sub-band structure of single walled carbon nanotube in the electrical measurement through the quantum capacitance effect [1].

The carbon nanotube-FET (CNT-FET) was fabricated the electrodes of which was made of Au/ Pt. The Electrical heating process (EHP) [2] was applied at the CNT-FET to desorb the adsorbed oxygen molecules. After the EHP, the CNT-FET was operated as Schottky barrier-transistor (SBT).

The electrical characteristics of the CNT-FET showed indicate the ambipolar characteristics at drain voltage of 1V. Further increase of the drain voltage up to VD=10 V at 8.6 K, current step characteristics became appeared in the semi-logarithmic ID-VG characteristics, which would be attributed to the oscillation characteristics of the quantum capacitance CQ. The gate capacitance consists of two components, one is the insulator capacitance Cins which is originated from the geometry of the SWNT-SBT. And the other is the CQ which is originated from the 1D sub-band structure of SWNT [1]. In the present device, the CQ limited the operation of the device. The current step characteristics would be resulted in the fact that the drain SB was modulated stepwise by the effect of the CQ. The CQ has the oscillation property corresponded to the saw teeth structure of the 1D sub-band structure of CNT. Therefore, the current step characteristics would indicate directly the sub-band structure in CNT.

This measurement technique would include a large potential to identify the chirality of the individual CNT even after the fabrication of the electrical device.

1 D. L. John et al., J. Appl. Phys 96, 5180 (2004), 2 T. Kamimura et al., Jpn. J. Appl. Phys. 44, 1603 (2005).

6127-42, Session 12

High-sensitive label-free biosensors based on single-walled carbon nanotubes

K. Maehashi, K. Matsumoto, Osaka Univ. (Japan)

Recently, high-sensitive detections of biomolecules have attracted great attention to a lot of fields such as genomics, clinical diagnosis, practical pharmacy, and so forth. Optical detection methods have commonly been used for detections of biomolecules, which are highly sensitive and specific methods. However, they need professional knowledge and techniques, and are very difficult to miniaturize. Therefore, alternative methods have been required to fabricate a compact hand-held apparatus, which are suitable to use for medical diagnostics at home. In this study, two kinds of biosensors have been fabricated based on single-walled carbon nanotubes (SWNTs).

DNA hybridization has sensitively been detected using carbon nanotube field-effect transistors (CNTFETs) without any labeling and in real time, where SWNTs are used as channels of CNTFETs. CNTFETs are functionalized with PNA probes on Au back-gate surfaces of the devices. For 11-mer PNA oligonucletide probe, full-complementary DNA with concentration as low as 1 fmol/L solution could be effectively detected.

We have also fabricated biosensors with multi-electrodes arrays of SWNTs and have detected amino acids by differential pulse voltammetry. The biosensors with multi-electrodes of SWNTs are high sensitive in detecting amino acids.

Our SWNT-based biosensors are one of promising candidates for the development of an integrated, high-throughput, multiplexed biosensor for medical, forensic and environmental diagnostics.

6127-43, Session 12

Island size control of carbon nanotube single electron transistor operating at room temperature by AFM electrical manipulation

C. Hyon, Japan Science and Technology Corp. (Japan) and National Institute of Advanced Industrial Science and Technology (Japan); T. Kamimura, Japan Science and Technology Corp. (Japan) and Osaka Univ. (Japan); M. Maeda, Univ. of Tsukuba (Japan) and Japan Science and Technology Corp. (Japan); K. Matsumoto, Osaka Univ. (Japan) and Japan Science and Technology Corp. (Japan) and National Institute of Advanced Industrial Science and Technology (Japan)

We have succeeded in fabricating and characterizing single electron transistors (SETs) operating at room temperature with carbon nanotube channel having different island sizes. Seamless one dimensional nanoscale wire provides a basis for zero dimensional device structure in which we introduce small defects using AFM. We propose a simple approach in which we cut or nick carbon nanotubes (CNTs) with an AFM operating in non-contact mode while scanning over the CNT.

First we fabricate MOSFET type transistor by conventional semiconducting process where the channel is comprised of semiconducting CNT. An n-type Si substrate is used as a back gate. The CNTs with diameters of 1-4 nm were synthesized by thermal CVD using ethanol as carbon source. An external voltage source was used to apply a cutting voltage VC between the CNT and the metal (Pt) coated AFM tip. We cut all undesired CNTs with AFM if more than one CNT connected the electrodes. Generally used cutting voltages ranged from -10 to -30 V. Finally, CNT SETs were fabricated by introducing two small nicks 15 ~ 30 nm apart. SETs having different island size (22 and 15 nm) were made in order to investigate the size dependence on the transport characteristics. The reduction in the island size is reflected as the change in the oscillation period. The oscillation period increases as expected when the size of the island decreases. The proposed method is very effective in the precise control of the CNT SETs island size.

6127-44, Session 13

Photonic engineering of quantum cascade lasers with novel functionalities

F. Capasso, M. A. Belkin, M. Loncar, M. Troccoli, L. Diehl, E. Cubuckcu, B. Lee, Harvard Univ.; O. J. Painter, J. Rosenberg, California Institute of Technology; A. A. Belyanin, Texas A&M Univ.

Electronic bandstructure engineering has played a central role in the design of high performance Quantum Cascade Lasers (QCLs) and in their commercialization. Even greater functionality can be achieved by adding advanced elements of cavity and waveguide design. We will discuss recent advances in monolithically integrating functional photonic elements (quasi phase matching, photonic crystals, surface plasmon nanostructures, etc.) within QCLs, which could lead to an even broader spectrum of applications.

6127-45, Session 13

Simultaneous inhibition and redistribution of spontaneous emission in 2D photonic crystal slabs

S. Noda, Kyoto Univ. (Japan)

Inhibiting spontaneous light emission and redistributing the energy into useful forms is desirable for advances in various fields including photonics, illuminations, displays, solar cells and even quantum-information systems. We demonstrate here both the ‘inhibition’ and ‘redistribution’ of spontaneous light emission by using two-dimensional (2D) photonic crystals. It is shown that the spontaneous emission lifetime is considerably increased due to the 2D photonic bandgap effect. Simultaneously, the light energy is found to be redistributed from the 2D plane to the direction normal to the photonic crystal. The effect of 3D carrier confinement by using quantum nanostructures is also explained.

6127-46, Session 13

Organic photonic devices utilizing nano-structured materials

H. Kajii, T. Morimune, H. Maki, Y. Hino, Z. Kin, Y. Ohmori, Osaka Univ. (Japan)

Organic photonic devices utilizing conducting polymers and dyes have attracted considerable interest because of their advantages in flexible and large-area device fabrication. It is important to control the nano-interface between the organic layers and electrodes. Organic photo-detectors (OPDs) and organic light-emitting diodes (OLEDs) can be applied to fields of optical sensors and optical link devices. We examined the structure and characteristics of OPDs and OLEDs for detecting and generating high-speed optical pulses as the initial step in realizing flexible optical integrated devices. We also demonstrated the possibility of a polymer devices with a cathode fabricated from Ag nanoparticles by wet processing to create organic devices using a simple printing process.

6127-47, Session 13

Photonic crystal microstructured fiber lasers

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

We report on successful drawing of highly doped microstructured fibers with large area cores and their operation as compact fiber lasers. The MOF was fabricated by the stack-and-draw technique. The fiber shown in the insert of figure 1 includes 7 doped solid core cells in the center of the fiber. The core was doped with 1.5 wt.% Er2O3 and 8 wt.% Yb2O3. There are four layers of air holes surrounding the core region, which form the inner cladding and provide confinement for the core mode. Special care was taken in the selection of core and cladding glass to provide single-mode operation for this particular fiber geometry. As shown in Fig. 1, we demonstrated near 8 W of output power from a 10 cm MOF laser with about 500 μm2 core area. The lower right inset in figure 1 shows that the laser is indeed operating in the fundamental mode. The far field pattern of this fundamental mode reflects the hexagonal symmetry of the microstructured cladding.

6127-48, Session 14

Development of ZnMgCdO-based alloys and heterostructures for optical applications

M. D. Gerhold, U.S. Army Research Office; A. Osinsky, SVT Associates, Inc.; D. C. Look, Wright State Univ.

In this presentation we review recent data and approaches for the successful development of all-ZnO and hybrid ZnO/GaN-based heterostructures, which hold great potential for Light Emitting Diodes (LED). The presentation compares properties of this semiconducting oxide material with that of III-Nitride counterparts and justifies their attractiveness for applications in solid state lighting.

Structural, optical, and electrical properties of high quality MgZnO and ZnCdO layers grown epitaxially by RF-plasma molecular beam epitaxy (MBE) and pulsed laser deposition (PLD) are presented. Data includes a summary of optical and electrical properties of CdxZn1-xO alloys with mole fraction of Cd up to 0.78 and a discussion of phase separation phenomenon which may be present in ternary alloys. Characterization from high resolution X-ray diffraction, SIMS, RBS, optical transmission, photoluminescence, and cathodoluminescence mapping is reported. Strong optical emission in the 380 nm to 574 nm spectral range was achieved at

RT from CdxZn1-xO with various compositions, demonstrating a great potential for use in LEDs. High conductivity and optical transparency of the CdZnO films with high Cd-mole fraction is attractive for making high performance electrodes. Dependence of the fundamental optical band gap on the composition of CdxZn1-xO alloys, band gap bowing, and the possible effect of composition micro-fluctuation in ternary CdxZn1-xO alloys on the optical bandgap is also discussed. Measurements and simulation of fundamental optical indices using waveguide coupling and ellipsometry techniques are presented in the context of potential applications in photonic devices and circuits.

1. A. Osinsky, J. W. Dong, M. Z. Kauser, B. Hertog, A. M. Dabiran, P. P.Chow, S. J. Pearton, O. Lopatiuk, and L. Chernyak, Appl. Phys. Lett. 85, 4272 (2004).

2. A. Osinsky, J.W. Dong, J.Q. Xie, B. Hertog, A.M. Dabiran, P.P.Chow, S.J. Pearton, D.C. Look W. Schoenfeld , O. Lopatiuk and L. Chernyak , M. Gerhold, ìZnCdO/ZnMgO and ZnO/AlGaN Heterostructures for UV and Visible Light Emittersî, invited talk MRS, December (2005)

6127-49, Session 14

III-nitride deep ultraviolet micro- and nano-photonics

H. Jiang, J. Y. Lin, Kansas State Univ.

A brief overview on recent advances in the deep ultraviolet (UV) photonic materials and devices based upon III-nitrides will be provided. Materials issues and progress for Al-rich AlGaN alloys and their electrical and optical properties will be updated. Exploitation of chip-level innovation, such as the incorporation of micro- and nano-scale photonic device integration and photonic crystals (PCs), to enhance the extraction efficiency of deep UV emitters will be reviewed.

6127-50, Session 14

Solar-blind avalanche photodiodes

R. P. McClintock, K. A. Mayes, A. Yasan, P. Kung, M. Razeghi, Northwestern Univ.

Avalanche photodetectors (APDs) operating at 280 nm, in the solar-blind region of the ultraviolet, are investigated. We start by presenting the state of the art in conventional p-i-n photodetectors, and then discuss the need for avalanche gain in order to realize better performance from these devices and effectively compete with photomultiplier tubes. The major technical issues associated with the realization of high-quality solar-blind APDs are discussed in detail and solutions to the major problems are outlined where available. Avalanche photodetectors device results are then presented. The devices consist of an Al0.38Ga0.62N active region grown atop a high quality AlN and AlxGa1-xN/AlN superlattice template layer designed for back illumination of the device through the sapphire substrate. The devices are processed into small area detectors using standard lithographic techniques and dry etching. The mesas are pasivated with SiO2 and ohmic contacts to the device are applied. The reverse bias I-V curves of these devices are investigated under illumination, and these devices demonstrate gain of the photocurrent with increasing reverse bias, the origins of which are discussed in detail. Modeling of the devices is used to investigate the electric field build up in the multiplication region. Finally, future prospects for improving upon the performance of these devices are outlined.

6127-51, Session 14

High-sensitivity rotation sensing with atomic interferometers using Aharonov-Bohm effect

M. Ozcan, Sabanci Univ. (Turkey)

In recent years there has been a lot of activity in research and development of high sensitivity accelerometers and gyroscopes using atom interferometers.

In these devices the interference of the atom de Broglie waves is observed and a fringe shift results if the interferometer is rotated.

Here we show that if an atom interforemeter is enclosed in a Faraday cage which is at some potential, the resultant phase difference in the counter propagating waves can be much larger than the Sagnac phase shift.

This is due to Aharonov-Bohm effect and it can be used to increase the rotation sensitivity of atomic interferometers.

Furthermore, in our interferometer-unlike the conventional Sagnac interferometer- the rotation response is inversely proportional to the square of the particle velocity which provides additional sensitivity by using slower particles.

6127-52, Session 15

Status of two-color and large format HgCdTe FPA technology at Raytheon Vision Systems

E. P. G. Smith, R. E. Bornfreund, I. Kasai, L. T. Pham, E. A. Patten, J. Peterson, Raytheon Vision Systems; J. A. Roth, B. Nosho, J. E. Jensen, HRL Labs., LLC; J. W. Bangs, S. M. Johnson, W. A. Radford, Raytheon Vision Systems

Raytheon Vision Systems (RVS) in collaboration with HRL Laboratories is developing two-color and large format single color HgCdTe infrared focal plane arrays (FPAs) to support Third Generation infrared imaging systems. For a wide variety of space and ground-based applications two-color FPA development addresses the need for improved target identification, signature recognition and clutter rejection while large format single color FPAs are being increasingly used for high resolution infrared imaging over very large fields of view.

Two-color and large format single color FPAs are fabricated from molecular beam epitaxy (MBE) grown HgCdTe triple layer heterojunction (TLHJ) wafers on CdZnTe substrates and double layer heterojunction (DLHJ) wafers on Si substrates, respectively. The FPAs use pixel pitches as small as 20μm and formats ranging from 256 x 256 to 1280 x 720 for two-color detection in the mid-wavelength infrared (MWIR) and long wavelength infrared (LWIR) spectral bands whereas single color short wavelength infrared (SWIR) and MWIR large format FPAs are as large as 2048 x 2048. The RVS two-color detector architecture is based on a bias-selectable back-to-back diode structure that allows for a single indium bump, single-mesa implementation. This approach provides producible FPAs with varying pixel pitch and format, and exploits mature fabrication processes that are in production at RVS for Second Generation FPAs and also applied to large format single color FPAs.

This paper will discuss key factors related to detector design and material growth, FPA fabrication, and detector and FPA performance for two-color and large format single color FPAs. Continuous development and improvement of two-color detector design, material growth and FPA fabrication processes has contributed to significantly improved LWIR dark current performance where recent two-color MWIR/LWIR detector dark current results are comparable to single color LWIR HgCdTe detector arrays. Maturing MBE HgCdTe growth on 4- and 6-inch diameter Si wafers is making it possible to realize increasingly large FPAs. In addition, a large number of FPAs with varied dimensions and configurations can also be realized on a single wafer with associated benefits for manufacturing yield, cost and throughput. Standard 4- and 6-inch wafer dimensions diminish requirements for custom wafer handling techniques typically used for CdZnTe substrates during wafer processing and provide greater compatibility with standard semiconductor tooling and manufacturing techniques available to the Si and III-V semiconductor industries.

6127-53, Session 15

Atomically accurate structure analysis for reliable bandgap engineering of strained layer superlattices

M. Weimer, Texas A&M Univ.; M. E. Flatte, The Univ. of Iowa; C.

H. Grein, Univ. of Illinois at Chicago and EPIR Technologies, Inc.; A. P. Ongstad, Air Force Research Lab.; G. J. Sullivan, Rockwell Scientific Co., LLC

As attempts to exploit the deliberate tailoring of optical transitions in quantum-confined semiconductor structures grow ever more sophisticated, accurate answers to the essential question of the atomic arrangements responsible for the confining potential frequently remain unavailable. Such ignorance forces an unfortunate reliance on bandgap engineering paradigms whose predictive utility is judged against assumed (intended) rather than known (as-grown) structures.

We describe a suitably powerful and general method for the complete solution of the relevant structure problem in InAs/GaSb strained layer superlattices whose fundamental bandgap may be tuned anywhere within the mid- to long-wave infrared region of the electromagnetic spectrum. This control, in principle exercised through appropriate design of the respective layer sequences and heterojunction bond types laid down during MBE growth, is, in practice, compromised by a combination of antimony segregation and background incorporation at the arsenide-on-antimonide interface, and by indium segregation at the antimonide-on-arsenide interface.

Our approach relies on atomically precise, layer-by-layer compositions derived from cross-sectional scanning tunneling microscopy together with high-resolution x-ray diffraction, and yields a unique, growth-direction-dependent x-ray structure factor that successfully reproduces the variation in (004) satellite peak intensities. A fourteen-band k.p model for the resulting wavelength-dependent optical absorption in a realistic superlattice with segregation-driven interface compromise and non-integer well-to-barrier ratio accurately predicts the abrupt absorption cutoff observed with Fourier-transform infrared spectroscopy.

Work supported by the Air Force Research Laboratory, Missile Defense Agency, and National Science Foundation.

6127-54, Session 15

Positive and negative luminescence in binary type II InAs/GaSb superlattice photodiodes

D. M. Hoffman, A. D. Hood, Y. Wei, E. J. Michel, F. Fuchs, M. Razeghi, Northwestern Univ.

Recently, several groups have investigated the aspects of positive and negative luminescence behavior in infrared materials. Under forward bias voltage, charge carriers are injected into the active region of a p-n junction giving rise to positive luminescence. In contrast, a p-n junction under reverse bias conditions can exhibit negative luminescence caused by a reduction of the electron-hole recombination of the device such that the photon flux is below that of the black body emission in equilibrium.

In the present work, we show measurements of both positive and negative luminescence of binary Type II InAs/GaSb superlattice photodiodes covering the entire infrared spectral range between 5 and 13 μm. Through a radiometric calibration technique, we demonstrate temperature independent negative luminescence efficiencies of 45 % around 5 μm from 220 K to 325 K without anti-reflective coating and values reaching 35 % in long wavelength infrared (LWIR) spectrum. With the radiative recombination constant obtained in the framework of k p theory a model is obtained to describe the temperature dependent behavior of the results near thermal equilibrium in both spectral windows. In the long wavelength regime, we demonstrate that the dominant non-radiative recombination channel in n-type material is Auger recombination with an electron-hole-electron (CHCC) Auger recombination coefficient of Cn = 1 x 1024 cm6s-1. While in the mid wavelength infrared (MWIR) window the primary non-radiative recombination is Shockley-Read-Hall recombination giving rise to a p-type residual background a capture cross-section of n = 7 x 10 16 cm2.

6127-55, Session 15

Short-period superlattices: is thinner better?

G. J. Brown, H. J. Haugan, F. Szmulowicz, K. Mahalingam, L. Grazulis, 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. For InAs/GaSb type superlattices, periods of 40≈ or less are relevant to mid-infrared detection. Characterization and modeling results for a series of InAs/GaSb superlattices with periods ranging 50≈ to 20≈ 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.

Conference 6128: Photonic Crystal Materials and Devices IV

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6128-01, Session 1

Nonlinear optical nanostructures for filtering and switching light

A. Scherer, M. Hochberg, T. Baehr-Jones, G. Wang, California Institute of Technology; R. Lawson, Y. Liao, P. A. Sullivan, L. R. Dalton, A. K. Jen, Univ. of Washington

A new generation of photonic devices has recently emerged that rely on the geometry of sub-wavelength microstructures with a high enough refractive index contrast to confine and manipulate light within small volumes. Very high optical field densities can be obtained within such structures, and these in turn can amplify optical nonlinearities. Moreover, many of these structures, as for example photonic crystals and slotted waveguides, can be engineered for the efficient localization of light within the low-index regions of high index contrast microstructures. When such structures are back-filled nonlinear polymers or liquids, devices can be tuned and novel phenomena can be observed. In particular, such devices are very interesting when constructed from silicon on insulator (SOI) material in which the optical waveguide also serves as a transparent electrical contact. Here we show examples of the design, fabrication and testing of optical microstructur3) nonlinearities are used for electro-optic tuning, frequency mixing, optical rectification, and high-speed switching of light.

6128-02, Session 1

To be announced

S. John, Univ. of Toronto (Canada)

No abstract available

6128-03, Session 1

Silicon integrated nanophotonics: advantages and challenges

Y. G. A. Vlasov, IBM Thomas J. Watson Research Ctr.

No abstract available

6128-04, Session 2

Cu coated square Si nanospring arrays as a 3D photonic crystal: fabricated by a novel oblique angle deposition technique and low-pressure chemical vapor deposition

S. Lin, D. Ye, J. A. Bur, T. Lu, Rensselaer Polytechnic Institute

Three-dimensional (3D) photonic crystals with complete bandgap have been successfully fabricated previously by complex lithographic procedures, self-assembly of colloidal opal structures, x-ray lithography, and holography. However, the photonic band edge on the shorter wavelength side is limited both by the fabrication methods and by the nature of the dielectric materials used to construct the photonic architectures. Here we will present our strategy of fabricating metallic 3D photonic crystals by the combination of a novel oblique angle deposition technique and conformal coating by low pressure chemical vapor deposition (CVD). As we demonstrated in the past, oblique angle deposition technique has the ability of depositing 3D nanostructures via shadowing growth, which is a physical self-assembly process that incoming flux can only reach the upper areas of the taller features of the growth front and the taller surface features block the incoming flux from reaching lower lying areas of the film. As a result, isolated nanostructures can be formed due to the shadowing effect during growth. This technique was first used to fabricate square Si nanospring arrays as a photonic crystal by M. J. Brett et al. However, the dimensions of the nanosprings cannot be maintained due to the fan-out growth phenomenon associated with this technique. We designed a substrate rotation method to overcome this shortcoming of oblique angle deposition which is referred as ìswingingî technique. In this technique, the substrate is rotated azimuthally back-and-forth within an angular range (swing angle) with a constant rotation speed . Uniform Si photonic structure can be fabricated without fan-out problem using this technique. We further coated the fabricated Si structure by copper CVD. The overall 3D photonic crystal shows a complete band gap in the near infrared wavelength. This approach has the potential of fabricating large scale photonic crystals in one experiment. With conformal coating of metals by low pressure CVD, the photonic band structure can be easily tuned to optical wavelength.

6128-05, Session 2

Tailorable, 3D microfabrication for photonic applications: Two-polymer microtransfer molding

J. Lee, C. Kim, K. Constant, K. Ho, Iowa State Univ.

For photonic devices, extending beyond the planar regime to the third dimension can allow a higher degree of integration and novel functionalities for applications such as photonic crystals and integrated optical circuits. Although conventional photolithography can achieve both high quality and structural control, it is still costly and slow for three-dimensional (3D) fabrication. Moreover, as diverse functional polymers emerge, there is potential to develop new techniques for quick and economical fabrication of 3D structures for polymers. We present 3D microfabrication technique based on soft lithographic technique, called two-polymer microtransfer molding (2P-μTM), to accomplish low cost, high structural fidelity and tailorable 3D microfabrication for polymers. Using the 2P-μTM, highly layered polymeric microstructures are achievable by stacking planar structures layer by layer. For increased processing control, the surface chemistry of the polymers is characterized with respect changing ultraviolet dosage to optimize yield in layer transfer. We discuss the application of the 2P-μTM to build polymer templates for woodpile photonic crystals, and demonstrate methods of converting the polymer templates to dielectric and metallic photonic crystal structures. Finally, we will show that 2P-μTM is promising for fabricating 3D polymeric optical waveguides.

6128-06, Session 2

Novel spatially distributed porous Si optical bandpass filters

N. Tokranova, SUNY/Univ. at Albany; I. A. Levitsky, Emitech, Inc.; A. Gracias, B. Xu, J. Castracane, SUNY/Univ. at Albany

To assist the growth of the telecommunication sector new types of optical components such as those based on optical interference filter technology are critical. Existing technologies based on thin-film processing for production of optical communications filters has rapidly advanced. Although the Fabry-Perot bandpass filters made by a deposition of alternate layers with high- and low- refractive index have a broad rejection band and a narrow passband, this technique does not allow the control of filter parameters such as specification and adjustment of the transmitted wavelength at any place of the filter. The new approach discussed in the paper directed toward the anodization of silicon to fabricate not only multilayer optical filters with a uniform passband across the field of view

but also specially designed passbands at any single point in the field of view of the optical system. In this paper, the realization and characterization of spatially distributed filters made of porous silicon is presented. These filters are able to select various passbands in the visible and IR regions. The filters were fabricated on p+ and p- -type doped substrates. By varying the electrode configuration on the backside of wafer and the applied potential during electrochemical etching, the desired filter design can be formed. The influence of wafer resistivity on the filter parameters is discussed.

6128-07, Session 2

Infrared photonic bandgap materials and structures

S. K. Sundaram, Pacific Northwest National Lab.

Three-dimensional periodic dielectric structure can be described by band theory, analogous to electron waves in a crystal. Photonic bandgap (PBG) structures have been introduced in 1987. The PBG is an energy band in which optical modes, spontaneous emission, and zero-point fluctuations are all absent. It was first theoretically predicted that a three-dimensional photonic crystal having a complete bandgap. E. Yablonovitch built the first three-dimensional photonic crystal (Yablonovite) on microwave length scale, with a complete PBG. In nature, photonic crystals occur as semi-precious opal and the microscopic structures on the wings of some tropical butterflies, which are repeating structures (PBG structure/materials) that inhibit the propagation of some frequencies of light. PNNL has been developing tunable (between 3.5 and 16 μm) quantum cascade lasers (QCL), chalcogenides, and all other components for an integrated approach to chemical sensing. We have made significant progress in modeling and fabrication of infrared photonic bandgap (PBG) materials and structures. We modeled several 2-D designs and defect configurations. Transmission spectra were computed by Finite Difference Time Domain Method (with FullWAVEô). The bandgaps were computed by Plane Wave Expansion Method (with BandSOLVEô). The modeled designs and defects were compared and the best design was identified. On the experimental front, chalcogenide glasses (e.g., As2S3 is an important infrared (IR) transparent material for a variety of potential applications such as IR sensors, waveguides, and photonic crystals) were used as the starting materials. Wet-chemical lithography has been extended to PBG fabrication and challenges identified. An overview of results and challenges will be presented.

6128-08, Session 3

Ultraflat bands in 2D photonic crystals

M. Ibanescu, Massachusetts Institute of Technology

No abstract available

6128-09, Session 3

Geometrical suppression of photonic band gaps

D. R. Solli, R. Y. Chiao, Univ. of California/Berkeley; J. M. Hickmann, Univ. Federal de Estado de Alagoas (Brazil)

One of the most surprising things about photonic crystals is not the existence of the band gap, but the fact that a large, ordered array of scatters can be transparent to light within certain spectral regions. In fact for random scattering we should observe localization not transmission. We have identified a new, general effect in which the band gap of a photonic lattice can be suppressed by unexpected mode degeneracy, rendering a photonic crystal completely transparent to all frequencies across two or more distinct bands.

As an example, we present numerical studies of two-dimensional photonic crystals composed of dielectric pipes and show that for a range of intermediate air-filling fractions (AFFs), the fundamental band gaps essentially vanish due to a balancing effect between pipe and interstitial holes, regardless of the index contrast. We quantify this effect with the fill-factor integrals, which measure the electrical energy in the photonic structure [1], and describe a simple analog in solid-state physics based on a mass-spring lattice. The result of these effects is that the widths and reflectivities of the primary band gaps do not monotonically increase with increasing AFF, but are maximized and minimized at special AFFs. We have also studied the effect of imperfections in these photonic crystals, and show that the unexpected band-gap suppression is stable against disorder.

These concepts may have application in the design of broad-band photonic crystal waveplates [2] and may be also useful for the construction of bistable devices based on nonlinear photonic crystals.[1] J. D. Joannopoulos, R. D. Meade, and J. Winn Photonic Crystals: Molding the Flow of Light, (Princeton University Press, Princeton, 1995) Chap 5. [2] D. R. Solli, C. F. McCormick, R. Y. Chiao, and J. M. Hickmann, Optics & Photonics News, Dec. 2003, p. 35.

6128-10, Session 3

Simulation of VO2-based electrically programmable photonic crystals

D. Xiao, K. W. Kim, North Carolina State Univ.; J. M. Zavada, U.S. Army Research Office

The feasibility of an electrically programmable photonic crystal (EPPC) is investigated theoretically based on the metal-insulator transition of vanadium dioxide (VO2). Recent experiments indicate that this first order phase transition can be produced via an external bias voltage resulting in significant changes in the electrical and optical properties. The proposed structure can be achieved by drilling an appropriate hole pattern in a silicon (Si) film, filling the holes with VO2, and then form a 2D array of metal contacts through standard lithography and metallization techniques. Since the dielectric constants of silicon and VO2 in the semiconductor phase are similar, this structure is expected to have similar optical properties as the original Si film. However, when an external bias is applied, the VO2 regions beneath the electrodes undergo the phase transition and become metallic. This results in a metallic photonic crystal (MPC) and formation of a band gap is possible. Contrary to the ordinary photonic crystals (PCs), the EPPC can be switched on and off, thereby changing the light propagation, by applying an electrical bias on the selective electrodes. To examine the feasibility of the VO2-based PC, a 2D photonic band structure (PBS) calculation was conducted. As a first step, we analyzed the optical properties of the semiconductor and metallic phase VO2 in the desired infrared frequency range. The finite difference time domain (FDTD) method is the most popular method dealing with the PCs with frequency-dependent medium since it is capable of computing PBS for arbitrary frequency dependency and arbitrary geometry. However, it requires manual observation of the peaks and it is difficult to differentiate the nearly degenerate points. Also, the PBS calculation of the MPCs with a line defect cannot be easily performed. Kuzmiak and co-workers extended the original plane wave expansion (PWE) method to compute the PBS in the MPCs. However, it is only applicable when the high frequency metal dielectric constant equals to the dielectric constant of the host medium. Since the requirement is hard to be satisfied in realistic materials, the PWE method has never been used in the practical modeling of the PBS calculation of the MPCs. Here we have eliminated this requirement by an iterative PWE technique. A PC structure of square lattice with the period of 0.4 um and the radius of 0.176 um has been designed. The host medium is silicon, whose refractive index is 3.4. Our calculation shows that a large band gap appears between the first and second band, which is between 0.61 / um and 0.738 /um. The cut-off frequency is 0.5 /um. The results are compared with FDTD method and show excellent agreement. Next, we analyzed a PC structure with a straight line defect. The supercell technique is combined with our iterative PWE method to calculate the PBS of VO2-based PCs with a line defect. One defect state below the cut-off and another inside the band gap were found. Further details of the dynamics of the electromagnetic wave propagation in such VO2-based PCs be discussed.

6128-11, Session 3

The impact of high-dielectric constant on photonic bandgaps in PbSe nanocrystal-based photonic crystal slabs

V. Nair, W. Zhou, The Univ. of Texas at Arlington

Photonic crystal slabs (PCS)[1], with the combination of in plane photonic bandgap (PBG) and vertical waveguide index confinements, offers an attractive nanophotonic platform for novel photonic devices and planar photonic integration[2,3]. Owing to its compatibility with Si microfabrication, PCS is the subject of intensive research work, on various material systems, such as silica on Si (SOS)[4], spin-coated organic materials on Si, and self assembled nanoparticles on Si, etc.

PBG properties are largely dependent upon the material dielectric constants. It is well known that higher dielectric contrast is desirable for larger PBG[1]. It is true in air hole based photonic crystals (l=1), where the high dielectric constant h can be as high as 12-14 for conventional semiconductor materials (e.g. Si, GaAs, InP). However, there is an increased interest in materials with even higher dielectric constant, such as high k dielectric materials for Si based microelectronics (=17 (Y2O3), 25 (HfO2), 60 (STO)) [5], and small bandgap materials for mid and far infrared applications (=16 (InSb), 18 (PbS), 24 (PbSe))[6]. These materials can potentially be integrated into photonic crystal design for integrated electronics and photonics applications, including infrared light sources and sensors.

We provide results on a detailed study of high dielectric constant impact on PBG in both ideal 2D photonic crystals and PCS with finite thickness, based on plane wave [7] and FDTD techniques [8]. The bandgap position, width, the field distribution characteristics and the defect mode properties will be reported by considering the dielectric constant impact (for h from 2 to 24), as well the geometrical configurations (air hole radius, vertical confinement and symmetry).

Detailed simulation reveals that further increase in dielectric constant (h=14-24) leads to a saturation in PBG width in the case of ideal 2D PC, yet a significant reduction in PBG width for PCS with symmetric confinement structure on the vertical direction. The field distribution also alters significantly for these two cases. Different design rules will be proposed, based on the desired PBG properties. We will also report the design and experimental results on a PbSe nanocrystal (with =24) based PCS for infrared applications.

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6128-12, Session 4

Two dimensional coupled photonic crystal microcavity arrays and its applications

H. Altug, J. Vuckovic, Stanford Univ.

A small group velocity is crucial in variety of applications, ranging from optical delay components and low-threshold lasers, to study of nonlinear optics. Although one-dimensional coupled resonator optical waveguides proposed by Yariv et al. in 1999 attracted significant attention because of their ability to provide a very small group velocity of light in the direction in which the cavities are coupled, the coupling into such structures is difficult as the input beam needs to be aligned in one particular direction and coupled efficiently into a cross-sectional area that is typically much smaller than one micrometer square. Similarly, photonic crystal microcavity lasers have been studied by many groups because of their small size, low threshold and possibility of high direct modulation rate; unfortunately, their output powers are very low for most applications. We have recently proposed two-dimensional coupled photonic crystal resonator arrays, which enable a small group velocity of light for all wavevectors and in all crystal directions with a very low group velocity dispersion. We experimentally measured the band diagram of such a structure made in silicon and demonstrated a group velocity below 0.008c. We also showed that when the rotational symmetry of the structure is broken one can control the polarization and construct miniaturized polarizing components. Currently we are fabricating the structure in InP material system that has multiple quantum well in it and investigating the lasing properties. In this talk we will talk about application of caoupled cavity structures as both passive and active devices.

6128-13, Session 4

Magneto-optical circulator in 2D photonic crystals

Z. Wang, S. Fan, Stanford Univ.

Long-range coupling between optical resonators in integrated optical systems can dramatically increase noise levels in lasers, cause frequency-drifting in passive resonators and give rise to parasitic fringes. This has become a limiting factor in achieving the integration scale demanded by all-optical information processing and biochemical sensing applications. Conventionally, magneto-optical effects have been exploited to break the time-reversal symmetry and transport photons only in the forward direction. In miniaturizing bulk magneto-optical isolation devices, previous research has focused on one-dimensional photonic crystals, where resonance-enhanced Friday rotation occurs in sub-wavelength optical paths. In this paper, we study an optical circulator formed of magneto-optical resonances infiltrated in a two dimensional silicon/air photonic crystal. The additional dimension of the field confinement allows further miniaturization and paves the way for monolithic in-plane integration with current integrated optical devices. The gyrotropic effects cross couple the two counter-propagating modes and split them in frequency, accomplished with geometrically-optimized iron-garnet domains. We use a coupled mode theory to derive the general scaling law between the magneto-coupling and device dimension for complete transmission and isolation for a given bandwidth. Numerical experiments with finite-difference time-domain methods confirmed the coupled mode theory and demonstrate a circulator with an isolation ratio greater than 40dB. The design principle for this two dimensional photonic crystal defect can be readily transferred to magneto-optical resonaces in three dimensional slab photonic crystals, which can be readily interfaced with existing planar optical devices.

6128-14, Session 4

Theoretical analysis of band gap formation in rotationally symmetric 2D photonic quasicrystal using rotational symmetry arguments

K. Mnaymneh, R. C. Gauthier, Carleton Univ. (Canada)

There has been steady interest in Photonic Crystal (PhC) structures for nearly the past two decades. The key feature that gives PhCs their ability to form photonic band gaps (PBGs) analogous to electronic band gaps of semiconductors is their translational symmetries. In recent years it has been found that structures possessing only rotational symmetries can also have PBGs. How these PBGs arise from purely rotational symmetry is currently a theoretical curiosity. There is a strong belief that these band

gaps come from long-range interactions. One-dimensional Fibonacci-like quasicrystals have shown the existence of PBGs and light localization effects. In two dimensions however, in addition to PBGs arising from long-range interactions, there are also PBGs that arise from short-range interactions. This presentation proposes an answer to these short-range interactions: take the one-dimensional Fibonacci-like state amplitude solution along the y-axis, and then project any state on the xy-plane back to the y-axis via its ìorbitalî angular momentum number. This process mimics the way electronic state amplitudes are calculated when such states have an angular dependence. Simulations results are presented.

6128-15, Session 4

Accuracy of the tight binding approximation for the description of the photonic crystal coupled cavities

T. Kamalakis, T. Sphicopoulos, S. Dimitris, Univ. of Athens (Greece)

Coupled optical cavities are constantly attracting increased attention in telecommunication applications. For an infinite chain of optical cavities, also known as the coupled resonator optical waveguide (CROW), the tight binding approximation has been used in order to evaluate its dispersion characteristics and the modal fields. In this paper, the tight binding formalism is applied in a finite chain of optical cavities of arbitrary length. This allows the derivation of simple analytical formulas for the resonant frequencies and the corresponding modal fields. These equations for the resonant frequencies involve only the resonant frequency of the isolated cavity and the coupling coefficients between two consecutive coupled cavities. The equations for the modal fields involve an expansion in terms of displaced versions of the field distribution of the mode of the isolated cavity and simple trigonometric functions. The analytical results are compared with the numerical results of the plane wave expansion method in the case of a finite photonic crystal chain of coupled resonators and an excellent agreement is observed even if the cavities are placed close together. The results clearly indicate the usefulness and accuracy of the tight binding formalism for the description of the tight binding formalism in finite chains of coupled optical resonators.

6128-16, Session 4

Design optimization of a high-Q channel add-drop filter with a twin stick-shaped resonator system

K. H. Hwang, Gwangju Institute of Science and Technology (South Korea) and Samsung SDI Co., Ltd. (South Korea); C. M. Lim, G. H. Song, Gwangju Institute of Science and Technology (South Korea)

We discuss design optimization of a high-Q channel add-drop filter with a twin stick-shaped resonator system based on the two-dimensional photonic-crystal (PhC) slab structure by three-dimensional (3D) finite-difference time-domain (FDTD) method.

Most of all, in order to achieve a successful design of the PhC filter with the high channel-drop efficiency and with the relatively low pass-through crosstalk, design of the stick-shaped resonator has been optimized to enhance the ratio of the out-of-plane quality factor (Q factor) to the in-plane Q factor. By exquisitely tuning the radii of each air hole in first layers siding the line of missed holes on the waveguide structure and of the nearest holes of the five missed holes on the stick-shaped resonator, the two essential conditions for the optimal design of the filter, the attuned degeneracy condition and the phase matching condition, have been satisfied in a reasonable degree. By inserting more hole layers between the twin stick-shaped resonator and each of the line-defect waveguide buses, the channel-selectivity Q factor of the filter has been enhanced and a quite symmetric frequency response of the forward drop has been achieved.

The 3D FDTD simulation has shown that theoretically it is possible to design a channel add-drop filter not only with 8,000 of the channel-selectivity Q factor but also with better than -0.41 dB (91 %) of the forward-drop efficiency and -26 dB of the pass-through and the backward-drop crosstalks. The prototype design is believed to provide the add-drop functionality with the sufficient channel-selectivity Q factor for DWDM applications.

6128-17, Session 4

Controllable polarization splitting in liquid crystal infiltrated photonic crystal

A. Gandhi, X. Sun, P. Shum, Nanyang Technological Univ. (Singapore); M. Yu, Institute of Microelectronics (Singapore)

Photonic crystals (PCs) can control propagation of light even in the absence of complete photonic band gap, through their rich dispersion properties. In this paper, we studied the control of polarization splitting, in two-dimensional (2D) PCs with liquid crystal (LC) infiltration in matrix mediums such as Si and SiON. In calculating the band structure of the PC, we used plane wave expansion method, with the dielectric property of the LC is considered as a tensor. In PC, the two polarizations of light can be decoupled as long as the optic axis LC is either parallel or perpendicular to the periodic plane of PC.

The intrinsic anisotropy of the PC, added with anisotropy of the LC, produces a very distinct dispersion curves for the two polarizations of light, for wide range of frequencies. This results in, one polarization is positively refracted and the other polarization is negatively refracted for all incident angles and hence, leads to large splitting angle between the two polarizations of light in PC. Comparing to the conventional polarization splitting using bulk anisotropic medium, where the refractions of both polarizations are limited to be positive, the splitting angle in PC, is substantially larger than the bulk case. In particular for a LC infiltrated 2D PC made of Silicon and with an effective birefringence of 0.1, the splitting angle can be as large as 90∫, and the angle is much smaller, if PC is considered as bulk, where the splitting angle is limited to be a maximum of 3∫. The large splitting angle between the two polarizations in PC is a function of incident angle, frequency of light and the optic axis orientation of LC. Upon appropriate choice of incident angle, it is possible to achieve large splitting angle, insensitive to optic axis orientation of LC, and the large splitting angle can be substantially reduced to zero by controlling the optic axis orientations of LC. Furthermore, we also analyze the influence of LCís birefringence and the refractive index of the background medium, to the control of polarization splitting in PC. This study serve as a basis for a new class of polarization splitting devices based on PC with controllable splitting angle between the two polarizations.

6128-18, Session 6

Photonic crystal fibres: with and without bandgaps

W. J. Wadsworth, Univ. of Bath (United Kingdom)

No abstract available

6128-19, Session 6

Recent advances in the development of holey optical fibers based on sulphide glasses

F. Smektala, Univ. de Rennes I (France); L. Brilland, PERFOS (France); T. Chartier, T. N. Nguyen, École Nationale Supérieure des Sciences Appliquées et de Technologie (France); N. Traynor, PERFOS (France); J. Troles, T. Jouan, Univ. de Rennes I (France)

Microstructured optical fibers as new optical objects have been developed in the recent past years, firstly from silica glass and then from other oxide glasses such as tellurite or different heavy cations oxide glasses. However very few results have been reported concerning non-oxide

glasses and more particularly chalcogenide glasses. In a photonic crystal fiber the arrangement of air holes along the transverse section of the fiber around a solid glassy core leads to unique optical properties, such as for example broadband single-mode guidance, adjustable dispersion, nonlinear properties. Since the effective modal area is adjustable thanks to geometrical parameters, chalcogenide microstructured fibers with small mode area are of interest for nonlinear components because of the intrinsic non linearity of chalcogenide glasses, several order of magnitude above these of the reference silica glass (100 to 1000 times the non linearity of silica glass). On the other hand, chalcogenide holey fibres with large mode area are of interest for infrared power transmission, in a wavelength range out of reach of silica fibers, and more particularly in the 3-5 μm atmospheric window. The aim of this paper is to present more specifically the recent results that have been achieved in the elaboration, light guidance and characterization of photonic crystal fibers from the sulphide Ge20Ga5Sb10S65 glass, which presents a large transparency window from 600 nm to 11 μm.

6128-20, Session 6

Modal solutions of photonic crystal fibers by using a full-vectorial finite element method

A. B. M. Rahman, S. A. K. M. Kabir, M. M. Vaghjani, I. Wijeratne, G. S. Sahota, M. Rajarajan, K. T. V. Grattan, City Univ. London (United Kingdom)

The photonic crystal fiber (PCF), which is also known as holey fiber, is a micro-structured fiber, where arrays of holes running along the waveguide length, has more controllable fabrication parameters than standard single mode fiber. Increasing interest is being shown in such PCFs for a range of applications in optical communications, sensing and signal processing. This has included the control and guidance of optical beams, taking advantage of their unique transmission characteristics, including being continuously single-moded, with controllable spot-sizes offering large spot size for high power delivery and small spot size for intense nonlinear activities. The fibers also allow tailored group velocity dispersion characteristics for various linear and nonlinear device applications.

To date, most of the research into these fibers has a strong experimental basis [1], which has recently been complemented by various modal solution approaches to their characterization, this having mostly been using scalar formulations or being limited to specific types of structures. The modal solution approach based on the powerful finite-element method (FEM) [2] is more flexible, can represent any arbitrary cross-section more accurately and has been widely used to find the modal solutions of a wide range of optical waveguides [2]. The flexibility of the FEM to represent a cross-section of a holey fiber, with its arbitrary hole sizes, materials, shapes, and their placement, makes it a powerful approach where many other simpler and semi-analytical approaches are proven to be unsatisfactory. The optical modes in a high-index contrast PCF with two-dimensional optical confinement are also hybrid in nature, with all six components of the E and H fields being present. To characterize accurately such fibers, a full-vectorial approach is necessary and such a H-field based full vectorial approach [2] has recently been extended to study the polarization issues in PCFs.

Modal solutions for the fundamental and higher order TE and TM polarized modes have been obtained including the variation of the propagation properties, the modal field profiles, spot-size, power confinement and the modal hybridism. An asymmetric air-hole has been introduced into the designs to enhance the modal birefringence and to create a single polarization PCF. The effect of material nonlinearity has also been studied and results on these activities will be presented.

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6128-21, Session 6

Propagation characteristics of highly elliptical core photonic crystal fiber

A. D. Varshney, R. K. Sinha, 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 complicated 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 indexes and modal birefringence, with those from accurate perturbation approach, showing relatively good agreement between the results.

6128-22, Session 7

Role of 1D singularities in the operation of some photonic-crystal based devices

H. Benisty, L. Martinelli, E. Viasnoff-Schwoob, M. A. Pinault, C. Weisbuch, École Polytechnique (France); G. Duan, Alcatel Research & Innovation (France); H. Heidrich, K. Janiak, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

Waveguides in photonic crystals are one-dimensional photonic systems, with a richer basic physics than micro/nanocavities thanks to their extended nature. We evidence various roles of the one-dimensional singularities that occur at zero-group velocity points dispersion relations and mode anticrossings : One role is the demultiplexing in a space-localized fashion, combining properties of the Fabry-Perot and grating dispersive devices in a miniature footprint. Various aspects of the realization of such devices will be presented, towards WDM or coarse WDM applications in the framework of the european FUNFOX project.

Another role is the possiblity to enhance gain in inverse proportion of the slwoed-down group velocity. A third possiblity is to produce a Purcell effect and thus a shorter lifetime for emitters embedded in such waveguides. This last possibility raises the prospect of an integrated high efficiency source with controlled photon modes.

6128-23, Session 7

Theoretical and experimrntal study of mode dispersion in biperiodic photonic crystal structures

A. Jafarpour, J. Huang, M. Soltani, M. Askari, A. Adibi, Georgia Institute of Technology

No abstract available

6128-24, Session 7

Tunable time delays in photonic-crystal waveguides

M. L. Povinelli, Stanford Univ.; S. G. Johnson, J. D. Joannopoulos, Massachusetts Institute of Technology

We propose the use of slow-light, band-edge waveguides for compact, integrated, tunable optical time delays. We show that slow group velocities at the photonic band edge give rise to large changes in time delay for small changes in refractive index, thereby shrinking device size. Figures of merit are introduced to quantify the sensitivity, as well as the accompanying signal degradation due to dispersion. It is shown that exact calculations of the figures of merit for a realistic, three-dimensional grating structure are well predicted by a simple quadratic-band model, simplifying device design. We present adiabatic taper designs that attain <0.1% reflection in short lengths of 10 to 20 times the grating period. We show further that cascading two gratings compensates for signal dispersion and gives rise to a constant tunable time delay across bandwidths greater than 100GHz. Given typical loss values for silicon-on-insulator waveguides, we estimate that gratings can be designed to exhibit tunable delays in the picosecond range using current fabrication technology.

6128-25, Session 7

Tammís surface states in photonic crystal

N. Malkova, C. Ning, NASA Ames Research Ctr.

We study theoretically and numerically coupled-cavity waveguide made of a straight line of the coupled defects in a photonic crystal. The defects supporting non-degenerate and double degenerate states are studied. We investigate a two-dimensional square photonic crystal doped by the identically, equally distant defects. Using the Finite Difference Time Domain technique we analyze the spectrum of the system. We found that the spectrum of the coupled-defect waveguide depends on its termination in the ideal host crystal. A position of the resonant peaks in frequency and the number of peaks are related with the boundary conditions of the coupled defects. We study the structure analytically in terms of tight-binding theory. The surface effect can be explained using the theory of the surface states developed by Tamm for solids.

6128-26, Session 7

Segmented cladding fibers for the middle infrared

A. Millo, Y. Lavi, I. Neah, A. Katzir, Tel Aviv Univ. (Israel)

We report the design, fabrication and optical characterization of total internal reflection segmented cladding fibers for the middle infrared range of 2-20μm. Segmented cladding fibers is a novel fiber design in which the uniform core of high refractive material is surrounded by a cladding of alternating areas of high and low refractive indices. Segmented cladding fibers are capable of maintaining a single-mode operation over a wide spectral range with a large core area. The design of the fibers and the simulations were made using the radial effective index method. The fibers were extruded from silver-halide crystals by using the 'rod in tube' method. Using this method we were able to construct large core few-modes fibers which exhibited relatively low losses at 10.6μm.

6128-27, Session 8

Dispersion engineering for 3D subwavelength imaging using photonic crystals

D. W. Prather, Z. Lu, S. Shi, C. A. Schuetz, Univ. of Delaware

No abstract available

6128-28, Session 8

Compact preconditioned photonic crystal demultiplexers based on combined focusing and superprism effects

B. Momeni, J. Huang, M. Soltani, M. Askari, A. Adibi, Georgia Institute of Technology

Wavelength demultiplexing is one of the major applications of unique dispersion properties of photonic crystals (PCs). Possibility of integration and compactness are two main advantages of PC based demultiplexers compared to other demultiplexing techniques for applications like compact spectrometers (for sensory applications) and WDM demultiplexers. Here, we show that resolution and size limitations of conventional superprism-based photonic crystal demultiplexers are caused by the choice of configuration. We suggest an alternative implementation (combining superprism effect and focusing) that improves the performance compared to the conventional implementation in terms of being more compact and relaxing the requirement for divergence angle of the incident beam. We use an effective index model to describe the beam propagation behavior inside the photonic crystal. Using this model, effective indices (second order and third order) are calculated directly from the band structure and are used to find the optimal operation parameters for the demultiplexing device. Detailed calculations show that the required size of preconditioned superprism photonic crystal demultiplexers scales up as N5/2 (N being the number of channels which is proportional to the resolution of the device) which has a significant advantage over N4 dependence in conventional superprism-based devices. Structures obtained through optimization have been fabricated in SOI wafers using e-beam writing and ICP etching, and for the first time spatial separation of channels in superprism-based devices are experimentally demonstrated.

6128-29, Session 8

Modulating dispersion properties of low index photonic crystal structures using microfluidics

A. S. Sharkawy, S. Shi, EM Photonics, Inc. and Univ. of Delaware; D. W. Prather, Univ. of Delaware; S. E. McBride, P. J. Zanzucchi, Sarnoff Corp.

Applications relying on the dispersive properties of low-index photonic crystal structures have recently attracted the attention of the wide majority within the photonic crystal community. The reason for such is the flexibility of implementing similar functionalities offered by the confinement properties if operating in the stop or bandgap but yet without the limitation of high fabrication tolerances, alignment required or the need for high index contrast between the materials used to construct a PhC structure. Recent experimental studies have shown that the dispersion properties in photonic crystal structures can be engineered to implement various optical devices. While almost all of the previous interest in examining the dispersion properties of photonic crystals in high index materials, we exploit the possibility of implementing similar functionalities using low index materials specifically polymers. In this paper, we present a technique for manipulating the dispersive properties of low index periodic structures using microfluidic materials that fill the lattice with various fluids of different refractive indices. In order to quantify the modulation of the optical properties of the periodic structure we use Equi-frequency contours (EFC) data to calculate the frequency dependant refractive index and the refractive angle. We further introduce various types of defects by selectively filling specific lattice sites and measuring the relative change in the index of refraction. Finally we design and optically characterize an adaptive low index photonic crystal based lens with tunable optical properties using various microfluidics. We also present experimental results for a silicon based PhC lens used an optical coupling element.

6128-30, Session 8

Organic nonlinear Kerr materials in Fabry-Perot cavities for all optical switching

N. Moll, A. Jebali, R. Harbers, S. Jochim, S. T. Gulde, R. F. Mahrt, B. J. Offrein, IBM Zürich Research Lab. (Switzerland)

Combining organic films with high Kerr-nonlinearities and highly optimized photonic nanostructures could lead to new fast switching elements. Fabry-Perot cavities are fabricated by incorporating an organic material between two dielectric mirrors. Using femto-second pump and probe measurements we characterize these hybrid 1-D photonic band gap structures for various organic materials. Promising organic materials are C60 and MEH-PPV. By varying the pump beam wavelength across the cavity resonance we are able to delineate between the various underlying nonlinear processes. It turns out that in the spectral region between 780 nm to 880 nm the nonlinear absorption dominates the signal. However, for larger wavelengths of around 1300 nm to 1500 nm refractive nonlinear effects dominate the signal. Comparing these measurements with computations we are able to quantify both the refractive and absorptive nonlinear coefficients of various organic materials.

6128-31, Session 8

Ultracompact current-injected optical modulator based on silicon photonic crystal waveguide

Y. Jiang, L. Gu, The Univ. of Texas at Austin; W. Jiang, Omega Optics Inc.; X. Chen, R. T. Chen, The Univ. of Texas at Austin

Nanotechnologies including photonic crystals (PhCs) promise to have a revolutionary impact on the landscape of photonics technology. PhCs are a new class of artificial optical materials with periodic dielectric structures, which result in unusual optical properties and promise to provide revolutionary solutions to the miniaturization of photonic devices. Photonic crystals with photonic band gaps (PBGs) are expected to be key platforms for future optical integrated circuits. Due to its unique properties, the size of most optical components can be greatly reduced. In initial studies it seems that 3-D PhC structures with 3-D PBGs are essentially required to obtain these unique properties. However, recent studies show that 2-D PhC slab can also obtain very good performance. PhC slabs are 2-D PhC structures located within the slab waveguide. In PhC slab, the light is confined by a combination of in-plane PBG confinement and vertical total-internal-reflection (TIR) confinement. One simple way to utilize the PBG effect is to introduce functional defects into PhCs, which is analogous to doping intentional defects in electronic crystals to introduce defect bands. Line defects can work as strongly confined waveguides. Due to all these unique properties and easy fabrication techniques, 2-D PhC slab line defect waveguides have been most extensively studied. At the meantime, silicon has long been the optimal materials for electronics, but silicon has only relatively recently been considered as an option for photonics. As silicon photonic technology is compatible with conventional complementary metal-oxide-semiconductor (CMOS) processing, monolithic integration of the silicon photonic devices with advanced electronics on a single silicon substrate becomes possible. Several research groups have demonstrated low loss silicon PhC waveguides. However, few active devices based on silicon PhCs have been demonstrated. In this conference, we will present the recent progress of our novel ultracompact current-injected optical modulator based on silicon photonic crystal waveguide.

6128-32, Session 9

The use of resonances in photonic crystals

S. Fan, Stanford Univ.

No abstract available

6128-33, Session 9

An optically triggered Q-switched photonic crystal laser

B. M. Maune, J. Witzens, M. Kolodrubetz, H. A. Atwater, California Institute of Technology; R. Hagen, Bayer AG (Germany); Y. Qiu, Jet Propulsion Lab. and California Institute of Technology; A. Scherer, California Institute of Technology

Significant design freedom enables photonic crystal (PC) cavities to be fabricated that support optical modes with specific, favorable characteristics. For example, PC cavities can be designed to possess modes that have electric field distributions with substantial overlap with the PC holes and cladding. Such structures are ideally suited for integrating fluidic optical materials within intense optical fields generated by PC lasers. In creating our optically triggered Q-switched PC laser, we designed and fabricated a PC cavity optimized to support two orthogonally polarized lasing modes [1]. The cavity was infiltrated with nematic liquid crystal which could then be aligned optically using a layer of photoaddressable polymer. The relative Qs of the cavity modes could be modulated by rotating the birefringent liquid crystal in the PC laserís top cladding layer which then enabled the laser emission to be reversibly switched between the two cavity modes. By largely decoupling the wavelength switching range from the birefringence of the infiltrated fluid, the Q-switching technique significantly increases the wavelength range over which the laserís emission can be controlled as compared to previous tuning efforts. The gain spectrum exhibited by the active InGaAsP quantum wells, itself, may be the ultimate limiting factor in the achievable wavelength switching range of these lasers. As such, using the Q-switching technique may eventually yield PC lasers with wavelength switching ranges exceeding 100 nm.

1 B. Maune, et. al., “Optically triggered Q-switched photonic crystal laser,” Opt. Express 13, 4699-4707 (2005).

6128-34, Session 9

Coupling of PbS quantum dots to photonic crystal cavities at room temperature

I. Fushman, D. R. Englund, J. Vuckovic, Stanford Univ.

We demonstrate the coupling of PbS quantum dot emission to photonic crystal cavities at room temperature. The cavities are defined in 33% Al, AlGaAs membranes on top of oxidized AlAs.

Quantum dots were dissolved in Poly-methyl-methacrylate (PMMA) and spun on top of the cavities.

Quantum dot emission is shown to map out the structure resonances, and may prove to be viable sources for room temperature cavity coupled single photon generation for quantum information processing applications. These results also indicate that such commercially available quantum dots can be used for passive structure characterization. The deposition technique is versatile and allows layers with different dot densities and emission wavelengths to be re-deposited on the same chip.

6128-35, Session 9

Resonant scattering and second harmonic generation spectroscopy of a photonic crystal microcavity

M. W. McCutcheon, G. W. Rieger, I. W. Cheung, J. F. Young, The Univ. of British Columbia (Canada); D. Dalacu, S. Frederick, P. J. Poole, National Research Council Canada (Canada); G. C. Aers, R. L. Williams, National Research Council Canada (Canada) and Univ. of Ottawa (Canada)

The resonant modes of two-dimensional planar photonic crystal microcavities patterned in a free-standing InP slab are probed in a novel fashion using a long working distance microscope objective to obtain cross-polarized resonant scattering and second harmonic spectra. We

show that these techniques can be used to do rapid, effective assays of wafers containing large arrays of microcavities that do not necessarily contain resonant light emitting layers. The techniques are demonstrated using microcavities comprised of single missing-hole defects in hexagonal photonic crystal hosts formed with elliptically-shaped holes. These cavities typically support two orthogonally-polarized resonant modes, and the resonant scattering and harmonic spectra are well fitted using a coherent sum of Lorentzian functions. The well-defined coherence between the two resonant features is explained in terms of a microscopic harmonic oscillator model. The relative merits of these techniques are quantitatively compared with the more commonly used cavity-enhanced quantum dot photoluminescence technique.

6128-36, Session 10

Experimental demonstration of sub-wavelength imaging by labyrinth based left handed composite metamaterials

E. Özbay, Bilkent Univ. (Turkey)

We propose and demonstrate a new labyrinth based metamaterial structure that solves two major problems related to the split-ring resonator based structures. One of the problems related to the split-ring resonator structure is the bianisotropy, and the other problem is the electric coupling to the magnetic resonance of the split-ring resonator structure. These two problems introduce difficulties in obtaining isotropic left-handed metamaterial mediums. The new structure that we propose here solves both of these problems. We further show that in addition to the magnetic resonance, when combined with a suitable wire medium, the structure that we propose exhibits left-handed transmission band. A two-dimensional metamaterial based on the labyrinth structure is used to study imaging of a point source. Our experimental results show that it is possible to image the point source with half widths as small as $\lambda/4$ by using the labyrinth based metamaterial.

6128-37, Session 10

Incorporation of electrooptic material in 2D photonic crystal microcavities: electrical tuning of cavity resonance

Y. Lee, G. S. Subramania, P. G. Clem, Sandia National Labs.

2-D photonic crystal microcavities with tunable resonant wavelengths have been demonstrated by controlling the cavity geometry using e-beam lithography.[1] Incorporation of functional materials with switchable optical properties into these microcavities may enable in situ tuning of the microcavity resonance. Electrooptic materials are attractive candidates for incorporation because their refractive index can be electrically modulated through an applied voltage.[2] Here, we present the fabrication and characterization of a 2-D photonic crystal microcavity containing an electrooptic material in the active region. The Si photonic crystal microcavity was fabricated using standard e-beam lithography, and (Pb,La)(Zr,Ti)O3 (8/65/35) ferroelectric film was introduced into the cavity using either sol-gel deposition or radio-frequency sputtering, followed by high temperature annealing. The application of electrical potential across the electrooptic material and its effect on the wavelength of the near-infrared resonance peak will be reported.

1. Subramania, G.; Lin, S. Y.; Wendt, J. R.; Rivera, J. M., Appl. Phys. Lett. 2003, 83, 4491.

2. Haertling, G. H., J. Am. Cer. Soc. 1999, 82, 797.

6128-38, Session 10

Silicon-on-insulator-based photonic-crystal Mach-Zehnder interferometers

L. Gu, Y. Jiang, W. Jiang, X. Chen, R. T. Chen, The Univ. of Texas at Austin

Si nanophotonics is anticipated to play a critical role in the future ultra-compact system integration due to the maturity of sub-micron silicon complementary metal oxide semiconductor (CMOS) technology. Photonic crystals (PhCs) provide a promising platform for developing novel optoelectronic devices with significantly reduced device size and power consumption. Thermo-optic (TO) silicon-on-insulator (SOI) PhC Mach-Zehnder (MZ) interferometers working at 1.5μm, which can be used as both switches and modulators, were recently reported. The unique feature of this device is the length of its active region can be reduced significantly due to the slow group velocity of the light wave in the PhC waveguide. In the previously work reported by a few groups, the microheater is usually put on top of the active region along one arm of the MZ interferometer. A layer of SiO2 has to be deposited between the metal heater and PC waveguide serving as a supporting layer for the heater as well as an optical barrier. However, this buffer layer could possibly introduce two problems. First, the CVD-deposited SiO2 will partially block the air holes of the PhC waveguide, which may change the transmission property and increase the propagation loss of the PhC device. Second, the SiO2 is an undesirable thermal buffer layer between the heater and Si PhC waveguide. It potentially degrades the device performance in terms of the switching speed and the power consumption. In this paper, we present a novel design of the PhC MZ interferometer, which enhances the heat exchange efficiency between the source and the active PhC region. A low-power (lower than any reported results) and comparatively high-speed TO PhC MZ interferometer will be demonstrated.

6128-39, Session 10

Tunable terahertz Bloch oscillations in chirped photonic crystals

V. M. P. Lousse, S. Fan, Stanford Univ.

We report simulations showing tunable terahertz oscillations of the electromagnetic field provided by the Bloch oscillations of a short photonic wave packet in a tilted band structure. The structure consists in a finite one-dimensional photonic crystal inhomogeneously chirped by a slowly-varying refractive index gradient. Tunability is obtained by relocating the Bloch oscillations center in regions characterized by different local band structure gradients. With reasonable refractive indexes, this mechanism may allow the generation of signals which cover a wide continuous part of the electromagnetic terahertz range, when used in combination of appropriate detection schemes.

6128-40, Session 11

Photonic crystals with negative index materials

I. V. Shadrivov, A. A. Sukhorukov, Y. S. Kivshar, The Australian National Univ. (Australia)

We present an overview of the band-gap properties of layered structures with negative-index materials. It is believed that modulation of the refractive index in all three spatial dimensions is required to open a complete bandgap and prevent the propagation of electromagnetic waves in all directions. We reveal that, in a sharp contrast to what was known before and contrary to the accepted physical intuition, a one-dimensional periodic structure containing the layers of transparent negative-index metamaterial can trap light in three-dimensional space due to the existence of a complete bandgap.

6128-41, Session 11

Plasmonic films with a periodic arrangement of subwavelength slits

P. B. Catrysse, G. Veronis, H. Shin, J. Shen, S. Fan, Stanford Univ.

In a recent paper [Phys. Rev. Lett. 94, 197401 (2005)], we introduced a mechanism for creating artificial high refractive index metamaterials by exploiting the existence of subwavelength propagating modes in metallic

systems. We showed that a perfect metal film with a periodic arrangement of sub-wavelength cut-through slits can be regarded as a dielectric slab with a frequency-independent effective index. Here, we discuss the similarities and differences when the perfect metal condition no longer holds for such a system, e.g., in the visible and near infrared wavelength regimes. If the metal obeys a plasmonic dispersion model, we find that this system supports two distinct types of guided modes: a surface mode and a set of effective dielectric slab modes.

6128-42, Session 11

Simultaneous localization of photons and phonons

M. Maldovan, E. L. Thomas, Massachusetts Institute of Technology

We demonstrate the simultaneous localization of photons and phonons in the same spatial region by introducing lattice defects in a periodic array of dielectric/elastic material that exhibits gaps for both electromagnetic and elastic waves. The coexistent localization of light and sound can have a strong influence on photon-phonon interactions, suggesting optical cooling, and the possibility of dual acoustic-optical devices. The simultaneous bounding of photons and phonons can be used to design a new class of acoustic-optical devices that can integrate the management of sound, heat, and light.

6128-43, Session 11

Lithium niobate phononic crystal for surface acoustic waves

S. Benchabane, A. Khelif, J. Rauch, L. Robert, V. Laude, Institut Femto-ST (France)

The demonstration of the viability of photonic crystals as actual optical devices over the past decade has led to increasing interest in their elastic counterparts, the so-called phononic crystals. These are periodic structures made of materials with different elastic properties which exhibit absolute stop bands under given geometrical conditions. The specificities of elastic waves with respect to optical waves besides provide them with additional features: wave propagation is strongly anisotropic, combinations of shear and longitudinal polarizations have to be taken into account, as well as surface modes in addition to bulk modes. These surface acoustic waves (SAW) are of particular interest, as they can be generated directly at the surface of a piezoelectric material by use of interdigital transducers (IDT) and are already widely employed in wireless telecommunication systems. Lithium Niobate, for instance, has strong piezoelectric coupling coefficients as well as rich optical properties. The realization of a phononic crystal combined with the already demonstrated possibility to achieve a photonic crystal in such a material thus offers interesting prospects in terms of confined acousto-optical interactions.

In this work, we study the SAW propagation in a square lattice, 2D void/Lithium Niobate phononic crystal. The hole diameter is 9 microns for a 10 micron pitch, leading to a filling fraction of 64 %. The crystal was fabricated using reactive ion etching of bulk Lithium Niobate leading to aspect ratios up to 1.5, and classical optical photolithography techniques were then used for the IDT fabrication. The crystal was characterized by electrical generation and detection of SAW. A full band gap with a fractional bandwidth of 20% was experimentally demonstrated, which is in close agreement with theoretical predictions.

6128-44, Session 12

Low interface reflection of rod-type photonic crystals: a bottom up approach

C. M. de Sterke, T. White, The Univ. of Sydney (Australia); L. C. Botten, Univ. of Technology/Sydney (Australia); R. C. McPhedran, The Univ. of Sydney (Australia)

No abstract available

6128-45, Session 12

Discontinuous Galerkin spectral element methods for photonic crystals

M. Min, Argonne National Lab. and Brown Univ.

Photonic band gap calculations have been requiring powerful numerical tools as an essential in analyzing the guided modes for various bulk crystals and their optimal designing into photonic devices. We will discuss that discontinuous Galerkin spectral element methods (DG-SEM) are very effective for predicting the forbidden eigenfrequencies accurately.

Computational results for the calculations of dispersion curves for various photonic crystal structures will be demonstrated. Time-domain simulations will be also conducted to analyze transmission process.

6128-46, Session 12

Application of the homogenization approximation to interfacial roughness in 1D photonic crystals

K. R. Maskaly, Los Alamos National Lab.; W. C. Carter, Massachusetts Institute of Technology; R. D. Averitt, J. L. Maxwell, Los Alamos National Lab.

Previously, we reported finite-difference time-domain (FDTD) results that demonstrated the decrease in the normal reflectivity of one-dimensional photonic crystals (1DPCs) due to the presence of interfacial roughness*. However, at that time, no physical explanation was given for this decreased optical performance. In order to gain further insight into this phenomenon, we have applied the homogenization approximation to the roughened quarter-wave stacks and compared the results to those from the FDTD simulations. We have found that the homogenization approximation is able to accurately predict the FDTD results, which suggests that the primary role of the roughness features is to grade the refractive index profile at each interface in the crystal, rather than diffusely scatter the incident light. Consequently, this also implies that the amount of incoherent reflected power from the roughened structures is small compared to the total amount of reflected power, even for extremely rough structures. This latter conclusion has been verified by extracting the amount of incoherent reflected power directly from the FDTD results, further strengthening the claims we put forth here.

* K. R. Maskaly, G. R. Maskaly, W. C. Carter, and J. L. Maxwell, Opt. Lett. 29, 2791 (2004).

6128-47, Session 12

Numerical band calculation of holographically formed periodic structures with irregular motif

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 produce isointensity contours that can be accurately recorded with photoresist and subsequently used as a template for creating photonic crystals with a complete bandgap. The periodic structures typically formed by HL comprise of highly convoluted shapes that do not conform to typically known geometrical shapes and therefore preclude the use of analytic approaches for the plane wave expansion (PWE) method to accurately generate the band-dispersion curves. In this paper, we present a numerical technique that decomposes the HL-formed structure into fine mesh grids and expands this material mesh into the PWE method to provide band-dispersion curves. Band diagrams obtained in this way are shown to accurately match the know solutions for opal, inverted opal, and woodpile structures. We extend the numerical technique to predict the band structure of HL templates formed with an Ar-ion laser using

phasemask interference. We examine skewed periodic structures with irregular symmetry and compare with spectroscopic observations.

6128-48, Session 12

Efficient modeling of photonic crystal structures under diffuse light illumination

M. Badieirostami, A. Adibi, Georgia Institute of Technology

No abstract available

6128-49, Session 13

Variation of a photonic crystal color with the Miller indices of the exposed surface

J. Vigneron, Facultes Univ. Notre Dame de la Paix (Belgium); V. M. P. Lousse, Stanford Univ. and Facultes Univ. Notre Dame de la Paix (Belgium)

A photonic crystal grain can be given different orientations when exposed to white visible light. It is shown that the reflectance spectrum and hence the global reflected color will strongly depend on the Miller indices of the reflecting surface. Systematic calculations are carried out in order to show that all basic colorimetric primitives can be generated in this way, even when rather low refractive indexes are involved. The simulations use a layer doubling techniques, in the framework of a state-of-the-art S transfer-matrix approach. Several photonic structures are considered with natural terminal surfaces. Among these, the [100], [111] and [110] surfaces of a layer-by-layer photonic crystal, and the [100], [111] and [110] surfaces of an opal or inverse opal will be considered. From these results, the average coloration of a randomly oriented distribution of micron-sized photonic crystal grains is investigated. This analysis is also carried out for the poly-crystalline photonic material recently discovered in the wings of the brazilian butterfly Cyanophrys remus. The implications for the development of specific color coatings containing no absorbing pigments will be addressed.

6128-50, Session 13

FDTD analysis of photonic quasicrystal

K. Mnaymneh, R. C. Gauthier, Carleton Univ. (Canada)

There has been steady interest in Photonic Crystal (PhC) structures for nearly the past two decades. The key feature that gives PhCs their ability to form photonic band gaps (PBGs) analogous to electronic band gaps of semiconductors is their translational symmetries. In recent years it has been found that structures that posses only rotational symmetries can also have PBGs. In addition, these structures, known as Photonic Quasicrystals (PhQs), have other interesting qualities that sets them apart of their translational cousins. For example, defect states in regular PhC structures are introduced by locally removing the translational symmetry. This leads to ibound statesî which is very familiar in solid-state physics, however in photonic crystals these states are known as defect states. People have taken defects of translationally symmetric PhCs and applied them to get similar defect states in PhQs. This presentation explores another possibility to generate defect states: to limit and remove the rotational symmetry in one direction. This leads to similar defect states and in this presentation, one such defect state is used to assist waveguide 90 degree bends. That is, propagation efficiency is increased around a 90 degree bend due to the coupling of the waveguide to this PhQ ìsymmetry-brokenî defect mode. Along with simulations, fabrication steps and measurement results are shown.

6128-51, Session 13

Resonant effect analysis at finite 1D anisotropic photonic crystal band edges

Y. Cao, M. A. Fiddy, Univ. of North Carolina/Charlotte

Using the transmission matrix method to analyze a 1D anisotropic photonic crystal usually involves a 4◊4 matrix, which means for any given ω and (kx, ky), four eigen values of kz , can always be found. Based on the degeneracy of kz, the band edge locations in the dispersion curves can be divided into two types. One is the regular band edge points (R.B.E) which has degeneracy of the order 2 and another is the degenerate band edge point (D.B.E) which has fourth order degeneracy. 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 N^4, where N is the total number of periods, while in the case of a regular band edge, the field intensity is proportional to N^2. Based on this prediction, we have calculated the band edge resonant effect of a novel D.B.E photonic crystal structure with a unit cell having two misaligned in-plane anisotropic layers and one isotropic layer. 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, whether the anisotropy is large or small, the field intensity increase is approximately proportional to N^4 once the number of the periods is large enough to cause the strong enough resonance effect inside the structure. We believe this DBE resonant effect will have applications in slow-light and nonlinear optics.

6128-52, Session 13

Photonic crystal devices analysis based on perturbation theory

M. Chamanzar, S. Khorasani, Sharif Univ. of Technology (Iran)

A novel approach for photonic crystals devices analysis, based on perturbation theory is reported. In this method the photonic crystal device is considered as the superposition of a perfect lattice and a perturbing one. Then the solution is investigated in terms of the eigensolutions of the perfect lattice. This way, arrays of resonators can be considered as perturbations in a perfect lattice. Also, a perfect photonic crystal can itself be analyzed by considering it as a perturbation in a simple dielectric medium. The perturbation theory employed in this work is typical of what is conventionally used in quantum mechanics literature. The presented formulation is carried out analytically, thus yielding analytic expressions from which one can readily investigate different parameters effects on the eigensolutions of the structure.

Although this approach can be used to obtain some rules of thumb about the eigensolutions of the device within the first order perturbation approximation, it can be further followed to higher order perturbation terms for acquiring any desired level of accuracy. Since the presented method is mostly formulated analytically, not much computational effort is required for analyzing complex structures. In this paper the approach is described in detail and some examples are given to show its usefulness.

6128-53, Session 13

Modeling and design of photonic band gap polarizer

Y. Kalra, R. K. Sinha, Delhi College of Engineering (India)

Photonic Crystals (PhCs) are artificial dielectric structures in which refractive index modulation gives rise to stop bands in certain frequencies known as photonic band gaps (PBGs). Various defects can be introduced in these structures to enhance their versatility. Variety of devices can be designed by tailoring the defects in PBG structures. In this paper, we utilize this property to design PBG polarizer that has been numerically analyzed using the plane wave expansion (PWE) method and the finite difference time domain (FDTD) method.

To design a PBG polarizer we consider a PBG structure composed of honeycomb lattice of Si (n=3.42) rods in air with normalized rod radius r/a = 0.24 with lattice constant a = 0.885 micrometer, that exhibits complete photonic band gap (CPBG) for normalized frequency range i.e. a/lambda from 0.53711 to 0.58793 as calculated using the PWE method. An input PBG waveguide is formed by creating a linear defect in the PBG structure in which light of both TE and TM polarization can be guided in

the normalized frequency range i.e. a/lambda from 0.53711 to 0.58793. To design a PBG polarizer at 1.55 micrometer wavelength a linear PhC defect waveguide with defect radius r = 0.08a is created after the input waveguide. This defect waveguide supports only TE modes but exhibits a PBG for TM mode. Thus if at the input end light of both TE and TM polarization is launched in the input waveguide then at output end light of only TE polarization is received as the defect waveguide supports only the TE mode and not the TM mode , as numerically investigated using the FDTD method.

Similarly another PBG polarizer can be designed at wavelength = 1.6 micrometer by engineering the defect wave guide which allows the TM mode to propagate in the defect waveguide. Thus, by tailoring the defect waveguide a PBG polarizer can be designed at the desired wavelength.

6128-54, Poster Session

Fabrication of reconfigurable photonic bandgap-MEMS waveguide device

M. A. Taysing-Lara, W. Zhou, G. Dang, D. M. Mackie, P. G. Newman, Army Research Lab.

We present the development of a fabrication technique for a semiconductor-based photonic bandgap (PBG) nano-membrane device with reconfigurable active waveguides using MEMS. This device can be used as a basic building block for optoelectronic integrated circuits that can be reprogrammed for different functionalities such as switches, modulators, time delay lines, etc. The device is fabricated three-dimensionally on GaAs/Alx1GaAs/Alx2GaAs epitaxial layers grown by molecular beam epitaxy (MBE) on a GaAs substrate. The device has a top PBG membrane layer structure composed of hexagonal holes in a triangular lattice, which is specially designed to satisfy the various fabrication constraints. Below that, a separate suspended bridge layer can insert a line of posts into the photonic crystal holes to create a defect line. This MEMS feature can generate/cancel a section of the waveguide in the PBG platform, or (by partial removal) it can change the dispersion of the waveguide. Therefore, the same structure can be used as different types of devices. In this paper, we will discuss detailed fabrication processes for such a multi-layer 3D device structure, including e-beam lithography, inductively coupled plasma (ICP) reactive ion etching, and multiple steps of regular photolithography and selective wet chemical etching. The unique processing sequence allow us to fabric the multi-layer 3D device structure from one top surface without regrowth, wafer bonding, or access from the back surface. This simplifies the device processing and reduces the fabrication cost.

6128-55, Poster Session

Investigation of an effective medium theory for metallic periodic structures: a fitting-based approach

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

While the effective medium theory (EMT) has been useful to explain optical characteristics of a dielectric periodic structure analytically, it has failed to describe metallic structures correctly. In this paper, a fitting-based approach is introduced to applying an effective medium theory to structures that include metallic material. The effective indices of a metallic medium were first obtained by numerically fitting to reflectance characteristics calculated with rigorous coupled wave analysis (RCWA). Searching for an effective medium has been performed through binary searches rather than a time-consuming simulated-annealing algorithm. The calculated effective medium showed results that are in good agreement with RCWA. The deviation was minimal in the long-wavelength limit when angles of incidence, grating depths, or refractive indices of a superstrate are varied. In particular, TE polarization showed more robust features against the variations while TM polarization was more sensitive to the modeling parameters. In terms of the standard deviation, the calculated effective medium was the least affected by the change of grating depths. The applicability of the fitting-based approach was investigated by applying it to a three-dimensional metallic photonic crystal. Simulation results based on the fitting-based EMT perfectly reproduced broad photonic bandgap as observed in published experimental data. Also, the fitting-based approach provided valid results in the wider wavelength range than a traditional EMT.

6128-56, Poster Session

Nanophotonic boxes to modify black-body radiation for visible light emission

C. Chao, C. Wu, C. F. Lin, National Taiwan Univ. (Taiwan)

Increasing illumination efficiency of lighting is very attractive for the concern of energy consumption. Nevertheless, the efficiency of incandescent lamps remains low because the visible spectrum of black-body radiation under 2500K possesses only 5% of the total radiation energy. State-of-the-art research on photonics crystal offers the possibility to modify black-body radiation for the enhancement of emission in infrared spectrum. However, enhancement in visible spectrum using photonic crystals has not been demonstrated yet. In addition, the physics of the enhancement is still not clear due to the complication of photonic crystals. Here we report another approach. Metallic photonic boxes could enhance black-body radiation in the desired spectrum, including the visible range.

The photonic box has insulating dielectric surrounded by metal outside, forming a resonant cavity to modify the characteristic of the radiation spectrum. Thus black-body radiation is modified to enhance the blue spectrum using photonic boxes of about 200 nm. The enhanced blue light has the peak intensity at 400 nm with an enhancement factor of over 5000. The spectral width is governed by the variation of the box size and can be controlled by fabrication condition. The physics can be easily explained by the significantly enhanced density of states at a certain spectrum as a result of photonic boxes. Our experiment demonstrates that black-body radiation has significantly enhanced light emission at around 400 nm with a narrow spectral width at a much lower temperature than conventional situation.

6128-57, Poster Session

Evaluation of manufacturability for 3D photonic crystal waveguide with nanoimprint

T. Shimomura, K. Ito, N. Toyama, Dai Nippon Printing Co., Ltd. (Japan)

Currently a few hundreds nm dimension is employed to achieve visible and infrared light optical elements for optics field as nano-optics. On the other hand there are a lot of reports of nano-imprint experiment including under 50 nm for storage, bio-technology or semiconductor application. And one of the biggest advantages of nano-imprint is three dimensional fabrications at one imprint procedure. However already introduced two or three dimensional imprinted optical elements are either just confirming replication of conventional Fresnel optics or defect negligible lattice structure.

Three dimensional nano-imprint mold (3D-mold) must have great potential for optics fabrication. The combination of 3D-mold and three dimensional nano-imprint method can create flexible optical behavior.

Here practical fabrication trials for three dimensional photonic crystal waveguide with 3D-mold and nano-imprint technology are discussed. Particularly fabrication 3D-mold with quarts, nano-imprint methodology and waveguide structure with evaluation and simulation are focused.

6128-58, Poster Session

Refractive index and geometrical structure measurement of a core-doped photonic crystal fiber

Y. Youk, D. Y. Kim, K. Oh, Gwangju Institute of Science and Technology (South Korea)

We have measured refractive index profile of a core-doped photonic crystal fiber with a modified confocal scanning optical microscope. As this method measures reflectivity change due to refractive index change on a waveguide facet it does not require index matching oil around a waveguide facet. The refractive index profile of a sample was obtained by moving sample while maintaining the confocal configuration with respect to the incoming beam. In the scanning process, we measured the reflected power as a function of longitudinal offset distance z from the focal point of the incoming beam for a fixed lateral position (x,y). We obtain the maximum reflected power when the sample facet is at the focal point of the incoming beam. This method is applicable to waveguides with complex and axially nonsymmetric structure such as a photonic crystal fiber because the refractive index measurement of a sample doesnít depend on the structure but the surface reflectivity. To investigate the refractive index of the core-doped photonic crystal fiber, the end face of the fiber was prepared by cutting the fiber with a tension cleaver. With this technique, we have obtained 2-dimensional refractive index profile and the fine structure geometry of a core-doped photonic crystal fiber.

6128-59, Poster Session

Analytical analysis of defect lines in 2D photonic crystals based on polynomial expansion of electromagnetic fields

M. Chamanzar, A. H. Atabaki, K. Mehrany, S. Khorasani, B. Rashidian, Sharif Univ. of Technology (Iran)

Analytical analysis of straight single-line defect optical waveguides in two dimensional photonic crystal slabs based on expanding electromagnetic fields in terms of orthonormal polynomial sets like Hermite and Legendre polynomials is reported. This novel electromagnetic field expression, in accordance with the well-known Bloch theorem, is substituted in Helmholtz equation; whereas appropriate boundary conditions are applied and defect modes, i.e. the guided modes propagating in the line defect waveguide, are analytically derived. Finite difference time domain simulation is also employed to confirm the accuracy of the results obtained by applying the proposed approach, where excellent agreements between those results obtained by following our proposed method and those achieved by applying finite difference time domain method are observed.

6128-60, Poster Session

Ultrahigh resolution photonic crystal nanoprobe for high-density optical data storage, near-field microscopy and nanolithography systems

A. S. Sharkawy, S. Shi, EM Photonics, Inc. and Univ. of Delaware; T. E. Dillon, G. J. Schneider, D. W. Prather, Univ. of Delaware

Scanning near-field optical microscopy (SNOM) and spectroscopy is at the forefront of science and technology today due to the fact that it combines the potentials of scanned probe technology with the power of optical microscopy/spectroscopy. SNOM is our eyes to the nanoworld. Among the main parameters that might be of interest for a nano structure under investigation are, its size, shape, chemical composition, molecular structure. In order to investigate such properties, microscopes with high spatial resolution as well as high spectral and temporal resolving power are required. Classical optical microscope excels with respect to spectroscopic and temporal selectivity, although its resolution is restricted by diffraction to about half a wavelength (200-500nm for the visible light). Today science and technology have an increasing need for tools that allow the characterization, generation, and manipulation of structures as small as few nanometers in size. The most critical element in near field optical microscopy or SNOM is an aperture probe, which is usually a tapered and metal-coated optical fiber. Such design has proven to exhibit both high insertion loss (~30dB) and a diffraction limited spot size. Hence, in this effort present a photonic crystal based nano-probe design which overcomes the limitations listed above, in addition it provide several advantages over the standard approach of tapering an optical fiber. Our nano-probe takes advantage of an ongoing revolution in the field of nano-photonic based structures namely; photonic crystals to develop an ultra high-resolution nano-probe, which will in turn replace the currently, used tapered fiber for applications in need of such high resolution.

6128-61, Poster Session

Tunable photonic crystals based on liquid crystals

P. Dardano, L. Sirleto, L. Moretti, V. Mocella, I. Rendina, Istituto per la Microelettronica e Microsistemi (Italy)

One of the most important optical properties of photonic crystals is that the waveguide dispersion relations can be tailored and allow for many non-conventional applications such as guiding and processing of the light signal. On the other hand, a variety of physical phenomena make liquid crystals (LC‘s) one of the most interesting subject of modern fundamental science. Moreover, in the last years, it has been proved that in order to obtain active tuning of the photonic crystals device a very promising approach can be achieved by infiltrating photonic structure with liquid crystals.

On this line of argument, in this paper, the design of an electro-optical switch based on 2D silicon photonic band-gap structure and using liquid crystals as active medium is presented. We consider a T-junction PhC diplexer in two dimensional photonic crystals composed of silicon rods with square lattices with a nematic liquid crystals as defect. We prove that efficient transmission as well as complete splitting of the entire wavelengths range supported by the input waveguide, in two sub-ranges symmetrical with respect to the middle (switching) wavelength and propagating in right and left waveguide respectively, can be achieved. Moreover, changing the refractive index of liquid crystals by electro-optical effect, a tuning of switching wavelength of about 60 nm can be obtained.

6128-62, Poster Session

Optical non-reciprocity and bandgap tunability in 2D magnetophotonic crystals

M. Vanwolleghem, P. Gogol, P. Beauvillain, J. Lourtioz, Univ. Paris Sud (France)

Up till now the use of magneto-optic materials in photonic crystals has been limited to obtaining an enhancement of the Kerr and/or Faraday rotation and ellipticity when such a material is introduced as a defect in a 1D Bragg-like photonic crystal structure. Recently however, theoretical interest has arisen in the peculiar behaviour of two- and three-dimensional photonic crystals using magneto-optic materials. We present a numerical analysis of two possible applications of two-dimensional magneto-photonic crystals based on (bismuth-substituted) iron garnet materials, namely band-gap tunability and spectral optical non-reciprocity. By locally or globally changing the magnetization in the garnet matrix material, either by applying an external magnetic field or by locally deforming the shape/size of the air holes of a standard hexagonal crystal structure, a band gap can be opened and/or can be tuned (over some 10%). This leads to interesting integrated photonic applications, such as tunable add-drop multiplexers and filters.

If on the other hand, the geometry of the crystal lattice is deformed (so that the motif looses its inversion symmetry), then it can be proven that under special conditions for the magnetization in the garnet material, optical spectral non-reciprocity will be observed in the band structure of the magneto-photonic crystal. This novel application might advantageously be used for the design of very compact integrated optical non-reciprocal components such as isolators. Up till now, this behaviour has never been studied in two-dimensional magneto-photonic crystals nor at optical telecom frequencies. We present the first numerical analysis of such non-reciprocal magneto-photonic crystals.

6128-63, Poster Session

Experimental demonstration of self-collimation in 3D photonic crystal at microwave frequencies

Z. Lu, S. Shi, J. A. Murakowski, C. A. Schuetz, G. J. Schneider, D. W. Prather, Univ. of Delaware

In this pressentation, we review our recent experimental results on dispersion-based 3D photonic crystals for microwave and millimeter-wave applications, where we focus on a simple cubic photonic crystal with self-collimation dispersion in certain frequency bands. Three-dimensional finite-difference time-domain simulations (FDTD) show that self-collimation modes can be selectively excited by launching a source with a particular polarization in spite of the degeneracy of propagation modes in the photonic crystal. To perform the experiment, first a computer-numerically-controlled router was employed to fabricate the photonic crystal in a high-dielectric-constant microwave material. A 3D imaging system based on a vector network analyzer was then established to map field distribution. By point-by-point scanning, we mapped the field distribution throughout the volume of the photonic crystal while microwaves were fed through a waveguide. The measured field distribution showed a narrow collimated beam in agreement with FDTD simulations, whereas the field distribution showed a diverged beam in the absence of the photonic crystal. Thus, self-collimation in the 3D photonic crystal has been experimentally demonstrated.

6128-64, Poster Session

Low splicing loss and high-tensile strength index-guiding holey fiber with new defect design

S. Kim, Y. Jung, K. Oh, Gwangju Institute of Science and Technology (South Korea); U. Röpke, J. Kirchhof, H. Bartelt, Institut für Physikalische Hochtechnologie e.V. (Germany)

We propose new design parameters for index-guiding holey-fiber (IGHF) that can provide flexibility in defect and lattice design as well as adiabatic mode transformation capability. The new type of IGHF is composed of two-layered inner-rings as the core and three-layered outer-rings as the cladding. In the core, the central air-holes are surrounded by Ge-doped rings with index difference, D and the outside rings in the cladding are index-matched to silica by co-doping P2O5 and F. The germanosilcate ring plays two pivotal roles, i) providing flexible defect design and ii) generating sub-lattice structure due to difference in viscosity relative to P2O5 and F co-doped rings in the cladding. With these inhomogeneous defects, complex lattice structures can be realized in comparison to the prior IGHF.

In this paper, we theoretically analyzed and experimentally demonstrated the low splicing loss with high tensile strength between the new defect type of IGHF and SMF for the first time to best knowledge of authors.

In contrast to prior IGHF, the proposed fibers can be achieved adiabatic mode conversion from annulus mode to a mode generated from solid multi-core fiber due to germanosilicate rings that is highly compatible to LP01 mode in conventional single mode. This adiabatic mode conversion contributed to low splicing loss, 0.4dB at l=1.55mm and high tensile strength, 3Gpa almost equivalent to that of SMF to SMF splice strength.

6128-65, Poster Session

Refractive index measurement by using a photonic crystal fiber

J. Sun, C. C. Chan, Nanyang Technological Univ. (Singapore)

An optical waveguide for measuring the change of refractive index by using a photonic crystal fiber is designed. The simulation results show that a variation of 0.032 refractive index unit (RIU) could shift the resonant wavelengths of 245nm and 68nm when the refractive indices of liquid are 1.5 and 1.7, respectively. The sensitivity for the refractive index measurement of about 1.3◊10-6RIU is achieved.

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6129-01, Session 1

Anticompetition of laser modes in quantum dot lasers

C. F. Lin, D. Chiang, National Taiwan Univ. (Taiwan)

Laser mode competition is a well-known phenomenon in a multi-mode laser system. The competition between different lasing modes is considered inevitable in all kinds of lasers. However, our experiments show that laser mode anti-competition can be observed in lasers that combine either quantum dots (QD) of different sizes or quantum wells of different composition and width. Here we report the anti-competition experiment from QD lasers. The QD structure is grown on a GaAs substrate. Two types of QD layers for 1.24μm emission and 1.28μm emission are grown alternatively in the active layer. The anti-competition behavior is observed in an external cavity laser controlled by the grating, oscillating at two different wavelengths. The operating wavelength is tuned to 1265nm and 1165nm by using two feedback mirrors. This external-cavity laser uses a Fabry-Perot laser diode fabricated on the QD substrate with a length of 488μm. A neutral-density filter is placed in front of the 1165nm-feedback mirror to change the intensity of the light gradually. Output power of the two wavelengths are separated by another grating and collected by two InGaAs photodiodes simultaneously. Experimental results show that when 1165nm light intensity increases from 0 mW to 0.55 mW, 1265 nm light intensity will also increase from 0.8 mW to 1.0 mW. This is the anti-competition behavior. When 1165nm light intensity continue to increase from 0.55 mW to 1.3 mW, the 1265nm light intensity decreases from 1.0 mW to 0.1 mW, which is the usual competition behavior. Further experiments show that anti-compeition is influenced by wavelength separation, the intensity of the short-wavelength mode, and injection current.

6129-03, Session 1

Experimental and theoretical study of multiple cations intermixing in InP-based quantum dot-in-well structure

Y. Wang, H. Susanto Djie, B. Ooi, Lehigh Univ.

Recently InAs-based quantum dot-in-well structures grown on InP substrate have attracted much attention due to their potential applications in long wavelength (1.55μm) laser for telecommunications. The dot-in-well structure has also been found to improve the carrier collection rate into QDs and to suppress the thermal escape of carriers out of QDs. Quantum well (QW) and quantum dot (QD) intermixing are promising technologies for the fabrication of high performance optoelectronic devices and photonic integrated circuits. Here, we study the effect of intermixing on the InAs dots-in-AlInGaAs quantum well structure with SiO2 and Si3N4 as capping layers. A wavelength blue-shift with a significant decrease in the full width at half maximum (FWHM) have been observed after rapid thermal processing (RTP) from both SiO2 and Si3N4 capped samples. In contrast to most reported results in other material systems, we found that Si3N4 capped samples produce a larger energy blue-shift than the SiO2 capped samples after annealing. A differential wavelength shift as large as 84 nm has been observed from samples capped with Si3N4 and SiO2 followed by an RTP step at 750 ∞C for 30s. Similar result has also been observed from the annealed AlInGaAs quantum-well samples that have similar wafer structure but without the presence of InAs QDs in the active region. A theoretical model based on multiple cations intermixing has been developed to explain the experimental observations. Our results are useful for understanding the multiple cations interdiffusion mechanism in III-V semiconductors, as well as for realizing high performance optoelectronic devices and photonic integrated circuits using intermixing technique in this material system.

6129-04, Session 1

Feasibility of conventional method of extracting internal loss and internal quantum efficiency in edge-emitting quantum dot lasers

L. V. Asryan, Virginia Polytechnic Institute and State Univ.

Feasibility is discussed of the conventional method of determining internal loss coefficient and internal quantum efficiency from a measured plot of the reciprocal slope efficiency versus the cavity length in semiconductor edge-emitting quantum dot lasers. The limitations are imposed by the cavity-length-dependence of internal loss and quantum efficiency themselves. The effect of internal loss is quantitatively analyzed. In short cavities, a plot of the reciprocal slope efficiency versus the cavity length can significantly deviate from a straight line; particularly, the reciprocal slope efficiency increases with reducing the cavity length in short cavities. This plot asymptotically approaches an inclined line only in long cavities. Correspondingly, only infinitely-long-cavity (no mirror loss) values of the internal loss coefficient and the internal quantum efficiency can be extracted using the standard procedure. These latter differ significantly from those in short-cavity devices, thus strongly limiting the practicality of the procedure.

6129-05, Session 1

Characteristics of In(Ga)As quantum dot lasers on InP emitting at 1.5um in continuous wave mode

N. J. Kim, J. S. Yim, D. Lee, Chungnam National Univ. (South Korea); S. H. Pyun, W. G. Jeong, Sungkyunkwan Univ. (South Korea)

Self-assembled semiconductor quantum dots (QDs) have been actively investigated since the low threshold current, high characteristic temperature (T0), and fast gain recovery are expected when QDs are used as a gain medium for a laser diode (LD). Recently, there were many reports on excellent results on GaAs-based QD LDs up to 1.3 μm. However, at 1.5 μm, mostly quantum dash LDs or InAs QD LDs on InP (311) substrate have been reported.

We have grown round and dome-shaped QDs on InP (100) substrate by MOCVD. The barrier was InGaAsP of 1.1 μm energy gap and the dot material was InGaAs with Ga 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 carrier lifetime was 1.6 ns and constant over the entire ground state photoluminescence (PL) band, clearly indicating no coupling between QDs even at this high dot density. 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 LDs of broad area type, as well as ridge type, with the above mentioned QDs. The LDs had a barrier of 1.1 μm emitting InGaAsP, lattice matched to InP, and a separate confinement hetero-structure with InP cladding layer. The internal quantum efficiency was about 45% and the transparency current density was 330 A/cm2. In ridge type QD LDs, the threshold current was 186 mA for a 3-stack 1.5 mm-long QD LD and 340 mA for a 7-stack 1.25 mm-long QD LD at room temperature in cw mode. The lasing wavelength was 1450 and 1490 nm, respectively. T0 near the room temperature was 97 K.

6129-06, Session 1

Growth and characterization of InGaN/GaN nanocolumn LED

A. Kikuchi, M. Tada, K. Miwa, K. Kishino, Sophia Univ. (Japan)

We report growth and characterization of GaN nanocolumn based LED with InGaN multiple quantum disk (MQD) active layers.

GaN nanocolumns are self-organized columnar nanocrystals (sometimes called as nanorods, nanowires, and nanopillars) with average diameter of from tens to hundreds nanometers. Each nanocolumn individually grows in a high density of ~1E10cm^2 with their c-axis normal to the substrate surface [1]. The GaN nanocolumns had superior optical properties due to their dislocation free nature. We have observed a strong photoluminescence emission and a low threshold optically pumped stimulated emission from GaN nanocolumns [2].

InGaN/GaN nanocolumn LEDs were fabricated on n-type (111) Si substrates by RF-MBE as a sequence of n-GaN nanocolumns, InGaN/GaN MQD active and p-GaN. The growth condition was changed in p-GaN cladding layer to enhance the lateral growth. The column diameters gradually increased and consequently a continuous film was produced at the surface. [3]. In this structure, the p-type semi-transparent electrodes can be easily fabricated by a simple metalization on top of nanocolumn devices, keeping superior optical properties of the isolated nanocolumn active region. By changing the growth conditions of the MQD active layer, the emission wavelength was controlled from violet to red region. We also observed multiple color emission from the nanocolumn LEDs. The microscope image showed that many small pixels (several micrometers in diameter) with various colors, for example blue, green, yellow, and red were existed in an electrode. This multiple color emission LED can be a new technology for multiple color nano-lasers, white light LED, addressable nano-pixel light sources and so on.

This study was supported by the New Energy and Industrial Technology Development Organization (NEDO) Industrial Technology Research Grant #02A23041d and Konica Minolta Imaging Foundation.

References: [1] M. Yoshizawa et al., Jpn. J. Appl. Phys. 36 (1997) L459. [2] A. Kikuchi et al. phys. stat. sol. (b) 241 (2004) 2754. [3] A. Kikuchi et al., Jpn. J. Appl. Phys., 43 (2004) L1524.

6129-07, Session 2

Quantum dot photonic crystal detectors

K. T. Posani, The Univ. of New Mexico; V. Tripathi, Indian Institute of Technology/Kanpur (India); S. Annamalai, S. Krishna, The Univ. of New Mexico; R. Perahia, O. Crisafulli, O. J. Painter, California Institute of Technology

Quantum dot infrared photo detectors have been explored extensively in the past few years due to their potential to provide low dark currents and high operating temperatures[1]. Recently long wave infrared focal plane arrays based on self-assembled QDs have also been fabricated[2]. However, QD detectors suffer from low responsivity and quantum efficiency. In this paper we report the use of a photonic crystal resonant cavity to increase the quantum efficiency, detectivity (D*) and the background limited infrared photodetector (BLIP) temperature of the QD detector.

InAs/InGaAs/GaAs dots-in-well (DWELL) detectors were grown by molecular beam epitaxy and consist of 15 stacks of n-doped InAs quantum dots placed in an In0.15Ga0.85As/GaAs quantum well sandwiched between doped contact layers. A photonic crystal cavity, with a hexagonal pattern of air holes, was fabricated using electron-beam lithography. From calibrated blackbody measurements, the conversion efficiency of the detector with the photonic crystal (DWELL-PC) is found to be 58.5% at -2.5 V while the control DWELL detectors have quantum efficiency of 7.6% at the same bias. We observed no significant increase in the dark current of the photonic crystal devices compared to the normal structure. The generation-recombination limited D* at 77K with a 300K F1.7 background, is estimated to be 6◊1010 cmHz1/2/W at -3V bias for the DWELL-PC which is a factor of 20 higher than that of the control sample. We also observed a 20% increase in the BLIP temperature for the DWELL-PCs. These results will be discussed in the presentation.

Keywords: Photonic crystal, Quantum dots, Infrared sensors, Detectors, Focal plane arrays

1 Bhattacharya et al

2 Krishna et al, Appl. Phys. Lett, 86, 193501, 2005.

6129-08, Session 2

Broad-band superluminescent light emitting diodes incorporating quantum dots in compositionally modulated quantum wells

R. A. Hogg, S. Ray, K. Groom, M. Beattie, H. Liu, M. Hopkinson, The Univ. of Sheffield (United Kingdom)

Superluminescent light emitting diodes (SLEDs) are of increasing interest for a wide range of applications. Recently interest has focused upon applications in optical coherence tomography for which a compact, cheap, broadband, high power optical source is required operating in the 1-1.8 μm range in order to realize low cost point of care screening and diagnostics.

A number of methods have been discussed to realise a broad emission spectrum for a SLED, which rely on techniques such as chirped, or intermixed quantum wells. More recently quantum dot (QD) materials have attracted attention due to their naturally broad emission spectrum due to the variation in size nd composition of the ensemble of QDs. Furthermore, QD emission characteristically composes a number of energy levels, resulting in the emission spectrum being made up of a series of broad Gaussian peaks.

Recently, we have developed QD lasers with very low CW, room temperature threshold current utilizing a dot-in-well (DWELL) structure where 1.31 um emission is obtained by depositing 3ML of InAs within an InGaAs well of 15%In. In this paper, we demonstrate a technique for tailoring the emission bandwidth of ~1.3μm quantum dot superluminescent light emitting diodes. A broadening of the emission is achieved by growing a multi-DWELL structure where the InAs quantum dots are incorporated within InGaAs quantum wells of different indium compositions. These structures exhibit a broader and flatter emission compared to a simple dot-in well structure comprised of wells of identical indium composition. Through the use of 5 DWELL layers with different indium compositions, a superluminescent LED operating CW at room temperature with peak wavelength of 1.27 μm, FWHM of 85nm, and 2.5mW output power has been realized. This design overlaps the ground and excited state emission of different DWELL layers, resulting in a broad, almost flat-topped emission spectrum. We compare the operating characteristics of these devices to an identical structure comprising of wells of identical indium composition. Furthermore, the effect of this novel chirping scheme on the characteristics of lasers fabricated from this material is discussed.

6129-09, Session 2

Tunnel quantum well-on-dots InGaAs-InAs high-gain medium for laser diodes

V. E. Tokranov, M. Yakimov, J. van Eisden, S. Oktyabrsky, SUNY/Univ. at Albany

Structures of tunnel pairs consisting of InGaAs quantum wells which were grown on top of self-assembled InAs quantum dots (QW-on-QDs) were employed to improve the gain medium in laser diodes. Photoluminescence, transmission electron microscopy and electroluminescence were used to study the influence of growth parameters and structure on the properties of multiple-layer QW-on-QDs active layers. QW-on-QDs tunnel structures with 5nm tunnel barrier thickness and with different ground state (GS) relative separation were grown by variation of InGaAs QW while fixing the QDs growth process. We have developed a tunnel QW-on-QDs structure with a resonance transition which is red-shifted ~35 meV to QW GS. This peak with narrow linewidth, 26 meV, likely indicates an efficient

resonant tunneling of carriers from QW into QD ensemble states. The highest gain was achieved with a QW-on-QDs active medium with GS relative separation of close to 35-40 meV. Optimized triple-pair tunnel QW-on-QDs laser diodes emitting at 1145 nm (corresponding to QD GS) exhibited a saturated modal gain exceeding 80 cm^-1 with minimum cavity length of 0.14 mm. These lasers demonstrated QD GS emission with a threshold current density Jth ranging from 225 A/cm^2 to 1.5 kA/cm^2 (depending on cavity length), switching to QW GS lasing at 1105 nm at higher Jth. RF small signal modulation characteristics of these lasers with QD-based emission wavelength were measured. From the damping factor and resonance frequency dependences on driving current, the damping-limited cut-off frequency for this QW-on-QDs medium can be estimated above 30 GHz.

6129-10, Session 2

GaAs-based 1.3 um quantum dot laser diode with 3-stacked InAs DWELL (dots-in-a-well) structure and Al0.7Ga0.3As cladding layer

K. W. Kim, Korea Institute of Science and Technology (South Korea) and Korea Univ. (South Korea); N. K. Cho, S. P. Ryu, J. D. Song, W. J. Choi, J. I. Lee, Korea Institute of Science and Technology (South Korea); J. H. Park, Korea Univ. (South Korea)

We have investigated the characteristics of GaAs-based 1.3 um quantum-dot laser diode (QD-LD) with Al0.7Ga0.3As cladding layers. The active region of QD-LD consists of 3-stacked InAs quantum-dots (QDs) in an In0.15Ga0.85As quantum well (dots-in-a-well: DWELL), which was grown by molecular beam epitaxy (MBE). We fabricated ridge waveguide structure LDs which had 10 ~ 50 um ridge width with various cavity lengths. The threshold current density was 219 A/cm2 and the lasing wavelength was 1.32 um for a 2-mm long cavity device, under a pulsed operation condition (0.1%) at room temperature. The QD-LD showed simultaneously lasing at 1.32 um and 1.23 um from the ground state and the first excited state, respectively at a certain condition. The lasing wavelength switching from the ground state to the first excited state depends on the cavity length and the injection current.

6129-11, Session 3

Infrared InN(As)Sb quantum dots for integrated smart sensor application

S. M. Kim, H. B. Yuen, F. Hatami, Stanford Univ.; A. Moto, Innovation Core SEI Ltd.; J. S. Harris, Stanford Univ.

Nanophotonics plays a major role in the development of smart sensors, which require integrated functionality in detecting various chemical and biological agents, simultaneous identification, and real time information transfer. Most bi-molecules and biological agents based on proteins have strong absorption and resonance fingerprints between the mid- and far-infrared wavelength range of 3um and 15um. Therefore highly efficient, and inexpensive infrared (IR) sources and detectors are essential to the smart sensor systems. Quantum dots lasers, which have been in development for decades, have several important advantages: (1) low power consumption due to low threshold current operation, (2) array operation and integration due to low voltage and low current operation, (3) large wavelength tuning due to broad gain spectrum, (4) low cost due to simple growth and fabrication techniques. However, there has been a lack of development of IR quantum dots lasers, mainly due to the limited material systems which can fulfill the condition of operating within IR spectrum.

In this work, we investigated nitrogen incorporated IR materials. In our model, small amounts of nitrogen incorporated into InSb and InAsSb can tune the energy bandgap from mid-IR to the far-IR. The mid-IR light emissions between 3um and 4um were obtained from InN(As)Sb grown by solid source MBE for the first time. We will discuss band structure calculation using 8-band method with localized nitrogen level. The band structure calculation confirms band-anticrossing occurs with localized nitrogen energy band, EN = 0.42 eV, and results in energy band gap reduction of 80 meV with adding 1% of nitrogen. The detailed modeling and experiment results of optical measurements will be presented.

6129-12, Session 3

Self-assembly of heterojunction quantum dots(HeQuaDs)

K. G. Eyink, D. H. Tomich, Air Force Research Lab.; L. Grazulis, Univ. of Dayton Research Institute; J. J. Pitz, Air Force Research Lab.; K. Mahalingam, Universal Technology Corp.; J. Shank, Air Force Research Lab.

Quantum dots (QDs) have been receiving considerable attention lately 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 multiple materials, can be formed through a marriage of these two concepts. In particular, we have fabricated a composite dot formed of an initial core of one material which result from normal self-assembly followed by the epitaxy of a crown composed of a similarly strained material. Finally the entire dot structure can be capped with a barrier material closely lattice matched with the substrate. 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. We have observed several factors determine the formation of the composite dot structure. This selection can be seen as a competition between the diffusion of GaSb to the InAs dots and nucleation of GaSb between the InAs dots. 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 2microns.

6129-13, Session 3

STEM and EDX study of material composition in Si/SiGe quantum dots

A. Elfving, Linköpings Univ. (Sweden); A. Karim, M. Larsson, G. V. Hansson, Linköping Univ. (Sweden)

Si/Ge quantum dot infrared emitters and detectors have attracted a huge interest due to the promising optical properties, low production cost and the compatibility with Si-based microelectronics. However, efficient photonic devices require careful optimization of the growth parameters. The island size, shape and material composition define the dot-related optical transition energies, but they are all strongly dependent on the growth temperature. In this work we have performed cross-sectional scanning transmission electron microscope studies combined with drift-corrected energy-dispersive x-ray (EDX) spectrometry experiments for investigation of the material composition in Si(001)/Ge islands. The samples were grown by MBE at temperatures ranging from 430 to 730° C, with two layers of Ge islands separated by 140 nm Si. The topmost dot layer was uncapped. The measurements show a Ge concentration in the islands very close to 100 % for the sample grown at 430° C. With a growth temperature of 530° C, a ~15 % reduction of the Ge fraction was observed, which is due to intermixing of Si and Ge. This is consistent with our previous photoluminescence results, which revealed a significant blue shift of the Ge dot-related emission peak in this growth temperature range. The Ge concentration decreases more slowly when the growth temperature is

increased above 530° C, which can be explained by geometrical arguments. The long distance between the interface and the core of these larger sized dome-shaped islands implies that less Si atoms reach the dot center. The uncapped Ge dots have essentially similar diameter dimensions as the embedded islands, but the height and Ge fraction are almost exclusively larger. This demonstrates that the intermixing mainly occurs during Si capping.

6129-14, Session 3

Lateral distributions of MBE and MOCVD In(Ga)As quantum dots

A. Roshko, National Institute of Standards and Technology; J. Cederberg, Sandia National Labs.

Self-assembled quantum dots are of interest for a variety of applications. The majority of the devices for which they are being considered will require that the dot size and density be uniform across the surfaces of wafers on which devices are processed. We have used atomic force microscopy (AFM) and photoluminescence (PL) to examine the lateral uniformity of In(Ga)As QDs grown on 5 cm, (100)GaAs wafers. Samples were grown by both molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) under a variety of conditions. It was found that dots grown by MBE had narrower size distributions but were less uniform in density, laterally across wafers, than dots grown by MOCVD. MBE grown QDs had nearly Gaussian height distributions, with maximum variations less than 15 nm. The majority of MOCVD grown dots were less than 5 nm in height, but there was a continuous distribution of larger dots, with heights up to 70 nm. For most of the MOCVD growth conditions the dot density standard deviation was 10% of the average while the height standard deviation was typically less than 5% of the average. PL mapping shows that the emission wavelength varies by less than 2% across these wafers. The standard deviation in dot density for MBE grown samples was larger, varying from 5 to 35 % of the average; the standard deviation in dot height varied from 3 to 11 % of the average. The specific influence of variables such as dot composition, growth temperature and As partial pressure will be discussed.

6129-15, Session 3

Strain-compensation in closely-spaced stacked quantum dot active regions grown by metalorganic chemical vapor deposition

N. Nuntawong, Y. C. Xin, P. Wong, C. P. Hains, S. Huang, L. F. Lester, D. L. Huffaker, CHTM/The Univ. of New Mexico

We discuss the design and optimization of strain-compensation (SC) layers to reduce strain accumulation in stacked quantum dot (QD) active regions. The compensation of compressive strain by inserting tensile layers allows very closely spaced QD layers (~ 15 nm) for increased modal gain especially in microcavity emitters. In an optimized structure, each layer of the stacked QD active region contains a thin GaP (Δao = -3.8 %) tensile layer embedded in a GaAs matrix to partially compensate the compressive strain of the InAs (Δao = 7 %) QD layer. The optimized GaP thickness is ~4 MLs and results in a 36% reduction of compressive strain in our device structure according to high-resolution x-ray diffraction spectra. Atomic force microscope images and room temperature photoluminescence confirm that strain compensation improves both structural and optical device properties. Transmission electron microscope reveals vertical alignment of QD and indicates residual strain propagation between the QD layers even with SC. Inspection of the strain field distribution and its effect on QD formation is underway. We hope to realized closely-spaced, but strain-decoupled QDs in the near future. At present, room temperature ground state lasing at λ=1.249 μm, Jth =550 A/cm2 has been demonstrated from compensated 3-stack laser structure. Further experimental details and device results will be presented at the conference.

6129-16, Session 3

Polarization dependent size of Ge nanoparticle formed by ultrafast laser

S. C. Jeoung, Korea Research Institute of Standards and Science (South Korea); M. Seo, Seoul National Univ. (South Korea); H. S. Kim, Korea Research Institute of Standards and Science (South Korea); D. S. Kim, Seoul National Univ. (South Korea)

We report to control size of Ge nanoparticle by varying the angle between ultrafast laser polarization and crystal axis of Ge. The nanoparticle size dependence on the laser polarization with respect to the Ge crystal axis exhibits a sinusoidal function with a minimum size at (100) axis. The optical polarization parallel to (100) axis of Ge crystal results in the smallest particle size, while the polarization parallel to (110) does the largest. There is no doubt of the presence of 2-3 nanometers thick GeOx from the characterization of the observed nanoparticles by a TEM (transmission electron microscopy) and EDS (energy dispersive spectroscopy). In addition, the reflectivity change on time is also measured with different polarization and laser fluence to convince the polarization dependent ablation. By close analyzing the temporal profiles, it should be noticed that there are at least more than two decaying components; one of them has a time constant less than our time-resolution of 150 fs, the other is longer than 1 ps. It is very interesting to note that the two components are evidently dependent on the azimuthal angle as well as the incident fluence. In this time-resolved reflectivity measurement, we observed a transition to the high reflectivity change indicative of the liquid state has anisotropically occurred. This ultrafast initial decrease in reflectivity, which is due to photoinduced absorption, provides clear evidence that a portion of the Ge crystal undergoes non-thermal melting within sub picoseconds and that encapsulation time of oxide layer is different as laser polarization. The result indicates that the molten layer thickness analogized from reflectivity changes plays an important role in nucleation and particle growth and finally determination of the particle size regardless of the oxidation velocity. This critical method to control the size of Ge nanoparticles using different polarization can be applicable for both optoelectronics and biosensor and give more insight of fundamental research in nanoparticle science.

6129-17, Session 3

Control of size, position, and density of self-assembled InAs/GaAs quantum dots grown by molecular beam epitaxy on dielectic paterned substrates

R. A. Hogg, J. Lin, M. Hopkinson, P. W. Fry, I. Ross, C. M. Tey, T. Cullis, R. Kolodka, A. Tartakovskii, M. Skolnick, The Univ. of Sheffield (United Kingdom)

Self assembled quantum dots (QDs) behave as artificial atoms, allowing a new class of devices with applications in the field of quantum information processing to be realized. To allow the routine production of such devices, technologies are required which allow the control of the self assembly process, and the positioning of QDs on a nm scale within a device structure. In addition, control of the formation of QDs over a larger scale, may have applications in the creation of integrated opto-electronic components.

Molecular beam epitaxy (MBE) is a widely used QD growth technique, yet the use of dielectric patterned substrates is rarely applied to MBE, yet for other growth techniques, it is emplyed to locally modify the composition and thickness of epitaxial material. In this paper we report, for the first time, the growth of QD structures on dielectric patterned substrates by MBE, and show how the positioning of QDs can be controlled on various length scales, in addition to modifying the QD size and hence emission energy. These QDs are optically active, exhibiting photoluminescence at room temperature.. We characterize uncapped structures by atomic force microscopy, and scanning electron microscopy, while capped structures

are characterized by scanning transmission electron microscopy, and micro-PL. We discuss the growth conditions required for selective area epitaxy, and show that for certain growth conditions selectivity is not entirely achieved and polycrystalline GaAs is deposited on the mask.

We discuss the effect of the dielectric mask on the size, areal density and emission energy of InAs QDs, utilizing a mask pattern consisting of line and box shapes oriented along various crystallographic directions. This results in the growth of faceted GaAs mesas in the gaps between the mask. For a partially polycrystalline GaAs covered mask, we show: a reduction in the areal density of QDs in the region (within ~30 um) of the dielectric mask, a thickness enhancement of the single crystal GaAs mesa structures, a modification of the QD areal density in these regions, a reduction in density and height of the QDs along the length of the mesa, the formation of lines of QDs along the mesa edges, and the isolation of a few QDs in box shaped dielectric features. These structural observations are confirmed by micro-PL studies. We discuss the origins of these effects and possible applications.

6129-18, Session 3

Experimental and theoretical investigation of the third-order nonlinearity in CdS quantum dots in a dendrimer matrix

M. Potasek, R. Dorsinville, M. Etienne, A. Walser, D. Bauer, V. Balogh-Nair, City College of New York

We have measured the nonlinear optical response of Cadmium Sulfide quantum dots in a poly(propyleneimine) dendrimer matrix having diaminobutane (DAB) core. Large refractive nonlinear coefficients and low absorption losses were observed at all wavelengths. Our calculations indicate that quantum dot-organic systems have large optical nonlinearity due to interactions between excitons in the quantum dots and the organic medium.

Dendrimers are nanosize, highly branched, tree like monodisperse macromolecules that emanate from a central core with a branch occurring at each monomer unit. Dendrimers encapsulations convey stability, control of emission wavelengths by QD size. The brancing points in the interior of the dendrimers are occupied by tertiary nitrogen to provide numerous nucleation sites to drive formation of QD clusters of small size.

The dendrimer-stabilized CdS QDs were stable at room temperature, both in solution and in solid state for several weeks. Thin films were deposited by spin casting from methanol solutions. The resulting samples consisted of a 1mm thick quartz substrate with a 200-400 ≈ nonlinear optical film on one side. The Z-scan technique was used to characterize the NLO response.

A mode-locked YAG laser provided the laser pulses with 30-ps duration at 355 nm, 532 nm and 1064 nm at a 20-Hz repetition rate with energies per pulse ranging from few microjoules to several mJ. The intensity of the incident beam was adjusted by an attenuation setup consisting of a half wave plate and two crossed Glan-Thomson polarizers. These results indicate relatively large values for the nonlinear response (> 1e-10 esu) at all three wavelengths.

6129-19, Session 3

Intense midinfrared emission from self-assembled PbTe/CdTe quantum dots fabricated by lattice type mismatched epitaxy

E. Kaufmann, W. Heiss, M. Boeberl, T. Schwarzl, G. Springholz, G. Hesser, F. Schaeffler, Johannes Kepler Univ. Linz (Austria); K. Koike, H. Harada, M. Yano, Osaka Institute of Technology (Japan)

We demonstrate intense mid-infrared emission at room temperature from self-assembled, epitaxial PbTe/CdTe quantum dots in continuous wave mode. The emission from a single quantum dot layer with an averaged coverage of only 5 nm is found to be more intense than that of a bulk like PbTe epilayers. Due to this high luminescence efficiency and the growth of the heterostructures on epiready GaAs substrates, this material combination is very promising for future optoelectronic mid-infrared devices. The different lattice structures of the dot and the matrix materials imply an intrinsic immiscibility between these materials, so that abrupt dot/barrier interfaces can be expected.

The quantum dot samples are prepared in two steps. First, two-dimensional PbTe/CdTe quantum wells are grown by molecular beam epitaxy and second, the quantum dot formation is thermally induced by annealing above growth temperature. After annealing, the quantum dot shape is found to approach that of a small rhombicuboctahedron with abrupt interfaces and diameters around 25 nm. The evolution of the dot formation upon thermal annealing is probed by luminescence experiments, giving spectra with maxima at wavelength between 2800 and 4700 nm. The advantageous optical properties of our quantum dots are a result of the (a) large quantum confinement between PbTe and CdTe, (b) almost perfect matching of the cubic lattice constants of the two materials and (c), the small nonradiative Auger recombination resulting from the mirror like band structure of PbTe.

6129-20, Session 3

Saturable SiO2/PbTe quntum dots waveguides for the 1.3-1.5 um region

E. Rodriguez, E. Jimenez, C. L. CÈsar, L. C. Barbosa, Univ. Estadual de Campinas (Brazil)

Saturable waveguides for the 1.3-1.5 μm region were fabricated using PbTe quantum dots embedded in a dielectric host (SiO2). The quantum dots were grown by pulsed laser deposition (PLD) of a PbTe target using the second harmonic of a Q-Switched Quantel Nd:YAG laser under high purity argon atmosphere. The glass matrix was fabricated by Plasma Enhanced Chemical Vapor Deposition (PECVD) using tetramethoxysilane (TMOS) as precursor. The alternating growth of the samples was achieved with a computer controlled interface using a LabView code. PbTe was chosen because their quantum dot absorption peaks can be controlled by its size to fall in the spectral window of optical communications, 1.3-1.5 μm. This, together with the quantum dot very high optical nonlinearity, makes this material an excellent candidate for development of optical devices. For the glass matrix, we studied the influence of growing parameters like RF power, distance between the RF electrodes and the total pressure in the quality of the SiO2 films. For the PLD we studied the influence of the laser energy, target-substrate distance and number of pulses in the size and size distribution of the quantum dots. The structural properties were characterized by scanning and transmission electron microscopy while the waveguide optical properties were determined by a metricom prism coupler and total internal reflection multipass optical absorption spectroscopy.

6129-21, Session 4

Time-resolved and antibunching measurements on single photons at 1300nm from InAs quantum dots

C. Zinoni, B. Alloing, V. Zwiller, C. Monat, L. Li, A. Fiore, École Polytechnique Fédérale de Lausanne (Switzerland); L. Lunghi, Univ. degli Studi di Roma (Italy); A. Gerardino, CNR-Universita degli Studi (Italy)

Efficient generation of single photons at telecom wavelength (1310nm and 1550nm) on request is crucial for quantum key distribution (QKD). The optical properties of single quantum dots (QDs) have the potential for satisfying the requirements of a convenient single photon source: QDs can be grown in conventional semiconductor epitaxial systems and the nature of the 3D confinement of the wavefunction generates atomic-like spectral features. A single QD can be populated by several electron-hole pairs (excitons), each recombining to emit a photon. Due to Coulomb interactions originating from the strong charge confinement the energy

levels are shifted and each transition can be spectrally isolated to produce a single photon source.

We have grown self assembled InAs/GaAs quantum dots embedded in a planar microcavity with an average spatial density of 1 per square micron. By means of metallic apertures or etched mesas it was possible to isolate a single QD. Photoluminescence measurements on single QDs reveal spectral lines at 1300nm characterized by a FWHM of 40meV, which are attributed to exciton, biexciton and charged exciton transitions in the ground state . The identification of the spectral lines is further supported by lifetime measurements, to our knowledge, the first ever to have been made at these wavelength. We demonstrate that our single QDs are efficient sources of triggered single photons coupled to O-band of single mode fibers. The experimental value of second-order correlation function, g(2)(0)=0.38, demonstrates strong suppression of multi-photon pulses per excitation cycle and was obtained for a photon count rate of 300 counts/sec per detector at a repetition rate of 4MHz. Assuming that at least one exciton is created in the QD for each laser pulse, we estimate that the coupling efficiency of single photons in the single-mode fiber is 0.5%. Progress in the development and characterization of single photon sources at telecom wavelength has been slowed down by the high noise levels and low quantum efficiencies of single photon detectors at telecom wavelength. To optimise the signal to noise ratio (SNR) we operate our APDs in geiger mode and set an optical active window of 300ps. Although this value is significantly shorter than the measured lifetime of the exciton (1.2ns) we achieve an overall gain in the SNR due to a drastic reduction of a dark events for very short gates. We are therefore able to measure the second order correlation function with integration times comparable to those made in the region of the spectrum where silicon technology is used. Emission wavelength, narrow spectral width, low multi-photon probability and high efficiency make our quantum dots particularly suited for quantum cryptography applications in telecom fibers over long distances.

6129-22, Session 4

Sub-micrometer electrically-pumped light emitting devices based on single quantum dots for single photon applications at 1300 nm

C. Monat, C. Zinoni, B. Alloing, L. H. Li, A. Fiore, Ecole Polytechnique Federale de Lausanne (Switzerland); L. Lunghi, G. Annamaria, CNR-Instituto di Fotonica e Nanotecnologie (Italy)

Quantum cryptography allows secure exchange of cryptographic keys, transmitted through optical pulses each containing exactly one photon. Whereas single-photon pulses can be obtained by exciting any single quantum system, solid-state single quantum dots (QDs) are well adapted for practical single photon sources.

For fiber-based quantum cryptography systems, efficient single-QD Light Emitting Diodes (LEDs), operating under electrical pumping and at telecom wavelengths, are important. Here we report two approaches to single QD based LED operating at 1300 nm.

The MBE growth of sparse arrays (a few QD/μm2) of self-organized InAs/GaAs QDs emitting at 1300 nm at low temperature has been optimized [1]. The first approach exploits narrow metal apertures to select spatially the emission from a few QDs. Within the second approach, sub-micrometer oxidized current apertures have been realized within LED structures [2]. A careful control of current spreading associated to the small diffusion length in QDs ensures a restricted injection area, including few QDs. Low temperature electroluminescence measurements show narrow spectral lines (linewidth <200 μeV) which can be attributed to emission from single QDs.

The efficiency of the device should further benefit from its integration with a wavelength-scale high quality factor microcavity. We have thus combined the oxidized current aperture based LED with a micropillar cavity. We report preliminary results from this approach, which may provide efficient single QD LEDs.

1 B. Alloing et al., Appl. Phys. Lett. 86, 101908 (2005)

2 A. Fiore et al., Appl. Phys. Lett. 81, 1756 (2002)

6129-23, Session 4

An electrically driven microcavity single photon source

P. See, M. Ward, O. Karimov, Z. Yuan, A. Shields, Toshiba Research Europe Ltd. (United Kingdom); T. Farrow, P. Atkinson, D. A. Ritchie, Univ. of Cambridge (United Kingdom)

Single photon sources are essential components for future quantum communication networks. Light emitting diodes based on emission from an embedded quantum dot could provide a compact integrated semiconductor device that can be fabricated using standard photolithographic techniques. Important outstanding challenges are tuning the emission to optical fibre compatible wavelengths and enhancing the photon collection efficiency.

We report here progress on 1300nm quantum dot single photon LEDs, which are suitable for fibre optic network applications. A low density of longer wavelength dots was produced by exploiting the second critical growth threshold for self-assembled InAs dots on GaAs. Emission of a single active dot was collected using a confocal microscope and coupled directly into a single mode fibre. Strong suppression in the multiphoton pulse emission rate was verified by a custom Hanbury-Brown and Twiss interferometer system implemented with fibre and InGaAs single photon avalanche photodetectors. The single photon collection efficiency is enhanced by incorporating the quantum dot between GaAs/AlGaAs distributed Bragg mirrors confined into etched micropillars. Resonance of the microcavity mode with the quantum dot emission leads to a strong enhancement in the collection intensity.

We will describe the integration of electrical contacts with the micropost cavity to form a p-i-n light emitting diode structure. Electroluminescence spectra recorded on such a device reveal sharp lines due to the excitonic recombination in a single quantum dot. Finally, the operation of the single photon source within our fibre based quantum cryptography system will be discussed.

6129-24, Session 4

Quantum dots in micropillar cavities as bright single photon sources

M. J. Stevens, R. P. Mirin, National Institute of Standards and Technology

This paper presents extensive studies of the optical emission of InGaAs quantum dots embedded in micropillar cavities, demonstrating their suitability as bright sources of single photons. The quantum dots are placed between a pair of GaAs/AlAs Bragg mirrors, with cavity Q in excess of 1000. The micropillars are defined with reactive ion etching, forming pillars about 6 um tall, with a range of diameters from 1.25-90 um. The dots are grown at low densities (~5 μm-2); hence, the smallest pillars contain at most a few dots. The micropillar cavities serve two primary purposes: to funnel emission so that it travels in a surface-normal optical mode for ease of detection and to decrease the spontaneous emission lifetime via the Purcell effect.

We have developed a comprehensive measurement apparatus for studying the photoluminescence from quantum dots that are optically pumped with a short (~1 ps) laser pulse. Techniques include high-resolution spectroscopy for identification of quantum dot and cavity emission, time-correlated single photon counting for measuring spontaneous emission lifetime, Michelson interferometry for determining coherence time, and Hanbury Brown-Twiss interferometry, which is used to verify single photon emission through antibunching measurements.

By adjusting the device temperature, we can tune a quantum dotís emission wavelength with respect to the cavity mode wavelength. We have observed that quantum dots on resonance have a shorter spontaneous emission lifetime than the same dots tuned near- or off-resonance. In addition, quantum dots that are well-aligned with the optical cavity, both spatially and spectrally, are significantly brighter than dots that are not in a cavity, while still emitting photons one at a time.

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6130-01, Session 1

Applications of slow light in telecommunication and optical switching

R. W. Boyd, A. Schweinsberg, P. T. Zerom, G. Piredda, Z. Shi, H. Shin, Univ. of Rochester

Practical applications of slow light methods require that one be able to controllably delay a pulse of light by many pulse lengths. In this contribution we analyze the possible limitations to the maximum achievable time delay and suggest methods for overcoming these limits. Research performed over the past half-dozen years has shown that it is possible to exercise great control over the velocity with which pulses of light propagate through material systems. Group indices of the order of 1 million or larger are routinely observed. The ability to control the velocity of light has opened up the possibility of many applications of slow light, including the construction of controllable optical delay lines for use in device such as optical buffers and true-time delay systems for synthetic aperture radar. A key figure of merit for many applications is the normalized time delay, that is, the maximum controllable time delay divided by the duration of the input pulse. This quantity can be thought of as the information storage capacity of the medium, that is, it gives the numerber of bits of information that can reside inside the delay line at any given time. The best result reported to date is the value 4 reported by Kasapi et al. However, data packets useful for telecommunication systems contain at least 1000 bits. The question addressed in this contribution are the prospects for the construction of slow-light delay lines with 1000 bit capacity.

6130-02, Session 1

Slow light in optical fibers

A. L. Gaeta, J. E. Sharping, Y. Okawachi, S. Ghosh, Cornell Univ.; M. Bigelow, A. Schweinsberg, R. W. Boyd, Univ. of Rochester; Z. Zhu, D. J. Gauthier, Duke Univ.; Y. Wang, A. E. Willner, Univ. of Southern California

A critical building block of communication networks and signal processors is an all-optical device that can buffer or delay the arrival of information. In this talk we will review our efforts to develop “slow-light” techniques in optical fibers for producing all-optical delays. The techniques we have investigated are based on stimulated Brillouin and Raman scattering, on electromagnetically-induced transparency in photonic bandgap fibers, and on four-wave mixing and dispersion.

6130-03, Session 1

Slow- and fast-light enhanced rotation sensing and Fabry-Perot interferometry

R. Tripathi, G. S. Pati, V. Gopal, K. Salit, M. Messal, S. M. Shahriar, Northwestern Univ.

We have recently shown that while slow light induced enhancement of sensitivity of a Sagnac effect based rotation sensor is limited to the case of relative rotation measurement only, use of fast light leads to an enhancement of absolute rotation sensing by many orders of magnitude. We present the results from our recent experiments using a passive ring resonator with a perimeter of 1 meter, and a rubidium vapor cell under the so-called CAD (Critically Anomalous Disperson) condition, corresponding to the group velocity approaching infinity. We also discuss how the same degree of enhancement of sensitivity can be achieved for general purpose sensing using a Fabry-Perot resonator loaded with a fast-light medium. Finally, we will discuss the process of light-slowing in a medium with constant velocity or acceleration, and the corresponding implication for the prospect of manifestly evident test of the Equivalence Principle in General Relativity using slow light.

6130-04, Session 1

Stopping light in photonic crystals: some practical considerations

S. Sandhu, M. L. Povinelli, M. F. Yanik, S. Fan, Stanford Univ.

Recently, Yanik et al showed the possibility of stopping a light pulse by dynamically modulating the refractive index of a coupled cavity system in a photonic crystal while a pulse is in the crystal. Here, we present an analysis of some of the practical aspects. In particular, we show that the dispersion effects that are prominent in many slow light structure are strongly suppressed during the dynamic bandwidth compression process.

6130-05, Session 2

Engineering nonlinearities in slow-light materials for photonic quantum information processing

C. M. Santori, S. M. Spillane, M. Fiorentino, R. G. Beausoleil, Hewlett-Packard Labs.

It has recently been shown that a cross-Kerr optical nonlinearity sufficient for photon number-resolving quantum non-demolition (QND) detection would enable a universal set of quantum gates for all-optical quantum information processing. While photon number-resolving QND detection in the optical domain has remained elusive since it was proposed 20 years ago, recent advances in nanophotonics and slow-light materials may finally make this possible. This talk will describe devices we are developing for producing a phase shift on a coherent probe beam due to the presence of a single photon in a signal beam. These devices contain four-level atom-like systems coupled to waveguides or cavities. Theoretical expressions will be shown for the expected nonlinear phase shifts achievable in these devices, and specific materials (NV centers in diamond, rare-earth-doped crystals, and impurity-bound excitons in GaAs) and nanostructure geometries (waveguides, microdisk cavities) will be compared. An additional complication with cavity-based devices is temporal correlations between the output beams that can occur due to the localized nature of the interaction. Simulations will be presented demonstrating this effect. Our latest experimental progress toward realization of these devices will also be described.

6130-06, Session 2

Towards integration of quantum interference in alkali atoms on a chip

H. Schmidt, W. Yang, D. Yin, Univ. of California/Santa Cruz; D. B. Conkey, J. P. Barber, A. R. Hawkins, Brigham Young Univ.

Quantum interference effects can change the optical properties of a medium dramatically and lead to observation of induced transparency, slow light, lasing without inversion, and resonantly enhanced nonlinearities. In order to exploit these effects in practical applications including optical delay lines, optical storage, single-photon sources and detectors, solid-state media or a solid-state based integrated platform are highly desirable. We have recently proposed the use of hollow-core waveguides on a silicon chip as a promising approach to build room-temperature quantum interference devices that utilize alkali vapor as the active medium. Based on the ARROW (antiresonant reflecting optical waveguide) principle, vapor cells with cross sections of a few μm2 can be fabricated in a fully

planar and monolithic process while at the same time guiding light through the low index vapor core. The use of integrated optics to reduce mode areas and provide automatic alignment of multiple propagating beams is especially beneficial for observation of nonlinear interference effects. In this talk, we will discuss the current status of quantum interference in integrated ARROW waveguides. In particular, we will discuss waveguide loss optimization, as well as integration and spectroscopy of rubidium vapor in hollow-core ARROWs. Relevant issues for the observation of quantum interference effects such as coherence dephasing and nonlinear parametric generation will be emphasized.

6130-07, Session 2

Improving the bandwidth of slow-light delay lines

Z. Zhu, A. M. Dawes, D. J. Gauthier, Duke Univ.; M. D. Stenner, M. A. Neifeld, The Univ. of Arizona

We present a method for increasing the pulse delay of a slow-light system without increasing the pulse distortion, thereby increasing the effective system bandwidth. The device is based on optically controllable slow-light via stimulated Brillouin scattering in a room-temperature optical fiber. By tailoring the dispersion, we observe a factor of ~9 improvement in the relative pulse delay and in the delay-bandwidth product in comparison with a standard slow-light medium. These results are obtained with a constraint of less than 5% pulse distortion.

6130-08, Session 2

Expanding of the bandwidth of slow light by artificial inhomogeneous broadening

D. Qing, Z. Deng, P. R. Hemmer, M. O. Scully, M. S. Zubairy, Texas A&M Univ.

Recently artificial inhomogeneous broadening was proposed to expand the bandwidth of slow light. The point is to independently slow down all harmonic components of the input pulse via inhomogeneous broadening. An input pulse or sequence of pulses can be split into independent spectral channels by a dispersive element such as a prism or grating. These sub-pulses are then slowed by bandwidth-matched slow-light array elements, and then recombined with another dispersive element to produce the output pulse. The proof of principle experiment was done with a photorefractive crystal Ce:BaTiO3, where the crystal functions as both dispersive elements and slow lights devices.

6130-09, Session 3

Losses in optical resonators in the slow light regime

Y. G. A. Vlasov, F. Xia, S. J. McNab, IBM Thomas J. Watson Research Ctr.

Optical micro-resonators based on photonic crystals (PhC) or single-mode strip waveguide microrings are considered promising for building an ultra-compact optical delay lines, dispersion compensators, etc. For example, electrically tunable group indices in excess of 300 have been reported recently for a PhC waveguide structure. It is expected, however, that slowing down the group velocity would result also in significant increase of the propagation losses. Recent theoretical studies indicate the square root scaling of losses with the group velocity. If true the increased loss might severely limit the performance of slow light devices based on optical resonators. We will present detailed experimental studies of the propagation losses in micro-optical resonators in the slow light regime.

6130-10, Session 3

Light pulse delay in semiconductor quantum well Bragg structures

N. H. Kwong, Z. S. Yang, D. T. Nguyen, R. H. Binder, The Univ. of Arizona; A. L. Smirl, The Univ. of Iowa

We present a comprehensive theoretical analysis of light pulse delay in resonant photonic bandgap structures made from Bragg-spaced semiconductor quantum wells. Quantum well Bragg structures offer the possibility for parametric manipulation of the polariton bandstructure. This, in turn, may be used for stopping, storing and releasing of light pulses. Based on a theoretical model utilizing a time-dependent transfer matrix approach to the solution of Maxwell's equations, we study light pulse propagation, light pulse trapping and releasing, and light pulse deformation in these structures. We present a feasibility study of light trapping in presently existing structures and outline optimization strategies for future generations of quantum-well Bragg structures used for light trapping. In addition, we show that light-pulse deformation can be avoided in a reflection geometry (as opposed to the more straightforward transmission geometry). We also discuss various light propagation issues related to quantum-well Bragg structures, such as the problem of reduced in-coupling of the light pulses into the structure due to Fabry-Perot effects, for which we outline a solution strategy based on a generalized anti-reflection coating scheme.

6130-11, Session 3

Buffer-gas induced absorption resonances and large negative pulse delay times in Rb vapor

G. R. Welch, E. E. Mikhailov, I. Novikova, V. A. Sautenkov, Y. V. Rostovtsev, Texas A&M Univ.

We experimentally study the group delay time for a light pulse propagating through hot 87Rb vapor in the presence of a strong coupling field in a Lambda type configuration. We demonstrate that the usual ultraslow pulse propagation is transformed into superluminal propagation when the one-photon detuning of the light is comparable to the Doppler width. This transformation is due to a drastic change in the transmission resonance line shape. We have measured negative group velocity as low as -c/3×106 = -80 m/s. We also find that the advance time in the regime of the superluminal propagation grows linearly with increasing laser field power. We have studied the transformation of the electromagnetically induced transparency (EIT) resonance lineshape as it changes from a transmission to an absorption resonance. This transformation occurs as the one-photon detuning of the coupling fields is varied from the atomic transition. No such absorption resonance is found in the absence of a buffer gas. The width of the absorption resonance is several times smaller than the width of the EIT resonance, and the changes of absorption near these resonances are about the same. Similar absorption resonances are detected in the Hanle configuration in a buffered cell.

6130-12, Session 3

Liouville-space descriptions for intense-field coherent electromagnetic interactions

V. L. Jacobs, Z. Dutton, M. Bashkansky, M. J. Steiner, J. F. Reintjes, Naval Research Lab.

Liouville-space (reduced-density-operator) descriptions are developed for linear and non-linear electromagnetic interactions of quantized electronic systems, taking into account environmental decoherence and relaxation phenomena. Applications of interest include many-electron atomic systems (in electron-ion beam interactions, gases, and high-temperature plasmas) and semiconductor materials (bulk crystals and nanostructures). Time-domain (equation-of-motion) and frequency-domain (resolvent-operator) formulations are developed in a unified manner. The standard Born (lowest-order perturbation-theory) and Markov (short-memory-time) ap-

proximations are systematically introduced within the framework of the general non-perturbative and non-Markovian formulations. A preliminary semiclassical treatment of the electromagnetic interaction is introduced. Compact Liouville-space operator expressions are derived for the linear and the general (níth order) non-linear electromagnetic-response tensors occurring in a perturbation-theory treatment of the electromagnetic interaction. These expressions can be evaluated for coherent initial electronic excitations and for the full tetradic-matrix form of the Liouville-space self-energy operator representing the environmental interactions in the Markov approximation. Intense-field electromagnetic interactions are treated by means of an alternative method, which is based on a Liouville-space Floquet representation of the reduced density operator. Electron-electron quantum correlations are treated by the introduction of a cluster decomposition of the reduced density operator and a coupled hierarchy of reduced-density-operator equations. This work is supported by the Department of Energy, by the Defense Advanced Research Projects Agency, and by the Office of Naval Research.

6130-13, Session 4

Rare Earth doped materials for quantum computing

A. Konhodzic, A. P. Adamczyk, Z. U. Hasan, Temple Univ.

No abstract available

6130-14, Session 4

VLSI quantum computer in diamond

P. R. Hemmer, Texas A&M Univ.; E. Trajkov, S. D. Prawer, The Univ. of Melbourne (Australia); F. Jelezko, J. Wrachtrup, N. B. Manson, The Australian National Univ. (Australia)

Recently, we have been exploring the possibility developing a diamond-based VLSI quantum computer. In analogy to the VLSI quantum computer based on phosphorous in silicon, we will use nuclear spin states of nitrogen-vacancy (NV) color centers in diamond as the qubits, and we will use gate electrodes to tune qubits into and out of resonance with each other and with control fields. However in our design, the qubits will be addressed optically, and it is the optical rather than the spin transitions that will be tuned with the electrodes. I will describe current status of the program and will briefly discuss the potential for room temperature solid-state quantum computers in NV diamond.

6130-15, Session 4

Ensemble-based quantum memory, quantum communication, and quantum computing

G. S. Pati, K. Salit, P. Kumar, S. M. Shahriar, Northwestern Univ.

It is well known that under certain conditions, the process for producing slow-light via the EIT process can be tailored to produce stopped light. When the probe consists of a single or a quantifiably small number of photons, the process can store and release quantum information, without any loss of fidelity under ideal conditions. In this talk, we describe the results of our efforts towards realizing this mechanism using an isotopically pure Rb vapor cell. We also discuss how, via the process of light-shift imbalance induced blockade, it is possible to realize an ensemble based qubit, which in turn can be used to perform deterministic quantum computation and quantum computing.

6130-16, Session 4

Optical interference logic in silicon-on-insulator waveguides

D. C. Wheeler, D. C. Hall, Univ. of Notre Dame

A novel means of realizing optical logic with passive silicon-on-insulator (SOI) waveguide elements is proposed and modeled. Using what we call interference logic, information is encoded and manipulated in the complex domain by properly setting the amplitude and phase of information inputs with specially designed waveguide structures, with the resulting wave interference used to compute the desired function output. We demonstrate that any arbitrary Boolean logic function can be realized in any physical system in which interference occurs. In this work, optical interference logic utilizing constructive and destructive interference of 1.55 micron light waves in multi-mode interference (MMI) couplers fabricated with SOI rib waveguides is described. Defining a vector representation of the complex information, a numerical function minimization algorithm is employed to compute the optimum input vector manipulations needed to realize a given operationís truth table. As such, with the definition of an output amplitude detection threshold separating ì0î and ì1î results, logic operations with 2 and 3 inputs can be performed. A 2x1 multiplexer (optical logic switch) is implemented in a single 4x1 MMI coupler where 1 of the 4 inputs serves as a reference input beam. With an input spacing of 40 micron, the 2x1 multiplexer has an overall dimension of 160 microns x 2.25 cm. Simple varied-dimension waveguide elements are used to adjust input wave amplitude and phase. To confirm and optimize the designs, device operation is simulated using 2D and full-vectorial 3D beam propagation methods.

6130-17, Session 5

Rare Earths vs. Rare Earths: spectral storage in f-d and f-f materials

A. E. Craig, Montana State Univ./Bozeman

No abstract available

6130-18, Session 5

Atomic tailoring for ultra-dense multi-layer spectral memories

J. Park, M. F. Aly, Z. U. Hasan, Temple Univ.

No abstract available

6130-19, Session 5

Fabrication of rare earth doped multi-layer structures for spectral storage

J. Park, M. F. Aly, L. Biyikli, Z. U. Hasan, Temple Univ.

No abstract available

6130-20, Session 5

Optoelectronic hybrid components for optical concurrent communications in peer-to-peer self-organizing network

T. Onishi, Y. Nozaki, W. Sasaki, Doshisha Univ. (Japan)

We have demonstrated our newly considered self-organizing network nodes which realize optical concurrent communications. Using optical devices such as laser diode (LD) and photo diode, we have experimentally composed the non-linear characteristics required for the practical adaptive nodes. We also have accomplished to incorporate some functions which realize the optical concurrent communications into our opto-electronic hybrid circuits. Therefore, without any problem of cross talking or miss formation of the propagation routes, a number of potential communicator pairs may have concurrent access to this self-organizing network formed by interconnecting our nodes. We confirmed the performance of our present nodes experimentally as well as numerically. Moreover, we also designed further advanced type of our opto-electronic hybrid network node components using LD and vertical cavity surface emitting la-

ser (VCSEL) for the creation of nonlinearity, resulting in miniaturization of the system. As a consequence, our present optical nodes have been proved to be practical for the optical peer-to-peer self-organizing network in which concurrent communications are allowed.

6130-21, Session 5

Realization of all-optical basic logic gates using cross gain modulation in semiconductor optical amplifiers

S. H. Kim, J. H. Kim, J. S. Lee, C. W. Son, Y. T. Byun, Y. M. Jhon, S. Lee, D. H. Woo, S. H. Kim, Korea Institute of Science and Technology (South Korea)

As the speed of telecommunication systems increases and reaches the limit of electronic devices, the demand for all-optical logic operations such as switching, decision-making, regenerating, and basic or complex computing is rapidly increasing. 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.

The carrier density changes in SOA will affect all of the input signals, so it is possible that a signal at one wavelength affect the gain of signal at another wavelength. Therefore, the Boolean function of output signal X can be defined by A inversed B when Signal A as probe beam and Signal B as pump beam pass through the SOA. Using devices based on this equation, we demonstrated various all-optical basic logic gates including to AND, NAND, OR, NOR, NXOR and XOR operated at 10Gbps. The extinction ratios of these gates are about 6.1 dB. By achieving this experiment, we also explored the possibilities for the enhanced complex logic operation and higher chances for multiple logic integration.

6130-22, Session 6

Progress in laser cooling of rare-Earth doped solids

R. I. Epstein, Los Alamos National Lab.

No abstract available

6130-23, Session 6

Laser cooling of rare-Earth doped solids: the next step

M. P. Hehlen, Los Alamos National Lab.

No abstract available

6130-24, Session 6

IR-visible upconversion materials for laser refrigerators

Z. U. Hasan, Z. Luo, Temple Univ.

No abstract available

6130-25, Session 6

Cavity-enhanced resonant absorption with application for laser cooling

D. V. Seletskiy, M. P. Hasselbeck, M. Sheik-Bahae, The Univ. of New Mexico; J. Thiede, R. I. Epstein, Los Alamos National Lab.

It has been established that the performance of an optical refrigerator is optimized when the pump laser light is completely absorbed in the cooling element. We present experiments that investigate the concept of cavity enhanced resonant absorption (CERA) for laser cooling of 2% ytterbium doped ZBLANP glass. In the CERA scheme, we have a Gires-Tournois optical cavity (an input coupler and a back mirror with reflectivity ~ 1) and the cooling element placed between the resonator mirrors. The absorption of the cooling element can be made unity provided two conditions are met: 1) the reflectivity of the input coupler is matched to the power loss per round-trip and 2) the cavity is on resonance.

We pump the system with a Yb:YAG disk laser at wavelength of 1030 nm. The absorption of the pump photons promotes Yb atoms of the cooling element from the ground state to the lower part of the continuum excited state. Phonon absorption followed by spontaneous emission at higher energy (anti-Stokes fluorescence) relaxes these atoms back into the ground state. In this cycle, the Yb atoms lose on average a kT of thermal energy, thereby cooling the host glass. The back reflector of our Gires-Tournois cavity is a dielectric stack mirror deposited directly on the end face of the cooling element. The input coupler mirror is piezo-driven by three-axes actuators, which allow tuning and scanning of the cavity. Resonance fringes are observed as the cavity length is scanned. The on-resonance condition can be maintained by a servo-loop driven by the isotropic fluorescence emitted by the sample.

The input coupler reflectivity of the Gires-Tournois cavity must precisely match the round trip power loss to attain maximum pump laser absorption. This makes the scheme difficult to implement in practice. We present a more robust approach using a coupled cavity (i.e. three mirror) design that relaxes this stringent condition. We also discuss other applications of CERA beyond laser cooling of solids.

6130-26, Session 6

Electro-magnetically induced transparency in a static magnetic field

X. Wei, J. Gao, J. Wu, G. Sun, Z. Kang, Z. Shao, Y. Jiang, Jilin Univ. (China)

We investigate both theoretically and experimentally the electro-magnetically induced transparency (EIT) phenomenon of atomic 87Rb at the room temperature with a static magnetic field lifting the degeneracy of all three involved hyperfine levels. Two collinearly propagating and linearly polarized laser fields (a probe field and a coupling field) are used to couple one hyperfine level (the upper level) of the 5P1/2 state to two hyperfine levels (the lower levels) of the 5S1/2 state, respectively. In the case of zero magnetic fields, we observed a deep EIT window with the contrast of about 66%. Here, the EIT window width is limited by both the spontaneous decay rate of the upper level and the coupling field intensity. When a magnetic field parallel to both laser beams is applied, the EIT window is split into three much narrower sub-windows with contrasts of about 32%. If the magnetic field is perpendicular to the laser beams, however, the EIT window is split into four much narrower sub-windows whose contrasts are 32% or 16%. This is because the decomposition of the linearly polarized optical fields strongly depends on the orientation of the used magnetic field. The underlying physics is that, in the limit of a weak probe field, an ideal degenerate three-level system can be split into three or four sets of independent three-level systems by a magnetic field due to the lifting of magnetic sublevels of the involved hyperfine levels. Our theoretical calculations are in good agreement with the experimental results.

6130-27, Session 7

Slow light in vertically coupled whispering gallery mode optical resonators

L. Maleki, Jet Propulsion Lab.

No abstract available

6130-28, Session 7

All optical controlled steering of light

M. S. Zubairy, Texas A&M Univ.

We discuss a scheme that provides steering of the direction via all optical control. The system is based on steep dispersion of coherently driven medium in which electromagnetically induced transparency (EIT) and slow light occurs.

6130-29, Session 7

Data bit distortion induced by slow light in optical commutation systems

Y. Wang, A. E. Willner, Univ. of Southern California

Slow-light components will degrade the data bits in an optical communication system due to dispersion and filtering. Moreover, a bit-pattern dependence is produced in the output data stream. These effects are observed in simulation as well as in an experiment based on slow light induced by stimulated Brillouin scattering in an optical fiber.

6130-30, Session 7

Slow-light solitons

U. Leonhardt, L. C. D·vila Romero, Univ. of St. Andrews (United Kingdom)

A new type of soliton with controllable speed is constructed generalizing the theory of slow-light propagation to an integrable regime of nonlinear dynamics. The scheme would allow the quantum-information transfer between optical solitons and atomic media.

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6131-01, Session 1

Atoms, molecules and optics on microchips

N. P. Bigelow, Univ. of Rochester

No abstract available

6131-02, Session 1

Entanglement generated by collective atom-light interaction: single photons and squeezed spins

V. Vuletic, J. K. Thompson, J. Simon, A. T. Black, Massachusetts Institute of Technology

We report on experiments using the collective interaction of a cold-atom sample with a cavity mode for the generation of entangled states of the sample. In particular, we coherently convert quantized atomic spin gratings into single photons following the scheme proposed by Duan, Lukin, Cirac, and Zoller (Nature 414, 413 (2001), where we achieve conversion efficiencies of 40% for single quanta, and above 80% for multiple quanta. The sampleís entangled-state lifetime is currently 3 microseconds, limited by Doppler broadening. We also report on progress towards spin squeezing on a microchip by collective atom-light interaction. The resulting entanglement should enable an atomic clock to be operated by a factor of ten below the standard quantum limit.

6131-03, Session 1

Transient optical angular momentum effects and atom trapping in multiple twisted beams

D. L. Andrews, Univ. of East Anglia Norwich (United Kingdom); A. C. Carter, M. Babiker, The Univ. of York (United Kingdom); M. Al-Amri, King Khalid Univ. (Saudi Arabia)

Theoretical work has already established the existence of a light-induced torque acting on the centre of mass of an atom, ion or molecule immersed in twisted light, where the transition frequency is suitably detuned from that of the twisted light beam. The twisted beam carries l units of orbital angular momentum per photon, and the steady-state saturation form of the torque is given by the product with the width of the upper state in the atomic transition. It has been shown that, to leading order, the transfer of orbital angular momentum can only occur between the twisted light and the centre of mass motion. We argue here that, for small linewidth, the full time-dependence of the torque is needed to account correctly for the dynamics of atoms in a twisted light beam. We outline the theoretical framework needed to derive this full time-dependence, applying the theory to the motion in a twisted light beam for Eu3+ ions, which possess a particularly narrow linewidth state. For relatively large linewidth the steady-state forces and torque are appropriate, but the processes of cooling and trapping require the application of several suitably oriented twisted beams. The description of atomic motion in multiple twisted beams demands the application of special coordinate transformations. We show how to construct the appropriate transformation matrices to produce a twisted light beam propagating in an arbitrary direction, and we proceed to investigate the cooling and trapping of Mg+ ions in sets of pairs of counter-propagating twisted beams in one-dimensional, two-dimensional as well as three-dimensional molasses configurations.

6131-04, Session 2

Optical vortex application concerns: coherence and topological dispersion

G. A. Swartzlander, Jr., College of Optical Sciences/The Univ. of Arizona

No abstract available

6131-05, Session 2

The phase-vortex flower garden: composite vortices of two Laguerre-Gauss beams

E. J. Galvez, N. M. Smiley, Colgate Univ.

We studied experimentally the superposition of Laguerre-Gauss beams of different order. We focused on optical beams with phase vortices. Experimentally we used nested Mach-Zehnder interferometers to combine the beams with adjustable relative intensities. Via interference with a reference beam we observed the creation/annihilation of phase vortices, and the change in their position as the relative intensity of the component beams was varied. The observations agree with theory.

6131-06, Session 2

Observation of new optical vortex in experiments with Hermite Gaussian and Laguerre-Gaussian laser modes

K. Contreras, G. Baldwin-Olguin, F. De Zela, Pontificia Univ. Catolica del Peru (Peru); E. J. Galvez, Colgate Univ.

It is well known the experiments that allow to show the intensity and phase structure of transverse modal patterns, Hermite-Gaussian and Laguerre-Gaussian laser modes. Moreover, it is not know about how the dynamical transverse patterns can to generate them. These new spatial configurations of the light depend on the dynamics of laser resonator, and on the boundary conditions of our laser. The Laguerre-Gaussian modes are obtained either by the direct conversion of Hermite-Gaussian modes using a modal converter, or a computer-generated hologram or with a SLM spatial light modulator. We show the phase structure and obtained optical phase singularities of laser modes with a Mach-Zehnder. The resulting interference patterns clearly illustrate the azimuthal phase dependence of the Laguerre-Gaussian modes, which is the origin of the orbital angular momentum associated with each one of them. Moreover, we try to give an explanation of the new generation of optical vortices and its temporal evolution.

6131-07, Session 2

Vectorial vortices obtained with quantized Pancharatnam-Berry phase optical elements

E. Hasman, A. Niv, G. Biener, V. Kleiner, Technion - Israel Institute of Technology (Israel)

Singularities in scalar wave fields appear at points or along lines where the phase or the amplitude of the wave is either undefined or abruptly changes. One class of singularities is the scalar vortex, which is a spiral phase ramp around a singularity. Until now, researchers had focused mainly on scalar vortices. However, if we allow the polarization to be space-varying, vectorial vortices may appear. A vectorial vortex occurs around a point where a scalar vortex is centered in at least one of the scalar components of the vectorial wave field. Vectorial vortices obtained with quantized Pancharatnam-Berry phase optical elements (PBOEs) are presented. QPBOEs utilize the geometric phase that accompanies space-variant polarization manipulations to achieve a desired phase modification. The geometric phase is formed through the use of discrete computer-generated space-variant subwavelength dielectric gratings. By discretely controlling the local grating orientation, we could form complex vectorial fields. Propagation-invariant vectorial Bessel beams with linearly polarized axial symmetry were experimentally demonstrated. Moreover, a new class of vectorial vortices based on coherent addition of two orthogonal circular

polarized Bessel beams of identical order, but with different propagation constant is presented. The transversely space-variant axially symmetric polarization distributions of these vectorial fields rotate as they propagate while still maintaining a propagation-invariant Bessel intensity distribution. The polarization properties were verified by both full space-variant polarization analysis and measurements. Rotating intensity patterns were also demonstrated by transmitting the vectorial vortices through a linear polarizer.

6131-08, Session 2

Angular momentum and astigmatism of bichromatic beams

G. Nienhuis, Univ. Leiden (Netherlands)

The paraxial wave equation describes the propagation of the transverse profile of a monochromatic light beam. This equation is equivalent to the Schr^dinger equation for a free particle. This analogy breaks down for a non-monochromatic beam, and the paraxial wave equation remains simple only when the frequency differences are relatively small. Non-monochromatic beams offer new possibilities for the manipulation of the interaction of the light with material particles. For a bichromatic light beam (the superposition of two beams with different frequencies), the transverse beam pattern oscillates at the frequency difference W. The density of linear and angular momentum of the light beam has the same oscillatory behavior.

The linear and angular momentum densities arise solely from the bichromaticity when the two composing monochromatic beams have opposite momenta. This is achieved when in the focal plane the two transverse profiles are each otherís complex conjugate.

Then at each position the intensity oscillates at the frequency W. In the relatively near field, where the diffraction of the two frequency components is still indistinguishable, the intensity has a spatial oscillation in the propagation direction with wave vector W/c. For simplicity we assume that the polarization is uniform. Then the momentum contains no polarization contributions. The remaining momentum density is naturally separated into two terms, one proportional to the intensity gradient of the component with the higher frequency, the other to its phase gradient. The intensity-gradient term vanishes when it is averaged over the oscillation time (~1/W). The proportionality constant in the phase-gradient term is always negative, so that the momentum density is directed opposite to the momentum contribution of the higher-frequency component.

Moreover, this contribution is always proportional to the local and instantaneous energy density of the total bichromatic light field, and it survives averaging over time. The properties of the orbital angular momentum of the field are determined by the momentum density.

As an illustrative special case, we consider the superposition of two Laguerre-Gaussian beams, with opposite values of the angular momentum mode number l. The positive l-value pertains to the high-frequency component. Due to the superposition, the field has a standing-wave structure as a function of the azimuthal angle f. Due to the frequency difference W, this structure rotates in the positive direction (from the x-axis to the y-axis), with the angular velocity W/2l. The density of angular momentum is proportional to the field intensity, with a negative proportionality constant. As a result, the intensity pattern that rotates in the positive direction corresponds to a negative angular momentum. In the special case of two Laguerre-Gaussian beams with l=1, this has been recently discussed. Here this result is obtained as a special case of a more general feature of bichromatic fields.

Another interesting case arises when both monochromatic components are astigmatic Gaussian beams, carrying angular momentum. The momentum and angular momentum properties of the resulting bichromatic beams will be discussed, along with some suggestions for applications.

Also we shall discuss various ways of preparing bichromatic astigmatic beams by using rotating beam converters.

6131-09, Session 2

New configurations in parametric downconversion for generating light with orbital angular momentum

J. P. Torres, Univ. PolitËcnica de Catalunya (Spain)

The spatial structure of light provides a new resource to explore quantum physics in a d-dimensional Hilbert space, beyond the two dimensional Hilbert space generated by the polarization state of the photons. Spontaneous parametric downconversion (SPDC) is a realiable source of entangled photons entangled in orbital angular momentum (OAM).

In general, the implementation of a d-dimensional quantum channel requires the generation of arbitrary engineered entangled states, thus controlling such structures is of paramount importance for many applications. For instance, two-photon states with well defined spatial properties, such as qutrits encoded in a well defined value of the OAM, are not harvested directly at the output of the downconverting crystal.

Here we address the orbital angular momentum, i.e. the spatial shape, of photons generated in SPDC in noncollinear geometries, when the interacting waves exhibit Poynting vector walk off. The OAM of entangled photons generated in noncollinear geometries exhibit new features in comparison with those known for collinear geometries. The spatial shape depends on the interplay between the state ellipticity caused by the nonlinear geometry, and the Poynting vector walk off.

The importance of both effects is dictated by the interplay between three characteristics lengths: the length of the nonlinear crystal, the walk off length and the noncollinear length. The effects described here are directly relevant to current experiments. We notice that this is particularly important for the implementation of quantum information protocols based on spatially encoded information. We will analyse the impact of the new features exhibited by walking entangled photons on the implementation of quantum protocols based on the spiral spectra of the entangled photons.

Finally, the consideration of new geometries for SPDC, especifically highly noncollinear configurations, will lead us to the discussion of the relationship between the OAM of the classical beam that pumps the downconverter source, and the quantum OAM of the downconverted photons. Regarding experimental measurements related to this issue, it is of great importance the make a distinction between the measurement of locally paraxial light beams in a suitable transverse frame, and the description of the global downconversion process, which is not necessarily paraxial.

6131-10, Session 2

PoincarÈ sphere for nondiffracting beams with orbital angular momentum

W. Soares, D. P. Caetano, J. M. Hickmann, Univ. Federal de Estado de Alagoas (Brazil)

The angular momentum of a light beam has two components, spin and orbital. The spin component is related to the polarization state and the orbital component is related to the transverse distribution of the field. The orbital angular momentum (OAM) is directly associated with the azimuthal phase structure of the light beam.

Light beams possessing OAM are usually described in terms of Laguerre-Gauss (LGpl) modes. These modes are solutions of the Helmholtz equation in the paraxial approximation. LG beams can be decomposed in terms of Hermite-Gauss modes HGmn.

The spin angular momentum component has a similar decomposition. Based on this similarity, it was proposed a PoincarÈ sphere equivalent for light beams possessing OAM, called the sphere of first-order modes. It was also demonstrated that these geometric representations are related to the SU(2) group of the transformations of both polarization states and transverse modes of the light beams.

Alternatively, one can describe light beams with OAM by using high-or-

der Bessel-Beams, which are solutions of the exact Helmholtz equation in cylindrical coordinates and present nondiffracting properties. In this work, we develop a SU(2) structure of the PoincarÈ sphere in terms of Bessel beams and investigate unitary transformations within the equivalent Poincaré sphere using linear optical elements. The idea is based on the decomposition of high-order Bessel beams, which for the case of first-order beams can be expressed as a superposition of a product of Bessel functions and Hermite polynomials with a $\pi/2$ phase difference.

6131-11, Session 3

Optical pumps and sensors for microfluidic devices

M. J. Padgett, J. Leach, J. M. Cooper, Univ. of Glasgow (United Kingdom); R. Di Leonardo, Univ. of Glasgow (United Kingdom) and Istituto Nazionale per la Fisica della Material (Italy); H. Mushfique, Univ. of Glasgow (United Kingdom)

Optical tweezers use light's momentum to manipulate micron-sized particles. Typically configured around a high magnification microscope which creates the tightly focused laser required to produce a 3D optical trap, tweezers have been revolutionized by the use of reconfigurable spatial light modulators that can split a single laser beam to trap and move many particles simultaneously. Furthermore the angular momentum of the laser light can be transferred to the trapped particles causing rotation. Lateral or rotational manipulation of these particles can be used to drive fluid flow in a controlled and efficient manner through micro-channels based on a number of configurations. For example, we use two micron-sized birefringent particles, set spinning with circularly polarized light to introduce a fluid flow within a micro channel, effectively forming a controlled pump/valve. In addition, these optical tools can be used for probing the chemical and physical properties of fluids in micro-fluidic devices. We show how it is possible to use measurement of the residual Brownian motion of these trapped particles to monitor the local temperature, viscosity and pH within a sample.

6131-12, Session 3

Optically driven microtools fabricated by UV-lithography

P. J. L. Rodrigo, Risø National Lab. (Denmark); L. Gammelgaard, Danmarks Tekniske Univ. (Denmark); I. R. Perch-Nielsen, Risø National Lab. (Denmark); P. Bøggild, Danmarks Tekniske Univ. (Denmark); J. Gl¸ckstad, Risø National Lab. (Denmark)

We demonstrate the use of multiple optical traps for driving various microfabricated silica structures in liquid host medium. Multiple optical traps are formed using two counterpropagating light fields, each of which is spatially reconfigurable in both cross-sectional geometry and intensity distribution, either in a user-interactive manner or under computer supervision. The design of microtools includes multiple appendages with rounded endings by which optical traps hold and actuate individual tools. UV-lithography is employed to fabricate the microtools. Experiments show the collective and user-coordinated utility of multiple beams for driving microstructured objects whose future integration may lead to optically controlled functional micromachineries.

6131-14, Session 3

Computational modeling of optical manipulation of dielectric objects in complex optical fields and microfluidic flow

Z. Sikorski, CFD Research Corp.; W. Butler, Genoptix, Inc.; Z. Chen, A. J. Przekwas, CFD Research Corp.

The response of the biological cells to optical manipulation in the bio-microfluidic devices is strongly influenced by the flow and motion inertia. There is a variety of microfluidic architectures in which both the cell-fluid interaction and the optical field are driving forces for segregation and manipulation of the cells. We developed a computational tool for analysis/optimization of these devices. The tool consist of two parts: an optical force library generator and the computational fluid dynamics solver with coupled optical force field.

The optical force library can be computed for spherical and non-spherical objects of rotational symmetry and for complex optical fields. The basic idea of our method is to a) represent an incident optical field at the biological cell location as an angular spectrum of plane waves; b) compute the scattered field, being a coherent superposition of the scattered fields coming from each of the incident plane waves, with the powerful T-matrix method used to compute the amplitude matrix; c) use the incident and computed scattered fields to build a spatial map of optical forces exerted on biological cells at different locations in the optical beam coordinate system, and d) apply the library of optical forces to compute laser beam manipulation in microfluidic devices. The position and intensity of the optical field in the microfluidic device may be dynamic, thus optical forces in microfluidic device are based on the instantaneous relative location of the cell in the beam coordinate system. The cell is simulated by the macroparticle that undergoes mutual interactions with the fluid. We will present the exemplary applications of the code.

6131-15, Session 3

Tunable acoustic gradient index of refraction lenses for controllable nondiffracting beams

E. J. McLeod, A. B. Hopkins, C. B. Arnold, Princeton Univ.

Optical tweezer systems have recently used nondiffracting Bessel beams for particle trapping. These beams provide the opportunity for trapping over an extended range and their self-healing properties allow the collinear trapping of multiple particles. Nondiffracting beams are typically created using axicons, diffractive elements, or holographic methods. In this study, we present a novel approach to creating such beams using a Tunable Acoustic Gradient Index of Refraction (TAG) lens. An amplified ultrasonic signal is used to establish a steady-state density fluctuation within a liquid effecting an oscillatory variation in local index of refraction. Light propagating through this liquid produces a Bessel-like beam whose properties primarily depend on driving amplitude, frequency, geometry and liquid properties. Preliminary results are obtained using 532nm light and a TAG lens containing glycerol. The theory behind the lens operation, its degrees of control, experimental results, and applicability to optical tweezing will be presented.

6131-16, Session 4

Optical tweezers 3D photonic force spectroscopy

A. ¡. R. Neves, A. Fontes, W. L. Moreira, A. A. de Thomaz, D. B. Almeida, L. C. Barbosa, C. L. Cesar, Univ. Estadual de Campinas (Brazil)

Since optical tweezers trapped microspheres can be used as an ultrasensitive force measurements technique, the knowledge of its theoretical description is of utmost importance. However, even the description of the incident electromagnetic fields under very tight focusing, typical of the optical trap, is not yet a closed problem. Therefore it is important to experimentally obtain whole accurate curves of the force as a function of wavelength, polarization and incident beam 3D position with respect to the center of the microsphere. Theoretical models for optical forces such as the generalized Lorenz-Mie theory can then be applied to the precisely evaluated experimental results. Using a dual trap in an upright standard optical microscope, one to keep the particle at the equilibrium position and the other to disturb it we have been able to obtain these force curves as a function of x, y and z position, incident beam polarization and wavelength. Further investigation of optical forces was conducted for wavelengths in and out Mie resonances of dielectric microspherical

cavities for both TM and TE modes. We also compared the force dependence of cw and pulsed Ti:sapphire femtosecond lasers to understand the optical force in the presence of multiphoton and/or self-focusing processes.

6131-18, Session 4

Optical ordering of nanoparticles trapped by Laguerre-Gaussian laser modes

D. L. Andrews, D. S. Bradshaw, Univ. of East Anglia Norwich (United Kingdom)

In earlier work, it has been established that laser-induced coupling between a pair of particles enables the generation of novel patterns, entirely determined and controlled by the frequency, intensity, and polarisation of the non-linear optical input. In this paper, the spatial disposition of the particles about the beam axis is determined for two-, three- and four-nanoparticle systems irradiated by a Laguerre-Gaussian (LG) laser mode. The range-dependent laser induced energy shift is identified by the employment of a quantum electrodynamical description and, from this expression, calculations are performed to determine the distribution of absolute minima for variable topological charge, and the results are graphically displayed. This analysis illustrates a number of interesting features, including the fact that on increasing the LG beamís topological charge the particles increasingly cluster, i.e. the order of the structure is significantly raised-also the number of minima for which the particles can be trapped is enhanced. Finally, it is shown that similar principles apply to other kinds of radially structured optical modes.

6131-19, Session 4

Light induced further aggregation of metal aggregates

Y. Zhang, C. Gu, A. M. Schwartzberg, J. Z. Zhang, Univ. of California/Santa Cruz

Abstract: The optical trapping of micrometer-sized metal particles with a TEM00 laser beam generated by a Verdi laser with 532 nm wavelength is demonstrated. Besides the successful optical trapping of 1-3um metal aggregates suspended in water with the light focused in the bottom of the particle, an unusual light induced further aggregation of metal aggregates is also observed. A 60-100 um donuts metal disk was formed by 50mW laser power with a 5 um beam waist. Two kinds of metal particles (Gold and Silver) were used to do the experiments. The donuts shape disk could be formed in both cases but the size is different. We attribute this unusual phenomenon not only to radiation force and radiometric force but we also introduce a new concept ìPhoton-induced-thermal-chemical effectî that has not been realized before.

6131-20, Session 5

From anisotropic photo-fluidity towards nanomanipulation in optical near-field

P. Karageorgiev, Ctr. of Advanced European Studies and Research (Germany) and Univ. Potsdam (Germany); D. Neher, B. Schulz, Univ. Potsdam (Germany); M. Giersig, Ctr. of Advanced European Studies and Research (Germany)

An increase in stochastic molecular vibrations of a solid due to heating above the melting point leads to a decrease in its long-range order and a loss of structural symmetry. Therefore conventional liquids are isotropic media. We report on a light-induced isothermal phase transition of a polymer film from an isotropic solid to an anisotropic liquid state in which the degree of mechanical anisotropy can be controlled by light. Whereas during irradiation by circular polarized light the film behaves as an isotropic viscoelastic fluid, it displays considerable fluidity only in the direction parallel to the light field vector under linear polarized light, demonstrating thus extraordinarily anisotropic mechanical properties. The fluidisation phenomenon is related to photoinduced motion of azobenzene-functionalized molecular units, which can be effectively activated only when their transition dipole moments are oriented close to the direction of the light polarization. Since the molecular motion can be induced also by spatially confined non-propagating optical fields, we are able to fluidise nanoscopic elements of the film surface and to trap and transfer a nanodrop of the polymer using the optical near-field of an illuminated metallic tip. Along with the phenomenological finding, our work allows us to make a substantial step in understanding the mass transport effect in azobenzene containing systems under conditions of far- and near-field illumination.

6131-21, Session 5

Experimental tests of the composite diffractive evanescent wave model

J. Weiner, G. Gay, R. Mathevet, H. J. Lezec, Univ. Paul Sabatier (France)

We present results of experiments testing the Composite Diffracted Evanescent Wave (CDEW) model of surface waves generated by subwavelength structures fabricated on silver films. These experiments consist of three types of data: (1) angular distributions of transmitted light through subwavelength slits flanked by grooves; (2) efficiency of transmission through a subwavelength slit flanked by narrow grooves as a function of slit-groove distance; (3) relative phase measurements by far-field interference patterns between directly propagating and surface-evanescent modes. These types of structures are of interest for the manipulation of cold atoms by optical potentials near surfaces.

6131-22, Session 5

Evanescent-wave bonding between nanophotonics waveguides

M. Loncar, Harvard Univ.; M. L. Povinelli, Stanford Univ.; M. Ibanescu, Massachusetts Institute of Technology; E. J. Smythe, Harvard Univ.; S. G. Johnson, Massachusetts Institute of Technology; F. Capasso, Harvard Univ.; J. D. Joannopoulos, Massachusetts Institute of Technology

Electronic bonding, resulting from overlap between electron wavefunctions, is a ubiquitous phenomenon that gives rise to material structure. It is intriguing to consider an analogous phenomenon of ìoptical bonding,î where overlapping modes of linear optical waveguides result in the attractive or repulsive force between the waveguides. Our work identifies forces arising from ìinternalî illumination by light traveling in coupled waveguides. We show that the sign of the force can be changed from attractive to repulsive at fixed frequency simply by tuning the relative phase of the systemís inputs. We use direct numerical solutions of Maxwellís equations in combination with micromechanical modeling to predict that optical coupling forces between the waveguides should lead to significant displacements.

For example, we consider two parallel silicon waveguides (Length L=50 microns, cross-sectional dimensions 310nm x 310nm) suspended in air and separated by a distance d=46.5nm. Assuming P=13mW of input power at wavelength of 1.55 microns, a displacement 20nm is obtained at the center of suspended section of each waveguide.

The opto-mechanical response can also be improved by exploiting the mechanical resonance of the suspended beams.

Optical evanescent-wave bonding forces are not restricted to the specific geometry and material system. We have calculated that significant forces also arise in coupled silica microspheres.

More generally, the use of optical, guided-wave signals to reposition the constituent parts of nanophotonics devices suggests a new class of artificial, microstructured materials in which the internal mechanical configuration and resultant optical properties are coupled to incoming light signals.

6131-23, Session 5

Space-variant polarization manipulation of a thermal emission by a polar material subwavelength grating supporting surface phonon-polaritons

E. Hasman, N. Dahan, A. Niv, G. Biener, V. Kleiner, Technion - Israel Institute of Technology (Israel)

Thermal emission from absorbing material is considered to be incoherent and unpolarized, and accordingly is regarded as spontaneous emission. The surface properties of the absorbing material have a profound impact on the emission's optical properties, and can be manipulated to produce a partially coherent and partially polarized radiation emission. Space-variant polarization manipulation of enhanced omnidirectional thermal emission in a narrow spectral peak is presented [1,2]. The emission is attributed to surface phonon-polaritons excitation from space-variant subwavelength SiO2 gratings. Surface phonon polaritons are supported by polar materials in the spectral range where the real part of the dielectric constant is smaller than -1. Fused silica behaves as a polar material in the spectral range of 8.65 to 9.18 micron. Polarization manipulation was obtained by discretely controlling the local orientation of the grating. We experimentally demonstrated space-variant thermal emission in an axially symmetric polarization distribution[2]. Furthermore, we utilized this effect to encrypt an image in the polarization state of an infrared thermal radiation field [3]. Decryption of the image was obtained by measuring the polarization state of the thermal radiation and applying the correct key. Theoretical calculations based on rigorous coupled-wave analysis are presented along with experimental results.

References:

1 E. Hasman, G. Biener, A. Niv, and V. Kleiner, Progress in Optics, Vol. 47, E. Wolf, ed. (Elsvier, Amsterdam 2005). 2 N. Dahan, A. Niv, G. Biener, V. Kleiner, E. Hasman, Appl. Phys. Lett. 86, 191102 (2005). 3 N. Dahan, A. Niv, G. Biener, V. Kleiner, E. Hasman, submitted to Opt. Lett.

6131-24, Session 5

Near-field optical manipulation with cavity enhanced evanescent fields

P. Reece, V. G. Garcés-Chávez, K. Dholakia, Univ. of St. Andrews (United Kingdom)

Near-field optical manipulation is an emerging area of research which offers much potential for extending the current capabilities of optical manipulation; particularly at the nanometer scale where optical landscapes with arbitrarily small feature sizes could potentially be realised. Recent results demonstrating the feasibility of this technology at the sub-micrometer scale include the collective organization of large-scale particle arrays, stable single-particle trapping and novel optical binding effects. One of the major challenges facing this technique is that optical interactions involving evanescent waves are very weak and thus have very limited practical use.

In the following presentation we show that near-field optical manipulation can be greatly increased through the use of cavity enhanced evanescent fields. This approach utilises a resonant dielectric structure and a prism coupler to produce Fabry-Perot like cavity modes which at the dielectric/fluid interface which can be utilised in optical manipulation. Using this structure we show an order of magnitude increase in the optical interaction of micrometer-sized colloids compared with the standard evanescent wave configuration. Furthermore the intimate coupling between the sample solution and the cavity resonance provides a very sensitive method for monitoring interactions at the surface. We believe that this technique has considerable scope for promoting the role of near-field optical manipulation at the nanometer scale.

Conference 6132: Vertical-Cavity Surface-Emitting Lasers X

Wednesday-Thursday 25-26 January 2006

Part of Proceedings of SPIE Vol. 6132 Vertical-Cavity Surface-Emitting Lasers X

6132-01, Session 1

Issues with the application of 1.3 micron VCSELs to communication applications: why is it taking so long?

D. W. Kisker, Opitcal Communication Products, Inc.; J. M. Van Hove, R. L. Naone, M. Adamcyk, L. M. F. Chirovsky, G. Giudice, J. M. Rossler, J. Xu, N. Wasinger, J. G. Beltran, Optical Communication Products, Inc.

No abstract available

6132-02, Session 1

High volume production of singlemode VCSELs

D. Wiedenmann, M. Grabherr, R. Jaeger, R. King, ULM Photonics GmbH (Germany)

In the past applications for singlemode VCSELs were in low volume, high prized applications like tuneable diode laser absorption spectroscopy (TDLAS) or optical interferometers. Typical volumes for these applications are in the range 1000pcs/year, with pricing levels of several 100USD/pcs. New applications of singlemode VCSELs for the consumer market require manufacturing in very high volumes and at very low cost. Examples are laser-based optical mouse sensors or rubidium atomic clocks for GPS systems. U-L-M photonics presents manufacturing aspects, device performance and reliability data for these devcies.

The first part of the paper is dealing with high volume manufacturing of 850nm single-mode VCSEL chips with very high efficiency and low operation current. Special processing technologies have been developed to achieve yields on 3 inch wafers of more than 90%. Procedures how wafer qualification is done are discussed.

The second part of the paper deals with the high volume packaging in TO type packages. Again very high packaging yields must be achieved. In the last part of the paper reliability issues are discussed. Especially the very high susceptibility of these devices to electrostatic discharge.

6132-03, Session 1

AOC moving forward: The impact of materials behavior

D. T. Mathes, J. K. Guenter, R. A. Hawthorne III, J. A. Tatum, B. M. Hawkins, C. W. Johnson, Advanced Optical Components

AOC will show how a solid commitment to understanding the materials-level behavior of VCSELs impacts design, production and customer support, as well as present an update on its VCSEL reliability statistics, and describe its broadening and intensified efforts to implement VCSELs in markets outside of datacom.

6132-04, Session 2

1310nm VCSELs in 1-10Gb/s commercial applications

J. L. Jewell, L. A. Graham, M. V. Crom, K. Maranowski, J. M. Smith, PicoLight, Inc.

No abstract available

6132-05, Session 2

Effects of optical back reflection on long wavelength VCSELs

M. Steib, Y. V. Vandyshev, H. Deng, Finisar Corp.

No abstract available

6132-06, Session 2

A TCAD based yield and reliability analysis for VCSELs

S. Odermatt, ETH Z¸rich (Switzerland); R. Hoevel, S. Eitel, Avalon Photonics Ltd. (Switzerland); G. Letay, Synopsys Switzerland AG (Switzerland); M. Streiff, B. Witzigmann, ETH Z¸rich (Switzerland)

Yield enhancement and reliability improvement are main requirements in todays industrial VCSEL manufacturing. This requires a thorough understanding of process tolerances and the effects resulting from design variations. So far, this has been done by statistical analysis of experimental data. In this work, we use a state-of-the art technology computer aided design (TCAD) tool to analyze device reliability and yield for multiple VCSEL designs. The starting point is a physics-based full 3-dimensional simulation model that is calibrated to temperature dependent static and dynamic measurements for a set of single- and multi-mode VCSELs lasing at 850nm. Applying statistical variations that result from design modifications or process fluctuations, yield and reliability data are extracted from the simulation. The yield will be derived by compliance to selected device specifications (such as threshold current, external efficiency or RIN), and the device reliability is determined from an analysis of the internal device properties (such as peak current density and temperature). As example, the oxide aperture design will be discussed, and a robust design will be presented.

6132-07, Session 2

1.3 μm strained InGaAs quantum well VCSELs: operation characteristics and transverse modes analysis

E. Pougeoise, P. Gilet, P. Grosse, S. Poncet, A. Chelnokov, J. Gérard, Commissariat à l'Energie Atomique (France); G. Bourgeois, Intexys Photonics (France); R. Stevens, R. R. Hamelin, Intexys Photonics (France); M. Hammar, P. Sundgren, J. Berggren, Kungliga Tekniska Högskolan (Sweden)

In this article, we report our results on strained InGaAs quantum well VCSELs for optical interconnection applications. 1300 nm room temperature continuous-wave lasing operation is demonstrated for a top emitting oxide-confined device. The conventional epitaxial structure was grown by MOCVD and contains fully doped GaAs/AlGaAs DBR. The active layer embedded two strained InGaAs quantum wells. Simple processing consisted in mesa etching, p contact ring deposition and n contact deposition at the back side of the substrate, and selective wet oxidation to realize current and optical confinement. Thus circular apertures from 2 μm to 12 μm diameters are defined.

At room temperature and in continuous wave operation, 2 and 4 μm diameter VCSEL achieve 1300 nm single mode lasing operation. Modal behavior changes with aperture diameter increase. Emission switches from fundamental to high order transverse mode concurrently with a strong lasing wavelength shift. Comparison between measurement and simula-

tion of modal behavior will be presented. The maximum output power varies from 0.15 to 1.8 mW with aperture diameter. Threshold current temperature dependence has been studied in continuous wave and pulsed operation. By increasing temperature from 10∞C to 50∞C of a 10 μm aperture diameter device, threshold current decreases from 2.96 to 1.86 mA, concurrently with differential external efficiency decrease from 16% to 12.6 %. The threshold current reduction is due to the detuning between gain peak and cavity resonance.We could estimate internal temperature of the device by comparing pulsed to continuous wave operation and thus evaluate this detuning.

6132-08, Session 3

VCSELs for atomic clocks

D. K. Serkland, G. M. Peake, K. M. Geib, Sandia National Labs.; R. Lutwak, R. M. Garvey, Symmetricom, Inc.; M. Varghese, M. Mescher, Charles Stark Draper Lab., Inc.

The spectroscopic technique called coherent population trapping (CPT) enables optical rather than microwave interrogation of the ground-state hyperfine splitting of cesium (or rubidium), which defines the fundamental unit of time, the second. Optical interrogation allows the volume and power consumption of an atomic clock to be reduced by orders of magnitude, and vertical-cavity surface-emitting lasers (VCSELs) are preferred optical sources for their low power consumption and circular output beam. Several research teams are currently using VCSELs for DARPAís chip-scale atomic clock (CSAC) program with the goal of producing an atomic clock having a volume < 1 cm^3, a power consumption < 30 mW, and an instability (Allen variance) < 1x10^-11 during a 1-hour averaging interval.

This paper will describe the VCSEL requirements for CPT-based atomic clocks, which include single mode operation, single polarization operation, modulation bandwidth > 4 GHz, low power consumption (for the CSAC), narrow linewidth, and low relative intensity noise (RIN). Data will be presented that show the advantage of operating at the D1 (rather than D2) resonance of the alkali atoms. A significant manufacturing challenge is to reproducibly obtain the required wavelength at the specified VCSEL operating temperature and drive current; the optical transition wavelengths (in vacuum) are 894.6 nm (D1) and 852.3 nm (D2) for cesium, and 795.0 nm (D1) and 780.2 nm (D2) for rubidium. Measurements of VCSEL linewidth and RIN will be discussed in particular, since atomic clock performance is particularly sensitive to these parameters.

6132-09, Session 3

Optical characterization of VCSELs in a CPT frequency standard

K. D. Choquette, C. Long, Univ. of Illinois at Urbana-Champaign

No abstract available

6132-11, Session 3

In-situ optical time-domain reflectometry (OTDR) for VCSEL-based communication systems

G. A. Keeler, D. K. Serkland, K. M. Geib, J. F. Klem, G. M. Peake, Sandia National Labs.

Optical time-domain reflectometry (OTDR) is a common and effective technique for locating faults in fiber communication links. Significant drawbacks stem from the fact that most OTDR measurements are performed manually, making them too costly for use in many short-distance networks and too slow for use in military avionic platforms. Here we describe and demonstrate an automated, low-cost, real-time approach to fault monitoring achieved by integrating OTDR functionality directly into a VCSEL-based transceiver. This in-situ capability is straightforward to implement and relevant to both multi-mode and single-mode networks.

In-situ OTDR uses the data communication VCSEL already present in data transceivers. Fiber monitoring is performed by emitting a brief optical pulse into the fiber and then turning the VCSEL off. If a fault exists, a portion of the optical pulse returns to the transceiver after a time equal to the round-trip fiber delay. In multi-mode OTDR, the signal is detected by a photodetector integrated with the VCSEL, while in single-mode OTDR, the VCSEL itself is used to detect the returning light. Modified VCSEL driver electronics perform the measurement and analysis.

We demonstrate that VCSEL-based OTDR has sufficient sensitivity to determine the location of most faults commonly seen in short-haul networks (i.e., the Fresnel reflections from unterminated fibers and scattering from raggedly-broken fibers). Results are described for single-mode and multi-mode experiments, at both 850 nm and 1.3 μm. We discuss the resolution and sensitivity that can be achieved, as well as the expected limitations of this unusual approach to network monitoring.

6132-12, Session 4

Mode polarization partition noise in multimode short-wavelength vertical cavity surface emitting lasers

J. Carstens, Univ. of Nevada/Reno

We present experimental results for mode polarization partition noise of bare-die multi-mode GaAs vertical-cavity surface-emitting lasers (VCSELs) at short wavelengths near 810nm. A NIR sheet polarizer was used to select only one polarization for all modes. The relative intensity noise characteristics of these VCSELs were measured, in order to compare the impact of both noise types on signal distortion. The comparison was made by measuring the associated power penalty from using bit-error ratio technique.

6132-13, Session 4

VCSEL structure embedded in metal heat sink for optimal thermal management

S. Q. Yu, R. Gupta, X. Jin, S. R. Johnson, J. Gu, Y. H. Zhang, Arizona State Univ.

Due to a high intrinsic serial resistance and a high current density, thermal management in vertical-cavity surface-emitting lasers (VCSELs) is critical for obtaining high performance and reliability. The lasing wavelength in VCSELs is determined by the cavity mode which reflects the average temperature of the total structure rather than the active region temperature. Therefore the need for thermal management in VCSELs can be overlooked since the active region temperature change is not totally reflected in the lasing spectrum. In this paper, a quasi-3D thermal model using finite element analysis is developed to evaluate the effects of various thermal management approaches that involve flip-chip bonding, substrate removal, and metal plating. The best thermal management solution we found uses a combination of these approaches; from which we have developed a novel VCSEL thermal management process, where the device is fully embedded in a metal heat sink. Compared to a VCSEL without any specific thermal management treatment, our modeling predicts a 48% temperature drop in the active region using this novel thermal management process. This process is demonstrated on a 1310 nm resonant cavity light emitting diode (RCLED) with a GaAsSb/GaAs active region. This structure is similar to a VCSEL structure in that it includes an active region in a cavity defined by distributed Bragg reflectors and a wet oxidation layer for current confinement. Preliminary testing results show a clear temperature drop in the active region, demonstrating the feasibility of this process for VCSEL fabrication. This thermal management technique can also be applied to edge-emitting lasers.

6132-14, Session 4

End-pumped vertical external cavity surface emitting laser

T. Kim, J. Lee, J. Y. Kim, K. Kim, S. Lee, S. Cho, J. Kim, G. Kim, S. Lim, Y. Park, SAMSUNG Advanced Institute of Technology

(South Korea)

We report on a 1060 nm single transverse mode operation of an end-pumped Vertical Cavity Surface Emitting Laser (VECSEL). End-pumping scheme is enabled by capillary bonding of a VECSEL chip with a diamond heat spreader followed by a GaAs substrate removal by selective wet etching. The VECSEL structure is consisted of 10 periods of resonant periodic gain with 8 nm InGaAs single quantum well at the antinodes of the standing wave field and a 35 pairs AlAl/AlGaAs bottom distributed Brag reflector (DBR). Optical pump efficiency through the bottom mirror is enhanced by a modified DBR structure with a reduced reflectance in 808 nm pump wavelength region. A low threshold pump density of 433 W/cm2 and over 40 % slope efficiency are measured with reflectivity of 94 % out coupler. The laser operates in a TEM00 circular mode (M2<1.5) up to 7 W which is limited by our pump laser power.

End-pumping scheme has a many advantages over conventional front pumping allowing simple cavity design and compact package, especially when it comes to the frequency doubling. Detailed comparison between the end-pumping and a front pumping will be discussed. Frequency doubling and green laser performance (~3 Watt) with end-pumped VECSEL also will be addressed.

6132-15, Session 4

Vertical-cavity laser based on interband-tunneling staggered-bandgap heterostructure

B. Gelmont, Univ. of Virginia; D. Woolard, U.S. Army Research Office; T. Globus, Univ. of Virginia

Optically pumped and electrically pumped type-II staggered-bandgap heterostructure (SBH) multiple-quantum-well (MQW) mid-IR Vertical-Cavity Surface-Emitting Laser (VCSEL) have been proposed earlier. Due to interband transitions, the gain in this device employing a four-constituent InAs-GaSb-InAs-AlSb configuration is expected to be larger in comparison with the intersubband-based quantum cascade laser. However, SBH lasers require a p-i-n junction to enable electrical pumping.

A new concept is presented for realizing vertical-cavity laser (VCLís) based on an interband-resonant-tunneling-diode (I-RTD). The laser consists of InAs quantum well between two AlGaSb barriers and the spacer region adjacent to the collector. The Zener interband tunneling through the spacer region of this staggered- bandgap heterostructure creates conditions at large applied biases for charge flowing and radiation recombination in this unipolar device. We have studied the I-RTD as a potential new candidate for a mid-infrared laser. Model equations are derived in terms of material and structure parameters for predicting the output power in this laser device. As follows from the developed theory, gain can be obtained in the InAs/AlGaSb I-RTD. Since the I-RTD preserves the large optical matrix elements this gain is 40 times larger than that of conventional GaAs/AlGaAs quantum-well lasers. Simulation results suggest that the radiation output power in this I-RTD laser is also much larger than that obtained by multiquantum-well semiconductor lasers and can be achieved of the order of 5 mw for mA levels of interband current at room temperature operation.

6132-16, Session 5

The physics of coupled VCSEL arrays as generic cases of active photonic lattices

S. Riyopoulos, Science Applications International Corp.

An active photonic lattice is characterized by cross-cavity gain modulation (hole-burning) due to carrier depletion from adjacent cavity interactions. A VCSEL array offers a generic example for studying the physics of such, inherently nonlinear, active photonic lattices. The interplay between the non-linear frequency pulling, which allows phase locking over the array, and the coupling among the individual slow cavity oscillations, creates a rich behavior involving both steady-state and dynamic effects.

This talk will address:

a) steady-state behavior

— phase selection vs. coupling strength

— boundary layers

—array defects

—phase-lock tolerance to manufacturing (random or systematic) variations

—incoherently phase locked arrays and far-field diffusion

b) dynamic behavior

—stability of array eigenmodes and the effect of the line-width alpha factor

— propagation of stable “photonic sound” waves on arrays

— self-excitation of unstable array oscillations

—bifurcations to spatial and temporal chaos

— parametric phase selection / beam steering

Many of these effects would be easy to observe experimentally (eg: self-excited VCSEL array oscillations under constant bias, and confirming the instability threshold in the line-width alpha-factor)

6132-17, Session 5

Leaky defect modes of 2D VCSEL arrays

L. J. Mawst, L. Bao, N. Kim, A. P. Napartovich, Univ. of Wisconsin/Madison

No abstract available

6132-18, Session 5

VCSEL-based photonic crystal heterostructures

E. E. Kapon, École Polytechnique F´d´érale de Lausanne (Switzerland)

No abstract available

6132-19, Session 6

Coherent transverse coupling in photonic crystal vertical cavity laser arrays

J. T. Raftery, U.S. Military Academy of West Point; A. C. Lehman, K. D. Choquette, Univ. of Illinois at Urbana-Champaign

No abstract available

6132-20, Session 6

A C-shaped nanoaperture VCSEL for ultrahigh-density optical data storage

Z. Rao, J. A. Matteo, L. Hesselink, J. S. Harris, Stanford Univ.

Very Small Apertured Lasers provide a promising solution to realize ultrahigh-density near-field optical data storage. Vertical Cavity Surface Emitting Lasers (VCSEL) is an excellent candidate in this application because data transfer rate can also be greatly increased by using VCSEL in parallel arrays. We apply on VCSEL a unique C-shaped nano-aperture, which from simulation has three orders of magnitude higher transmission efficiency than a conventional square aperture producing the same near-field spot size. Our VCSEL structure is designed to operate around 972nm and consists of 38.5 pairs of n-DBR, three InGaAs/GaAsP quantum wells and only 9.5 pairs of p-DBR. The reflectivity of the top mirror is enhanced by depositing a 100nm Au film after conventional VCSEL processing. A nano-aperture is opened in the Au film by Focused Ion Beam etching. For a device with an 80nm C-shaped nano-aperture opened on a VCSEL with a 4um-diameter aluminum oxide aperture, we achieved a very low lasing

threshold current of 140uA and a maximum power of 43uW at 5.5mA. The power is collected with a 1cm^2 circular Silicon detector at 5mm away from the device. Under the assumption of uniform hemispherical radiation from the nano-aperture, the collection efficiency of our detection system is 33.7% and we estimate the maximum total power coming out of the nano-aperture to be 130uW. The near-field spot size of the 80nm C-shaped nano-aperture is 120nm at 20nm away by simulation. This indicates that itís very promising to obtain near-field intensity of over 10mW/um^2 to realize optical recording with our C-shaped nano-aperture VCSEL.

6132-21, Session 6

2W continuous wave operation of an optically pumped blue VECSEL with frequency doubling

T. Kim, K. Kim, J. Y. Kim, S. Lee, S. Cho, J. Kim, S. Lim, J. Lee, G. Kim, Y. Park, SAMSUNG Advanced Institute of Technology (South Korea)

We have achieved 2 W single transverse mode operation of a frequency doubled blue (~460nm) laser from an InGaAs based VECSEL (Vertical Cavity Surface Emitting Laser) chip. The maximum power of a 920 nm VECSEL is 4.5 W at a 20 W input power with a 94 % reflectance out coupler. A blue laser is achieved from an intra-cavity frequency doubling with an out coupler of 100 % reflectance at 920 nm and anti reflection at 460 nm. A 10 mm long LBO crystal is used as a frequency doubler. The conversion efficiency from 808 nm pump laser to blue laser is measured to be 10 %.

The VECSEL structure is consisted of 10 periods of resonant periodic gain (RPG) and a 35 pairs AlAs/Al0.2Ga0.8As distributed bragg reflector. Three In0.09Ga0.91As quantum wells are positioned at the each anti-node positions of the RPG. Tensile strained GaAsP layers are used to compensate the compressive stain caused by the quantum wells. When a GaAs layer is used as an absorption layer in the RPG, In0.09Ga0.91As quantum well is too shallow to allow recombination of all the carriers generated in the GaAs layer, even though the thickness of the GaAs layer is well within the carrier diffusion length. As a result, a GaAs recombination becomes dominant at a high injection level and the laser operation is difficult. We modify the RPG structure so that the GaAs recombination is minimized.

We will discuss the details of the optimization and characteristics of the VECSEL. We also will compare the frequency doubling efficiency with different doubling crystals.

6132-22, Poster Session

Temperature dependent VCSEL optical characteristics based on graded AlxGa1-xAs/ GaAs distributed Bragg reflectors: reflectivity and beam profile analyses

S. Su, Chung Cheng Institute of Technology (Taiwan); S. Tang, Chung Shan Institute of Science and Technology (Taiwan); T. Chen, Chung Cheng Institute of Technology (Taiwan); C. Chiang, S. Yang, Chung Shan Institute of Science and Technology (Taiwan)

In this article, the vertical cavity surface emitting laser (VCSEL) based on graded distributed Bragg reflectors (DBR) consisted of a top mirror of 20 pairs of AlxGa1-xAs/AlyGa1-yAs (x=0~0.9, y=0~0.12) quarter-wave stacks and a bottom mirror of 34 pairs of AlyGa1-yAs/AlxGa1-xAs quarter-wave stacks has been demonstrated. Compared with two proposed transfer matrix methods, the simulation of DBR reflectivity depending on temperature refractive index of AlxGa1-xAs and AlyGa1-yAs are discussed and proposed. The simulation results could be well predicted the DBR performance due to operation temperature variances, i.e., the varying reflectivity and full width half maximum (FWHM), wavelength band shifts of the laser reflector, using the multi-layer films evolution software of essential Macleod and modified transfer matrix method, respectively. In our simulation, assuming the specially physical conditions such as the linear grading DBR structure sandwiched with a n-type GaAs substrate and air films, we have systematically studied the temperature effects on the key parameters of top and bottom DBR. In contrast with the temperature dependent characteristics simulated using the above two transfer methods, the temperature varying spectra characteristics of VCSEL are agreed with the simulated results presented in this paper. Also the temperature dependent model of DBR based on refractive index of graded multi-AlxGa1-xAs/ AlyGa1-yAs has been proposed. So, a series of optoelectronic measurements experimentally confirm our simulated results again. The maximum reflectivity of the top and bottom DBRs are 96.4 and 99.9%. The central wavelengths of the bandwidth spectra in the top and bottom DBR are same. i.e., 840nm. These results can be provided the criteria for the high performance VCSEL design.

6132-23, Poster Session

Optimization of oxide-confinement and active layers for high-speed 850-nm VCSELs

Y. K. Kuo, J. Chen, National Changhua Univ. of Education (Taiwan); J. Ho, C. Wu, GigaComm Corp. (Taiwan); B. Pong, C. Chen, National Central Univ. (Taiwan)

High-performance multimode 850-nm vertical-cavity surface-emitting lasers (VCSELs) with oxide-confinement layers are developed for applications in low-cost high-bandwidth multimode fiber. In this work, the optical properties of the high-speed modulated 850-nm VCSELs with oxide-confinement layers, under various oxide-confinement structures and driving currents, are studied numerically by means of the commercial laser simulation software PICS3D (Photonic Integrated Circuit Simulator in 3D). Some of the simulated results are verified experimentally. Specifically, the laser performance and the characteristics of lateral modes and far field patterns at various driving currents are investigated. It is found that mode variation is strongly related to the thickness, position, and size of the oxide-confinement layer. Moreover, the calculated band structures, optical gain spectra, and transparency radiative current densities of unstrained GaAs/AlGaAs active layer structure, and compressively strained InGaAs/AlGaAs and InAlGaAs/AlGaAs active layer structures for 850-nm VCSELs are studied by solving the 8x8 k.p Luttinger-Kohn Hamiltonian. The results suggest that, among the three active layer structures under study, the strained InAlGaAs/AlGaAs active layer structure provides the highest material gain and differential gain, and the lowest transparency carrier concentration, which could be due to the large amount of strain available in the InAlGaAs/AlGaAs material system. Our simulated results also indicate that the peak gain of the InAlGaAs/AlGaAs active layer structure tends to saturate when the compressive strain is higher than approximately 1.1%. The laser performance of the 850-nm InAlGaAs/AlGaAs VCSELs with different compressive-strained active layer structures will be further investigated. Optimization of oxide-confinement and active layers for high-speed 850-nm VCSELs and experimental verification of the optimized laser structure will be attempted.

6132-24, Poster Session

Mode partition noise in 850 nm VCSELs

J. Carstens, Univ. of Nevada/Reno

It is well known that VCSELs mode partition noise (MPN) and polarization partition mode (PPN) can impair the performance of high-speed digital communication links. MPN and PPN can impair backplane optical interconnects links where 850 nm multitransverse VCSELs and multimode fiber are deployed. These phenomenons have not been previously characterized. In this paper we present a simple and practical way to evaluate the power penalty due to MPN and PPN and we also experimentally measure the k factor for different VCSELs. To the best of our knowledge the k factor for VCSELs never been measured.

Conference 6133: Novel In-Plane Semiconductor Lasers V

Monday-Thursday 23-26 January 2006

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6133-01, Session 1

Room-temperature continuous-wave single-mode quantum cascade lasers

S. Blaser, L. Hvozdara, Y. Bonetti, A. Netuschill, A. Muller, Alpes Lasers SA (Switzerland); M. Giovannini, J. Faist, Univ. de Neuchâtel (Switzerland)

High-resolution spectroscopy requires tunable single-frequency light sources with very narrow linewidth (< 3.5 MHz); this can be achieved using quantum-cascade (QC) distributed-feedback (DFB) lasers operating in continuous-wave (CW) mode, which are already commercialized as cryogenic devices available from 4.3 to 10 um, but having the disadvantage of increased cooling and size.

Alpes Lasers aims at producing commercial CW QC lasers operating on thermo-electrical cooler (TEC). In this domain, we report realization of single-frequency QC lasers in CW mode on TEC at frequencies of ~ 1830 cm-1 (~ 5.46 um) and ~ 1885 cm-1 (~ 5.3 um). The active region of the lasers is based on the bound-to-continuum concept, which allows for generation of broad gain.

We report a 1.5mm-long, 18um-wide CW DFB QC laser exhibiting single-mode emission over the entire investigated temperature and current ranges with a side-mode suppression ratio > 25 dB. Output power up to 55mW at -30°C, 22mW at 0°C and 1mw at 27°C are demonstrated. A tuning range of 12cm-1 (0.68%) can be obtained between 1823 and 1835 cm-1.

An other device, 1.5mm-long, 16um-wide, is reported in the range 1883-1887 cm-1, exhibiting output power of 6.5mW at -33°C and 0.5mW at -17°C (maximal operating temperature). Development of these devices is dedicated to obtain RT-CW QC lasers at 1900cm-1, an important issue in NO (nitric oxide) measurements.

6133-02, Session 1

Recent research development of InAs-based quantum cascade lasers

H. Ohno, K. Ohtani, Tohoku Univ. (Japan)

InAs-based quantum cascade lasers (QCLs) are one of the good candidates for high-performance long-wavelength semiconductor lasera[1,2]. Its high conduction-band offset energy of 2.1eV offers widely tunable intersubband emission energies. A large optical gain is expected due to an increased optical dipole matrix element and a small nonradiative relaxation rate. Here we report our recent experimental results on InAs-based QCLs containing InAs/AlGaSb quantum well and superlattice (SL) active structures.

All the laser samples are grown on n-InAs (100) substrate by solid-source molecular beam epitaxy. In order to decrease the lattice mismatch between the InAs substrate and the active region, AlAs interface bonds are adopted at each interface by controlling the shutter sequence. An InAs double plasmon waveguide is used for the optical confinement. The active region contains the 20-50 repeated active/injection layers. Typical total thickness of the grown structures is 6-14μm.

The completed InAs-based QCLs operate at the 4-14 μm wavelength range. The laser emission wavelength is in close agreement with the designed wavelength. The observed lowest threshold current density at 80 K is 0.42 kA/cm2 by using the 50-repeated SL active structures operating at 10 μm. This is among the lowest threshold current density of QCLs operating at the mid-infrared region. The present maximum operation temperature in pulsed regime is 305 K and the room-temperature threshold current density is 12 kA/cm2. The operating temperature is limited by the insufficient heat dissipation of our sample coming partly from the low thermal conductivity of InAs compared to that of GaAs and InP.

1 H. Ohno, L. Esaki and E. E. Mendez, Appl. Phys. Lett. 60, 3153 (1992) 2 K. Ohtani and H. Ohno, Appl. Phys. Lett. 82, 1003 (2003)

6133-03, Session 1

High-performance GaInAs/AlAsSb and GaInAs/AlGaAsSb quantum cascade lasers

Q. Yang, C. Manz, W. Bronner, C. Mann, L. Kirste, K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

High-temperature (Tmax ≥ 400 K) pulsed-mode operation of quantum cascade (QC) lasers based on the GaInAs/AlAsSb and GaInAs/AlGaAsSb material systems has been demonstrated[1,2], and will be detailed on in this contribution. The emission wavelengths of the present QC lasers are in the l < 5 μm wavelength range.

The motivation for using the GaInAs/AlAsSb material system to fabricate QC lasers in the short wavelength range (l < 5 μm) comes from the high conduction-band offset of 1.6 eV (G-valley) between the quantum well and the barrier. Further, the GaInAs/AlAsSb material system is lattice-matched to InP substrates and is compatible with InP waveguide technology.

We have used 25 stages of active/injection regions based on a triple-quantum-well, vertical-transition design for our QC lasers, and have achieved the first above room-temperature (up to at least 400 K) operation of QC lasers in the GaInAs/AlAsSb material system[1]. The emission wavelength of the QC lasers is l~4.5 μm at room temperature, and the characteristic temperature T0 of the threshold current density in pulsed mode is 171 K in the temperature range between 280 K and 400 K. For a typical device with the size of 18 μm - 2.8 mm mounted substrate-side down with as-cleaved facets, a maximum peak power per facet of 750 mW has been achieved at room temperature.

In order to further improve the performance of the QC lasers by enhancing the tunneling probability of electrons through the active and injection regions, we have introduced quaternary AlGaAsSb instead of ternary AlAsSb barrier layers in the QC lasers to reduce the barrier height to approximately 1 eV. QC lasers based on GaInAs/AlGaAsSb heterostructures could be operated up to T \> 400 K (Tmax extrapolated to be around 450 K)[2]. For a typical device with the size of 14 μm ¥ 1.5 mm mounted substrate-side down with as-cleaved facets, a maximum peak power per facet of 190 mW has been achieved at 400 K, which is the maximum heat sink temperature in our experimental setup.

By placing a 2.5-μm-thick gold layer on both sides of the laser ridge and mounting the device epilayer-down to extract heat from the active region in the lateral direction, we have also achieved the first continuous-wave (CW) operation of GaInAs/AlGaAsSb QC lasers with Tmax = 94 K.

References:

1. Q. Yang et al., Appl. Phys. Lett. 86, 131107 (2005).
2. Q. Yang et al., Appl. Phys. Lett. 86, 131109 (2005).

6133-04, Session 1

InP based QCL in MBE production machine

M. Garcia, F. Vermersch, X. Marcadet, S. Bansropun, C. Sirtori, Thales Research & Technology (France); A. Wilk, C. Chaix, RIBER (France)

Since the first demonstration of Quantum Cascade laser (QCL) emitting in the mid-infrared spectral range, this type of semiconductor lasers has demonstrated huge potential thanks to its wide emission range, high operating temperature and high power output. Chemical detection, spec-

troscopy, infrared optical counter measures and free space communications are among a few examples of their area of applications. In this paper, we report the realization of lasers emitting between 5μm and 9μm. The growth has been carried out in a multiwafer Riber 49 MBE production system (13x2" platen) equipped with arsenic and phosphorus valved cracker cells. All layers were grown on n doped InP substrate in a single growth step. While the 9 μm laser was based on a 4-quantum well structure, the strain balanced 5.4 μm laser was designed on a 3-quantum wells structure. Laser wafers were processed based on a double-channel ridge waveguide using Inductively Coupled Plasma (ICP) etching system to ensure reproducibility and homogeneity over 2 inches wafer. For characterization purposes, the chips were Indium bonded epilayer-side up on a copper submount. 22μm wide and 2mm long cavities have been defined and characterized under pulsed operation (5kHz, 100ns), at room temperature. At 9μm, the lasers exhibited an optical peak power of 380mW. The threshold current density was measured at 4.2kA/cm≤ with a slope efficiency of 170mW/A. For the 5.4μm QCL, laser action has been achieved with a threshold current density of 4.3kA/cm≤. These results represent the state of the art in QCL using standard processing. Better performances are expected with optimized device fabrication.

6133-05, Session 1

Quantum cascade lasers by MOCVD

G. E. Hofler, D. P. Bour, S. W. Corzine, Agilent Technologies; M. Troccoli, F. Capasso, Harvard Univ.

No abstract available

6133-06, Session 2

High-power and wide wavelength range GaN-based laser diodes

T. Kozaki, H. Matsumura, Y. Sugimoto, S. Nagahama, T. Mukai, Nichia Corp. (Japan)

No abstract available

6133-07, Session 2

Near- and deep-UV InAlGaN MQW lasers

M. Kneissl, Palo Alto Research Ctr.

No abstract available

6133-08, Session 2

Nitride laser diodes

S. Tomiya, Sony Corp. (Japan)

No abstract available

6133-09, Session 3

Mid-IR type-II "W" lasers emitting high-Cw powers

J. R. Meyer, Naval Research Lab.

No abstract available

6133-11, Session 3

External-cavity tunable mid-IR semiconductor lasers and applications

C. Peng, H. Q. Le, Y. Wang, G. Luo, H. Zhang, Y. Wang, B. Guo, Univ. of Houston

No abstract available

6133-12, Session 4

Highly reliable 75W InGaAs/AlGaAs laser bars with over 70% conversion efficiency

G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

There is an increasing demand on power, brightness and reliability of diode lasers. One of the most important issues, which pushes the limits up, is the wall plug efficiency. A high wall plug efficiency results in a lower internal operating temperature and therefore reduces the impact of heating on index profile, defect mobility and differential efficiency. Additionally a high wall plug efficiency will enable the use of powerful light sources in mobile systems.

Actually high power diode lasers at 9xx nm are of great importance for pumping disk and fibre lasers and medical applications. The contribution will focus on this wavelength range including a little outlook at very promising designs at slightly longer wavelength.

Optimising the wall plug efficiency has taken several, partly detrimental requirements into account and has to include the desired goal of output power. Results are given from laser structures with a relatively low vertical divergence of about 45∞ including 95% of optical power based on the well established InGaAs/AlGaAs material. 940nm laser bars were processed and mounted on passively cooled heat sinks. We achieved a wall plug efficiency over 70% for diode laser bars at 75W output power. 150μm stripe lasers with only 1500μm resonator length mounted on usual C-mounts have a thermal rollover of about 18W, which is a record high value for a resonator length below 2mm. Reliability tests show an excellent stability at 75-80W in CW and 95W in long pulse operation mode over more than 6000h test time up to now.

6133-13, Session 4

Optical system integration of very large arrays of individually addressable, high-power, single-mode lasers

S. P. Najda, G. Bacchin, A. Kendall, S. Wilson, M. Murad, E. Goutain, C. J. Hamilton, J. H. Marsh, Intense Photonics Ltd. (United Kingdom)

Very large arrays (up to 100 elements) of high power (up to 300mW), single mode, individually addressable lasers in the 800-1000nm wavelength range with exceptional parametric uniformity are fabricated using a quantum well intermixing (QWI) process to create passive non-absorbing mirrors (NAMs). The NAM regions dramatically improve the catastrophic optical damage (COD) power of the device. An additional benefit of the NAM regions is that much of the randomness in the various fabrication processes can be significantly reduced removing many of killer defects that are associated with conventional laser manufacture. Lifetime analysis reveals that the MTTF rate for a large element array is similar to a single element Telecordia standard laser and that the main failure mechanism is identical for a single laser compared to a multi-element array with no neighbouring interacting effects.

For exceptional laser array parametric uniformity and reliability to be realized at system level, packaging issues have to be considered otherwise thermal, optical and electrical cross-talk issues can give rise to significant non-uniformities and reliability issues. Integration of a large element laser chip incorporated into a small form-factor, cost-effective optical system is described.

6133-14, Session 4

High-efficient 650 nm laser bars with an output power of about 10 W and a wall-plug efficiency of 30%

B. Sumpf, M. Zorn, R. Staske, J. Fricke, P. Ressel, G. Erbert, M. Weyers, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

High-power red-emitting laser diodes are requested light sources for the pumping of Cr:LiSAF/Cr:LiCAF solid-state lasers, laser display technology, and for photodynamic therapy. Up to now, these devices suffer from wall-plug efficiencies of only 15%.

In this paper, results for 650 nm high-power broad area lasers and bars will be presented. The optimized layer structure consists of GaInP double quantum wells embedded in AlGaInP waveguide layers. The n-cladding layer consists of AlGaInP, the p-cladding layer of AlGaAs. The vertical far field of this structure has a width below 32∞ (FWHM). The characteristic temperature of the threshold current T0 is 70 K, the internal efficiency hI [a] 0.8, the internal losses are below 2 cm-1, and the transparency current density is 360 A/cm2.

Devices were fabricated in a standard process and mounted p-side down on CuW heat spreader using AuSn solder. These subassemblies were mounted on copper heat sinks (C-mount or bar heat sink).

Broad area lasers with the dimension of 100 μm x 750 μm reach at 15∞C a maximum output power of 940 mW limited by thermal roll-over. At T = 0∞C up to 1.26 W were measured without COD. The spectral width of the emission is below 1 nm (FWHM). The devices have an expected MTTF of more than 11000 h at 400 mW and 15∞C.

Bars consisting of 19 emitters with 30 μm x 750 μm reached a maximum output power of 9.6 W and a wall-plug efficiency of 30%. 1000 h operation at 4 W was demonstrated.

6133-15, Session 4

High-power, high-brightness tapered lasers with an Al-free active region at 915 nm

N. Michel, I. Hassiaoui, M. Lecomte, O. Parillaud, M. Calligaro, M. M. Krakowski, Thales Research & Technology (France); I. Esquivias, L. Borruel, Univ. Politécnica de Madrid (Spain); S. Sujecki, E. C. Larkins, The Univ. of Nottingham (United Kingdom)

High-power and high-brightness tapered lasers at 915 and 975 nm are used as pump sources for Er, Yb and Er/Yb solid-state and fiber lasers. Narrow beam divergences in the slow axis are also required for the collective coupling of tapered bars. We present our first index-guided, narrow-aperture tapered lasers at 915 nm, based on an aluminium-free active region for improved reliability. On this structure, we have obtained very low optical losses of 0.5 cm-1, and a very low threshold current density of 88 A/cm2, and a high internal efficiency of 86%. Based on these good results, we have realized tapered lasers with a narrow angle of less than 1∞Z (IG1 lasers). They deliver 1W at 1.5A CW, with an M2 beam quality factor of less than 3.5 at 1/e2, a divergence angle in the slow axis of 6.0∞ FWHM and 10.2∞ at 1/e2, and a nearly Gaussian shape. We have also fabricated Clarinet lasers, which were recently proposed to reduce the divergence angle in the slow axis. Clarinet lasers have a shorter tapered section and a larger taper angle of 2∞. They deliver 0.65 W at 1 A CW, with an M2 of 1.3 at 1/e2. Their divergence at 0.65W is only 2.6∞ FWHM and 4.8∞ at 1/e2, with a Gaussian shape. In order to asses the feasibility of tapered lasers minibars, we have also realized small arrays of 6 IG1 tapered lasers, which deliver more than 4W CW, with a divergence of 6.2∞ FWHM and 11.2∞ at 1/e2.

6133-16, Session 4

High-power broad-area 808 nm DFB lasers for pumping solid state lasers

A. Klehr, F. Bugge, G. Erbert, A. Knauer, P. Ressel, H. Wenzel, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

Diode lasers with a small line width, stable lasing frequency and high output power are of particular interest for applications as pump sources for advanced solid state lasers, for second harmonic generation and measuring techniques (3D pattern projection). For these applications, Watt-range cw power and narrow spectral width, below 0.2nm full width half maximum, are required. A spectral narrowing emission can be achieved by external or internal measures. Diode lasers with internal Bragg reflector need no additional expensive parts and external adjustment.

We present experimental results on high power broad area distributed feedback lasers emitting in the wavelength range of 808 nm. An output power of more than 4.4 W at 20 ∞C with a differential quantum efficiency of 1 W/A is achieved with BA-DFB lasers having a stripe width of 100 μm and a cavity length of 3000 μm. The emission has a small spectral width of < 0.2 nm up to this high output power. A mapping of the spectra shows a spectral tuning with current of 0.4 pm/mA. The measured lateral far field angle is about 8∞ at 2.5 W and the vertical far field angle is around 26∞.

The application of the fabrication technique on other wavelength will be also presented.

These lasers are ideally suited for the above mentioned applications because of ease of handling, compactness and high yield.

6133-17, Session 5

Passively mode-locked quantum dot lasers for optical clocking

L. F. Lester, Univ. of New Mexico

No abstract available

6133-18, Session 5

Carrier lifetime and recombination in 1.3 μm P-doped InAs qauntum dot lasers

A. A. Dikshit, J. M. Pikal, V. V. Vangapally, Univ. of Wyoming

In this talk we report on carrier lifetime measurements performed on 1.3 μm p-doped InAs quantum-dot lasers. The carrier lifetimes were determined by fitting the measured sub-threshold optical modulation response to a single pole response function, and then correcting this time constant for the diode junction capacitance to obtain the carrier lifetime. The sub-threshold frequency response curves did indeed show a single pole behavior at all the bias currents and, as expected, the extracted carrier lifetimes monotonically decrease with increasing bias currents. The differential carrier lifetime versus bias current data was then fitted, using a simple single carrier level rate equation analysis, to determine the recombination coefficients. Using this simplified analysis, the values of the recombination coefficients are found to be: A = 1.0 x 107 /s, B = 2.5 x 10-11 cm3/s, and C = 1.1 x 10-29 cm6/s at room temperature. The dominant contribution to threshold is Auger recombination which accounts for 78 % of the threshold current. This is consistent with other reports despite the very different measurement technique used here. Since, the carriers are distributed among the dots in a complicated manner that depends on bias, the lifetimes and recombination coefficients extracted using the single carrier level analysis are the effective or average values. Thus we have also built a multi-level rate equation model and a more complicated master equation of microstates model. These models include the capture and escape times between various QD and wetting layer states and their results will also be discussed.

6133-19, Session 5

Achieving narrow linewidth, low-phase noise external cavity semiconductor lasers through the reduction of 1/f noise.

R. E. Bartolo, C. K. Kirkendall, Naval Research Lab.; V. Kupershmidt, K2 Optronics, Inc.

The presence of laser phase noise (or frequency jitter) limits the resolution of a variety of interferometric sensors ranging from fiber optic acoustic sensors to gravitational wave detectors. At low frequencies, 0 to 100 kHz, the laser phase noise in semiconductor and diode pumped solid-state lasers is dominated by 1/f noise, the source of which is not well understood. We report on phase noise measurements for external cavity semiconductor lasers (ECSLs) utilizing a fiber Bragg grating in a compact butterfly package design produced by K2 Optronics. The results show that the phase noise is dominated by 1/f noise for low frequencies (10 to 100 kHz) transitioning to a white noise due to spontaneous emission for f > 100 kHz. We observed a factor of 40 improvement in the magnitude of the 1/f phase noise as compared to previously published results for a Hitachi HLP 1400 830 nm diode laser. The magnitude of the low frequency phase noise ranges from 100 to 10 microradians per meter per root Hz for frequencies ranging from 10 Hz to 2 kHz. These results are within a factor of 10 for phase noise measurements of the more expensive Lightwave Electronics Nd:YAG laser and a variety of Er-doped fiber lasers in this frequency range. For nominally similar ECSLs, experimental results indicate that the phase noise increases for lasers with larger leakage currents. Linewidth measurement results showed a Schalow-Townes inverse power dependence for output powers up to 31 mWatts with the observed onset of a linewidth floor of 44 kHz. The RIN of the ECSLs varied from -120 to -155 dB Vrms per root Hz for frequencies ranging from 10 to 500 kHz. These RIN results are roughly equal to those observed for the Nd:YAG laser for frequencies less that 100 kHz. In summary, such low phase noise and RIN results make such ECSLs suitable for all but the most sensitive fiber optic sensing applications where the frequency range of interest is below 1 MHz.

6133-20, Session 5

Measurement of gain and dispersion curves in GaInAsP multiple quantum well semiconductor lasers utilizing transfer matrix method

P. Bovas, A. Bhattacharya, R. K. Sinha, Delhi College of Engineering (India)

The gain spectrum measurement is an important tool for the optimization and characterization of MQWs semiconductor lasers. A number of different methods for the determination of the net gain spectrum have been proposed in the literature. For e.g. in conventional Fabry-PÈrot semiconductor lasers, the amplified spontaneous emission modulated by the laser cavity is usually used for measuring the gain spectrum by the Hakki-Paoli (HP) method. The HP method derives the gain from the modulation depth of the amplified spontaneous emission (ASE) spectrum and is sensitive to the resolution of the measurement system.

As a modification of the HP method, Cassidy proposed to use the ratio of the average mode intensity to the corresponding minimum intensity instead of the maximum-minimum intensity ratio to obtain the gain spectrum. Cassidyís method decreases the sensitivity on the resolution and can measure the gain spectrum even as the laser approaches threshold. Recently, the Fourier transform (FT) method was proposed, which behaves as an integral scheme instead of using local properties of the ASE spectrum to derive the gain.

In this paper, we aim to present a novel method for the measurement of semiconductor laser gain spectra and dispersion curves. The proposed technique is based on an analysis of the sub threshold emission spectrum by TMM. Applications of this method to Al free GaInAsP-InP-based interband laser diodes are discussed. A good agreement between the measured dispersion of the refractive index and tabulated values in the literature was found.

6133-21, Session 6

Terahertz quantum cascade lasers

A. Tredicucci, Scuola Normale Superiore di Pisa (Italy)

No abstract available

6133-22, Session 6

Non-equilibrium electronic distribution in THz quantum cascade lasers

M. S. Vitiello, V. Spagnolo, G. Scarmarcio, Univ. degli Studi di Bari (Italy)

No abstract available

6133-23, Session 6

THz generation and mixing in quantum cascade lasers

C. Sirtori, Univ. Paris 7-Denis Diderot (France) and Thales Group (France)

No abstract available

6133-24, Session 6

Phase matched frequency mixing between telecom wavelengths and THz radiation in a quantum cascade laser

S. S. Dhillon, Thales Research & Technology (France) and Univ. Paris 7-Denis Diderot (France); C. Sirtori, Thales Research & Technology (France); S. Barbieri, TeraView Ltd (United Kingdom); J. Alton, TeraView Ltd. (United Kingdom); A. De Rossi, M. Calligaro, Thales Research & Technology (France); H. E. Beere, D. A. Ritchie, Univ. of Cambridge (United Kingdom)

Owing to its large second-order susceptibility, GaAs is an interesting material for non-linear optical generation. The lack of birefringence on the other hand makes phase matching difficult to realize, therefore limiting the non-linear conversion efficiency. However, owing to the anomalous dispersion produced by the restrahlenband, the refractive index at long wavelengths (the far-infrared or terahertz (THz) range) is larger than that in the mid- and most of the near infrared (NIR). This opens up the possibility of a ëpolaritonicí phase matching between the THz range and the NIR.

In this investigation a GaAs-based QCL operating at 104μm (f=2.9THz) is used both as a THz source and a non-linear medium. A low power (~5mW) NIR tunable diode laser, operating around 1300nm, is coupled into the THz QCL. The generated intra-cavity side-bands are clearly observed at the difference and sum frequency of the THz and NIR radiation. The phase matching condition was verified by tuning the NIR wavelength between 1260nm and 1340nm and showed a phase matched point at 1305nm. The possibility of shifting this phase matching point towards 1550nm will also be demonstrated by using modal engineering of the THz guide.

These results illustrate the possibility of detecting the THz radiation using a up-conversion process of a low power NIR laser and to transport the THz radiation on an optical carrier.

6133-25, Session 7

High-performance AlInGaN blue-violet laser diodes

O. Nam, SAMSUNG Advanced Institute of Technology (South Korea)

High performance and high efficiency AlInGaN laser diodes with 405 nm were fabricated for the post-DVD applications. InGaN underlying layer was used to improve the crystal quality and efficiency of InGaN multiple quantum wells. Magnesium doped AlGaN/GaN multiple quantum barrier (MQB) layers were also introduced into the laser diode structure, which resulted in considerable improvement in lasing performances such as threshold current and slope efficiency.

High catastrophic optical damage (COD) level must be guaranteed, because the output power over 100mW is needed for dual layer recording in blu-ray system. Asymmetric waveguide structure was used in order to improve the characteristics of laser diodes. Aluminium content in the n-cladding layer was varied in connection with the vertical beam divergence angle and COD level. By decreasing Al content in the n-cladding layer, the vertical divergence angle was reduced to 17 degree and the COD level was enhanced to over 300mW. A high COD level could be obtained by reducing the optical power density at the laser facet.

The results suggest that our laser diodes are suitable as light sources for the post-DVD system.

Detailed experimental results will be presented and discussed at the conference.

6133-26, Session 7

Characteristics of CW violet laser diodes grown by MBE

J. F. Heffernan, M. Kauer, S. E. Hooper, V. Bousquet, J. Windle, T. Smeeton, C. Zellweger, J. Barnes, Sharp Labs. of Europe, Ltd. (United Kingdom)

It has taken MBE ten years to catch up with MOCVD in the demonstration of nitride violet laser diodes. In 2004, the present authors reported the first MBE-grown nitride laser diodes which were fabricated on GaN template (sapphire) substrates. These devices had a high threshold current density of 30kAcm-2 and required pulsed current injection at room temperature to exhibit laser action. Nevertheless it was the first demonstration that there were no intrinsic limits to demonstrating laser action by MBE in these materials. In mid-2005 the authors followed up this success with the demonstration of room temperature CW operation. This was achieved by reducing the threshold current density to 5.6kAcm-2, and by gaining significant processing and thermal management improvements by growing on free-standing GaN substrates. In this paper we report on the characteristics of these MBE-grown nitride lasers and assess the potential of MBE as a growth technique compared to MOCVD. We will report on ongoing efforts to reduce power dissipation (threshold current and voltage) in the devices and the impact on device lifetime. We will also report on work to understand the microscopic nature of device degradation. Continued development of these devices places more and more demand on the growth technique and achieving commercially significant lifetimes of several thousand hours is a strong test of the viability of MBE for nitride optoelectronics.

6133-27, Session 7

Characteristics of intensity noise in blue-violet InGaN semiconductor lasers

K. Matsuoka, K. Saeki, E. Teraoka, Y. Kuwamura, M. Yamada, Kanazawa Univ. (Japan)

InGaN semiconductor lasers are utilized as light sources in optical disc systems having larger storage capacity. Noise level in these systems is required to be lower than -125dB/Hz as RIN(Relative Intensity Noise).

We determined the quantum noise level by setting to be free from the optical feedback, and found that RIN exceeds -122dB/Hz for operation with 1.5mW as the output power. This value was almost 10dB/Hz higher than that of near-infrared AlGaAs laser. Since the RIN increases inversely with triple power of the photon number just above the threshold level, a laser operating with the shorter wave-length must reveal the higher noise than that in longer wave-length when both lasers are operated with same lasing powers. The result told us that blue-violet can not reduce the operating power due to limit of the quantum noise.

We also determined the feedback induced noise under operation with optical injection of the reflected light from an external reflecting mirror. The RIN reached to -90dB/Hz as the worst case. We also confirmed two types of the generating mechanism of the feedback induced noise. One type was due to mode competition phenomena among the internal modes of the laser cavity, which revealed the higher noise in the lower frequency range. Another type was generated by the mode competition among the external modes built by the space between the laser facet and the reflecting point, which revealed almost flat dispersion on the noise frequency spectrum from DC to 100MHz.

6133-28, Session 7

Broad-area, high-power, CW operated InGaN laser diodes

P. Perlin, Instytut Wysokich Cisnien (Poland) and TopGaN Ltd. (Poland); P. Wisniewski, R. Czernecki, P. Prystawko, M. Leszczynski, T. Suski, I. Grzegory, S. A. Porowski, Instytut Wysokich Cisnien (Poland)

One of the important future application of blue nitride laser diodes is to become a source of high intensity blue light in the projection TV sets. In order to fulfill this role, such a laser should have an optical output power at the range of 1 W. To construct such a device we need to use a broad area (wide stripe), low dislocation density laser. Even in nitrides devices, characterized by high resistance to catastrophic optical damage (40-50 MW/cm2) a narrow stripe laser design would prevent from reaching that high output power. We would like to demonstrate here the performance of 1000 um x 20 um laser diode fabricated on top of the low dislocation density bulk GaN substrate (grown under high nitrogen pressure). The devices were mounted in the p-down configuration on Au/Sn eutectic covered diamond heat spreaders. Whole system was then sited on the thermoelectric cooler assembly. These lasers were able to operate at currents up to 1. 8 A while emitting above 25 mW of light at 410 nm. That means that it was possible to successfully dissipate more than 10 W of the heat. The lifetimes of these devices reach 100 hour under CW operation. We believe that with the further improvement of the mounting technology these devices will be able to provide 1 W of output light for current not exceeding 1.5 A.

6133-29, Session 8

Advances in quantum dot lasers and single photon emitters

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

No abstract available

6133-30, Session 8

1.3-1.5 μm quantum dot lasers on foreign substrates: growth using defect reduction technique, high-power CW operation, and degradation resistance

N. Ledentsov, V. A. Shchukin, NL Nanosemiconductor GmbH (Germany) and Technical Univ. of Berlin (Germany) and A.F. Ioffe Physico-Technical Institute (Russia); A. R. Kovsh, A. V. Kozhukhov, I. L. Krestnikov, S. S. Mikhrin, C. Mˆller, NL Nanosemiconductor GmbH (Germany); L. Y. Karachinsky, N. Y. Gordeev, I. I. Novikov, M. V. Maximov, Y. M. Shernyakov, N. V. Kryzhanovskaya, A. E. Zhukov, E. S. Semenova, A. P. Vasil'ev, V. M. Ustinov, A.F. Ioffe Physico-Technical Institute (Russia); T. Kettler, D. Bimberg, Technical Univ. of Berlin (Germany)

No abstract available

6133-31, Session 8

Characterisation of modulation doped quantum dot lasers

P. M. Smowton, I. C. Sandall, C. L. Walker, J. D. Thomson, A. Sobiesierski, Cardiff Univ. (United Kingdom); T. Badcock, D. J. Mowbray, H. Liu, M. Hopkinson, The Univ. of Sheffield (United Kingdom)

Self-assembled In(Ga)As quantum dot (QD) lasers incorporating p-type modulation doping have generated much interest recently due to reports of a temperature insensitive threshold current and increased modulation bandwidth. The mechanism by which p-type doping improves the performance of QD lasers is thought to be similar to that envisaged for quantum well lasers, where increased gain is expected for a given quasi-Fermi level separation due to a shift in both quasi-Fermi levels towards the valence states. However, the benefits may be much more pronounced in quantum dot structures since the population of the smaller number of dot states can be dramatically affected using relatively low doping levels, which may incur less penalty with regard to increased non-radiative recombination and internal optical mode loss.

We present results of direct measurements of the modal gain measured as a function of the quasi-Fermi level separation for samples with different degrees of doping, which demonstrate unambiguously the increased gain that can be obtained at a fixed quasi-Fermi level separation. In addition, we have measured the internal optical mode loss and radiative and non-radiative recombination currents for samples containing 0, 15 and 50 dopant atoms per dot and show that, although the internal optical mode loss is similar for all three samples, the non-radiative recombination current increases for samples containing p-doping. We show that our experimental results are consistent with a simple computer simulation of the operation of our structures.

6133-32, Session 8

High-performance 1.3μm quantum dot lasers on GaAs and Si

P. K. Bhattacharya, Z. Mi, J. Yang, S. Fathpour, Univ. of Michigan

Since the first demonstration of 1.3 μm quantum dot (QD) lasers[1], many groups have reported the characteristics of these devices. However, the achievement of large modulation bandwidths (>10 GHz), accompanied by low chirp and α-parameter, has been elusive. A small-signal modulation bandwidth of 12 GHz was recently reported for an InGaAs QD laser in which the quantum dots were grown on an InGaP buffer layer[2]. However, no data on chirp and α-parameter were reported by these authors. In order to extract enhanced performance from these devices, it is first important to understand some fundamental limitation arising from the unique hot carrier dynamics in quantum dots.

Tunnel injection has been used very effectively in suppressing hot-carrier related problems in quantum well lasers and in achieving high speed modulation of 1 μm QD lasers[3]. In this technique cold carriers (electrons) are injected by tunneling in the QD lasing states and so they do not heat other carriers or phonons as much, resulting in reduced carrier leakage from the active region and recombination in the cladding layers. As a result, the characteristic temperature T0 is enhanced and the differential gain dg/dn increases substantially, leading to enhanced modulation bandwidth (24.5 GHz in 1.1 μm QD lasers) and reduced threshold current. The technique of acceptor (p) doping of the quantum dots has also been proposed as a means of improving QD laser performance[4,5]. Acceptor doping ensures that the hole ground states are filled, thereby substantially increasing the gain and also the differential gain by a small amount. In this letter we report the small signal modulation characteristics of high-performance near single mode InAs quantum dot lasers in which tunnel injection and p-doping are both incorporated. The lasers are characterized by Jth=180 A/cm2, T0=∞, dg/dn≈1×10-14 cm2, f-3dB =11 GHz, chirp of 0.1 ≈ and zero α-parameter.

Future high-speed systems will, in all probability, require the monolithic integration of electronic circuits and optoelectronic components on silicon substrates. An urgent need in such technology is the development of high performance and reliable electrically-injected light sources that can be integrated on silicon in a CMOS-compatible process. We have investigated the molecular beam epitaxial growth and characteristics of room-temperature InGaAs quantum dot lasers grown directly on silicon utilizing thin (≤ 2 μm) GaAs buffer layers and quantum dot layers as dislocation filters. The best lasers are characterized by relatively low threshold current (Jth ~ 900 A/cm2), high output power (> 150 mW), large characteristic temperature (T0 = 244 K) and constant output slope efficiency (≥ 0.3 W/A) in the temperature range of 5 to 95 oC. The emission wavelength of these lasers is around 1.0 μm. We are currently investigating the growth and characteristics of 1.3 μm QD lasers on Si. The performance characteristics and reliability of these devices will also be presented.

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6133-33, Session 9

Silicon and germanium-silicon raman lasers

B. Jalali, V. Raghunathan, D. P. Dimitropoulos, O. Boyraz, R. Claps, Univ. of California/Los Angeles

Silicon-on-Insulator integrated optics has attracted considerable attention recently as a viable technology for realizing low-cost, high speed and high density optical devices. Much of the research effort is focused on active optical functionalities in Silicon structures. In particular, the Stimulated Raman scattering process holds the potential for realizing amplification, light generation and wavelength conversion in chip-scale devices. This is evident from the recent demonstrations of pulsed and continuous wave Raman lasers with electronic modulation capabilities and high gain Raman amplifiers. In addition to this, Germanium-Silicon waveguiding structures have been proposed as flexible Raman media to tune the Raman shift and bandwidth. A pulsed Germanium-Silicon Raman laser has also been demonstrated. This paper reviews some of the recent research efforts in realizing Silicon and Germanium-Silicon Raman lasers. Some exciting applications of these lasers are also discussed.

6133-34, Session 9

Heterogeneous integration of silicon and AlGaInAs for a silicon evanescent laser

A. Fang, H. Park, Univ. of California/Santa Barbara; R. Jones, Intel Corp.; O. Cohen, Intel Corp. (Israel); M. J. Paniccia, Intel Corp.; J. E. Bowers, Univ. of California/Santa Barbara

We report a novel laser architecture, the silicon evanescent laser (SEL), that utilizes a silicon waveguide and offset AlGaInAs quantum wells. The silicon waveguide is fabricated on a Silicon-On-Insulator (SOI) wafer using a CMOS-compatible process, and is bonded with the AlGaInAs quantum well structure using low temperature O2 plasma-assisted wafer bonding. The optical mode in the SEL is predominantly confined in the passive silicon waveguide and evanescently couples into the III-V active region providing optical gain. This approach combines the advantages of high gain III-V materials and the integration capability of silicon technology. Moreover, the difficulty of coupling an external laser source is overcome as the hybrid waveguide can be self-aligned to silicon-based passive optical devices. The SEL lases cw at 1551 nm with a threshold of 53 mW. The maximum single-sided fiber-coupled cw output power is 3.2 mW

with a slope efficiency of 6 %. The SEL characteristics are dependent on the silicon waveguide dimensions resulting in different confinement factors in the III-V gain region. The characteristics of several devices fabricated with different waveguide dimensions will be presented and compared in the talk.

6133-35, Session 10

Nonlinear quantum cascade lasers

C. F. Gmachl, Princeton Univ.

No abstract available

6133-36, Session 10

Intra-cavity raman lasing by electrical injection in quantum cascade devices

M. Troccoli, Harvard Univ.

No abstract available

6133-37, Session 10

Performance limits of nonlinear quantum cascade lasers

A. A. Belyanin, F. Xie, Texas A&M Univ.; F. Capasso, Harvard Univ.; C. F. Gmachl, Princeton Univ.; O. Malis, Lucent Technologies/Bell Labs.

No abstract available

6133-38, Session 11

Folded cavity resonant filters and modulators

K. Djordjev, C. Lin, M. R. Tan, D. P. Bour, J. Zhu, Agilent Technologies

Folded cavity resonators, based on shallow-etched straight ridge waveguides combined with four deeply etched turning mirrors are designed and fabricated. The device consists of a resonant folded cavity and a bus waveguide coupled to it through a directional coupler. Optical passive filters based on this technology exhibit quality factors in the excess of 5000, with a low insertion loss of 5dB (including the input coupling loss to a fiber) and more than 15dB extinction at resonance. When combined with an electroabsorption active region and designed to operate in the overcoupled regime a low-voltage/high-extinction-ratio resonant modulation becomes feasible. The electroabsorption resonant modulators exhibit low insertion loss, greater than 22dB extinction at resonance and low-voltage operation. A change in the applied voltage by 0.7V (close to the critically coupled conditions) leads to a transmission change of more than 16dB. To decrease the insertion loss, multiple bandgaps are monolithically integrated across the wafer by using quantum well intermixing techniques. High-speed modulation results will be presented.

6133-39, Session 11

Single-mode equal lateral triangle resonant microcavity laser diode at 1.2 μm

Y. Cao, S. R. Johnson, Y. H. Zhang, Ariozna State Univ.

Laser devices based on micro-resonator structures have been the focus of research for more than a decade. Recently, Huang [1] showed that semiconductor microlasers with an equilateral triangle resonator (ETR) are suitable for single-mode operation. In an ETR, the fundamental transverse mode forms a pattern of three equilateral triangles within the ETR where the light rays impinge on the sidewalls with an incident angle of 30∫, experiencing total internal reflection. The incident angle of the higher order transverse modes rapidly decreases with mode number, strongly limiting the number of the confined transverse modes. Furthermore the number of longitudinal modes is restricted by the short effective cavity length which is 3/2 times the length of one side of the ETR and on the order of 10 μm. Therefore, single-mode operation with the ETR design is straightforward. In this paper, we reported the development of a single-mode microcavity laser diode using the ETR structure design. The fabricated lasers were characterized at liquid nitrogen temperatures using a Fourier transform IR spectrometer. The ETR laser diode operated at a single mode wavelength of 1183.8 nm with a FWHM of 0.1 nm. The ETR microcavity laser has a sidewall length of 10 μm and a threshold current of 1.2 mA, which results in an effective threshold current density of 2.5 kA/cm2. The high threshold current density can be attributed to non-ideal sidewalls, which increase cavity loss and carrier surface recombination.

1 Yong-Zhen Huang, Wei-Hua Guo, and Qi-Ming Wang, Appl. Phys. Lett., 77, 3511, 2002.

6133-40, Session 11

High-index-contrast ridge waveguide lasers fabricated via oxygen-enhanced wet thermal oxidation

D. Liang, J. Wang, D. C. Hall, Univ. of Notre Dame; G. M. Peake, Sandia National Labs.; Q. J. Hartmann, Epiworks, Inc.

A simple, novel self-aligned deep etch plus wet thermal oxidization process is demonstrated which enables high-index-contrast (HIC) ridge waveguide (RWG) lasers fabricated in a high-efficiency, high-power AlGaAs/InAlGaAs/GaAs graded-index separate confinement heterostructure to operate with a curved half-ring resonator geometry having a bend radius as low as 10 μm. A wet thermal oxidation process modified through addition of <1% O2 to the N2 carrier gas is shown to smooth the sidewall roughness of etched AlGaAs ridge structures 10-100 fold as the oxidation front progresses inward. The reduction of propagation scattering loss due to the reduced sidewall roughness is examined. The thermal oxide grown on the deeply-etched RWG sidewalls and base also provides electrical isolation from the contact metallization, resulting in a simplified, self-aligned process, and yields a RWG structure which effectively prevents current spreading. The thermal oxide appears to be of sufficiently high quality to passivate the etched active region surface based on a comparative analysis of straight RWG lasers of varying stripe widths (w=5 to 150 μm) passivated with native-oxide vs. PECVD-deposited SiO2. For example, at w<25 μm, the SiO2-insulated devices have 2-3X higher threshold current densities than the native-oxide devices for comparable bar lengths. The resulting high lateral optical confinement factor at the semiconductor/oxide interface (delta=1.69) significantly enhances the laser gain and efficiency. A native-oxide-defined straight laser (w=7 μm, L= 452 μm) operates cw (300 K, unbonded, p-side up) with a threshold current of Ith=23 mA (Jth=727 A/cm2) and slope efficiency of 1.14 A/W (differential quantum efficiency = 75%) at a wavelength of ~814 nm.

6133-41, Session 11

High characteristic temperature 1.3-um GaInNAs/GaAs laser diode

X. Zhang, Univ. of Ottawa (Canada) and National Research Council Canada (Canada); J. A. Gupta, P. J. Barrios, G. J. Pakulski, National Research Council Canada (Canada); T. J. Hall, Univ. of Ottawa (Canada)

GaInNAs has been extensively investigated in recent years as one of the promising materials for 1.3μm coolerless laser diodes, which are of significant interest for data communication. In this work, we report 1.3μm GaInNAs/GaAs double quantum well ridge waveguide (RWG) lasers with characteristic temperatures as high as T0 = 155K. The lasers were grown by molecular beam epitaxy and processed into RWG devices with ridge widths from 2 to 10μm using inductively-coupled plasma reactive ion etch-

ing (ICP-RIE) and standard metallization. The properties of the diode lasers and the GaInNAs active material were extensively studied by light-current (L-I), spectral and gain measurements from 20 to 75∞C. The room temperature (RT) threshold current for a short cavity, 3μm by 448μm device was 36mA under continuous wave (CW) operation. After lateral leakage current correction, the measured threshold current density was found to be 550Acm-2 per quantum well for longer, 1204μm cavity devices. Gain spectra were measured as a function of sub-threshold current for a 2μm by 448μm device. The internal loss was found to be 7cm-1 and the transparency current was found to be 6.6mA after lateral leakage current correction. The peak net modal gain was 31.4cm-1. High resolution spectra revealed single lateral mode operation for 2μm and 3μm-wide devices. The RT emission wavelength was 1275nm at 20∞C with a 0.58nm/∞C temperature dependence. The remarkably high T0 and other characteristics of these lasers reaffirm the potential of GaInNAs as a promising light source for optical communication systems at 1.3μm and beyond.

6133-43, Session 12

Mid-IR interband cascade lasers: progress and prospects

R. Q. Yang, Jet Propulsion Lab.

No abstract available

6133-44, Session 12

Advances in design and performance of high-power GaSb-based lasers and laser arrays

G. L. Belenky, Stony Brook Univ.

No abstract available

6133-45, Session 12

High-power diode laser arrays emitting at 2 μm with reduced far-field angle

M. T. Kelemen, J. Weber, M. Rattunde, G. Kaufel, R. Moritz, J. Schmitz, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

GaSb based diode laser arrays emitting at wavelengths around 2 μm have a significant potential for a variety of applications including materials processing, such as welding of transparent plastic materials, and optical pumping of mid-infrared solid state lasers. Even though high output power broad area single emitters and laser arrays have already been demonstrated, they all suffer from a large fast axis beam divergence of typically 65∞ FWHM due to the broadened waveguide design employed.

We will present results on (AlGaIn)(AsSb) quantum-well diode laser single emitters and linear arrays consisting of 19 emitters on a 1 cm long bar emitting at 1.907 μm. To improve on the poor fast axis beam divergence we abandoned the broadened waveguide concept and changed over to a novel waveguide design which features a rather narrow waveguide core. This results in a remarkable reduction in fast axis beam divergence to 43∞ FWHM for the new waveguide design. For single emitters a cw output power of 2 W with an excellent long term stability have been observed. More than 17 W in continuous-wave mode at a heat sink temperature of 20 ∞C have been achieved for arrays, which show the same high maximum wall-plug efficiency of more than 26% as the single emitters. These efficiencies are among the highest values reported so far for GaSb based diode lasers, and allow us to use passively cooled and thus less expensive packaging technologies.

6133-46, Session 13

850-nm surface etched distributed Bragg reflector semiconductors lasers with narrow spectral linewidth

R. K. Price, V. C. Elarde, J. J. Coleman, Univ. of Illinois at Urbana-Champaign

Narrow-linewidth semiconductor lasers are essential for high-resolution spectroscopic applications. We have fabricated surface etched distributed Bragg reflector (DBR) lasers at 850-nm with very narrow spectral linewidth values of 40 kHz. Our results show that extremely narrow linewidths can be achieved using one-step epitaxial growth with surface etched first-order gratings on asymmetric claddings, and demonstrate the lowest reported spectral linewidths to date at 850-nm.

Two separate asymmetric cladding SCH (separate confinement heterostructures) lasers with spontaneous emission gain peak of 850-nm and 835-nm were grown by MOCVD on (100) n-type GaAs substrates. First-order surface etched gratings with a nominal period of 125 nm were fabricated via electron beam lithography.

The device with peak gain at 850-nm exhibits a threshold current value of 22 mA, with a corresponding threshold current density of 915 A/cm2, and a differential slope efficiency of 0.322 W/A. The device with peak gain at 835-nm exhibits a threshold current of 25 mA and a maximum slope efficiency of 0.271 W/A. Both devices display side-mode suppression ratio values \> 40 dB.

Using an optical self-heterodyning measurement system, spectral lineshape measurements were taken at various output power levels on two 850-nm and one 835-nm peak gain devices. Minimum spectral linewidths are measured below 100 kHz for all devices. The devices with the 835-nm gain peak exhibit the overall lowest spectral linewidths, with values measured as low as 40 kHz.

6133-47, Session 13

Al-free active region InGaAsP/GaAs (lambda = 852nm) DFB laser diodes for atomic clocks and interferometry applications

F. Vermersch, S. Bansropun, V. Ligeret, M. Lecomte, M. Calligaro, O. Parillaud, M. M. Krakowski, Thales Research & Technology (France)

Atomic clocks will be used in the future European positioning system Galileo. Among them, the optically pumped clocks provide a more accurate alternative. For these systems, diode lasers emitting at 852nm are strategic components. The laser in a conventional bench for atomic clocks presents disadvantages for spatial applications. A better approach would be to realise a system based on a distributed-feedback (DFB) laser. Thus we have developed laser structures emitting at 852nm, using an aluminium free active region. The device is a separate confinement heterostructure with a GaInP large optical cavity and a single compressive-strained GaInAsP quantum well. The broad-area laser diodes are characterised by low internal losses (<3 cm-1), a high internal efficiency (94%) and a low transparency current density (100A/cm≤). For an AR/HR coated 2mm long around 4μm wide ridge diode, we obtain a low threshold current (40mA) and a high slope efficiency (0.90W/A). We obtain 852nm wavelength at 145mW (I=200mA, 15∞C). We measure an optical power of 230mW (I=280mA) in a single spatial mode with the beam quality parameter M≤=1.3.

From our first attempt for a DFB laser, we obtained a threshold at 20∞C of 45mA and a slope efficiency about 0.45W/A with an uncoated 2mm long around 4μm wide device. At 40mW (I=140mA,), both near and far fields in the slow axis are gaussian-shaped with respective full widths at 1/e≤ of 7μm and 10.4∞, corresponding to a single spatial mode emission with the beam quality parameter M≤=1.2. At this power, the laser wavelength is 853.8nm with a side-mode-suppression ratio over 30dB.

6133-48, Session 13

High-frequency tuning of high-powered DFB MOPA system with diffraction limited power up to 1.5W

J. R. Sacher, R. Knispel, S. Stry, Sacher Lasertechnik GmbH (Germany)

The combination of high power, small linewidth and fast tunability is essential for many fields in high resolution spectroscopy. External cavity laser diode systems are limited in tuning speed to several kHz by the resonance frequency of the mechanical assembly together with the actuator.

We report on the application of a directly modulated DFB laser as master laser within a MOPA configuration. This DFB MOPA system combines fast frequency tuning up to more then 100kHz tuning speed, a tuning amplitude of more than 10GHz, a narrow linewidth below 5MHz with high output power of 1000mW and an almost Gaussian shaped beam quality (M2<1.2). The coupling efficiency for a optical waveguides as well as single mode fibers exceeds 60%. This concept can be realized within the wavelength regime between 730nm and 1060nm.

We approved this light source for high resolution spectroscopy by frequency locking to the saturated Rubidium absorption at 780nm. Applying two DFB lasers as master laser of the MOPA configuration opens the choice to high frequency modulated THz radiation.

6133-49, Session 13

Dual mode lasing from index patterned Fabry-Perot laser diodes

S. W. Osborne, S. O'Brien, R. Fehse, E. P. O'Reilly, Tyndall National Institute (Ireland)

Multi-wavelength lasers are important photonic components for many applications, including optical communications and environmental sensing. Semiconductor lasers, utilizing two different Distributed Bragg Reflectors (DBR) and extended cavity schemes, have demonstrated dual-mode lasing [1]. However, the fabrication of a DBR mirror requires complex processing and re-growth, while extended cavity schemes require careful component alignment.

Here we demonstrate dual mode lasing centered at a wavelength of 1300 nm in an edge-emitting ridge waveguide Fabry-Perot (FP) laser. Dual mode lasing is achieved through the introduction of a carefully designed effective index pattern along the cavity during the processing of the ridge waveguide; thus requiring no additional processing steps. This technique has enabled stable, single mode emission in FP lasers [2] and relies on a transmission matrix approach to relate the index profile along the cavity to the threshold gain spectrum as a function of cavity mode index.

Experimental spectra at 300K show lasing at wavelengths separated by four cavity modes, as designed and with a frequency spacing of 0.5 THz. Simultaneous lasing and strong nonlinear interaction between the modes with increasing current density is indicated by the appearance of Four-Wave Mixing (FWM) sidebands. We discuss potential applications of this technique in optical clock generation, discretely tunable sources and direct THz generation.

1 G. Grosskopf et. al. IEEE Photon. Tech. Letts., 12 1692 (2000).

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6133-50, Session 13

High power conversion efficiency diode lasers

M. Kanskar, J. Cai, Y. He, E. Stiers, S. R. Tatavarti-Bharatam, Alfalight, Inc.; D. Botez, L. J. Mawst, Univ. of Wisconsin/ Madison

High electrical-to-optical power conversion efficiency (PCE) diode lasers have important applications for solid-state lasers, fiber-lasers, telecommunication pump lasers and industrial lasers. Current commercially available diode lasers operate with approximately 50% PCE. Additional 20 to 30% more PCE will have far-reaching implication for reduction in size and cost. Additionally, having higher PCE will allow judicious laser designs for higher power and higher temperature operation with greater reliability than currently possible. We report on the improvement due to increase in injection efficiency via strained quantum-well barriers, moderately-low doping of the broad-waveguide core, and reductions in series resistance as well as operating voltage via doping optimization of the broad-waveguide structure.

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6134-01, Session 1

High-power LEDs for visible and infra-red emision

S. Illek, OSRAM Opto Semiconductors GmbH (Germany)

No abstract available

6134-02, Session 1

High power LEDs and the organization of light

S. Paolini, G. Harbers, Lumileds Lighting, LLC

LEDs in general and high power LEDs in particular continue to improve and diversify. A brief review of the technology and its progress will be followed by some recent examples of new developments and their potential impact on specific markets. Finally, the concept of organizing light will be introduced. Solid state devices are well suited to organization in multiple ways and this ability should further drive the adoption of the technology in unique ways.

6134-03, Session 1

Optimum arrangement of LEDs in a base station of optical wireless LANs

T. Matsumoto, N. Inoue, Tokyo Denki Univ. (Japan)

In commercial optical wireless LAN systems, a base station is set on the ceiling, and a number of LEDs therein broadcast optical beams to movable stations below. The movable stations are guaranteed to communicate with the base station when they exist in a service area. The LEDs should be arranged so that their combined optical beams effectively irradiate the service area. However, studies concerning such design have not been reported so far and thus the LEDs in a base station have been arranged empirically. The minimum optical power density in the service area is a key parameter in designing the system because it determines the optical power margin of the system, and it should be increased as much as possible. In this paper, we theoretically examine the optimum arrangement of the LEDs, with which the minimum optical power density in the service area is maximized, assuming that the total number and total power of LEDs are fixed. Referring to the commercial systems, we assume that LEDs are aligned on coaxial circles in an axially symmetric scheme and thus a disk-shaped service area is implemented. All the LEDs are assumed to have the same beam profile, but each group aligned on a different circle has its own number of elements and inclination angle with respect to the vertical axis. We obtain the numbers of LEDs on the circles, their inclination angles and beam profile of the optimum arrangement. Numerical results are compared with our experimental results. The results of this study will contribute to designing the base stations of optical wireless LANs.

6134-04, Session 1

High-power LED arrays- special requirements on packaging technology

O. Kueckmann, PerkinElmer, Inc. (Germany)

The market for high power LED solutions is expanding rapidly with the significant efficiency increase of LED chips. This revolutionizes the optoelectronics market, enabling engineers to use LEDs for general lighting applications as well as medical, specialty lighting and automotive solutions, where previously less efficient technologies had to be used.

In order to reap the benefits of high power LEDs, however, special requirements concerning thermal management and optomechanical layout have to be met. We will show concepts of thermal management and technological solutions for the choice of different materials and assembly. Furthermore, we will discuss the gain and challenges of chip-on-board solutions using intelligent optical design in specific applications.

6134-05, Session 2

LEDs in automotive lighting

K. Eichhorn, Hella KGaA Hueck & Co. (Germany)

Light emitting diodes (LED) become more and more significant in interior and exterior automotive lighting. The long life-time, energy-, space savings, shock and vibration resistance and new styling potential are the main advantages of using LEDs in automotive applications.

Today most of the central high mounted stop lamps using LEDs. In rear combination lamps the number of LEDs in amber and red increasing rapidly. Additionally first signal functions in headlamps using white High Power LEDs launch the market.

Exterior automotive applications, including requirements and performance will be discussed and an outlook will be given on future scenarios.

6134-06, Session 2

LEDs on the threshold for use in projection systems: challenges, limitations and applications

B. A. Moffat, Carl Zeiss Jena GmbH (Germany)

This paper discusses the use of coloured LEDs as light sources in very compact digital projectors as well as in next-generation rear-projection television.

Despite the remarkable recent advances in high brightness LED technology at the chip and module level it is vital to make the most of the available light from the LEDs. Therefore it is necessary to develop an integrated system of light source, projection optics and electronics in an attempt to find an optimal combination of light output, size, power consumption, thermal dissipation, cost, and market potential.

Concepts for beam shaping, intensity homogenization, and colour mixing of monochrome LEDs in high efficiency projection engines are described, as well as experimental results from digital micro-mirror (DMD) based optical modules. Operating parameters for the LEDs were chosen to trim the system to high optical output, but these conditions must be balanced against LED lifetime and thermal requirements. Dynamic colour management and intensity control using an electronic feedback system can produce a new quality of illumination light source-but are also necessary to compensate effects such as differential ageing of individual LEDs.

Existing trends towards smaller microdisplays, compact projection modules, and brighter LEDs indicate that the development of projection systems will continue to provide interesting multidisciplinary challenges and exciting opportunities in the near future.

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6134-07, Session 2

LEDs for automotive applications

M. S. Dassanayake, Ford Motor Co.

No abstract available

6134-08, Session 2

The innovations with the medical applications of white LEDs and the breakthrough for new business

J. Shimada, Kyoto Prefectural Univ. of Medicine (Japan) and Kyoto Univ. (Japan) and Tsuji Plastic Co. (Japan); Y. Kawakami, Kyoto Univ. (Japan); K. Itoh, M. Nishimura, Kyoto Prefectural Univ. of Medicine (Japan); K. Tsuji, Tsuji Plastic Co. (Japan)

The distance between the LED and the surface of the target organ is about 4-5 cm, and we think this will become the ìultimate super-localized LED lightingî. In an experiment with swine, we placed a LED module at the tip of the retractor. When compared to endoscopic lighting, this method illuminated the entire thoracic cavity more brightly. Since the light is emitted from the cylinder-shaped camera component, the light is unidirectional, and the shadows from the surgical instruments are moved to the side of the incision. Retractor LED lights provided enough light in the thoracic cavity. We believe that ìmedical white LEDsî can contribute in clinical settings as a light source for performing safe operations with bright surgical fields in the near future. Also, we use our LEDs for new real business. In the summer of 2004, LED lighting was world first used in the 1200 year-old Gion Festival for the first time in history as ìa lighting device that does not destroy cultural assets by light heatî. And the next is ìLighting at the ìDiva status at diva gateî and the ìThousand Armed Avalokiteshwara in inner adytum in the main hallî at Kiyomizudera in Kyotoî. It was a great success, and we were invited back in the spring of 2005 and for future applications. We think this is the first real application of LEDs as an outdoor lighting device. The number of people who visit Kiyomizudera is 4000,000 annually, and LEDs were adopted to illuminate the diva gate.

6134-09, Session 2

Trichromatic LED Backlights for Mobile LCDs

J. Kim, M. Park, J. Kim, H. Kim, J. Jun, J. Park, S. Cho, H. Jeong, Samsung Electro-Mechanics Co Ltd (South Korea)

We present strongly supporting ideas and demonstration results of trichromatic LED backlights for usage in mobile LCDs. In realization, several technical challenges arise, such as color mixing, minimizing the total number of chips, maintaining color balance, complex driving circuit, and most importantly, the cost. We designed and demonstrated a prototype backlight unit that could address the problems. Two 3-in-1 sideview LEDs are used in the backlight unit for a 2.2 inch TFT-LCD. The average brightness of the first prototype is 1140cd/m2 at input power of 240mW. The power efficiency has yet to be increased for commercialization. However, the color gamut is very wide as expected. The LCD panel lit by this backlight unit has color gamut of 73% NTSC, while a conventional LCD panel that is measured together shows only 39%. The color gamut of the backlight unit itself is 109%. This ultimate performance can be reached when it is used with a field-sequential LCD.

6134-10, Session 3

Recent developments on OLED lighting

H. Antoniadis, OSRAM Opto Semiconductors Inc.

No abstract available

6134-11, Session 3

Recent progress in vapor-phase deposition as a production tool for inorganic and organic optoelectronic devices

M. Heuken, B. Marheineke, M. Schwambera, N. Meyer, O. Schoen, B. Schineller, AIXTRON AG (Germany)

The deposition of layer structures from the vapor phase has proven to be a viable method for the mass production of (opto)electronic devices.

We present Organic Vapor Phase Deposition (OVPDÆ), an innovative manufacturing technology for volume production of OLEDs for Display, lighting and organic electronics (solar cells, transistors, etc.) applications. OVPDÆ in combination with our close-coupled Showerhead technology enables low-cost manufacturing due to high efficient material utilization. Superior thin film thickness uniformities are achieved on large area substrates, e.g. Gen 2 (400 x 400 mm2). OVPDÆ enables a precise layer switching and high controllability of single & multiple material concentrations, like hosts and dopands for co-hosting in devices with deposition rates of 30 ≈/s and beyond.

The hot wall and stationary deposition without any moving parts minimizes parasitic condensation and particles assuring high yield and maintenance cycles. Analysis by AFM has confirmed low roughness values of 5 ≈ RMS with controlled layer morphology and interfaces for layers deposited by OVPDÆ. Latest results demonstrate that OLED devices by OVPDÆ processed with high deposition rates of more than 10 ≈/s have state-of-the-art performance. We demonstrated peak luminous efficiency of 25 cd/A at 1000 cd/m2 and a device lifetime of 10.000 h at 600 cd/m2.

These results demonstrate that the OVPDÆ technology is proven for state-of-the-art OLED device performance. OVPDÆ offers high potential for cost reduction in manufacturing enabling low tact times by high deposition rates.

Inorganic semiconductors will receive their next boost from the introduction of white lighting by LEDs. One of the most promising approaches is the introduction of larger wafer sizes effectively increasing the deposited area per growth run and decreasing the load on the subsequent processing pipeline.

By using a technique for the ex-situ estimation of the strain during the growth run in the MOCVD reactor we were able to optimise the growth hardware and the process for the uniform growth on 4 inch sapphire. Photoluminescence mappings showed standard deviations of the wavelength of less than 1 nm without edge exclusion for a wafer emitting in the blue spectral range at 469 nm. The total thickness of the layer stack was on the order of 5.5 μm. To our knowledge this is a world record result in this material system. Additional experiments were performed, extending the range of wavelengths into the green spectral range. Consecutive runs of test structures with p-type cap layers yielded wavelengths of 520.9 nm, 522.8 nm, 522.3 nm and 522.9 nm with on wafer uniformities on the order of 1.8 nm standard deviation, evidencing good stability of this production tool and a negligible amount of In-redistribution during the subsequent high-temperature GaN:Mg step.

We will provide additional results on the growth on 4 inch, discuss special requirements for the wafer quality and surface preparation, especially with respect to the influence of the surface off-cut on the width of the temperature process window and give an outlook on further developments on larger wafer sizes for the mass production of GaN-based devices.

6134-12, Session 3

Superluminescent organic light-emitting diode with a novel anode structure

S. Han, Y. Yuan, Z. Lu, Univ. of Toronto (Canada)

A novel anode structure comprising a nanocomposite and metal, has enabled highly efficient and stable superluminescent organic light-emitting diodes (SOLED). For C545T singlet green emitter, SOLED can reach 33 cd/A at 1000 cd/m2, doubled the efficiency as comparing to conventional devices with ITO/CuPc structure. More importantly, the SOLED can

still hold 24 cd/A at 50000 cd/m2, indicating a highly efficient hole injection capability at ultra-high brightness. In addition, the simulated electronluminescent spectra with angle dependence, agree with experimental results. It is expected that SOLED might find wide applications, not only in display but in general lighting or ultra-high brightness application, by eliminating the problematic ITO anode.

6134-13, Session 4

Omni-directional reflectors for light-emitting diodes

J. K. Kim, Rensselaer Polytechnic Institute

This talk discusses possible solutions to limitations in light extraction efficiency of light-emitting diodes (LEDs) including new types of omni-directional reflectors (ODRs) with lower mirror losses than metal reflectors and distributed Bragg reflectors (DBRs), and new types of packaging configuration for white LEDs. High-reflectivity ODRs have been incorporated into AlGaInP LEDs and GaInN LEDs. It is shown that the ODR significantly increases light extraction from the LEDs as compared to reference LEDs employing DBR or metal reflector. Other examples of innovative concepts in ODRs to be presented include novel materials with unprecedented low-refractive index, and partially diffuse reflectors.

With the rapid development of phosphor-based high-power white LEDs, advances in packaging are required to further improve the light extraction efficiency of LED lamps. An optimized packaging configuration is presented along with experimental results and ray-tracing simulations. Enhancement of phosphorescence efficiency is obtained experimentally by employing diffuse reflector cups and a remote-phosphor configuration, which is fully consistent with the ray tracing simulation. This improvement is attributed to reduced absorption of the phosphorescence by the LED chip and the reduction of deterministic optical modes trapped inside the encapsulant.

6134-14, Session 4

100 mW high-power depolarized-superluminescent diode at 1550nm wavelength

S. Park, J. Wei, Y. Hu, P. J. S. Heim, R. Enck, V. Luciani, O. A. Konoplev, Covega Corp.; S. W. Wilson, Palomar Medical Technologies, Inc.

High-power superluminescent light emitting diodes (SLEDs) have been used as light sources for optical time domain reflectometers, fiber gyroscopes, fiber sensors, optical coherence tomography, and ìspectral slicingî wavelength division multiplexing (WDM) systems. Most SLEDs that have been reported are highly polarized at the output of the SLED chip. However there are many applications where a depolarized optical source is desirable such as in highly sensitive fiber gyroscopes, fiber-grating based optical sensors, and wavelength division multiplexing passive optical networks (WDM-PON) using spectral slicing and injection locking techniques. High output power, large spectral bandwidth, small spectral modulation and low degree of polarization are key features for these applications. In particular for WDM-PON, high output power with reasonable spectral bandwidth and modulation is crucial for practical implementation of these systems. One approach to achieve a depolarized SLED is to polarization combine the output of one or more polarized devices. Until recently, there have been no reports on the high power polarization-insensitive single-chip SLEDs that can be utilized in WDM-PON.

We demonstrate here a high power (> 100mW), broad-band (> 40nm) polarization-insensitive SLED at 1550nm with less than 1 dB polarization dependence. The SLED consists of an InGaAsP tensile-strained bulk layer and two-step SCH layers. The device was grown by solid source molecular beam epitaxy (MBE) and processed into a ridge waveguide structure with 4 mm ridge width using standard lithography and metallization. The waveguide strip was angled to reduce the facet reflectivity with both facets anti-reflection (AR) coated. The SLED chip was cleaved at a length of 2mm, mounted p-side up on a ceramic submount cooled by a thermal-electric cooler (TEC) at 10 and 20°C. At driving current of 1000mA and 20∞C, a continuous wave (CW) output power of 84mW, 43nm FWHM bandwidth of a Gaussian-shape spectrum, and <0.7dB peak-to-peak ripple were achieved. The polarization dependence of the output power spectrum is less than 1dB over the C-band. The far field pattern is singlelobed with horizontal and vertical FWHM values of about 21∞ and 37∞, respectively. As the TEC temperature was cooled to 10∞C, the CW output power reached more than 100mW.

6134-15, Session 4

Correct wavelength-scale numerical modeling of optical characteristics of planar RCLED structures by the method of single expression

H. V. Baghdasaryan, T. M. Knyazyan, R. I. Simonyan, A. Mankulov, State Engineering Univ. of Armenia (Armenia)

Resonant-cavity light emitting diodes (RCLEDs) are novel, highly efficient semiconductor devices employing very small microcavities in the scale of the wavelength. RCLEDs are an advancement of light emitting diodes and are product of a continuous improvement of LEDs characteristics during the last decade. An essential reduction of LEDs spectral linewidth and the enhancement of the emission power and directionality are achieved by incorporating the LED structure into the resonant cavity. The enhancement of the external quantum efficiency by optimizing the design of the micro-resonator, the positioning of the active layer inside the micro-resonator and the spontaneous emission modification are the key issues for RCLEDs design. While it is commonly known that the optimal position of the active layer is the optical standing wave anti-node, there have not been investigations on the impact of the active layer thickness. Precise wavelength-scale modeling of optical characteristics of planar RCLED structures with metallic and DBR mirrors on substrates is performed.

For modeling an advanced numerical method of single expression (MSE) is used. Resonant amplification is obtained for the certain thickness of the active layer located at the specific distance from the highly reflective mirror. The active layer should be located not exactly in the anti-node of optical wave field, but with a little shift stipulated by absorption in the highly reflective mirror and surrounding media. Obtained distributions of optical wave's electric field amplitude and power flow density along the structure, and spectral dependences will be useful in understanding and design of RCLEDs.

6134-31, Session 4

Realization of highly efficient InGaN vertical LED on metal alloy substrate

C. A. Tran, C. F. Chu, C. C. Chen, W. H. Liu, H. C. Chen, C. I. Chu, F. H. Fan, J. K. Yen, T. T. Doan, SemiLEDs Corp.

A highly efficient vertical LED devices on metal alloy substrates were realized for advanced applications, including solid state lighting. Device with the size up to 3mmx 3mm shows operation under extreme conditions that are not suitable for conventional InGaN LEDs on sapphire or vertical LED on SiC.. Utilizing vertical structure and thinned n-GaN up structure, LED chips maximize the vertical injection of current into the active layers resulting in higher light output efficiency. In addition these LED exhibit a nearly perfect Lambertian light emission pattern. Furthermore, metal alloy substrate technologies offer the best solutions for current spreading and heat removal. Opto-electrical tests have shown that these LED chips are extremely efficient in photonic extraction and are capable of producing emitting output power among the best in the industry. A light output efficiency of 60 lumens/Watt and better is achieved for 1 W device.

6134-24, Poster Session

Linear position sensor

I. V. Friedland, I. Gurwich, M. Velger, ElOp Electrooptics Industries Ltd. (Israel)

The simple and popular linear position sensor, holding temperatures relevant to industrial applications, comprises LED as a light source, a rectangular photodiode (or a few overlapped photodiodes to increase sensor's linear excursion) and a cover, which position is measured, fixed on a mechanical moving part. The cover position determines the light energy that reaches the photodiode surface. The energy is transformed in sensor output voltage. This voltage is proportional to the cover displacement only by condition that photodiode illumination is absolutely uniform. In practice the linear sensor is volume limited therefore the sensor illumination is not uniform and the sensor's scale factor (the voltage per the unit displacement) as a result is not a constant value. Non-compensated variable sensor scale factor causes control system destabilization where sensor provides cover linear position measurement.

This paper proposes the expression which approximates the LED's irradiance intensity. We used this approximation to calculate voltage versus displacement characteristic of a linear sensor consisting of two overlapped photodiodes. These calculations are compared with laboratory test, and a good agreement is obtained. Using this characteristic we provided its linearization and stability of control closed position system, where nonlinear sensor was main destabilized factor.

6134-26, Poster Session

Numerical simulation of optical and electronic properties for multilayer organic light-emitting diodes

S. Chang, Y. Chang, C. Yang, J. Chen, Y. K. Kuo, National Changhua Univ. of Education (Taiwan)

Organic light-emitting diodes (OLED) have been extensively developed in the past few years. The OLED displays have advantages over other displays, such as CRT, LCD, and PDP, in thickness, weight, brightness, response time, viewing angle, contrast, driving power, flexibility, and self-emission. Compared to experimental researches, fewer reports have been published in device simulations lately. In this work, the optical and electronic properties for multilayer OLEDs are numerically studied with an APSYS (Advanced Physical Model of Semiconductor Devices) simulation program, which is developed by the Crosslight Inc. Specifically, the emission/absorption spectra of the Alq3, DCM, Alq3:DCM, PBD, and SA light-emitting layers (EML), and energy band diagrams, electron-hole recombination rates, and current-voltage (I-V) characteristics of the simulated OLED devices, typically with a structure of metal/Alq3/EML/TPD/ITO, are investigated and compared to experimental results if available. The physical models utilized in this work are similar to those presented by Vragovic et al. (Europhysics Letters 57, 288-294, 2002) and Hoffmann et al. (Physical Review B 66, 024305, 2002). The preliminary simulated results indicate that the emission spectra of the Alq3, DCM, PBD, and SA light-emitting layers obtained in this study are in good agreement with those obtained experimentally by Zugang et al. (Synthetic Metals 111-112, 47-51, 2000); in the mean time, the I-V characteristics of the simulated multilayer OLED devices are also in close agreement with those observed experimentally by Lim et al. (Optical Materials 21, 217-220, 2002). Optimization of the optical and electronic performance for the OLED devices under study will be attempted.

6134-27, Poster Session

Problems of linear birefringence in optical glass current

Z. P. Wang, X. Liu, Z. Huang, Harbin Engineering Univ. (China)

The formulae reflecting the effects of the linear birefringence (LB) upon the Bulk Glass Optical Current Transformers (BGOCTs) with return-back optical paths, such as the Orthoconjugate Reflector (OCR)-typed, the Direct Reflection (DR)-typed and the Roof-prism Reflection (RPR)-typed BGOCT, are derived in this paper. Comparing them with that of the BGOCT with a single optical path, one can know that the return-back dual-loop current sensing designs with conventional signal processing scheme of ì î cannot eliminate the harmful effects of the LB thoroughly, if suitable signal processing schemes which can separate the LB from Faraday effect are not used.

6134-28, Poster Session

Precise formula of emission spectrum for light-emitting diodes

T. Yang, H. Chou, National Central Univ. (Taiwan)

More and more applications of light-emitting diodes (LEDs) are increasing in our daily life. Due to the advantages of small size, energy saving, long lifetime, etc., LED becomes the promising light source for display and illumination in the short future. However, there are several crucial issues in practical application so far. The most important one is the optical emission properties will drift as the time past by. As well-known, the peak wavelength, the bandwidth, the color, and the output power of the emission light from LEDs are strongly depend on the materials made of LEDs, the working temperature, and the electric driving current. In this work, a novel formula is proposed to describe the emission spectra of LEDs, which is more precise than the traditional Gaussian formula. There exist four parameters in our precise formula. One is related to the spectral power strength, another to the peak wavelength; and the other two both are corresponding to the bandwidth of the emission spectrum. Our precise formula has been compared to the emission spectra of several LEDs with various colors under different electric current driving levels. By nonlinearly fitting our precise formula to the measured spectral data, it is found that the coefficient of determination R-squared values can be all above 0.995 higher than 0.975 of the Gaussian formula. Especially, the sidebands of the emission spectrum have been in much better following in addition to the peak wavelength around. Further, the dependency of the fitting parameters on the driving electric current and the working temperature is also delineated in details. This novel formula indeed allows to predict and to evaluate the changes in the light flux, the chromaticity coordinate, the color rendering index, and the color temperature of LEDs in use.

6134-17, Session 5

To be announced

J. Han, Yale Univ.

No abstract available

6134-18, Session 5

Kelvinn force microscopy on a (GaxAl1-x)0.5In0.5P light-emitting diode

W. Mertin, K. Katzer, G. Bacher, Univ. Duisburg-Essen (Germany); A. Jaeger, K. P. Streubel, OSRAM Opto Semiconductors GmbH (Germany)

High-brightness light-emitting diodes (LED) based on GaAlInP combines the possibility to achieve high efficiency with the flexibility to tune the emission wavelength over a large range of the visible spectrum [1]. For optimizing the device characteristics an accurate determination of the electronic properties, like e.g. the voltage drop across the semiconductor layer stack, is desirable. However, an experimental access is quite difficult due to the mesoscopic dimensions.

Because of its inherent high spatial resolution and its ability to extract voltage drops across heterointerfaces quantitatively, Kelvin Force Microscopy is highly suitable for this task. Some groups have successfully applied this technique to study the electronic properties of non-operating and operating LEDs, however, these experiments were either only qualitative [2] or have been applied to different material systems [3].

We demonstrate the potential of Kelvin Force Microscopy for quantitative investigations of the voltage drop across the heterostructure layers of an operating InGaAlP LED. The contact potential difference was measured for external biases between -2.0 V and +1.86 V and by subtracting the

zero bias result the voltage drop could be extracted quantitatively. In the low voltage regime, most of the voltage drops in the active layer, as expected. Surprisingly, we found that above +1.5 V an additional voltage drop occurs on the p-side of the device. We will discuss possible mechanisms of these findings which reduce the efficiency of the LED.

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2 J. J. O'Shea et al., J. Appl. Phys. 90, 4791, 2001

3 R. Shikler et al., J. Appl. Phys. 86, 107, 1999, G. Lévíque et al., Appl. Surf. Sci 157, 251, 2000

6134-19, Session 5

High-brightness AlInGaN light-emitting diodes

T. Margalith, M. O. Holcomb, S. Boles, D. A. Steigerwald, Lumileds Lighting, LLC

High efficiency light emitting diodes (LEDs) have enabled solid-state based lighting to push the boundaries of conventional technologies, creating never-before-possible innovations in the automotive, medical, and consumer electronics fields. However, for the technology to become ubiquitous, continuing improvements must be made in light output and power consumption. Using a novel flip-chip die design, incorporating an intermetallic dielectric and increased reflector area, we have achieved 321 mW operation for blue LEDs (447 nm), and 65 lum/W for green LEDs (520 nm) at 350 mA DC. The devices had an external quantum efficiency (EQE) of 33% (wall plug efficiency of 29%) and 20% for blue and green, respectively. Robust performance at 1A of drive current was also measured, with 729 mW output power for blue LEDs (26% EQE) and 38 lum/W for green LEDs.

6134-20, Session 5

GaN light-emitting triodes for high-efficiency hole injection and light emission

J. K. Kim, J. Xi, H. Luo, Rensselaer Polytechnic Institute; J. Cho, C. Sone, Y. Park, SAMSUNG Advanced Institute of Technology (South Korea); T. Gessmann, E. F. Schubert, Rensselaer Polytechnic Institute

Experimental results on a new type of light-emitting device, the light-emitting triode (LET), are presented. The LET is a three-terminal p-n junction device that accelerates carriers in the lateral direction, i.e. parallel to the p-n junction plane, by means of an electric field between two anodes. The lateral field provides additional energy to carriers thereby allowing them to overcome barriers and increasing the carrier injection efficiency into the active region. LETs were fabricated using a ultraviolet LED structure that has an AlGaN/GaN superlattice in the p-type confinement region for high-conductivity 2 dimensional hole gas. LET mesa structures were obtained by standard photolithographic patterning followed by chemically-assisted ion-beam etching using Cl2 and Ar to expose the n type cladding layer. The n-type contact was fabricated by electron-beam evaporation of Ti/Al/Ni/Au. Ni/Au (50/50 ≈) metallization was deposited for both anodes, Anode 1 and Anode 2, and subsequently annealed at 500 C in an O2 ambient. It is shown that both the current between Anode 1 and the cathode, and the light-output power increase with increasing negative bias to the Anode 2. This is consistent with the expectation that a negative bias to the second anode allows carriers to acquire a high kinetic energy thereby enabling them to overcome the barrier for holes, resulting in high injection efficiency into the active region that lies beyond the barrier.

6134-29, Session 5

InN-on-Si heteroepitaxy: growth, optical properties, and applications

S. Gwo, C. L. Wu, C. H. Shen, H. W. Lin, H. Y. Chen, H. M. Lee, National Tsing Hua Univ. (Taiwan)

Because of its direct band gap at ~0.65 eV and superior electronic transport properties (small effective mass, high mobility, and large drift velocity), indium nitride (InN) heterostructures are promising building blocks for near-infrared light-emitting devices, solar cells, and high-speed/high-frequency transistors. To realize these applications, it is important to grow InN heterostructures with high crystalline quality, atomically abrupt interfaces, and large band offsets. The heterojunction formed between InN and AlN is particularly interesting because of a large band gap difference (0.65 vs. 6.2 eV). However, the large differences in lattice parameters (~12% for InN grown on AlN) and the lack of III-nitride substrates post daunting challenges for growing high-quality InN/AlN heterostructures. We report here the growth and properties of the 8:9 commensurately matched InN/AlN heterojunction as well as vertically aligned InN nanorod array deposited on the Si(111) substrate by plasma-assisted molecular-beam epitaxy (PAMBE). By using the techniques of in-situ reflection high-energy electron diffraction (RHEED) and ex-situ transmission electron microscopy (TEM), we have found that the pseudomorphic to 8:9 commensurate lattice transition occurs within the first monolayer growth of InN on AlN. As a result, the InN/AlN heterojunction can be made perfectly commensurate at the atomic level. Furthermore, very large heterojunction band offset and type-I band alignment have been confirmed by X-ray photoelectron spectroscopy. Due to the excellent structural and electronic properties, we propose that the InN/AlN heterojunction technology can provide a platform for future InN device applications.

6134-21, Session 6

Fabrication and simulation of ultraviolet AlGaInN light-emitting diodes

S. H. Yen, B. Chen, M. Chen, Y. K. Kuo, National Changhua Univ. of Education (Taiwan); Y. Chang, H. Kuo, National Chiao Tung Univ. (Taiwan)

Ultraviolet AlGaInN light-emitting diode (LED) is grown on a c-face sapphire substrate by low-pressure horizontal-flow metalorganic chemical vapor deposition (MOCVD). With increasing input current from 10 to 100 mA, the main peak of the emission wavelength shifts from 368 to 372 nm. The room-temperature output power is 0.8 mW at 20 mA. Under continuous-wave operation, an output power of 4 mW is achieved at a driving current of 125 mA. The simulation program, advanced physical model of semiconductor devices (APSYS) which is developed by Crosslight Inc., is used to fit in our experimental results in order to obtain an optimized structure. The device performance affected by piezoelectric and thermal effects is studied via drift-diffusion model for carrier transport, optical gain and loss. The optical gain from photon generation is mainly due to the spontaneous emission of LED. The optical loss comes from the heat flow which includes the Joule heat, recombination heat and Thomson heat. The optical performance of the ultraviolet LEDs of different numbers of quantum wells at various temperatures is numerically investigated. Preliminary simulated results indicate that when the number of quantum wells is 5 to 7, better output performance is obtained. The further work of size-dependence structure and energy barrier height of electronic blocking layer will be investigated. It can be expected that the barrier height of electronic blocking layer will be increased gradually if the device temperature is increased. The internal quantum efficiency of various structures at different temperatures will be investigated too.

6134-22, Session 6

Improvement of ultradeep ultraviolet light-emitting diodes with asymmetric active region

M. Huang, C. Lu, National Changhua Univ. of Education (Taiwan)

Ultra-deep ultraviolet AlGaN light-emitting diodes (LEDs), emitting at 253.7 nm, can be used to pump traditional fluorescent lamp phosphors and is expected to replace toxic low-pressure mercury lamps in the future. However, owing to large spontaneous polarization and piezoelectric coupling

fields, the band diagrams of quantum wells become tilted and the properties of AlGaN LEDs are hence degraded. In our previous work, we have theoretically shown that the optimized quantum well structure is to use one quantum well with a width of 1~3 nm and a barrier with small Al composition.

In this paper, we further employ the asymmetric active region to reduce the polarization charges in the barrier-well interface and modify the band structure to enhance the power efficiency of the AlGaN LED. By increasing the thickness of barrier, which is close to the p-doping layer side only, from 5 nm to 15 nm, the deformation slope of conduction band across the well region is reduced due to the reduction of polarization effect. Accordingly, the hole concentration is increased and the carrier distributions are more uniform caused by the declined polarization field in the well. Therefore, a higher recombination rate and a higher output power can be obtained. Moreover, if a linearly graded well structure is utilized to compensate for the different band offset between barriers and well interfaces, the power efficiency can be further improved due to the enhanced hole concentration and uniform carriers distribution in the well.

6134-23, Session 6

Reliability of AlGaN-based deep UV LEDs on sapphire

M. Shatalov, Z. Gong, M. Gaevski, S. Wu, W. Sun, V. Adivarahan, A. M. Khan, Univ. of South Carolina

Deep UV LEDs emitting at on 280 nm with powers as high as 1 mW at 20 mA have been reported recently. These devices have mesa size of 100um x 100um to avoid current crowding due to the high Al-composition of the AlxGa1-xN buffer layers. Small mesa size results in pump current density of 200 A/cm2 for a device current of 20 mA. Small area of p-contact also leads to higher operating voltage and higher thermal impedance for the flip-chip packaged device. These factors limit the device lifetime for 50 % power reduction to only a few hundred hours.

From temperature and bias dependent power degradation measurements we found the output power to decay with two characteristic time constants indicating two degradation mechanisms. The faster time constant is bias dependent and temperature independent. The slower time constant varies exponentially with junction temperature having the activation energy of 0.28 eV at 200 A/cm2 pump current density. For the devices with high thermal impedance this degradation mechanism controls the long term power degradation.

To increase the device area for better reliability we used the interconnected micro-pixel device design with 10x10 array of 22um in diameter pixels. This design allowed for the four-fold increase of the junction area and thereby led to improved reliability performance with the operation life-time for 50 % power reduction of about 1000 hours.

In this paper we will present the details of the reliability measurements and use the experimental results to determine possible degradation mechanisms.

6134-30, Session 6

Aluminum nitride substrates for ultra-violet LED development

L. J. Schowalter, Crystal IS, Inc.

No abstract available

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6135-01, Session 1

Enhancement of the characteristics of LCDs by doping nanoparticles: reduction of operating voltage, viscosity, and response times

S. Kobayashi, Tokyo Univ. of Science (Japan); S. Sano, Ube Material Industries, Ltd. (Japan); T. Miyama, Tokyo Univ. of Science (Japan)

Physical properties of nanoparticle doped LCD cells, such as their dielectric anisotropy, birefringence, elastic constant Ki, viscosity, and response time, threshold voltage, operation voltage, and so forth, are more or less modified from those of a LCD cell with pure LC host material.1) A similar effect occurs when a polymeric nanostructure is introduced into an LCD; e.g. in an FLC a PSV-FLCD is produced.2) We have explored both metal nanoparticles and a series of inorganic nanoparticles including MgO. In the present paper, we report a result using inorganic nanoparticles. As a result, it is shown that doping MgO nonaparticles, which are synthesized by Ube Material Ind. (10nm size), produces the following enhancement in a TN-LCD cell with 5CB: operation voltage by 26%; viscosity by 10%; response time, particularly delay time 8%, this in turn results in the enhancement of optical throughput by 20% or more for a driving waveform at 100Hz with 1.5V. The magnitudes of these reductions generally depend on the combination of the material of nanoparticles and those of host LCs. Through those investigations, it is shown that the effects of doping inorganic nanoparticles into LCD cells completely different the case of metal nanoparticles are used.

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6135-02, Session 1

Wide-viewing angle IPS-LCD for TV applications using optical compensation technology

D. Kajita, I. Hiyama, Y. Utsumi, Hitachi, Ltd. (Japan); M. Ishii, K. Ono, Hitachi Displays, Ltd. (Japan)

Recently, various LCD modes have been proposed to enhance the viewing angle of LCDs including the IPS mode, Vertical-Aligned (VA) mode and Optically-Compensated-Bend (OCB) mode.

We have developed IPS-LCDs for TV use, which have excellent viewing angle performance except for low gray level images such as used in horror movies. Therefore, by overcoming this weak point, IPS-LCDs would be suited to TV use exceeding that for all other LCDs.

Our studies have attributed this weakness to light leakage and a color shift at an oblique angle in the black representation. We have clarified that the viewing angle property in low gray level images in IPS-LCDs is affected by not only the intrinsic property of polarizers but also unnecessary retardation due to the polarizers and liquid crystal layer. We have developed the optical compensation technology for IPS-LCDs with one biaxial film to deal with these issues.

It was found that the achievement of the high contrast ratio (CR) and the low color shift at an oblique angle at the same time was difficult. To overcome the difficulty, new cell technology (IPS-Pro) which enhances the CR in all viewing angles has been developed together with the improvements in the optical compensation method.

32-inch IPS-LCD has been newly developed, using our solution. Minimum contrast ratio and the maximum color shift Du fv f in the black state in all viewing angles has been improved to over 4 times and 2/3 compared with the conventional.

In our paper, we compare the viewing angle characteristics of the conventional IPS-LCD and the new one, and we describe the compensation mechanism.

6135-03, Session 2

High performance TAC film for LCDs

H. Mori, Fuji Photo Film Co., Ltd. (Japan)

TAC (tri-acetyl cellulose) films are widely used as a protective film for polarizers because it has high light transmittance, low birefringence, high moisture permeability, high uniformity and good curling property. This paper describes TAC film technologies, especially about the birefringence control of TAC film. Making use of the controlled birefringence, the TAC film comes to take an active role in optical compensation of LCDs as well as protection of polarizers. The out-of-plane birefringence of the TAC film can be controlled by additives, and the in-plane birefringence can be controlled by stretching. Coating a discotic material on the TAC film gives an additional optical compensation layer. With these technologies, we were able to develop an optical compensation film called WV film, which remarkably improves the viewing angle characteristics for TN-LCDs. Recently, we have developed and commercialized a new WV film for the OCB mode. OCB is known to have a very fast optical response time and promising as a next generation LCD-TV. The OCB-WV film has realized excellent viewing angle characteristics for OCB as well as a high on-axis contrast ratio. TAC film technologies open up possibilities of developing various types of optical compensation films suited for all LCD modes.

6135-04, Session 2

The use of germanium liquid crystals in the quest for perfect ferroelectric liquid crystal displays

M. D. Wand, LC Vision, LLC; K. M. More, W. N. Thurmes, Displaytech, Inc.

Commercialization of FLC-based displays has been a goal for many companies throughout the past two decades. Advances in FLC materials and cell design have lead to breakthroughs in FLC operating and storage temperature range as well as LC alignment quality.

Novel FLCs incorporating silicon and fluorine into their structure have been designed and synthesized. They have been shown to effectively lower melting point while still retaining, or increasing the SmC* upper temperature range.

The automation of LC measurement and evaluation has proved to be a key step in dramatically enhancing the speed of LC compound and mixture development. We will briefly touch on the instrumentation used.

We also will describe a new class of FLC materials that do not show the typical shrinking effect upon cooling, leading to defect minimization. X-ray data will be presented that demonstrates near bookshelf behavior. The high quality alignment afforded by these mixtures will be demonstrated in an SXGA LCOS panel. In addition, the fast switching speed that these new FLC mixtures afford allows operation in the field sequential color mode with no blurring or other color artifacts.

6135-05, Session 2

Optical microscopy studies of polymer/liquid-crystal composites

D. A. Higgins, Kansas State Univ.

Static and dynamic near-field scanning optical microscopy (NSOM) and multiphoton-excited fluorescence microscopy (MPEFM) methods are used to study physical phenomena associated with the photorefractive effect in dye-doped polymer dispersed liquid crystals (PDLCs). Micrometer-sized LC droplets doped with electron donor and acceptor are studied. Simultaneously-recorded topographic, fluorescence and birefringence NSOM images show the films to be morphologically complex, containing ellipsoidal and collapsed ellipsoidal droplets. Fluorescence NSOM images prove the dye is contained within well-defined LC droplets. Data on the local ion migration and LC reorientation dynamics are obtained by dynamic NSOM imaging methods. MPEFM studies provide supporting information on field-induced LC reorientation and relaxation. Dynamics images recorded before, during, and after photogeneration of ions show spatial variations in the ion generation and migration dynamics and the LC orientation state. Finite difference time domain methods are used to simulate the field-dependent ion dynamics and the subsequent LC response. This model provides a detailed picture of the local dynamics behind the photorefractive effect in PDLC materials.

6135-07, Session 3

A new method for simultaneous measurement of phase retardation and optical axis of a compensation film

Y. Wu, J. Lee, Y. Lin, H. Ren, S. Wu, College of Optics and Photonics/Univ. of Central Florida

Phase compensation films have been commonly used for improving the viewing angle and contrast ratio of liquid crystal display devices. For a compensation film, the refractive indices and optical axis need to be specified. Several methods, such as Soleil-Babinet compensator and photoelastic modulator, have been developed for measuring the phase retardation value of a phase compensation film. The former is a mechanically adjustable retardation plate using two crystal wedges. The latter is an electrically controllable compensator. By analyzing the modulated signal from photoelastic modulators, we can determine the phase retardation information. The major shortcoming of these methods is that they cannot determine the retardation and optical axis simultaneously.

In this paper, we develop a new method for simultaneous detection of phase retardation and optical axis of a phase compensation film using an axially-symmetric Sheared Polymer Network Liquid Crystal (SPNLC). The axially-symmetric SPNLC exhibits two unique features: 1) its optical axis is radial in all directions, and 2) its phase retardation has a gradient distribution from center to edges. In experiment, we first characterize the phase retardation profile of our axially-symmetric SPNLC film. Then we overlay a phase compensation film, whose retardation value and optical axis are yet to be determined, on top of our SPNLC film. The transmitted image between crossed polarizers is recorded by a CCD camera. After analyzing the compensation pattern of the CCD image, we can precisely identify the phase retardation value and optical axis of the tested phase compensation film. To demonstrate this powerful technique, we use a quarter-wave plate with an arbitrary axis as an example to illustrate the measurement principles. Excellent agreement between experiment and simulation is obtained. This new method is particularly useful for those optical systems whose optical axis and phase retardation are dynamically changing.

6135-08, Session 3

Advances in OCB mode LCDs: improvement of moving picture quality and control of bend alignment

H. Wakemoto, K. Nakao, A. Takimoto, Toshiba Matsushita Display Technology Co., Ltd. (Japan)

Toshiba Matsushita Display Technology (TMD) has firstly succeeded in mass production of OCB (Optically Compensated Bend) mode liquid crystal display panels which have excellent moving picture quality almost the same as CRT.

The OCB mode requires complete transition from initial splay to bend alignment in all pixel of the LCD. It was one of the most difficult problems to put OCB mode LCD to practical use. To solve this problem, we have developed a new bend transition method using twisted electric field. We researched the bend transition behavior, so the relation to the properties of the liquid crystal materials and the device parameters were clarified.

In OCB mode LCD, maintaining the bend alignment with stability is important as well as the bend transition. Then, we researched the stability of the bend alignment in relating to the black insertion driving (i.e. dynamic driving) for eliminating of the moving picture blur. We have investigated the difference of bend stability between static driving and dynamic driving. We found out that bend stability with dynamic driving is related to the electric field response of bend and splay domain. The liquid crystal response of the bend state is much faster than that of the splay state. Furthermore, we enabled estimation of bend stability from physical constants of liquid crystal materials and cell parameters.

6135-09, Session 3

Novel U-shaped liquid crystals for electro-optic devices

A. Yoshizawa, Hirosaki Univ. (Japan)

We reported a U-shaped molecule that induces a smectic-like layer ordering in the nematic phase and noted possibility that the nematic (N) phase has biaxiality. A polar U-shaped system is expected to induce unusual dipole ordering in a nematic phase of a mixture consisting of a host liquid crystal and the U-shaped compound. Furthermore, coupling between a U-shaped system and chirality can produce new physical properties in liquid-crystalline phases. We would like to report here novel molecular design for electro-optic liquid crystal devices, i.e. catechol derivatives for reduction in threshold voltage and binaphthyl derivatives for blue phases with wide temperature range.

Reduction in driving voltage is one of the most important problems for improvement of liquid crystal displays (LCDs). Liquid-crystalline materials with high dielectric anisotropy (De) are known to decrease the threshold voltage. On the other hand, a high voltage holding ratio (VHR) of liquid crystalline materials is also necessary for display applications. However, a compound possessing a polar group, i. e., -CN, decreases VHR. Thus, general molecular design for the liquid crystalline materials that reduce the threshold voltage is to introduce fluorine atoms at a ring, a side chain or a linkage group of a liquid crystalline compound. A novel U-shaped liquid-crystalline molecule where two polar mesogenic groups are connected via catechol, 1-{6-(3,4-difluorophenyloxy)hexyloxy}-2-{6-[4-(4-fluorophenyl)phenyloxy]hexyloxy}benzene, has been prepared and the electro-optic properties investigated. A threshold voltage of a nematic mixture consisting of a host liquid crystal and 10wt% of the U-shaped compound was markedly lower than that of the host LC. The U-shaped compound was found to induce higher De in the nematic phase of the mixture than the corresponding monomeric compound, indicating that the U-shaped molecule induces favorable dipole ordering in the nematic phase of the mixture. The U-shaped system is a novel approach for reduction in threshold voltage of liquid-crystalline materials.

Blue phases are of particular interest because they have a fluid lattice whose structure is stabilized by lattice defects. Appearance of blue phases results from the competition between the chiral twisting force and the

desire for molecules to pack in ways such that they fill space uniformly. From the view point of applications, blue phases are interesting for fast light modulators or tunable photonic crystals. However, the narrow temperature range is a critical problem. We prepared a homologous series of novel chiral dimeric compounds, (R)-2,2'-Bis{6-[4-(2-(2-fluoro-4-butyloxyphenyl)pyrimidine-5-yl)phenyloxy]alkyloxy}-1,1'-binaphthyl. The binaphthyl derivatives with an even number of atoms in the spacers showed a chiral nematic phase, however, those with an odd number of atoms showed a blue phase in a relatively wide temperature range between the isotropic and SmA phases. The present chiral U-shaped system is thought to be a new molecular design for appearance of blue phases.

6135-10, Session 4

Influence of morphology on the optical properties of photonic structures in holographic-polymer dispersed liquid crystals

R. Jakubiak, D. P. Brown, Air Force Research Lab.; L. V. Natarajan, Science Applications International Corp.; P. Lloyd, UES, Inc.; R. L. Sutherland, V. P. Tondiglia, Science Applications International Corp.; R. A. Vaia, T. J. Bunning, Air Force Research Lab.

Holographic polymerization of liquid crystal containing photopolymerizable resins (H-PDLCs) enables one-step, rapid formation of multi-phase structures that exhibit partial photonic band gaps. Although the low index contrast of organics precludes the formation of complete band gaps, 2-D structures create strongly coupled electromagnetic bands that lead to low group velocity dispersion over a wide range of wave vectors, termed the group velocity anomaly, and consequent local field enhancement. This is evidenced by the laser action achieved by an embedded laser dye, pyrromethene 597, in a 2-D columnar H-PDLC. Resolution limited linewidths as narrow as 1.9 nm are observed with laser thresholds below 1 mJ/cm2 in 2-D columnar structures compared to 9 nm and 25 mJ/cm2 thresholds observed in 1-D Bragg stacks. By changing the photopolymerizable monomer from an acrylate to a thiol-ene based system, the LC-droplets became more spherical and evenly spaced with a commensurate improvement in electro-optic properties. Distributed feedback lasers formed from the thiol-ene H-PDLCs exhibit lower switching voltages and wider wavelength tunability. This can be understood by examining the morphology of the LC-polymer interfaces and the LC-droplet dispersion.

6135-11, Session 4

Potential applications of nematic liquid crystal materials in the millimeter wave region

T. Nose, S. Saito, S. Yanagihara, M. Honma, Akita Prefectural Univ. (Japan)

Large tunable properties induced by the change of LC molecular orientation states can be expected for wider frequency region except for visible rays. Focusing on the millimeter wave (MMW) region, a novel measurement method for LC materials is investigated using the rectangular waveguide test cell and several commercially available nematic LC materials have been actually evaluated for V-band (50GHz-75GHz) and W-band (65GHz-110GHz) regions. Refractive indices for the direction parallel to the LC molecular orientation in the MMW region are almost the same with that in the visible rays, on the other hand the indices for the direction perpendicular to the LC orientation show a little larger value. Consequently, refractive index anisotropy which is most important for the tunable LC devices reduces to be 1/2 through 1/3 of that in the visible rays. Although the larger refractive anisotropy is desired for the better performance, the anisotropy of the usual LC materials is still large and the loss properties are fairly good.

Based on the materials data, we have investigated the CPW type LC devices combining with an ITO glass substrate on it. Phase and amplitude changes of the transmitted MMW by the LC driving are investigated considering with the influences of the upper substrate and electrode to improve the transmission properties of the MMW. Molecular orientation effects in the CPW cell are also investigated to improve the LC driving electrode structure.

6135-12, Session 4

Switchable lasing configurations using structures of liquid crystal and polymer dispersions

S. J. Woltman, M. E. Sousa, G. P. Crawford, Brown Univ.; H. Zhang, Scientific Solutions, Inc.

We investigate the fabrication of holographic polymer dispersed liquid crystals (H-PDLCs) for use as switchable laser cavities. H-PDLCs are liquid crystal and polymer dispersions used in grating applications for displays, optical communications and optical security. By controlling the pitch of the H-PDLC and the laser dye used, we are able to fabricate a tunable laser. H-PDLCs were made in both reflection and transmission modes to vary the method by which lasing action occurs. The dye-doped H-PDLCs were pumped with nanosecond pulses from a laser with emission at 532 nm and a power of approximately 4.5 mJ. Lasing action was observed using a spectrometer at several locations inside and out of the H-PDLC grating; peak wavelengths occurred between 590 nm and 605 nm with the full width of the emission peaks approximately 6-8 nm at half maximum. The lasing action can be turned on and off by the application and removal of an electric field due to the properties of an H-PDLC. Furthermore, we investigate multidimensional architectures, quasicrystal symmetries, and slanted configurations for lasing applications. Applications for these cells include use in small-scale portable devices requiring a tunable laser source.

6135-13, Session 4

Transmissive spatial light modulators with high figure-of-merit liquid crystals for foveated imaging applications

J. L. Harriman, Boulder Nonlinear Systems, Inc.; S. Gauza, S. Wu, College of Optics and Photonics/Univ. of Central Florida; D. V. Wick, Sandia National Labs.; T. Martinez, Naval Research Lab.; D. Payne, Narrascape; S. A. Serati, Boulder Nonlinear Systems, Inc.

Unique liquid crystal (LC) spatial light modulators (SLMs) are being developed for foveated imaging systems that provide wide field-of-view (FOV) coverage (±60 in azimuth and elevation) without requiring gimbals or other mechanical scanners. Recently, a transmissive-SLM-based system operating in the visible (*=532 nm) has been demonstrated. The LC SLM development is addressing implementation issues through the development of high figure-of-merit (FoM) liquid crystal materials and transmissive high-resolution SLMs. Transmissive SLM operation allows the foveated imaging configuration to be very compact using a very simple lens system. The reduction in the size, weight and cost of the imaging optics and in data acquisition/processing hardware makes the foveated approach attractive for small platforms such as unmanned airborne vehicles (UAVs) or missile seekers.

6135-14, Session 5

Recent progress in liquid crystal THz optics

C. Pan, R. Pan, National Chiao Tung Univ. (Taiwan)

In the past decade, THz studies ranging from investigations of ultrafast dynamics in materials to medical, environmental sensing and imaging have been actively explored. For these and future applications in THz communication and surveillance, quasi-optic components such as phase shifters are indispensable. The birefringence of liquid crystals (LCís) is well known and extensively utilized for the manipulation of optical radia-

tion in the visible and near-infrared range. Recently, there have been increasing interests in the study of liquid-crystal-based devices for application in the sub-millimeter wave or THz (1 THz = 10**12 Hz) frequency range. In this talk, we present recent progress in liquid crystal THz optics from our group. Using time-domain THz spectroscopy, we have determined the complex indices of refraction of a nematic liquid crystal, 5CB, PCH5 and E7 from 0.2 to beyond 1 THz for the first time. Significantly, the birefringence of 5CB and E7 are as large as 0.2 at THz frequencies, while the absorption is negligible. Electrical-field and magnetic-field-controlled birefringence in LC were also reported. Our work clearly demonstrates the device potential of liquid crystal devices. A tunable room-temperature THz phase shifter using magnetic-field-controlled birefringence in nematic 5CB gives a phase shift as large as 108 degrees at 1.0 THz. Phase shift exceeding 360 degrees at 1 THz, an important milestone, was realized by using a sandwiched LC (E7, Merck) cell as thick as 3 mm. The phase shifters were used to construct Tunable THz Lyot filters Finally, we will present results on control of enhanced THz transmission through a metallic hole array with nematic liquid crystals.

6135-15, Session 5

Achromatic linear polarization switch for near infrared

A. B. Golovin, O. P. Pishnyak, S. V. Shiyanovskii, O. D. Lavrentovich, Kent State Univ.

We developed a broad band achromatic linear polarization switch for visible and near infrared radiation. Proposed switch based on twisted nematic cells filled with dual frequency nematic material. Cells are capable of fast switching of linearly polarized light between two orthogonal planes with a time response of millisecond range. Our achromatic linear polarization switch can be used in spatial light modulators, beam deflectors, liquid crystal displays, and projectors.

6135-16, Session 5

Molecular orientation effects in the CPW type LC devices for MMW phase shifting

T. Nose, S. Yanagihara, M. Honma, Akita Prefectural Univ. (Japan)

Molecular orientation states in the liquid crystal (LC) cell can easily be deformed by applying low driving voltage with low power consumption. This future is also attractive for the various functional devices in the millimeter wave (MMW) region, although only the display application is well known.

Waveguide systems are well investigated to make a low loss circuit in the ultrahigh frequency region such as microwaves and millimeter waves, and then the LC devices utilizing the waveguide have been proposed so far. However, the planar waveguide has gathered more attractions for wider functionality by integration. We adopt here a coplanar waveguide (CPW) substrate to prepare the planar type of LC MMW devices combined with an ITO substrate. Since the ITO film acts as a floating electrode to simplify the electrode structure, LC molecules can be driven by applying the voltage only to the CPW substrate. Unfortunately, since the ITO electrode on the CPW for LC driving tends to decrease the transmission of the MMW, the molecular orientation effects related with the electrode structure are investigated in detail to minimize the electrode area by using a polarization microscope. It becomes clear that only the narrow area above the signal electrode of the CPW affects strongly to the phase change of the MMW propagation in the CPW type LC cell. Although further improvements of the cell materials and structures are necessary for lower loss properties, at least 10 degrees of phase sifting properties can be obtained at 15GHz with the LC propagation length of 10mm and its thickness of 10 micrometers.

6135-17, Session 5

Optical behaviour of hybrid LC/inorganic nanostructures

N. G. Wakefield, A. C. van Popta, M. J. Brett, J. C. Sit, Univ. of Alberta (Canada)

Porous thin films of dielectric materials have been deposited using e-beam evaporation onto substrates held at highly oblique angles (\> 80∞), coupled with simultaneous computer controlled substrate motion about two independent axes. This technique, known as glancing angle deposition (GLAD), enables the formation of shaped, isolated nanostructures, including vertical posts, zig-zags, and both helical and polygonal spirals. GLAD films are used to form the backbone of liquid crystal (LC) hybrid optical materials and devices, and afford key advantages. The porous nature of the GLAD structures allows LCís to uniformly penetrate the film and modify its optical properties. Addition of LCís to GLAD films improves the properties of the films by reducing optical scattering, enhancing transmission, and accentuating existing chiral and linear optical anisotropies. Further, the dielectric columns of the GLAD film induce alignment and long range order in the LCís throughout the entire volume of the film, allowing one to engineer the structure of the LC network itself. This long range ability to tailor the LC structure offers advantages and greater control over more traditional methods of inducing LC order and alignment via substrate surface treatments alone. It has been found that addressing hybrid GLAD films with an electric field reorients the LCís, allowing one to switch the optical properties of the composite film. Using results based on spectroscopic ellipsometry and spectrophotometry, we will discuss the optical properties and switching behaviour of LC hybrid GLAD films employing both novel LC filling protocols and sophisticated GLAD film architectures.

6135-18, Session 6

Electronic and ionic conduction in liquid crystals

J. Hanna, Tokyo Institute of Technology (Japan)

Since the first electronic conduction was established in discotic and semectic liquid crystals in 1990s, the liquid crystal has attracted a new attention as a self-organizing molecular semiconductor. In this decay, the experimental and theoretical understandings about electrical properties of liquid crystals have been accumulated, and thus, we come to recognize the intrinsic nature of their electrical properties. In this talk, we discuss the electronic and ionic conduction in liquid crystals, leading to their scope and limitation as a quality organic semiconductor for opto-electronic device applications.

6135-19, Session 6

Liquid crystalline supramolecular polymers formed via complementary nucleobase pair interactions

P. T. Mather, Case Western Reserve Univ. and Univ. of Connecticut; S. Sivakova, Case Western Reserve Univ.; J. Wu, Univ. of Connecticut; C. Campo, S. J. Rowan, Case Western Reserve Univ.

We report on the effect of placement of nucleobase units, thymine or N6-(4-methoxybenzoyl)-adenine onto the ends of the mesogenic and fluorescent core: bis-4-alkoxy-substituted bis(phenylethynyl)-benzene (AA and BB type monomers). We show that addition of these bulky polar groups significantly reduces the range of liquid crystalline behavior but that mixing two complementary nucleobase-containing monomer units together yields stable thermotropic liquid crystalline phases. Hydrogen bonding is shown to play an important role in the formation of these LC phases consistent with the formation of oligomeric or polymeric hydrogen bonding aggregates. X-ray analyses of these mixed materials are consistent with the formation of Smectic-C phases. In addition, we report the preparation

of AB-type monomers in which a thymine unit is placed at one end of a 4-alkoxyphenyl 4-[4-alkoxyphenyl]benzoate core and N6-(4-methoxybenzoyl)-adenine is placed on the other end. While this compound does not show any liquid crystalline properties it does exhibit some basic polymeric properties, i.e. fiber formation.

6135-20, Session 6

To be announced

Y. B. Kim, Konkuk Univ. (South Korea)

No abstract available

6135-21, Session 7

2D/3D switchable displays

T. Dekker, S. De Zwart, O. Willemsen, Philips Research Labs. (Netherlands)

A prerequisite for a wide market acceptance of 3D displays is the ability to switch between 3D and full resolution 2D. In this paper we present a robust and cost effective concept for an auto-stereoscopic switchable 2D/3D display. The display is based on an LCD panel, equipped with switchable LC-filled lenticular lenses. A demonstrator proofing this concept has been made. We will discuss measurements and numerical simulations of the key optical characteristics of this display. The switching characteristics of LC-filled lenticular lenses are discussed and the overlap of the view distributions is introduced as a figure of merit for crosstalk between views. Finally, a new concept to improve the brightness non-uniformity of the screen will be discussed.

6135-22, Session 7

Designing rules for weak anchoring nematic mixtures used in bistable displays

D. N. Stoenescu, D. Gallaire, L. Faget, S. Lamarque-Forget, S. Joly, J. Dubois, P. Martinot-Lagarde, I. Dozov, Nemoptic (France)

BiNem is a bistable nematic LCD technology offering ultra-low power consumption without multiplexing ratio limitations. The two nematic bistable textures, different by almost p-twist, are obtained using simple monostable anchorings. The in-plane bistable textures give excellent optical properties : high contrast and large viewing angle without optical compensation films. Bistable gray levels are easy to obtain and control.

The switching between the bistable textures is achieved by breaking the surface anchoring on one of the plates. The voltage threshold depends mainly on the zenithal anchoring strength. For this reason the BiNem technology needs specific low anchoring materials-alignment layers and nematic mixtures.

We developed several alignment polymers giving weak anchoring. Here, we focus mainly on the advances in liquid crystal mixtures with weak zenithal anchoring. We confirm experimentally that the anchoring strength of a nematic mixture is a linear function of the anchoring strength of the components. This model allows to predict the anchoring strength of a mixture by study of pure compounds.

We established the design rules for low anchoring strength mixtures. Our work demonstrates the way to achieve nematic mixtures with weak zenithal anchoring, high dielectric anisotropy, optimized birefringence and high electrochemical reliability in a wide temperature range for bistable displays.

6135-23, Session 7

A novel WV film for fast-response-time OCB-LCD

R. Matsubara, Y. Ito, S. Nakamura, H. Mori, K. Mihayashi, Fuji Photo Film Co., Ltd. (Japan)

We have successfully developed and commercialized an optical compensation film for OCB-LCD mode(OCB-WV film). OCB-LCD mode is known to have a very fast optical response time and makes next-generation fast-response LCD-TVs possible and free from image blurring. The OCB-WV film, which has a simple structure composed with TAC(tri-acetyl cellulose) film and PDM(polymerized discotic material) layer, can realize the widest viewing angle of OCB-cell very well. In order to provide the best performance of OCB-cell, we optimized an optical parameter of not only WV film but also OCB cell by numerical simulation. In this paper, we will discuss a concept of its optimization, which provide excellent results of a numerical simulation.

6135-24, Session 7

Lasing in a wide-temperature range liquid crystal blue phase I

M. N. Pivnenko, A. D. Ford, H. J. Coles, Univ. of Cambridge (United Kingdom)

Organic lasers, particularly photonic-band-edge liquid crystal lasers, broaden horizons for optoelectronic and photonic devices. A new generation of micron sized continuously tunable lasers based on ordered organic chiral structures show large coherence areas and high slope efficiencies. Here we report mirror-less photonic-band-edge lasing in recently discovered dimeric or bimesogenic liquid crystals exhibiting a wide temperature range blue phase I[1,2]. A mixture of three symmetric liquid crystal dimers doped with a small percentage of a highly twisting chiral additive and fluorescent DCM dye showed typically the following phase sequence on cooling (∞C): Iso* 56.9 BPIII* 56.7 BPII* 56.2 BPI* 16.5 SmX* -28 Glass in a conventional 7 μm thick liquid crystal cell with no aligning layers. The sample was pumped using a focused Nd: YAG laser (λ=532 nm) which emits 6 ns long pulses at a repetition rate of 1 Hz. At the sample the spot size of the pump laser is estimated to be 160 μm in diameter. We observed a sharp lasing peak at the low energy band edge (570 nm) of a single BPI* domain with a (110) orientation. The excitation threshold was estimated to be 1 μJ per pulse, which is comparable with the threshold for helical cholesteric samples with the same dye concentration and excitation conditions. Ways and means to widen the spectral range of lasing, electrical tunability and possible applications for dye-doped blue phase lasers will be discussed.

1. H.J. Coles, M.N. Pivnenko and J.P. Hannington, pending GB Patent Application 0402006.1, filed 30.01.2004.

2. H.J. Coles and M.N. Pivnenko, “Liquid crystal ëblue phasesí with a wide temperature range”, Nature, August 2005.

6135-25, Session 8

Doubling the output power of dye-doped cholesteric liquid crystal lasers

Y. Zhou, Y. Huang, A. Rapaport, M. A. Bass, S. Wu, College of Optics and Photonics/Univ. of Central Florida

Dye-doped cholesteric liquid crystals (CLC) have attracted a lot of research interests because of their low threshold and mirrorless lasing action. Usually, a circularly polarized laser light is emitted from both directions of the lasing cell along the cholesteric helical axis. In reality, only the laser light from one direction is fully utilized.

In this paper, we demonstrate a simple method for doubling the laser output of a dye-doped CLC laser. Although the intrinsic pumping efficiency remains the same, the extracted laser output is nearly doubled. In experiment, we use a 6-ns, frequency-doubled Nd:YAG laser to pump the CLC lasing sample at ~20 degree incident angle. A reflector: a metal mirror or a cholesteric liquid crystal reflector is placed on the backside of the CLC sample. The reflector is in proximity contact with the CLC sample and the laser action occurs only in one direction. For the metal mirror reflector, the two orthogonal circularly polarized lights are mixed by incoherent superposition. While for the cholesteric liquid crystal reflector (same

handedness as the lasing cell and highly reflective of the laser light), the enhanced laser output could also be achieved except the output is dominated by a single polarization state. For this case the incoherent multiple reflections on the glass-CLC surfaces result in a dramatic increase in the transmittance of the circularly polarized laser light which is supposedly highly reflective by a single dye-doped cholesteric liquid crystal cell. For both cases the laser output is associated with a loss of coherence. Hence a nearly unpolarized CLC laser or a partially-coherent CLC laser with nearly doubled output intensity is obtained.

6135-26, Session 8

Ultrafast optical nonlinearity enhancement of azo-dye doped liquid crystals

L. Xu, X. Liu, L. Ji, L. Liu, Fudan Univ. (China)

Dye doped liquid crystals are known to enhance the orientation of liquid crystals with a factor 100 times higher when pumped by linearly polarized light. This kind of enhancement has been observed for different dyes due to various kinds of mechanism and could be very useful in achieving high nonlinearity and for the possibility of large area optical controlled orientation. On the other hand, optical induced orientation of liquid crystals in the isotropic phase reflects fundamental information about guest-host interaction which exists generally in physical and chemical systems.

Anthraquinone type molecule doped liquid crystal was found to be oriented because excited dye molecules react different with the liquid crystal molecules than ground state molecules do. Azo-dye doped liquid crystals also show enhanced orientation ability under cw optical pump because azo-dyes undergo photo-isomerization when they are resonantly excited. Trans molecules interact differently with liquid crystals than cis molecules do. However, up to now, no direct experimental data has been found in the ultrafast region (less than 1 nano-second) regarding the isomerization induced interaction is the same.

In this presentation, we will report on the new findings of ultrafast photo-isomerization induced liquid crystal orientation in its isotropic phase. Ultrafast optical Kerr effect measurement together with ultrafast photo-induced dichroism measurement were taken to understand the early dynamics of the system. We found that trans and cis molecules interact with liquid crystal molecules orthogonally. Thus, when dye molecules were excited, the orientation force to the liquid crystal molecules competes with each other and eventually reach a maximum at proper optical pump intensity. This is the first time that the ultrafast orientaion behavior is revealed.

6135-27, Session 8

Liquid crystal fresnel lens using a surface relief structure

D. Wang, L. Chien, Kent State Univ.

This paper describes a method of fabrication a polarization-independent liquid crystal Fresnel lens (LCFL) using a surface relief structure. The surface relief structure is molded onto substrate surfaces by photopolymerization of a polymer-precursor initiated by UV light with a lens mold. The surfaces of the lens mode are modified by the LC molecular alignment process to give optimum LC molecules alignment conditions. The optical and electro-optical properties of the fabricated LCFLs were experimentally determined. Good focusing properties are confirmed and the light intensity of the focusing spot is found to be controllable by adjusting applied voltage. By positioning two LCFL with careful alignment with respect to their focal length, we were able to obtain the optical properties of LCFL which is independent to the polarization state of incident light.

We demonstrate stacked LCFLs showing the focusing and defocusing effect responding to the applied field, which changes the effective refractive index of liquid crystal molecules in different regions of patterned surface structure.

6135-28, Session 8

Anisotropic layers in waveguides for mode tuning and tunable filtering

I. S. Abdulhalim, Ben-Gurion Univ. of the Negev (Israel)

Nowadays, a multitude of photonic switching technologies are candidates for all-optical networks, e.g. two- and three dimensional micro-electro-mechanical systems (MEMSs), electro-holography, thermo-optics, liquid crystals and acoustooptics; probably, in the future, a typical telecommunications system could make use of several levels of switching technology. At present, two principal categories of optical switches can be considered, i.e. free space switches and guided wave switches. Optical properties of thin anisotropic layers as part of an optical waveguide for tunability and switching will be described theoretically and experimental results will be presented for liquid crystals. The thin layer allows for fast switching, stability, less scattering and single mode operation over a wide spectral range. The dependence of the tuning range on the LC parameters, geometry and coupling parameters to the waveguide will be discussed. Clear distinction between TE and TM modes and the coupling between them will be presented.

6135-29, Session 9

Cross-display-technology video motion measurement tools

J. W. Roberts, National Institute of Standards and Technology

High performance video places severe demands on playback system and display device resources. Motion playback errors such as irregular motion playback and image breakup are common, making accurate measurement of motion critically important for device selection and system tuning to ensure the desired viewing experience. Direct observation of the actual displayed image (screen capture) is the only way to perform a complete end-to-end system test that accounts for all possible sources of motion errors, including original video capture, compression/decompression, playback system performance, and display device operation. Unfortunately for the development of measurement techniques, the fundamentally different ways that different display technologies present imagery can easily confound sensitive measurement techniques, producing measured playback performance differences across multiple display technologies (e.g. DMD, LCD, plasma, and CRT) that are disproportionately large compared to the actual differences (if any) seen by a human viewer. Cross-technology measurement tools are necessary to ensure the validity of measures across multiple technologies. The methods being used include a combination of test materials (both selected live video clips and synthetic clips), capture technique (including control of capture rate, triggering, and timestamping), and analysis. The NIST Motion Image Quality project uses a combination of quantitative measures and subjective analysis to evaluate motion imagery and to identify the factors that determine overall performance. The NIST project has conducted tests to measure (1) perceived image quality and (2) motion image interpretability, as a function of factors including compression, video motion and other scene content, playback system performance, and frame rate. Tests have been conducted using a variety of playback systems with different levels of performance, and using a variety of display technologies.

6135-30, Session 9

Visible laser and laser array sources for projection displays

A. V. Shchegrov, J. P. Watson, A. Umbrasas, D. Lee, G. P. Carey, S. Hallstein, R. Dato, R. F. Nabiev, S. G. Anikitchev, G. Giaretta, B. D. Cantos, W. R. Hitchens, M. Jansen, A. Mooradian, Novalux Inc.

Laser-based projection displays have long attracted interest because of the multiple advantages (expanded color gamut, high resolution, longer lifetime, etc.) expected from lasers compared to light bulbs. However,

most of these advantages have been largely negated by the significant cost, size, and cooling requirements associated with lasers, and their inability to produce red, green, and blue colors in the same platform. In this paper, we review the progress of different laser technologies aimed at projection display markets and introduce a new, laser array technology based of frequency-doubled, semiconductor, surface-emitting lasers. The key features of this technology such as demonstrated multi-Watt output for rear-projection TVs, power levels scalable with the number of emitters, speckle suppression due to multi-emitter array, and low-cost, compact design will be discussed in detail.

6135-31, Session 9

Vertical alignment of high-birefringence and negative dielectric anisotropic liquid crystals for projection displays

C. Wen, B. Wu, S. Gauza, S. Wu, College of Optics and Photonics/Univ. of Central Florida

For projection displays using homeotropic-alignment Liquid-Crystal-On-Silicon (LCOS) panels, a thin LC layer not only reduces the fringing field but also shortens the response time. To realize the advantages of the thin cell approach, the LC birefringence has to be increased in order to retain sufficient phase retardation. It is essential to develop high birefringence, large negative dielectric anisotropy ($\Delta\varepsilon$), and low viscosity LC mixtures for LCOS projection displays. However, some laterally fluorinated LC compounds are difficult to align. A poor molecular alignment leads to light leakage and degrades the contrast ratio.

In this paper, we develop a simple method for aligning the high birefringence (Δn~0.15 - 0.3) laterally difluorinated biphenyl, terphenyl, and tolane LC compounds. We investigated these compounds individually by filling them into a buffed polyimide VA cell. Since these compounds have different nematic range, we compare their electro-optic properties at the same reduced temperature (Tr=0.96). Here, the reduced temperature is defined as T/Tc. We found that the biphenyl compounds are much easier to align than terphenyls. Moreover, we formulate a LC host to align these high birefringence negative $\Delta\varepsilon$ LCs. By doping some positive or neutral LC materials into the host LCs, we obtain a very dark and sharp threshold. To understand the molecular alignment mechanisms, we evaporate a positive or a neutral LC compound onto a glass substrate and then fill in the negative LC compounds. We find that these agents form a monolayer to help align the negative LCs. This doping method is not limited by the molecular structure of polyimide. Moreover, by selecting a proper dopant the mixtureís figure-of-merit can be improved significantly.

6135-32, Session 9

Dual conical reflector systems with high coupling efficiency for projection displays

K. K. Li, S. Inatsugu, Wavien, Inc.

The dual paraboloid reflector system had been used efficiently to couple light from arc lamp into specific targets with higher efficiency than traditional parabolic and elliptical reflector systems. This improvement is not limited to dual parabolic, but can be extended to other conical reflector shapes in which the aberration and distortion from one reflector is compensated by the second reflector. This paper describes the basic operations of the dual paraboloid reflector system and the improvements using optimized reflector pair with this basic design. Another conical curve, the elliptical shape is also used. This dual ellipsoidal reflector is also described with 1:1 imaging properties and the effect of aberration and distortion corrections are shown. The used of these dual conical reflectors are also used to form retro-reflectors such that the brightness of the arc can be increased with multiple reflections.

6135-33, Session 9

Imaging properties of dual parabolic reflector and its application in lamp manufacturing

Y. J. Wang, S. Inatsugu, K. K. Li, Wavien, Inc.

The dual paraboloid reflectorís 1:1 imaging property allow higher coupling efficiency as compared to traditional parabolic and elliptical reflectors especially for small etendue system or burners with long arcs. The imaging properties of two conjugation focal points and their periphery areas were studied by ASAP simulations and observations. The reticle with grid patterns was generated using ASAP at the output focal plane using a standard grid pattern at the input focal plane. When the generated grid pattern was placed at the input focal plane and the standard grid pattern was observed at the output plane. The result confirms that the dual parabolic reflector can produce one to one image at the conjugated focal points, which is one of the basic reason of the benefits of dual parabolic reflector. In the periphery area at a distance away from the focus, the image is very much distorted. The image distortion was characterized. Based this distortion, a method to find the focal points of dual parabolic reflector was proposed. New lamp manufacture procedure and system were setup and tested based on the new method.

6135-41, Session 9

Low cost spatial color LCOS projection engine using automotive HID burners in dual paraboloid reflector system

K. K. Li, S. Inatsugu, Wavien, Inc.; H. S. Kwok, The Hong Kong Univ. of Science and Technology (Hong Kong China)

There is a very large market for extremely low cost projectors in which the costs of the image panel and burner have to be reduced significantly. Standard engine designs with UHP-type of burners will not meet the cost target. In this paper, an extremely low cost project engine is described, which uses a low cost spatial color LCOS panel, and an automotive HID burner as the light source. The spatial color LCOS panel provides a low cost approach to image forming and projection. The HID burner with a long arc gap, about 4.2 mm, allows low manufacturing cost. Although this long arc is not suitable for use with standard elliptical or parabolic reflectors, when used with the Dual Paraboloid Reflector system, the output efficiency is greatly enhance providing sufficient light for a practical low cost projection use. The construction of the system and preliminary performance will be described.

6135-34, Session 10

Highly efficient fluorescent materials and device structures for AM-OLED

S. Kim, H. Oh, M. Kim, Y. Han, LG Electronics Inc. (South Korea)

We obtained 30 cd/A for the fluorescent green (0.28, 0.63) and 10 cd/A (0.14, 0.15) for the fluorescent blue. The efficiencies are quite high with the external quantum efficiency being higher than 10%. The author will present on the materials, device structures and characteristics along with the AM-OLED program at LG Electronics.

6135-35, Session 10

To be announced

T. J. Marks, Northwestern Univ.

No abstract available

6135-36, Session 10

OLEDs for lighting: challenges and opportunities

P. Duine, Philips Central Development Lighting (Netherlands); D. Bertram, Philips Central Development Lighting (Germany)

Philips Lighting is developing OLEDs for flat diffuse lighting because it offers any 2D form, color, and, in the future, transparency and flexibility. The state-of-the-art devices are described (in terms of Lumen efficacy, brightness, and lifetime) with emphasis on the difference between a lighting application and a display application for OLEDs. Potential future markets (Automotive, Signage, and Luminance Lighting) are described and the state-of-the-art performance of OLEDs is compared with the existing solutions. Finally, a roadmap for OLED lighting is disclosed.

6135-37, Session 10

Circularly polarized luminescence from chiral thin films

B. S. Szeto, P. C. Hrudey, M. J. Brett, Univ. of Alberta (Canada)

Photoluminescent nanostructured thin films have been fabricated using physical vapour deposition and the glancing angle deposition (GLAD) technique. Precision controlled substrate motion and oblique incidence (\>80∞) enable fabrication of a variety of 3-D morphologies including vertical posts, helical (chiral) columns or chevrons. Scanning electron microscopy and X-ray diffraction are used to characterize the film nanostructure. These experiments focussed on the chiral morphology which exhibits intriguing polarization behaviour such as selective transmission of circularly polarized light and circular polarized photoluminescence. Helical films of Y2O3:Eu and other materials were fabricated with thicknesses in excess of 2 micrometres and densities nominally 60% of bulk. Transmission spectroscopic ellipsometry measurements were used to determine the degree of selective transmission of polarized light through the samples. The emission polarization from helical films was measured with the use of a quarterwave plate and linear polarizer. Polarized emission efficiencies were consistent with the observed selective transmission through the films. By using the GLAD technique to control the nanoscale morphology of the thin films, the spectral location and the chiral optical effects can be altered. Variation in the number of helical periods was found to affect the optical response. It is hoped that optimization of the chiral luminescence phenomena may enable new display architectures.

6135-39, Poster Session

Finite-difference time-domain method simulation of light propagation through H-PDLC film

K. O. Viacheslav, V. Y. Reshetnyak, National Taras Shevchenko Univ. of Kyiv (Ukraine); T. V. Galstian, Univ. Laval (Canada)

Holographic polymer dispersed liquid crystal(H-PDLC) material are formed exposing a light-sensitive monomer and LC mixture to an interference patterns. H-PDLC divided into polymer and LC-rich regions, thereby setting a periodic perturbation in refracting index of material. Therefore, the refractive index modulation, as well as the diffraction efficiency, of such H-PDLC materials strongly depends on LC droplet parameters. We obtained LC director orientation profiles inside droplet using a Lebwohl-Lasher lattice model of nematic LC, and minimize energy of the cell by Monte-Carlo method.

To describe the diffraction properties of anisotropic holographic gratings under the action of externally applied voltage we used coupled-wave theory[1], and compare it with rigorous full-wave simulation of light propagation through the H-PDLC device by means of the Finite-Difference Time-Domain (FDTD)[2] method. This method is a numerical approach for directly solving Maxwellís time-dependent curl equations in a three-dimensional domain with no other assumptions involved.

The results show how to obtain optimized conditions for high diffraction efficiency by adjusting the liquid crystal parameters, grating geometric structure, and applied voltages. The light propagation direction and efficiency can be accurately calculated and visualized concurrently.

1. G. Montemezzani, and M. Zgonik. Phys. Rev. E, 55, 1035-1047 (1997).

2. K. Yee, ìNumerical solution of initial boundary value problems involving Maxwellís equations in isotropic media,î IEEE Trans. Antennas Propag. 14, 302-307 (1966).

6135-40, Poster Session

Development of desktop display for collaborative tasks

K. Sakamoto, M. Yoshigi, M. Nishida, Shimane Univ. (Japan)

This paper describes tabletop display systems utilizing the stereoscopic 3D display technology. The authors have ever researched 3D display systems using the polarized glasses and liquid crystal shutter glasses, image splitter such as the parallax barrier or lenticular screen and holographic optical elements. These image splitting technologies for displaying stereoscopic 3D image are available for developing the tabletop display that can provide different images to different users surrounding the system.

The method of image separation is two types ie, type1 and type2. One is the method using glasses such as the polarized glasses and liquid crystal shutter glasses system, the other is the method no requiring the special glasses. Type1 display systems consist of a conventional glasses displaying system. These systems require viewers to wear special glasses to see different images. The image separation method is a conventional anaglyph(red/blue), polarized or liquid crystal shutter glasses. Type2 display systems are used image split techniques such as the parallax barrier or lenticular screen. Type2 displays are useful systems no requiring the special glasses. Moreover we proposed the enhanced glasses-free displays using the polarized slit method and holographic technology. A conventional image split method has disadvantage such that the resolution is reduced by half because each user only sees half the pixels. However newly proposed display can solve the problems of conventional display system because this display shows twice the image resolution by projecting two different images. The images projected by two projectors are separated different images to different users. Further, holographic screen can provide different images to more than 2 users.

These display systems can provide different images to another user surrounding the table. When the user-2 sits down opposite the user-1, each user must view the different image so as not to perceive upside down images. The display image consists of the text area and the regions of graphics image such as a figure and picture. Each user can view the graphics image at the same position on the table. Then each user can indicate the figures and pictures. The text character is automatically rotated inside the text area according to the viewerís position. Each user can understand the notes connected with the figure.

Conference 6136: Practical Holography XX: Materials and Applications

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6136-01, Session 1

Engineering applications of HOEs manufactured with enhanced performance DCG films.

C. G. Stojanoff, RWTH Aachen (Germany) and Holotec GmbH (Germany)

The scope of this presentation covers over a decade of research and development work on the improvement of the properties of DCG holographic materials conducted at the Aachen University of Technology and at Holotec GmbH. The objective of this research program was the development of the technology for the industrial manufacturing of high efficiency holographic optical elements (HOEs) with predetermined spectral characteristics ranging in format from few square millimeters to square meters. The desired optical properties of the holographic material for specific engineering applications are determined during the making of the film and are modified during the exposure and the development and the post-treatment of the HOE. The developed technology includes the machine fabrication of precision holographic films with 1 to 50 micron thickness on glass or plastic substrata, the use of filler material to modify the spectral characteristics of HOEs, multiple exposure techniques, contact-copying procedures and chemically and thermally adapted hologram development and post-treatment processes.

The developed technology comprises film fabrication techniques and specialized hologram development processes that extend the applicability of DCG into the blue and infrared spectral domains and is a viable tool in the control of the holographic properties of the manufactured HOEs. The applicability of the technology is illustrated with results obtained from existing HOE installations. Design and performance information will be presented for manufactured reflection and transmission HOEs that are used in a variety of technical applications, such as: holographic concentrators for photo-voltaic and thermal energy conversion, special collectors for solar photo-chemistry, holographic stacks for day-lighting, glazing and shading in buildings, optical interconnects in multi-chip modules, robotic sensors and holographic beam forming optics for LED applications.

Multiple exposures technique is used to record up to four holograms in the same DCG film that are used to generate simultaneously several monochrome or RGB beams. Experimental results are presented illustrating the use of a single aperture illumination to generate up to four monochrome images or the simultaneous generation of RGB beams, whose superposition produces white light effect.

6136-02, Session 1

High-spatial resolution measurement of volume holographic gratings

G. J. Steckman, F. Havermeyer, Ondax, Inc.

The conventional approach for measuring volume holographic gratings typically requires measuring the transmitted and diffracted beams simultaneously while rotating the grating. To obtain the spectral response a tunable laser is used with a fixed angle of incidence. In the former case, the motion of the diffracted beam requires the detector to move with it, or otherwise the range of angles must be limited. Furthermore it is often difficult to separate the diffraction from the specular surface reflections, increasing the error of the measurement. In the latter case, a high cost tunable laser is required.

We describe methods for the measurement of volume holographic gratings with high spatial resolution. A fixed wavelength laser in conjunction with a high-resolution digital camera is used to measure the angle selectivity of the transmitted beam only. The measured data are fit to a model of the grating diffraction combined with the cyclical interference from the surface reflections in order to increase the accuracy when measuring uncoated gratings. The system is capable of simultaneously measuring diffraction efficiency, loss, surface reflectivity, Bragg angle, and grating tilt in one plane, with a resolution of better than 250 micrometers over the area of a 45 mm by 35 mm wafer. Through a transformation utilizing the de-phasing term of the coupled wave analysis of thick hologram gratings, the wavelength selectivity is also obtained.

6136-03, Session 1

Hologram in acrylic copolymer adhesive

S. Toxqui López, A. Olivares Pérez II, A. L. V. Padilla, G. P. Trujillo Páez, I. Fuentes Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Replication holograms with high diffraction efficiency can be generated into acrylic copolymer adhesive coating by applying heat, the principal characteristics from this matrial are nontoxic, soluble- water, clear and cheap, we show technique used to obtained the replication holograms and some experimental results.

6136-04, Session 1

Transparent acrylic enamel holograms

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

We using a microlithography technique to record computer holograms generated in an acrylic enamel transparent (ComexÆ), getting phase holograms. The information in the mask is transferred to the material by temperature gradients generated by exposition to the heat. The refraction index is transformed at each material point by the temperature changes, thus the film is recorded and developed by it self. This material can be used for soft lithography.

6136-05, Session 2

Managing and directing innovation in the holography business

J. E. Gortych, Opticus IP; H. Abilock, JapanLink Translations

The intellectual property (IP) space associated with core high-tech innovations such as holography tends to rapidly expand in many directions as new applications and improvements to the core technology are realized. Patents soon start to rapidly fill regions of the IP space to varying densities, often well before any commercial product is available. Complicating matters is the fact that the patents typically range wildly in quality and business value for a host of reasons, not the least of which is that many high tech companies lack an IP strategy designed to drive their patenting efforts. Sophisticated high-tech companies are relying more and more on some type of IP space analysis to more fully understand the IP landscape in which they do business. However, after an IP space analysis is performed, it needs to be integrated into a larger IP management system that includes an IP strategy. This paper/presentation examines several holography IP space analyses, including some performed and discussed by Nadya Reingand of Landon, IP, Inc., and highlights how such analyses can and should be used effectively in strategically managing and directing innovation in the holography business.

6136-06, Session 2

Intellectual property analysis of holographic materials business

N. O. Reingand, D. Hunt, Landon IP, Inc.

The paper provides a brief overview of worldwide Intellectual Property centered around Holographic Materials. Worldwide IP was selected by means of comprehensive search of patents and published applications; it includes a review of thousands of patent documents granted or published by USPTO, EPO, JPO, and WIPO from January 1971 to November 2005. EAST database in United States Patent Office building Search room was used to perform the search within US IP. Micropatent and Delphion databases were used for worldwide patent search and processing tools applied for the data evaluation and analysis. The number of relevant patents is around 500; it is different depending on database used, family membersí inclusion/exclusion, and foreign (for example, Korean or Russian) database availability.

The patents retrieval itself is not a complicated process, however combined with statistical processing features offered by modern software, it allows to make an interesting observations and conclusions on the existing trends and development perspectives, to unveil the major trends in holographic materials business development.

The present paper shows the results of statistical and autocorrelation analyses in worldwide IP, however the goal of this paper is to provide more sophisticated study. The patents are categorized into three major invention types: product design, manufacturing method, and applications; and then further splitted into subcategories within each large category. These results show the technical areas crowded with patents and some others forgotten by inventors, which open the door for start-ups. Top assigneesí patents distribution over the technical categories show the areas considered the most progressive and investment rewarding from the point of view of large companies.

6136-07, Session 2

Intellectual property licensing issues in the holography business

J. E. Gortych, Opticus IP; H. Abilock, JapanLink Translations

Increasingly, many high-tech optical companies are acquiring or transferring ìleasesî to the innovations used to make optical products. In legal parlance, these innovationsówhich may include new manufacturing methods, applications, devices or improvementsóare considered ìintellectual propertyî (IP), and the ìleasesî are referred to as ìlicenses.î Though the holography business has evolved over many decades and is arguably relatively mature, the IP space is constantly expanding through new innovations and applications such as security and storage applications, and new materials. This makes for a challenging IP licensing environment. This presentation/paper addresses IP licensing issues in the holography business, including some basics about IP licensing, the role of an IP space analysis in licensing activities, how licensing activities are managed, how royalty rates are determined, and how IP is properly scrutinized to assess licensing potential. Also discussed are the concepts of IP holding companies, patent pools, and licensing activities by academic institutions.

6136-08, Session 2

Intellectual property analysis of embossed hologram business

N. O. Reingand, D. Hunt, Landon IP, Inc.

The paper provides a brief overview of worldwide Intellectual Property centered around Embossed Hologram. Worldwide IP was selected by means of comprehensive search of patents and published applications; it includes a review of thousands of patent documents granted or published by USPTO, EPO, JPO, and WIPO from January 1971 to November 2005. EAST database in United States Patent Office building Search room was used to perform the search within US IP. Micropatent and Delphion databases were used for worldwide patent search and processing tools applied for the data evaluation and analysis. The number of relevant patents is different (from 1,894 to 3,122) depending on database used, family membersí inclusion/exclusion, and foreign (for example, Korean or Russian) database availability.

The patents retrieval itself is not a complicated process, however combined with statistical processing features offered by modern software, it allows to make an interesting observations and conclusions on the existing trends and development perspectives, to unveil the major trends in embossed hologram business development.

The present paper shows the results of statistical and autocorrelation analysis in worldwide IP, however the goal of this paper is to provide more sophisticated study. The patents are categorized into three major invention types: product design, manufacturing method, and applications; and then further splitted into subcategories within each large category. These results show the technical areas crowded with patents and some others forgotten by inventors, which open the door for start-ups. Top assigneesí patents distribution over the technical categories show the areas considered the most progressive and investment rewarding from the point of view of large companies.

Analysis of the patent landscape is significantly helpful in developing strategic plans for:

- Research and development (R&D) programs
- Business alliances
- Licensing strategies
- Mergers and acquisitions (M&A) strategies.

6136-09, Session 3

Bronze rainbow hologram mirrors

P. H. Dawson, Univ. of New South Wales (Australia)

This project draws on holographic embossing techniques, ancient artistic conventions of bronze mirror design and modelling and casting processes to accomplish a portraiture of reflection. Laser scanning, 3D computer graphics and holographic imaging are employed to enable a permanent 3D static holographic image to appear integrated with the real-time moving reflection of a viewerís face in a polished bronze disc. The disc and the figure which holds it (caryatid) are cast in bronze from a lost wax model, a technique which has been used for millennia to make personal mirrors.

The Caryatid form of bronze mirror which went through many permutations in ancient Egyptian, Greece and Rome shows a plethora of expressive figure poses ranging from sleek nudes to highly embellished multifigure arrangements. The prototype of this series was made for Australian choreographer Graeme Murphy, Artistic Director of the Sydney Dance Company. Each subsequent mirror will be unique in figure and holographic imagery as arranged between artist and subject.

Conceptually this project references both the modern experience of viewing mirrors retrieved from ancient tombs, which due to deterioration of the surface no longer reflect, and the functioning of Chinese Magic mirrors, which have the ability to project a predetermined image. Inspired by the metaphorical potential of these mirrors, which do not reflect the immediate reality of the viewer, Dawson’s bronze hologram mirror series enables each viewer to reflect upon himself or herself observing simultaneously the holographic image and their own partially obliterated reflection.

6136-10, Session 3

Physical aspects of digital synthesis and reconstruction of the multiview diffractive images

I. S. Borisov, V. I. Grygoruk, National Taras Shevchenko Univ. of Kyiv (Ukraine); S. A. Kostyukevych, Institute of Semiconductor

Physics (Ukraine)

The present research deals with the digital synthesis of the Multiview Diffractive Images (MDIs) designed to be included in Optical Security Devices (OSDs) in order to make them more visually impressive and to improve their security properties.

The idea of the MDI is to unite several Diffractive Images (DIs) representing different views of the 3D scene within it. MDI will reconstruct the adjusted view under the corresponding Lighting and Observation (LO) geometry. So, under the appropriate lighting human eyes can see the required views, and a human perceives MDI as a three-dimensional image according to the principle of the binocular stereoscopy. Itís important that a human can also look over the scene from different points. This means that MDI has the linear parallax, usually (but not obligatory!) horizontal.

In this work we examine the distinctions in two general modes of the multiview image observation, which have not been sufficiently studied until now. The first mode implies rotating MDI and motionless observer, the second-moving observer and fixed MDI. The difference is in fact that in the first mode at the calculation of MDI topology the source must accomplish moving equivalent for the MDI rotation. The exact quantitative estimations for choice of the number of channels and the angle distance between them are also adduced.

We analyse the computation of parameters for Diffractive Structures (DSs) composing the MDI topology by two different approaches. The first approach is based on the concept of the Elemental Diffractive Grating (EDG)-the model of the region of the real Diffractive Structure (DS). In this case the strict quantitative formulation of Huygens-Fresnel principle given by Kirchhoff is used to find out the stroke slope and period for EDG. The second approach is based on the geometrical concepts and enables us to find DSs composed from the curved strokes. The innovative DSs based on the curvilinear strokes provide larger diffraction efficiency and better integrity of the scene for any variant of the LO as well as for the arbitrary parameters of LO geometry.

The topics related to the DIsí digital reconstruction have also been discussed. This is a powerful method helping to evaluate the DI appearance and behavior before it will be recorded by Electron-Beam Lithography Equipment. The basic expressions for calculation of diffraction on DI topology, which were obtained starting from the strict quantitative formulation of Huygens-Fresnel principle given by Kirchhoff, are cited. The advanced expressions appear as a result of taking into account the physical aspects of visual perception for diffractive images. These aspects are also explored.

So, the present investigations clarify the main topics connected with the diffractive images synthesis and allow to master the controlled creation of striking images, particularly multiview ones. They enable us to create rainbow, achromatic and natural-color MDI as well as to obtain their digital reconstruction imperceptibly distinguished from their actual appearance.

6136-11, Session 3

Optimal design and evaluation for color separation gratings using rigorous coupled wave analysis

M. Nagayoshi, Japan Women's Univ. (Japan); K. Oka, Hitachi, Ltd. (Japan); Y. Komai, Japan Women's Univ. (Japan); W. Klaus, National Institute of Information and Communications Technology (Japan); K. Kodate, Japan Women's Univ. (Japan)

Color visual equipments necessitates the technology which can separate white light into the three primary colors of R (Red), G (Green) and B (Blue) and combine them to generate arbitrary colors. Dichroic mirrors and blazed gratings used as color separation elements still need to combine some optical elements in order to separate colors.

Recently, we have proposed the six phase level gratings which can transform themselves into R, G and B, aiming at the reduction in size and weight of the color separation systems, and the improvement of diffraction efficiency and color reproduction. We analyzed the optimal design and evaluation of fabricated grating using RCWA. We set optimal conditions where the diffraction efficiency is more than 70% and the ratio of the grating to NTSC is more than 72%, and designed optimally for the grating using RCWA.

We fabricated a grating with 6 levels, the depth of grooves 5.75 micrometer, and the period 50 micrometer. It is made of quartz with EB drawing and succeeded in obtaining a highly precise grating with minimal errors of depth 0.14% and of width 2.86%. Using a xenon lamp as light source, we evaluated the grating experimentally. We acquired more than 77% for the diffraction efficiency and 74.2% for the ratio of the grating to NTSC and confirmed that the experimental values agree well with calculated values.

Furthermore, we estimated the tolerance of errors, obtaining some guiding principles for the accurate fabrication of multilevel gratings with deep grooves. In this paper we will discuss the gratingís theoretical and experimental evaluation and present a color separation system based on the fabricated grating.

6136-12, Session 3

Recording and reconstruction of 3D color images by phase-shifting in-line holography

H. Fujiwara, Y. Hamada, K. Sato, K. Fujii, M. Morimoto, Univ. of Hyogo (Japan)

One of the purposes of this paper is to develop a holography system for recording and reconstruction of practical 3D color images. Another is to extend the viewing zone and the visual field of the holography system by adopting a multi-channel CCD and a multi-channel LCD modulator. In this work, 3D images are recorded using an in-line hologram 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. Phase of RGB reference lights is precisely be shifted by changing fringe patterns displayed on a reflective LCD panel in the system. Since the phase shift in this method is independent of the wavelength of the light, 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 proposed in order to reconstruct 3D images with wide visual field from the recorded in-line hologram. Fine phase-shifting in-line holograms for reconstruction of RGB images are obtained from recorded fringe patterns, and animated color images with high quality of the practical object are reconstructed from the holograms. We record in-line holograms with the multi-channel CCD and reconstruct 3D images from the holograms with the multi-channel LCD modulator in order to extend the viewing zone and the visual field of the holographic system.

6136-13, Session 3

3D display with wide-viewing zone using holograms with reduced information

S. Hamada, K. Sato, K. Fujii, M. Morimoto, Univ. of Hyogo (Japan)

An ordinary hologram contains far more information than necessary for the purpose to reconstruct virtual 3D images. There are two purposes of this paper. One is to develop a time-sharing display system for reconstruction of real-time 3D images from several Fourier transform holograms with reduced information. Another is to propose a novel 3D display with wide viewing zone using sampled small holograms with reduced information. The image with no visual depth is reconstructed from the hologram with reduced information if the hologram width is taken to be smaller than the diameter of observer's pupil. Real-time 3D images with full parallax are reconstructed from several Fourier transform holograms with reduced information by the developed time-sharing display system. The visual field is divided into several fields in order to display the visual depth of images, and partial images in divided fields are recorded on several Fourier transform holograms. Reference light sources on the Fourier trans-

form planes, which are rotationally reconstructed from a LCD panel, illuminate another LCD panel for rotational reconstruction of partial images on the Fourier transform planes by the time-sharing system. Hologram of any area between sampled areas is produced by weighting and superimposing small holograms sampled from the original hologram. 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 depth-fusing perceptual phenomenon. Experiments are carried out using six or twelve LCD panels in order to demonstrate 3D display with wide viewing zone. Drastic information reduction by the present method is useful for electronic processing of the practical electro-holography.

6136-14, Session 4

Photopolymer films based on triazine functionalized monomers

E. Kim, H. Lee, J. Park, B. Sarwade, Yonsei Univ. (South Korea); N. Kim, Chungbuk National Univ. (South Korea); C. W. Shin, Prism Technology, Inc. (South Korea) and Chungbuk National Univ. (South Korea)

Dispersion of photopolymerizable monomers and particles in a polymeric binder is of considerable interest for the development of photosensitive polymer films as a method to improve high optical quality and mechanical properties. In particular, photopolymer films are interesting because of their possible application in holographic recording, which requires low polymerization-induced shrinkage, high diffraction efficiency and recording stability. Here in we report diffraction efficiency of photopolymer films containing triazine functionalized monomers. Triazine functionalized monomers were synthesized starting from cyanuric acid to improve diffraction efficiency and recording stability. The monomer was photopolymerized upon exposure to a visible light source in the presence of a photo initiator. Diffraction efficiency and response time were a function of monomer content as well as the composition of the photopolymer film. High diffraction efficiency (> 98%) with long recording stability was achieved from the photopolymer containing triazine and multifunctional monomers. Optimization of holographic recording properties will be presented.

6136-15, Session 4

Advances with holographic DESA emulsions

L. Duenkel, J. P. Eichler, C. Schneeweiss, G. K. Ackermann, Technische Fachhochschule Berlin (Germany)

The holographic DESA emulsion has been presented at the IS&T/SPIE International Symposium Electronic Imaging 2004 as well as at the SPIE International Symposium Photonics West 2005 for the first time to the holographic commomunity (SPIE Vol. 5290, 5742). The new procedure for ultra-fine grained AgX emulsion manufacturing is now part of different collaborations between the University of Applied Sciences in Berlin and industrial users referring as well as to emulsion manufacturing and to hologram application. In this context, new advances in technology and material investigation were reported such as stability tests against temperature and illumination, application of the silver halide sensitized gelatine SHSG technology and development of lamination technology. From theoretical point of view, some new results of spectral sensitization will be discussed in context with latent image formation. The emprovements in layer performance will be demonstrated by holograms in larger formats taken as well as in single beam and split beam geometries. Examples of the lamination technology will be demonstrated, too.

6136-16, Session 4

Lactose Holograms

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

The study and optimization of new materials for holographic recording open new application about these, we find the biopolymers, which offer a high response, in the same way the lactose present these characteristics, studies preliminary show, owing to, some properties that it has these can be used as holography recording medium. We present analysis of the properties they are: refraction index, diffraction efficiency, the technique that allowed us to obtain the hologram and experimental results of the replication of computer holograms. The advantage that this material it is that it does not need of a process of developed an important aspect of this study is that is realized in environment conditions.

6136-17, Session 4

Polymerization-induced diffusion as a tool to generate periodic relief structures: A combinatorial study

C. Sanchez, Technische Univ. Eindhoven (Netherlands) and Univ. de Zaragoza (Spain); B. J. de Gans, D. Kozodaev, A. Alexeev, Technische Univ. Eindhoven (Netherlands); M. J. Escuti, Technische Univ. Eindhoven (Netherlands) and North Carolina State Univ.; C. M. van Heesch, Technische Univ. Eindhoven (Netherlands); T. Bel, Philips Research Labs. (Netherlands); U. Schubert, C. W. Bastiaansen, Technische Univ. Eindhoven (Netherlands); D. J. Broer, Technische Univ. Eindhoven (Netherlands) and Philips Research Labs. (Netherlands)

Polymeric relief micro-structures are commonly used in display technology since they can redistribute incoming light in a controlled way. Replication methods as embossing or replica-molding have been extensively employed for the production of these relief structures. These can also be generated by holographic or photo-lithographic techniques using polymeric photo-resists. Patterned irradiation induces a change in the solubility of the photo-resist and the final relief structure is obtained after appropriate thermal and etching steps.

Recently a new solvent-free photo-lithographic technique, that we will refer to as photo-embossing, has been proposed to generate surface relief micro-structures. A photopolymer blend comprising polymers, monomers and appropriate photo-initiators is processed as a thin film. After patterned irradiation a heating step promotes local polymerization in the irradiated areas resulting in a spatial modulation of the reactive species. This compositional gradient triggers a diffusion process that results in a surface relief deformation resembling the original light pattern. The final shape of the relief structure is determined by different parameters as the period of the patterned structure, composition of the photo-polymer, energy dose, development temperature and thickness of the photo-polymer film.

We present a combinatorial study trying to unravel how these parameters influence the final topography of the relief structure. We have generated two dimensional libraries of periodic surface relief structures with systematic variations of the period of the structure in one axis of the sample and either the energy dose, processing temperature, composition or film thickness in the other. These libraries are characterized using automated atomic force microscopy (AFM). The results obtained are explained in the framework of a diffusion-polymerization model. This combinatorial approach allows us to better understand the photo-embossing process. In addition this methodology has shown to be an effective tool to identify processing conditions resulting in optimum shape and height of polymeric relief microstructures to be used in specific applications.

6136-18, Session 4

Pineapple holograms

S. Toxqui-Lopez, L. Calixte, A. Olivares Pérez II, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); A. L. V. Padilla, Benemérita Univ. Autónoma de Puebla (Mexico); E. L.

Ponce-Lee, J. B. R. Ruiz-Limón, I. Fuentes Tapia, Instituto Nacional de Astrofísica, Öptica y Electrónica (Mexico)

We propose that juice pineapple can be considering a new unconventional holographic recorded medium, because it has good chemical and optical properties. Some structures of computers phase holograms are copied into this material by polymerization therefore in this research we present a preliminary analysis and experimental results. The major improvements from our material are: good diffraction efficiency, reduced cost, easily to apply on any substrate and the hologram is making with out develop process.The nature sweetener from pineapple can be applied for the food industry mainly in the candy industry.

6136-19, Session 4

The recent holographic material, Konica P7000

M. Iwasaki, T. Kubota, Kyoto Institute of Technology (Japan); M. Watanabe, T. Yamauchi, T. Kumasawa, K. Ueda, Dai Nippon Printing Co., Ltd. (Japan)

A new holographic material, Konica P7000, having the sensitivity for red was examined. The holograms were recorded on P7000 plates to evaluate the holographic characteristics, such as diffraction efficiency and reconstructed wavelength. The results are discussed comparing with those of former Agfa products.

6136-20, Session 5

An application of polymethylmethacrylate (PMMA) holographic grating with frustrated-total-internal-reflection coupling structure to space-time coding for optical wireless communication

S. Chung, S. Han, Y. J. Lim, Y. Kim, B. Lee, Seoul National Univ. (South Korea)

Spatial confinement of paths in wireless optical communication enables bandwidth and resources reuse in adjacent environments. This property can also result in undesirable shadowing that occurs whenever an obstacle blocks signal paths between transceivers. Shadowing can result in service interruption and increased error rate. Spatial coding is possible to improve link performance and alleviate shadowing effect in wireless communication environment. In this paper, we propose an application of the frustrated-total-internal-reflection (FTIR) structure using a polymethylmethacrylate (PMMA) holographic grating to space-time coding in optical wireless communication. PMMA is a widely used optical host polymer and is perfectly compatible with the nano imprinting process and a PMMA holographic grating is fabricated by two beam interference at the wavelength of 248 nm. In the system, a multi-channel source is incident to serially connected PMMA holographic gratings with FTIR coupling structure. The FTIR coupling structure is made by a prism and PMMA grating layer with metal/dielectric stacks between them and acts as a wavelength selective filter. We can induce a larger amount of relative time delay to each channel by controlling the locations of FTIR coupled PMMA holographic gratings. This scheme can be used in various systems which need flexible and relative large time delay according to each channel.

6136-21, Session 5

A PMMA-metal lamella grating-based surface plasmon resonance device

Y. J. Lim, K. Choi, S. Han, B. Lee, Seoul National Univ. (South Korea)

Recently, a lot of interests have been focused on surface plasmon resonance (SPR), a phenomenon generated by the charge density oscillation existing on the interface between dielectric and metal surface. This particular surface wave has been widely used for sub-wavelength scale photonic circuits, fluorescence microscopy, bio-sensing devices, and photonic display applications. Also, it has a lot of potentials from holographic optical devices to holographic display applications. The measurement of SPR can be simply evaluated by the well-known Kretchmann-Raether attenuated total reflection geometry using angle multiplexing of the incident wave. Particularly, the intensity caused by the surface plasmon wave is considerably high on the interface when the incident angle is matched with Bragg condition. When this wave is used as a reference wave in hologram, it is expected that the signal beam can be reconstructed efficiently. Based on this concept, we propose a polymethyl-methacrylate (PMMA) and metal stacked thin film grating structure for optical beam coupling and splitting applications. For an efficient grating structure design, we rigorously analyze the SPR phenomenon and design the grating structure for efficient beam coupling and splitting. To form the PMMA-metal lamella grating structure, we inscribe the grating on the PMMA layer using Argon laser with the wavelength of 248nm. Then, we deposit gold (Au) on the PMMA grating. Finally some experimental results, discussion, and its practical photonic applications are provided.

6136-22, Session 5

Digital in-line holographic microscopy with enhance resolution power

J. I. Garcia-Sucerquia, Dalhousie Univ. (Canada)

The resolution power in Digital In-line Holographic Microscopy (DIHM) is as in compound microscopy, determined by the numerical aperture of the system and the wavelength. Additionally, in DIHM the pinhole dimensions as well as the distance between it and the sample play an essential role to determine the maximum achievable resolution.

By means of numerical simulations and experimental results we show that submicron resolution can be reached in DIHM with optical light by increasing the refractive index of the space between the sample and the recording system. This essentially increases the numerical aperture of the system in analogy to an immersion microscopic technique. We show that the geometric parameters entering the reconstruction process must be accordingly tuned-to obtain the right reconstruction.

6136-23, Session 5

Ulexite-based animation recording system by random reference patterns

M. Irisawa, Y. Ishii, Japan Women's Univ. (Japan); Y. Takayama, Japan Aerospace Exploration Agency (Japan); E. Watanabe, K. Kodate, Japan Women's Univ. (Japan)

We present a simple method for hologram multiplexing in which a fiber bundle is employed as a device for producing random reference patterns with a rotary movement. In the experiment, 100 holograms were recorded one after another in a LiNbO3 crystal. Each stored hologram is clearly read out by rewinding the bundle's rotation angle of 0.2$B!k(B adjusted as the hologram is being written. Since such a rotary movement requires no excessive space in the setup, we show that this new method approach enables us to perform the hologram multiplexing and also contributes to the building of a compact optical setup. We also investigated each part of the recorded images as a proof of the quality of readout images. Using the bit error rate as a criterion, reproducing the stored holograms proved successful. Besides, the smooth and stable reproduction of recorded images enables us to make an animation out of these readout images. Furthermore, aiming at improving the security function of information recording, we attempted to generate random reference patterns, instead of fiber bundle, by Ulexite (NaCaB5O9, 8H2O). Results will be presented, as they demonstrate its equally efficient performance as that of fiber bundles.

6136-24, Session 6

Impact measurements using double pulse digital holography

J. Müller, J. Geldmacher, C. von Kopylow, W. P. Jüptner, Bremer Institut für Angewandte Strahltechnik (Germany)

The design of modern airplanes and automobiles makes extensive use of carbon fibre reinforced structures. These composites have advantages concerning weight and durability and therefore reduce costs. But due to high motion speeds they are exposed to damage by impacts caused e.g. by stones, birds or hail. To design structures that resist these impacts it is necessary to know the effects of different impact induced wave forms on these structures[1]. Calculations and simulations are difficult because most of the provided material parameters consider only the case of static loads. Therefore it is necessary to extract the dynamic characteristics like frequency-dependent damping and dissipation experimentally.

In this work an application of double exposure digital holography for the analysis of perpendicular impacts on carbon fibre structures is presented.

An impact is defined as a force acting shorter than the travelling time of the impact waves through the structure. The measurements are therefore performed using a pulsed ruby laser and a CCD-camera, making it possible to record digital holograms at different times after the impact[2]. For the evaluation two holograms are recorded. The first one is recorded before the impact and represents the unloaded state. The second is recorded at a defined time after the impact. The numerical evaluation is carried out by calculating the phase difference between the two holograms. The out of plane displacement of the surface is then directly related to the resulting phase difference.

The experiments cover the identification of the wave forms initiated by the impact and their damping characteristics. Results for different layer designs and impact parameters are presented. The possibility of secondary damages outside a non-damaging impact is investigated.

References:

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2 Th. Kreis “Handbook of Holographic Interferometry”, Wiley-VCH, 2005

6136-25, Session 6

A fully computer-synthesized holographic display for medical 3D data

Y. Sakamoto, Hokkaido Univ. (Japan); K. Matsushima, Kansai Univ. (Japan); A. Myojoyama, Tokyo Metropolitan Univ. (Japan)

Recently, various three-dimensional sensors have been developing, and it collects volume data. Specially, in the medical field, MRI (Magnetic Resonance Imaging) or CT (Computer Tomography) gets three-dimensional images of inside the human body. It is hoped to observe these images not only on a two-dimensional display but also on an auto-stereoscopic display such as integral photography and holographic displays. In conventional holographic display systems, there are many restrictions in the display because an optical process made it. To improve the problem, we have been developing an auto-stereoscopic display system that is based on the fully computer-synthesized hologram. It is possible to provide flexibility of displaying such as a removal of phantom imaging, various textures of the objects, etc. That system is composed by a CT device, a computer system for hologram calculations and a fringe printer, which are put on three universities and connected by the Internet. Using this system, we have made ID photo size holograms of human bodies and the holograms showed us three-dimensional images. Although the size is too small for practical use, the results show that the fully computer-synthesized hologram has an ability to display volume data such as medical 3D images.

To realize the system, we had to solve the following problems.

(1) A high resolution fringe printer,

(2) Hologram calculation algorithm of volume data and

(3) Volume data compression method.

In this paper, we discuss the system, methods of program solving and optical experiments.

6136-27, Session 6

3D CGH registration on organic and non-organic resists: comparative analysis

E. V. Braginets, National Taras Shevchenko Univ. of Kyiv (Ukraine); S. A. Kostyukevych, Institute of Semiconductor Physics (Ukraine); V. I. Girnyk, National Taras Shevchenko Univ. of Kyiv (Ukraine) and Optronics, Ltd. (Ukraine)

3D computer-synthesized hologram ó is one of the most promising technologies that today is used in modern optical protection elements. Usage of 3D CGH as hologram component allows not only to increase the level of their authenticity but also expand the field of designer solutions, which is very important for increase of hologram quality. Without completely substitute of classical 2D/3D elements 3D CGH technology allows to provide them with especial visual effects. One of key recording 3D CGH problems is the registration of high (more that 2500 lines per mm) spatial frequencies of synthesized interferogram on to the recording medium used. Because, out of existing 3D CGH recording methods today the most widely used method is the E-Beam lithography, during the method development and 3D CGH recording, researches face number of problems as follows:

1. According to research figures maximum resolution of most EBPS is usually limited to 5-6 thousands lines per millimeter, e.g. it is practically the highest permissible level for recording of synthesized binarized interferogram.

2. Most of the existing organic and non-organic resists have substantial of gain-frequency characteristic reduction in the area of frequences that have more than 3-4 thousands lines per millimeters and therefore need extra correction depending on the type of resist.

Based on early researches of organic and non-organic resists and a series of trial recordings three widely used resist were chosen with intention to carry out detail comparative analysis testing an efficiency of their using for e-beam recording of holograms with 3D CGH elements.

In the given research two organic PMMA resists were researched: Shipley 1800 (c) Series and electronic resist ‘EPR-40’ and non-organic semiconductor chalcogenide resist As40S60-xSex (where x=20,30,40).

Theoretically, in comparsion with organic resist semiconductor resist can have special advantage for E-Beam recording because it is conductive (usually for electric charge pick-up independend conductive layer is used, for exapmle, chrome for PMMA EPR-40).

Another special feature that was taken into the count while choosing the resist was itís registration ability for both optical (classical) and electronical holograms.

While conducting the research such objectives were completed:

1. Impulse response and gain-frequence characteristics were built for every resist

2. For every resist optimal exposure doses and respective parameters of dose corrections for high frequency recordings were determined.

3. Trial recording of 3D CGH holograms and general analysis of recording qualiy were completed.

In order to record the impulse-response charactristics of ‘EBPS-resist’ system a such method was used:

Onto the resist with different exposure doses a series of test topologies were recorded. These topologies contained structures with different spatial frequencies from 900 to 5000 lines per millimeter. After the development these topologies were scanned using an atom microscope and correlation of the depth modulation from the exposure dose and grating frequency was built for the given recording/development conditions. Also based on topology surface photos received integrity of recorded struc-

tures was evaluated.

At the next stage a series of single-dimensional diffractive grates with different spatial density (900-5000 lines per millimeter) on investigated resists were recorded.

Based on diffractive efficiency correlation of grate from itís spatial frequency and recording parameters (exposure dose) gain characteristic and gain-frequency characteristic for all resists were built.

At the third research stage trial 3D CGH holograms were recorded in order visually evaluate quality of recording on different types of resist.

6136-28, Session 6

Applications of the high-resolution optical reconstruction of digital holograms

G. K. Wernicke, Humboldt-Univ. zu Berlin (Germany); S. Krueger, HOLOEYE Photonics AG (Germany)

Approaching the ideal high resolution phase addressable modulator is the main task for current SLM (Spatail Light Modulator) developments Originally designed and fabricated for projection systems, they are used as spatial light modulator in optical correlators or in fringe projection systems. An adapted driver electronics and measurements of the phase modulation behavior can lead to a dynamical phase modulating system with an almost linear modulation and a maximum phase shift of 2p.

Different technologies, such as optical addressed, modal and electrical addressed spatial light modulators compete in performance and applicability. The requested high Space-Bandwidth-Product (SBWP) can be served by the actual micro-structuring technology used to fabricate LCoS(Liquid Crystal on Silicon) micro-displays. Liquid crystal displays in different modes are suitable due to their birefringence properties and wide transmission range. The paper discusses advantages of different modulator technologies and focuses on boundary conditions for the application in digital holography (generation of 3D light waves) and for dynamic pattern generation.

The quality measures of our dynamical diffraction patterns in the output plane of the system are promising for a wide range of applications. Since the display is addressed directly from the graphics card, series of diffraction patterns and animations can be realized.

Beside the dynamic range of complex modulation for nematic LCoS devices, also theoretical considerations based on the different LC-modes are discussed in order to derive a compendium of advantages and disadvantages of the different technologies. Implementation demands are discussed on the example of an optical system for parallel recording and optical reconstruction of digital holograms at a frame rate of 9 frames per second.

The latter opens new applictions for non-destructive testing devices especially in the field of holographic microscopy and holographic interferometry and the combination of both.

6136-29, Session 7

New type holographic 3D display system using two liquid crystal panels

X. Chen, X. Liu, Zhejiang Univ. (China)

Holographic three-dimensional (3D) display contains all the depth cues required by the human vision. In this paper, a new and practical method for achieving 3D holographic display system that can reconstruct the large 3D object with high resolution is presented. In the proposed method, the display system employs two liquid crystal devices (LCD) are employed, one to display the hologram and the other to display a diffractive lens with variable focal length and off-axis value. Thereby, the hologram and the lens can be changed very quickly.

Because of the limited resolution of the LCD in comparison to the traditional recording material, a conventional LCD canít need the requirement of the hologram of large 3D object. So the hologram only reconstructs the different part of the data of the object at the different time in a period. The lens displayed in the second LCD adjusts the reconstructed position of the part of object and magnifies it at the available time. Through time sequential superposition, the high resolution of the magnified reconstruction is achieved.

A new algorithm of multicomputing hologram to adaptive the new display method and improve the computing time is given. Computer simulations are performed. Experimental results confirm the effectiveness of the proposed method.

6136-31, Session 7

Real time calculation for holographic video display

T. Yamaguchi, H. Yoshikawa, Nihon Univ. (Japan)

For practical holographic video system, it is important to generated holographic fringe as fast as possible. We have proposed an approximation method that can calculate the hologram fast. With the proposed method, tens of holograms with more than one million pixels can be calculated in one second with a personal computer. To compute the hologram, an object is assumed as a collection of self-illuminated points and the fringes from each object point are superposed. To determine the fringe, a distance between object point and sampling point on the hologram is used to obtain phase of the light. Since sampled hologram usually has small pixel intervals, the difference of the distance values between adjacent pixels is also small and its second order difference becomes a constant. Therefore, the distance value at certain pixel can be obtained from the neighbor pixel with simple additions. The experimental results show that the proposed method is quite effective. We also change the type of hologram from Fresnel to image. Since the object points of the image hologram are located very close to the hologram, calculations for single object point require only fractional part of the hologram. This also makes computation quite fast.

Experimantal results demonstrate that the interactive computation of complex object can be done with regular PC.

6136-32, Session 7

Holographic stereogram using graphic accelerator

G. Kanno, Y. Sakamoto, Hokkaido Univ. (Japan)

A holographic stereogram is one of methods for displaying 3-D image data from Multiple-view images. In this paper, we propose a method for computing holographic stereogram using graphic accelerator. We use graphic accelerator at two stages of method. One is creating Multiple-view images, and another is synthesizing holographic stereogram. To create and rasterize Multiple-view images, we use CG rendered from the point of view on the projection plain of hologram. This CG makes effect like ray tracing. In rendering, we use vertex-transforming rebuiled by VertexShader for the negative parallax. This vertex transforming makes negative near clipping possible. And To Synthesize holographic stereogram, we use texture mapping feature of graphic accelerator. This method befits raster output device, because this method output raster data sequentially. And this method befits also PC, because this method doesnít need memory that buffers all Multiple-view images, needs processing power for rendering and sampling and synthesizing for each unit of projection plain.

6136-33, Session 7

Reconstruction of color images of high-quality by a holographic display

K. Sato, Univ. of Hyogo (Japan)

The use of red, green, and blue low-power lasers and a high-resolution reflective LCD panel makes a compact holographic color display possible to be developed. Purposes of this paper are to improve the quality

of color images reconstructed from reflective LCD panels, and to demonstrate the possibility of displaying 3D color images of good quality with the developed holographic display. 3D full-color images are reproduced by rotational reconstruction of red, green, and blue images at high frame rate. The output power of RGB reference light sources is varied in wide dynamic range in order to adjust color balance of reconstructed 3D full-color images. Reconstructed images with high-resolution are exhibited a large color gamut and fine color expression for various color models. Chromaticity of color images plotted in the CIE diagram shows how the color gamut of the reconstructed color images is substantially large. In this paper, a new method is proposed to eliminate the speckle noise in reconstructed color images by modifying interference fringe patterns. Experimental results show that modification of the fringe patterns reduces the speckle noise successfully and reproduces fine images without color shading. Animated color images of high quality are reconstructed from the computer-generated hologram or the practically recorded hologram displayed with the developed holographic system. Full-color auto-stereoscopic images in the wide visual field are reconstructed by adopting the multi-channel LCD modulator. Angle of the visual field or the viewing zone of the display is extended proportionally to the number of LCD panels.

6136-34, Session 7

Hologram technology in the display field

L. M. Murillo-Mora, H. Honma, F. Iwata, Toppan Printing Co., Ltd. (Japan)

Application of holography to the commercial products has been seen to increase in recent times. One of the reasons for this occurrence is due to the optical advantages that can be introduced using adequately the properties inherent in holographic products. In this presentation a survey of some holographic techniques including diffractive applications developed and applied to the display field are reviewed. For this occasion, this review is performed on display devices such as liquid crystal display devices where the inclusion of holographic elements have been used successfully for light redirection, front luminance intensification, diffusing, among others. Besides, novel ideas and applications making use of the characteristics of diffractive elements not only on the addition of optical elements but applied directly on other components of the lcd display are reviewed.

6136-30, Poster Session

Electro-holography system using an array of water particle 3D screen

K. Sato, Shonan Institute of Technology (Japan)

We are developing electr-holographic display systemusing water particle 3D screen. Now we could reduce flickers by flow controlled nozzle and expand image deptg using array of water particle 3D screen and constructed wide view angle electro-holography system with this method.

6136-35, Poster Session

Photo-induced birefringence and cooperative molecular reorientation in azo copolymer

T. Fukuda, J. Y. Kim, D. Barada, K. Yase, National Institute of Advanced Industrial Science and Technology (Japan)

Holographic memory is one of the promising candidates for the next generation ultra-high-density data storage. New co-polymers consist of photo-responsible azo compound and co-monomers with large optical birefringence attaching as side-chains are synthesized and investigated. As a result, a co-polymer with large photo-induced birefringence of 0.24 was developed. In order to increase the value of photo-induced birefringence, it was found that a co-polymerization ratio between azo moiety and co-monomers with large birefringence was very important in this system. At an appropriate co-polymerization ratio, the photo-responsible azo moieties effectively trigger a cooperative motion of another co-monomer side chain and resulting a large photo-induced birefringence of the bulk. This unique result originating in the molecular cooperative motion might be qualitatively explained by considering dipolar and steric interactions between two moieties of side-chaines. Experimental results on this point will be talked in my presentation. 488nm beam of Ar ion laser was employed for generating photo-induced birefringence and the characteristics was monitored by 633nm beam of He-Ne laser. Samples were thin films (approximately 1 micron thick) of newly synthesized co-polymer, that were prepared by spin-coating technique.

6136-36, Poster Session

Optical characteristics of holographic input-beam coupler using a photopolymer

C. W. Shin, Prism Technology, Inc. (South Korea) and Chungbuk National Univ. (South Korea); N. Kim, Chungbuk National Univ. (South Korea); D. W. Suh, M. C. Paek, Y. J. Sohn, H. S. Chung, K. Y. Kang, Electronics and Telecommunications Research Institute (South Korea)

Holographic gratings with asymmetric structure are widely used to couple light into and out of waveguides due to their high diffraction efficiencies and planar packaging. In this paper, a holographic grating coupler based on the photopolymer has been designed and experimentally demonstrated at wavelength of 405nm. To achieve the high diffraction efficiencies in the structure, we investigated the optical properties of the coupler according to the exposure energy at the 405nm wavelength. In the holographic recording for the asymmetrical geometry, we researched the optical characteristics of the Dupont photopolymer HRF150-38 as the correction of the Bragg angles shift because of shrinkage factor and the diffraction efficiency. The performance and the optical characteristics of the coupler using volume holographic grating will discussed in detail.

6136-37, Poster Session

Stability of holographic gratings recorded in photopolymer films using different dyes

K. Tsuchida, Nagaoka Univ. of Technology (Japan); M. Ohkawa, S. Sekine, Niigata Univ. (Japan)

In this study, stability of holographic gratings recorded in four photopolymer films with different dyes was experimentally examined, and dye concentration was optimized to get high diffraction efficiency. Four sets of films were fabricated. Each set contains triethanolamine and acrylamide in polyvinyl alcohol matrix, and one type of dye — eosin Y, methyl violet, rhodamine B or rose bengal. Dye concentrations were adjusted so that transmittances of all films 60 μm thick were approximately 94%. The photopolymer films were exposed by two intersecting beams of a YVO laser at 532 nm to form holographic grating with spatial frequency of 653 line/mm until the diffraction efficiency reached its maximum. The recording intensity of each beam was 10 mW, and the beam diameter was 2.25 mm.

The diffraction efficiencies of the recorded films were measured, for 300 sec just after the recording, and again after five-days in dark storage, using the YVO laser beam. The photopolymer film containing eosin Y showed the best stability for a 300 sec interrogation and five-days storage period although its diffraction efficiency dropped from 74% to 58%.

To optimize dye concentration in photopolymer with eosin Y, the films were prepared, changing the concentration of eosin Y from 0.001 wt% to 30 wt%. The maximum diffraction efficiency and the time required to reach to the maximum efficiency were measured using a weak He-Ne laser beam for each film. The maximum diffraction efficiency was 67% when the concentration was 0.05 wt%. The required recording time was 13 sec.

6136-38, Poster Session

Real-time holographic gratings recorded in NOA 65 and crystal violet dye

M. Ortíz-Gutiérrez, A. M. Martínez-Basurto, Univ. Michoacana de San Nicolás de Hidalgo (Mexico); J. C. Ibarra-Torres, Univ. de Guadalajara (Mexico); A. Olivares Pérez II, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); M. Pérez-Cortés, Univ. Autónoma de Yucatán (Mexico) and Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We recorded real time holographic gratings in a photosensitive liquid material. This material is Norland Optical Adhesive (NOA 65) mixed with crystal violet dye (CV). The NOA 65 is a clear, colorless, liquid photopolymer that cures when is exposed to ultraviolet light (UV). To record the gratings we used the interference between two beams from a He-Ne laser obtaining phase modulation gratings by refraction index changes. We use different wavelengths 543.5, 594.5 and 612 nm for recording the gratings and its highest diffraction efficiency at wavelength 612 nm was of 10 %. This mixture of NOA 65 and CV open the possibility to make diffractive elements and no requires developed process.

6136-39, Poster Session

Properties comparison of holograms using PVA doped with MgCl2 as conductor polymer

M. de la Paz Hernández-Garay, L. Calixte, A. Olivares Pérez II, I. Fuentes-Tapia, E. L. Ponce-Lee, J. B. R. Ruiz-Limón, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The metallic salt MgCl2 as dopant, his concentration, his electro-chemical behaviour, in general the physico-chemicals changes that interfere in the doped process; these are elements determinant to obtain as final product a conductive polymer.

We present some results from properties electro-optics of the PVA doped with MgCl2 , for this form will be use as conductive polymer and as holographic material and we present the diffraction efficiency of the gratings made with our conductor polymer material.

6136-40, Poster Session

Holograms using PVA doped with CoCl2 as conductor polymer

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

We used CoCl2 as dopant with PVA, to do holograms for different concentrations and process as photo and thermo-polymerizations under environmental conditions. We present the quantitative results of the diffraction efficiency parameter from digital holograms storage, bearing in mind variable so much physical and chemical to different concentrations.

6136-41, Poster Session

Epoxy resin holograms

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

We observed that a commercial epoxy resin (ComexÆ) is enable to record images by means of lithography techniques. We can generate a hologram using a digital image and a computer simulation program and transferred it on our resin by microlithography techniques to get a phase hologram and increase its efficiency. The exposition to the heat produce temperature gradients and the information in the mask is transferred to the material by the refraction index changes, thus the film is recorded. At the same time the hologram is cured.

6136-42, Poster Session

Successive encryption and transmission with phase-shifting digital holography

S. Gil, Univ. of Suwon (South Korea); S. Jeon, Univ. of Inchon (South Korea); N. Kim, Chungbuk National Univ. (South Korea); J. Jeong, Suwon Science College (South Korea)

We present a novel information or key encryption and transmission technique based on phase-shifting digital holography for a security system. Phase-shifting digital holography is used for recording phase and amplitude information with CCD device. 4-steps phase-shifting is implemented by moving the PZT mirror with equidistant phase steps of $\pi/2$. The information data and the secret key is expressed with random amplitude and random phase. Digital hologram in this method is Fourier transform hologram and digitized with 256 gray-level. The basic idea is that we use a 256 gray-level digital hologram data to encrypt an information data or a key with 4-steps phase-shifting digital holography. The communication of secret key or information data is performed in a successive way. The simulation shows that the proposed method gives good results for encryption.

6136-43, Poster Session

Fabrication of holographic optical elements

S. Nakahara, T. Fujita, Kansai Univ. (Japan); T. Tuchitani, Opticom Research (Japan); H. Tottori, Hanshin Expressway Public Corp. (Japan); S. Shinguhara, S. Hisada, J. Nakaichi, Kansai Univ. (Japan)

We fabricated holographic optical elements (HOEs) for transmitting visual information to a long distance by applying holographic technology. The HOEs were fabricated by a direct laser lithography system with high-resolution, high-speed, and high-accuracy positioning system. In order to improve diffraction efficiency of HOEs, the phase type holograms were fabricated by etching the glass substrate. Comparison of the fidelity of reconstruction images of the amplitude-type and the phase-type HOEs was made.

6136-44, Poster Session

High-resolution fringe printer for studying synthetic holograms

K. Matsushima, S. Kobayashi, Kansai Univ (Japan); H. Miyauchi, Kansai Univ. (Japan)

Computer-Generated Holograms, sometimes called Digitally Synthetic Holograms, are one of candidates for sophisticated three-dimensional digital imaging system in the future. But the CGHs at current stage are suffering from twin problems before growing into practical use. One is the problem of its computation. Generation of CGHs is, in general, much time-consuming process even in modern CPU technology. The other is the problem of its fabrication. Resolution of printed fringe pattern of CGHs directly leads to angle of its viewing-zone. For example, a laser printer in resolution of 1200 dpi can generate a hologram with only an angle of viewing-zone of 1.7 degree. If we can use micro-processing technology such as e-beam writing or photo-lithography for fabricating LSI device, we can print CHGs with larger viewing zone than that of conventional analog holograms. However, these technologies are, in general, too expensive to print only a piece of 3-D picture, and the fabrication time is usually too long. This printing-problem blocks progress in the other side,

i.e. the computing problem. Someone who invents an algorithm to create fine holograms very fast can not verify his/her idea because of no instrument to print the synthetic hologram.

In this report, we will present a high resolution fringe printer developed for driving the research in the computing as well as printing of CGHs. This fringe printer consists of rotating drum, laser diode and its focusing system, and is capable of printing an elliptical dot in diameters of 1.5 x 3.0 microns on photo-sensitive films. These dot sizes are approximately converted resolutions of 17,000dpi x 8,500dpi, and therefore, the horizontal and vertical view-zone is 24 and 12 degree, respectively. The designed maximum scan speed is more than 200mm/s. At current stage of development, a hologram of approximately one inch square in dimensions can be drawn in approximately 1 hour.

We will demonstrate holograms fabricated by the constructed fringe printer.

6136-45, Poster Session

Stude of methode of reconstruction of object wave plane in digital holography

J. Li, Kunming Univ. of Science and Technology (China); Y. Li, Purple Labs. (France)

With the development of computer and CCD detecting technology, the digital holography technique to obtain the complex amplitude of an object wave via image processing is studied increasingly [1 ~5] in holographic measurement, which the intensity distribution of interferogram produced by object and reference wave is recoded by CCD array. Because a hologram irradiated by conjugate reference light will generate the diffractive wave of real object image , the current general model in reconstructing wave front of a plane object is to calculate the real image along the diffractive direction by means of diffraction formulation [2~5]. In order to get perspicuous measurement, a parallel beam was often used as irradiating and reference light. The beam was transformed by such a 4f system, in which object plane and CCD detector plane form a pair of conjugate plane, that objects with different dimensions could be measured.

By analyzing the physical essence of interference measurement, the wave coming from object plane can be worked out through inverse diffraction formulation, once the amplitude and phase of object wave arriving at the recording screen is known. If inverse diffraction formulation is founded correctly, there is no need to make CCD detector plane the conjugate plane of object plane.Thanks to above analysing, we could find some ways to simplify our mesure system and necessary calculations. So we deduced the diffraction formula of Kirchoff, the formula of Rayleigh-Sommefeld, the formula of Fresnel and the reverse expression of the formula of Collins. We studed the model of reconstruction of object wave plane with some practical experiments, and obtained good results.

This article describes the way we deduce the reverse calculation of diffraction formula. Based on Collins formula and its reverse calculation, we will demonstrate in detail the theory of reconstruction of object wave plane in digital holography and will give some pragmatic experiment samples.

6136-46, Poster Session

Data compression for transmission of holographic 3D images using digital-SSTV

K. Takano, Tokyo Metropolitan College of Aeronautical Engineering (Japan); K. Sato, Shonan Institute of Technology (Japan)

In this paper, the quality of images recovered by a CGH through Jpeg2000 is investigated. Applicability of Jpeg2000 to the transmission of 3D holographic images is also studied. As this result,Jpeg2000 is seen to be applicable to realize a transmission of 3D holographic images.

6136-47, Poster Session

Development of interactive tabletop hologram

K. Sakamoto, T. Nishida, T. Morii, Shimane Univ. (Japan)

We developed prototype interactive tabletop holographic display system. This system consists of the object recognition system and the spatial imaging system. In this paper, we describe the recognition system using a QR Code label or RFID tag and 3D display system using a holographic technology.

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 purpose of this paper is to propose the interactive system using these 3D imaging technologies. In this paper, the authors describe the interactive tabletop 3D display system. The observer can view virtual images when the user puts the special object on the display table. The key technologies of this system are the object recognition system and the spatial imaging display.

When kids put objects on the table, the display system gives users virtual 3D images, which is floating in the air, and the observers can touch these floating images. The hologram reconstructs some virtual images when the hologram is partly illuminated or the hologram is reconstructed using some angles of illumination light. This system interacts; these virtual images are selectively displayed according to circumstances and the users and floating images take mutual action when the user touches the virtual image. Thus this system displays the same color and shape virtual image as the user puts an object on the table. The components of this interactive tabletop display system are the object recognition system and the spatial imaging system. The object recognition system recognizes the kind of objects and attributions by its unique IDs. The spatial imaging system provides floating virtual 3D images to the users. According to the ID tags, illuminated partial hologram is selected or the angle of incident beam changes, then the hologram interactively reconstructs spatial images.

6136-48, Poster Session

Color evaluation of full-color hologram

T. Kumasawa, A. Tanaka, T. Yamauchi, M. Watanabe, K. Ueda, Dai Nippon Printing Co., Ltd. (Japan); M. Iwasaki, T. Kubota, Kyoto Institute of Technology (Japan)

In 1998, Dai Nippon Printing succeeded in mass-producing full-color Lippmann holograms (TRUE IMAGE TM) for the first time in the world. The TRUE IMAGE TM holograms are volume-type holograms that diffract selected wavelengths of the ambient light to desired angles.

We have previously reported our technologies such as mass-producing, layer structures and mastering. This paper concerns the new full-color mastering process in order to obtain much brighter holograms than that of previously reported. As holographic recording materials, both newly developed panchromatic silver halide and photopolymer were used.

In this study, the color reproduction and the viewing angle of full-color Lippmann holograms were examined. The measuring system allows the incident angle and the observation angle to be changed. Angle dependency of holographic color was evaluated using this system. Two types of holograms that were exposed of color chips using previous and new methods were made and evaluated. The holograms using new method had better performances than the holograms using previous method.

To combine above mastering technique with mass-producing technology and layer structure technique, we have succeeded in mass-producing full-color holograms with switching effect of two images.