SYMPOSIUM J

Microphotonics, Nanophotonics, and Photonic Crystals

April 22 – 24, 2003

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SESSION J1/P2/Q4: JOINT SESSION
SELF-ASSEMBLY
Chair: David J. Norris
Tuesday Afternoon, April 22, 2003
Metropolitan II (Argent)

1:30 PM *J1.1/P2.1/Q4.1
MULTICOMPOSITIONAL ASSEMBLY AND FUNCTION IN THREE DIMENSIONS. Galen D. Stucky, University of California, Dept of Chemistry & Biochemistry and Materials Dept.

Numerous examples exist, both biological and synthetic, of composite materials that are structurally organized on multiple length scales and dimensions. The 3-d organized molecular assembly of components that are both functionally and compositionally unique into an integrated system remains a challenge, albeit exciting advances in this area are being made, as evidenced by presentations in this symposium. In biogenesis the components of the system are created via non-linear parallel multivalent synthesis and processing. On the benchtop, a first approximation to this is to use a 3-d "living polymer" approach with distinctly defined chemical potential domains in which specific molecular assembly processes can be carried out on specified time scales. The overall system organization is then determined by the molecular definition of the interfaces between the domains. This talk will review some selected recent observations made on the 3-d molecular assembly of two or more inorganic species with distinct functionalities. The a priori simpler configuration of homogeneous solution-like phases makes possible electro-otpic or magneto-optical composite arrays that are otherwise not easily accessible. An alternative is to carry out the molecular assembly of species with different composition and function into phase separated extended domains. An example of this is the use of block polypeptides to co-assemble capped CdSe(CdS) quantum dots and silica nanoparticles into a microcavity configuration. In this case the electronic states of the three-dimensional confined semiconductor nanocrystallites are coupled to the photonic states of the spherical microcavity to give single mode lasing.

2:00 PM *J1.2/P2.2/Q4.2
COLLOIDAL SELF-ASSEMBLY, MULTI-BEAM INTERFERENCE LITHOGRAPHY, AND PHOTONIC CRYSTALS. Pierre Wiltzius, University of Illinois, Beckman Institute for Advanced Science and Technology, Dept. of Materials Science and Engineering, Dept. of Physics, Urbana, IL.

Photonic crystals are materials that allow us to manipulate light in new and unexpected ways. Semiconducting materials played a tremendous role in microelectronics and we expect photonic crystals to revolutionize the world of microphotonics in a similar way. Colloidal self-assembly and multi-beam interference lithography are great tools to build crystals with interesting optical properties. I will review some recent progress towards constructing photonic band-gap materials and switchable 3D Bragg gratings.

2:30 PM *J1.3/P2.3/Q4.3
FORMATION OF 2D COLLOIDAL MONOLAYERS AT LIQUID SURFACES UNDER THE ACTION OF LONG-RANGE ELECTROSTATIC AND CAPILLARY INTERACTIONS. Vesselin Paunov, Department of Chemistry, University of Hull, Hull, UNITED KINGDOM.

Recent progress on preparation of 2D structured micro-particle monolayers has demonstrated the potential application of non-specific colloid interactions between particles trapped at liquid surfaces or into liquid layers for fabrication of high technology coatings and materials. The characterization of the long-range colloidal forces operating between particles at liquid surfaces is a major step towards understanding and controlling of the self-assembly of the particle monolayers by fine-tuning of the interparticle interactions. This presentation summarizes our findings on the long-range lateral capillary interactions between particles in several different configurations, including freely floating particles and particles trapped in a liquid film. We reveal the formal analogy between the lateral capillary interaction between particles at a liquid-fluid interface and the DLVO-type of electrostatic interaction between charged surfaces in electrolyte solution. We also analyze the super long-ranged electrostatic repulsion between charged micron-sized latex particles adsorbed at an oil-water interface. It was found that latex particle monolayers at octane-water interface remain highly ordered as a result of long-range repulsion, even on concentrated electrolyte solution. In the case of air-water interfaces, the lateral electrostatic repulsion between the particles was found to be sensitive to the electrolyte concentration in the aqueous phase. Using a laser tweezers method, we have determined the long-range repulsive force as a function of separation between two charged polystyrene micro-spheres trapped at the oil-water interface. At large separations the force is found to decay with distance to the power 4 and is insensitive to the ionic strength of the aqueous phase. The results are consistent with a model in which the repulsion arises primarily from the presence of a very small residual electric charge at the particle-oil interface. We discuss how super-structured 2D mixed monolayers of different particles can be assembled by using such long-range interactions.

3:30 PM *J1.4/P2.4/Q4.4
TOWARDS PHOTONIC INK (P-INK): A POLYCHROME COLLOIDAL CRYSTAL DEVICE. Andre C. Arsenault, Vladimir Kitaev, Geoffrey A. Ozin, and Ian Manners, University of Toronto, Chemistry Department, Toronto, CANADA; Hernan Miguez, Universidad Politecnica de Valencia, Centro Tecnologico de Ondas, Valencia, SPAIN.

We demonstrate here a planarized colloidal photonic crystal device whose optical stop-band position, width and intensity can be reversibly redox and solvent tuned over a broad wavelength range by an anisotropic expansion of the photonic lattice. The material is composed of silica microspheres in a matrix of crosslinked polyferrocenylsilane, a metallopolymer network with a continuously variable state of oxidation. Optical data was fitted using scalar wave theory, with a congruence to experimental data, allowing facile extraction of information concerning polymer swelling behaviour. The chemo-mechanical polychrome optical response of the material was exceptionally fast, attaining its fully swollen state from the dry shrunken state on a sub-second time-scale.

4:00 PM *J1.5/P2.5/Q4.5
COLLOIDAL CRYSTAL TEMPLATING OF POROUS SOLIDS FOR APPLICATIONS BEYOND PHOTONICS. Andreas Stein, Hongwei Yan, Sergey Sokolov, Justin C. Lytle, Mohammed Al-Daous, University of Minnesota, Department of Chemistry, Minneapolis, MN.

A variety of colloidal crystal templating methods have been developed to produce three-dimensionally ordered macroporous (3DOM) or "inverse opal" structures. Many studies have focussed on photonic crystals as target materials, with interesting projected applications involving confinement and control of electromagnetic waves. Structural requirements on such photonic crystals are rigorous, and strict control of defects is necessary to obtain photonic bandgaps. A number of other applications of 3DOM materials pose less rigorous requirements on structural periodicity, but benefit from the 3D arrays of relatively large interconnected pores, highly accessible surfaces, and compositional flexibility of the synthesis. Such applications include optical sensing, catalysis, battery materials, and bioactive materials. This presentation will provide a general overview of relevant issues of structural control in these applications and will then focus on 3DOM materials for nanostructured electrodes (V_2O_5, $LiNiO_2$, $LiCoO_2$, $LiMn_2O_4$, and SnO_2) and bioactive glasses (SiO_2/CaO).

4:30 PM *J1.6/P2.6/Q4.6
SELF-ASSEMBLY OF NANOSTRUCTURED LIQUID CRYSTALS. Takashi Kato, The Univ of Tokyo, Dept of Chemistry and Biotechnology, School of Engineering, Tokyo, JAPAN.

Self-assembly of liquid crystalline (LC) materials with functional moieties is one of versatile approaches to obtain functional molecular soft materials. Here we show two of our approaches to the fabrication of functional LC materials built by non-covalent interactions such as hydrogen bonding and ion-dipolar interactions. The combination of self-assembly through such non-covalent interactions and nanophase segregation behavior is the key for the formation of these functional structures. (1) Low-Dimensional Ion-Conductors: Phase-segregated nanostructures formed by self-assembly processes are useful for the design of functional materials such as ion and electron conductors. Macroscopically oriented one- and two-dimensional ion-conductive materials have been obtained by self-assembly of ionic liquids and hydroxyl-functionalized aromatic molecules. They are partially incompatible and their mixtures form columnar and smectic phases. For one-dimensional conductors, macroscopic homogeneous orientation of the columnar structures is easily achieved by shearing the materials for those assembled materials at room temperature, which leads to high anisotropic ion-conductivity. (2) Ion-Induced Chiral Supramolecular Assemblies: We have designed LC folic acid derivatives having oligo(amino acid) moieties. These materials exhibit columnar and cubic phases due to the formation of hydrogen-bonded tetramers. The addition of a sodium salt induces and stabilizes the cubic phases. Moreover, the addition of the salt has induced the formation of supramolecular chiral LC assemblies. This materials design might lead to the fabrication of materials that are responsive to stimuli such as ions and environments.

SESSION J2: ANOMALOUS PHENOMENA IN PHOTONICS
Chairs: Thomas W. Ebbesen and Francisco J. Garcia-Vidal
Wednesday Morning, April 23, 2003
Golden Gate A3 (Marriott)

8:30 AM *J2.1
NEGATIVE INDEX MATERIALS: STATUS AND FUTURE. Sheldon Schultz, UCSD, Dept. of Physics, La Jolla, CA.

Our group has developed composite structured metamaterials whose permittivity and permeability can be simultaneously negative, which result in frequency bands that exhibit a negative index of refraction (these materials were termed "left handed" because their phase and group velocities are in opposite directions). A remarkable property subsequently predicted by John Pendry is that point sources illuminating a flat slab of homogeneous negative index material can produce reconstructed images well below the usual defraction limit. Further generalization to metamaterials whose permittivity and permeability tensors which can have negative and positive diagonal components reveal other new electromagnetic wave properties not known to exist in nature.

9:00 AM *J2.2
ENABLING ANOMALOUS LIGHT BEHAVIOR WITH PHOTONIC CRYSTALS. John Joannopoulos, Massachusetts Institute of Technology, Dept. of Physics, Cambridge, MA.

It is demonstrated analytically and computationally that photonic crystals can be designed to create a variety of unusual light phenomena. Specific examples will include the possibilities of (1) negative refraction of light with a positive effective index of refraction; (2) novel and anomalous Cherenkov radiation; and (3) reverse Doppler shifts, light-capture with tunable re-emission, and bandwidth-narrowing in shocked photonic crystals.

9:30 AM J2.3
A METALLIC MESH BASED ANTENNA. S. Enoch, G. Tayeb, P. Sabouroux, N. Guérin and P. Vincent, Institut Fresnel, Faculté des Sciences et Techniques de St. Jérôme, Marseille, FRANCE.

The electromagnetic metamaterials have been subject of intensive research in the past few years. It has been shown for example that such a material could simulate a homogeneous media with a plasma frequency in the microwave range or even a homogenous media with negative effective permeability. Numerous effects are expected from these materials, one of the more promising being the controversial perfect lens proposed by Pr. J. Pendry using left-handed metamaterial (both the permittivity and the permeability are negative simultaneously). Recently we have investigated how the specific properties of metallic composite material can modify the emission of an embedded source [S. Enoch, G. Tayeb, P. Sabouroux, N. Guérin and P. Vincent, "A metamaterial for directive emission", Phys. Rev. Lett. in press.]. The richness of the dispersion relation of these metamaterials allows to obtain a material equivalent to a homogeneous media with optical index less than one (eventually negative). We show using very simple arguments, that under proper conditions the energy radiated by a source embedded in a slab of metamaterial will be concentrated in a narrow cone in the surrounding media. We have designed an antenna that uses a metamaterial that is a composite stack of metallic grids and foam layer. The constructed antenna has a directivity equivalent to the best reported results with photonic crystals based antennas. One of the objectives is to obtain antennas much more compact than classical solutions. Another interesting feature is that these antennas can be excited by a single feeding device (patch, monopole). Such antennas could be useful for microwave telecommunications. The experimental measurements are in good agreement with the theoretical predictions.

9:45 AM J2.4
STRONG PLASMON-POLARITON MODE SPLITTING IN A METALLIC GRATING-WAVEGUIDE STRUCTURE. A. Christ and J. Kuhl, Max-Planck-Institut für Festkörperforschung, Stuttgart, GERMANY; N.A. Gippius and S.G. Tikhodeev, General Physics Institute RAS, Moscow, RUSSIA; H. Giessen, Institute of Applied Physics, University of Bonn, Bonn, GERMANY.

The optical properties of solid state materials can be effectively manipulated by periodic structuring on a scale comparable to the wavelength of light. Similarly to the commonly employed dielectric structures, photonic structures based on metals provide remarkable optical properties. Here we present a new type of metallic photonic structure composed of an array of parallel metallic nanowires deposited on a substrate supporting guided optical modes within the spectral range of the nanowire surface plasmon. Such a structure leads to strong interaction of the nanowire surface plasmon with optically active waveguide modes. For our experiments, we used 100 nm wide gold stripes with a thickness of 20 nm. Our quartz substrate was covered on top with a 140-nm-thick indium tin oxide (ITO) film. Transmission measurements show pronounced changes of the extinction spectrum in dependence on the nanowire grating period. The detuning between the waveguide mode and the plasmon resonance is determined by this grating period. For light polarization perpendicular to the nanowires, a strong anticrossing behavior between the plasmon resonance and the TM waveguide mode is demonstrated. The measured Rabi splitting of 240 meV reveals the formation of mixed plasmon-waveguide polaritons in the grating-waveguide structure. Angular dependent transmission measurements at the plasmon polariton resonance for a grating period of 450 nm reveal the full overlap of the stopbands for guided light in the sample for all polarizations. For full theoretical description of the optical properties of such coupled grating-waveguide devices a scattering matrix based method is applied. The theoretical results agree well with the experimental data.

10:30 AM *J2.5
NEGATIVE REFTACTION AND LEFT-HANDED BEHAVIOR IN PHOTONIC CRYSTALS. C.M. Soukoulis, Ames Laboratory and Department of Physics, Iowa State University, and Research Center of Crete, FORTH, Heraklion, Crete, GREECE.

The conditions of obtaining left-handed (LH) behavior in a photonic crystal are carefully examined. Finite difference time domain (FDTD) simulations were used to show that the existence of negative refraction does not necessarily imply LH behavior (i.e. negative index of refraction) for the photonic crystal. The appropriate choices of signs for the phase and group refractive index have been also examined. FDTD simulations are used to study the time evolution of an EM wave as it hits the interface between a positive and a negative refractive index material. It is shown that the wave is temporarily trapped on the interface and after along time the wave moves eventually in the negative direction. This way it is realized how negative refraction can occur on the interface of a material with negative index of refraction without violating causality and the speed of light limit.

11:00 AM *J2.6
EXTRAORDINARY OPTICAL PROPERTIES OF NANO-STRUCTURED METALS. F.J. Garcia-Vidal, Universidad Autonoma de Madrid, Dpto. Fisica Teorica de la Materia Condensada, Madrid, SPAIN; L. Martin-Moreno, Universidad de Zaragoza, Dpto. de Fisica de la Materia Condensada, Zaragoza, SPAIN.

The dielectric response of a metal is completely governed by the free electron plasma. Associated to that it is the existence of electromagnetic resonances localized in the vicinity of its surface (surface plasmons). These modes have an extremely high density and can couple to external radiation. First we will illustrate how these surface plasmons can be exploited for two opposite purposes: localize light in very small volumes [1,2] or to transmit light through arrays of subwavelength slits [3] or holes [4,5] periodically located in a metal film. Then we will show how these two abilities can be implemented to enhance optical transmission through a SINGLE sub-wavelength aperture. Moreover, we will demontrate how by creating a periodic texture on the exit side of a metal film, the shape of the emerging radiation pattern can be tailored [6]. [1] F.J. Garcia-Vidal and J.B. Pendry, Phys. Rev. Lett. 77, 1163 (1996). [2] T. Lopez-Rios, D. Mendoza, F.J. Garcia-Vidal, J. Sanchez-Dehesa, B. Pannetier, Phys. Rev. Lett. 81, 665 (1998). [3] J.A. Porto, F.J. Garcia-Vidal and J.B. Pendry, Phys. Rev. Lett. 83, 2845 (1999). [4] T.W. Ebbesen et al., Nature (London) 391, 667 (1998). [5] L. Martin-Moreno, F.J. Garcia-Vidal, H.J. Lezec, K.M. Pellerin, T. Thio, J.B. Pendry and T.W. Ebbesen, Phys. Rev. Lett. 86, 1114 (2001). [6] H.J. Lezec, A. Degiron, E. Devaux, R.A. Linke, L. Martin-Moreno, F.J. Garcia-Vidal and T.W. Ebbesen, Science 297, 820 (2002).

11:30 AM J2.7
THE RELATIONSHIP BETWEEN THE SUPERPRISM EFFECT, GROUP DELAY, AND STORED ENERGY IN 1-D PHOTONIC CRYSTALS AND PHOTONIC NANOSTRUCTURES. Martina Gerken and David A.B. Miller, Stanford University, Ginzton Lab, Stanford, CA.

The superprism effect is the rapid variation of the group propagation angle with wavelength observed just outside the stop band of one-dimensional, two-dimensional, and three-dimensional photonic crystals. This effect is interesting for future compact wavelength multiplexing and demultiplexing devices. We are particularly interested in multilayer thin-film stacks acting as one-dimensional photonic crystals as they can be fabricated very accurately and cost-effectively. Here we investigate the relationship between superprism effect, group delay, and stored energy in multilayer thin-film stacks. First, we show that the tangent of the group propagation angle is approximately proportional to the group delay through the structure. The only wavelength dependent part of the proportionality constant is the group velocity along the layers. Thus, a device using the angular dispersion of a multilayer thin-film stack exhibits temporal dispersion as well. Next, we use the relationship between stored energy and delay previously derived for microwave circuits from Tellegens theorem. For many thin-film stacks of interest, the group delay is proportional to the stored energy divided by the incident power. Combining these two results, we conclude that the superprism effect is an energy storage effect, i.e. for a larger change in the stored energy with wavelength, a larger change in the propagation direction with wavelength is obtained and vice versa. This physical insight allows us to consider how we might modify periodic structures to obtain superior dispersion characteristics. Different types of non-periodic stacks and their wavelength-dependent energy distributions are investigated. We show experimental and simulation results for several such non-periodic structures with large constant dispersion. Furthermore, the relationship is also interesting from a fabrication point of view as it suggests that regions of the structure that experience a large change in the stored energy with wavelength are crucial for device operation and thus more susceptible to fabrication errors.

11:45 AM J2.8
DIFFRACTION CONTROL AND ENHANCED TRANSMISSION THROUGH SUBWAVELENGTH APERTURES.
Thomas W. Ebbesen, Henri Lezec, Eloise Devaux, Aloyse Degiron, ISIS, University Louis Pasteur, Strasbourg, FRANCE.

Sub-wavelength apertures in optically thick metal films surrounded by surface corrugations display unique optical properties. Not only can the optical transmission be enhanced but it can also be directed in a given direction with a narrow angular divergence. The latest results in this work will be presented together with illustrations of potential applications.

SESSION J3: PLASMONICS AND PHOTONIC CRYSTAL FIBERS

Chair: James A. West
Wednesday Afternoon, April 23, 2003
Golden Gate A3 (Marriott)

1:30 PM *J3.1
BESSEL BEAMS OF THE SECOND KIND AND SURFACE PLASMONS.
J.B. Pendry, The Blackett Laboratory, Imperial College, London, UNITED KINGDOM.

The concept of Bessel beams shows how a pencil thin beam may propagate for large distances with constant cross section. I shall show how surface plasmons can be used to generate a new sort of Bessel beam which also has a constant cross section but one in which the pencil may be much thinner that the wavelength of radiation employed.

2:00 PM *J3.2
OXIDE AND METAL NANOSTRUCTURES FOR CONTROLLING OPTICAL PROCESSES AT THE SUBWAVELENGTH SCALE.
A. Dereux, Y. Lacroute, R. Quidant, J.C. Weeber, Submicron Optics Lab., University of Burgundy, Dijon, FRANCE.

This contribution will first present the fundamental concepts underlying the control of optical processes at the subwavelength scale. The fabrication of oxide-metal nanostructures will then turn out to be a key issue for the development of submicrometre sizes optical devices pertinent for inter- and intra-chips optical interconnects or useful to address single molecular structures in nanosensing applications. Finally, we will present several prototypes which we have already tested experimentally: 1) Made of high refractive index oxide materials: a toolbox of sub-wavelength optical waveguides, Y junctions and add-drop filters featuring 200 nm of transverse size; 2) Experimental demonstration of controlling the resonant optical tunnel effet through chains of mesoscopic oxides particles; 3) Made of metal structures : a toolbox of surface plasmons waveguides and how to control them in order to achieve beam spitting and other optical functionalities. 4) Combining oxides and metal materials : the experimental demonstration of controlling the transmission spectrum of the sub-wavelength waveguides mentionned in 1) by the deposition of metal nanoparticles.

2:30 PM J3.3
SUB-DIFFRACTION-LIMIT FOCUSING AND IMAGING IN THE NEAR FIELD WITH REAL MATERIALS.
Pieter G. Kik, Stefan A. Maier, and Harry A. Atwater, California Institute of Technology, Thomas J. Watson Laboratory of Applied Physics, Pasadena, CA.

We present calculations and experiments on sub-diffraction-limit focusing and imaging using thin (10-50 nm) metal films. While conventional optical imaging relies on applying phase corrections to propagating optical waves, near-field imaging requires the reproduction of non-radiating (evanescent) electromagnetic fields. It has been shown theoretically by Pendry that thin metal films can in fact partially reconstruct evanescent waves, allowing for imaging at sub-wavelength scale.
To assess the feasibility of near-field imaging using real materials, we have performed Finite Difference Time Domain (FDTD) simulations. The simulated system consists of a suspended 30 nm Ag film in air. The Ag dielectric function in the frequency region of interest is quite accurately described by a Drude model. Placing an oscillating dipole source (f=8.9×10^{14} Hz; λ=337 nm) near the Ag layer, surface plasmons are seen to build up on both Ag-air interfaces. A 90° phase difference develops in the field distribution on front and back surface, suggesting a resonant coupling of surface plasmons on opposite sides of the film. Optimum imaging is observed at when $\epsilon_{Ag}= 1$ as predicted by analytical calculations, yielding an image FWHM of 34 nm, equivalent to $\lambda/10$. This resolution is a factor two better than obtained without the silver film, showing the beneficial effect of the Ag layer.
Our FDTD simulations suggest that experimental verification of the imaging is difficult but not impossible. Materials systems and experimental configurations that could be used in such experiments are discussed. We discuss our sample fabrication method and initial experimental results will be presented involving 30 nm Ag films deposited on thin dielectrics.

2:45 PM J3.4
SIMULATION AND EXPERIMENTAL CHARACTERIZATION OF ENERGY TRANSPORT IN NANOPARTICLE PLASMON WAVEGUIDES.
Stefan A. Maier, Pieter G. Kik, and Harry A. Atwater, California Institute of Technology, Thomas Watson Laboratory of Applied Physics, Pasadena, CA; Sheffer Meltzer, Elad Harel, Bruce E. Koel, and Ari A.G. Requicha, University of Southern California, Laboratory for Molecular Robotics, Los Angeles, CA.

The ultimate miniaturization of optical devices to spatial dimensions approaching the molecular scale will require structures that guide electromagnetic energy with lateral confinement below the diffraction limit of light, which is not possible using conventional dielectric optical or photonic crystal waveguides. We have shown theoretically that arrays of closely spaced metal nanoparticles can work as plasmon waveguides that guide electromagnetic energy on the nanoscale. Energy transport in these arrays occurs via near-field coupling between metal nanoparticles which sets up plasmon modes. This coupling leads to coherent propagation of energy with group velocities of about 0.1c. We report on FDTD calculations of energy guiding in locally excited plasmon waveguides consisting of spherical noble metal nanoparticles. The simulations allow the determination of the dispersion relation and group velocities for energy transport and quantitatively confirm the results of point-dipole calculations. Using ellipsoidal nanoparticles with a 3:1 aspect ratio, group velocities up to 0.2c are predicted for longitudinal excitations in waveguide geometries that can be fabricated using electron beam lithography. We also present the results of optical characterization of the guiding properties of plasmon waveguides consisting of closely spaced gold and silver nanoparticles fabricated using electron beam lithography. Far-field spectroscopy confirms the existence of longitudinal and transverse collective modes of excitation and allows for the estimation of the dispersion relation and group velocities. Measurements of the polarization-dependent absorption confirm that the collective modes arise from near-field optical interactions. Using the tip of a near-field optical microscope as a local excitation source and fluorescent polystyrene nanobeads as detectors, we present experimental evidence for energy transport over a distance of about 0.5 micron for plasmon waveguides consisting of silver rods with a 3:1 aspect ratio and a center-to-center distance of 80 nm. This is the first direct evidence for localized energy transport in nanoparticle plasmon waveguides.

3:30 PM *J3.5
PHOTONIC CRYSTAL FIBERS: STATE OF THE ART AND RECENT ADVANCES.
Natesan Venkataraman, Michael T. Gallagher, Charlene M. Smith, Dirk Mueller, James A. West, Douglas C. Allan, Nicholas F. Borrelli, and Karl W. Koch, Corning Incorporated, Corning, NY.

Photonic Crystal Fibers belong to a class of fibers that have either a 1-dimensional or 2-dimensional periodic array of materials with varying refractive indices. One of the most common arrays consists of air holes in glass. Photonic crystal fibers (PCF) can be further classified as solid-core and hollow-core photonic crystal fibers. While light is guided in the solid-core version by total internal reflection, the hollow-core photonic crystal fiber or photonic band-gap fiber (PBGF) guides light by band-gap effects. The biggest promise of PBGF has been the potential of guiding light in air and the associated ultra low loss (less than 0.2 dB/km) and ultra low nonlinear (1000 times less than silica) transmission of light signals. This paper will present the recent advances made at Corning Incorporated, towards achieving a low loss PBGF. In particular, we report here the fabrication of a PBGF with a minimum loss of 13 dB/km at 1500 nm.

4:00 PM *J3.6
HYBRID MICROSTRUCTURED OPTICAL FIBERS ENABLING INTEGRATED TUNABILITY. Charles Kerbage, Benjamin J. Eggleton, OFS Laboratories, Murray Hill, NJ.

Microstructured optical fibers display unique optical capabilities in manipulating light. These fibers, typically all-silica, incorporate numerous air-holes that run along the length of the fiber in the cladding region. By introducing certain materials into the air-holes and by engineering the fiber, it is possible to actively manipulate light, creating the potential for novel hybrid all-fiber optical devices in which the tunability is incorporated into the fiber itself. To manipulate light propagating in the microstructured optical fiber, efficient interaction between the field and tunable materials infused in the air-holes is required. This can be achieved in two ways. One way is to spread the mode field into the cladding by tapering the fiber. The other method involves coupling the core and cladding modes using a grating written in the core of the fiber. To obtain tunability, materials such as index temperature dependent polymers or microfluids are incorporated into the air-holes of the microstructured optical fiber. Tunability is achieved by changing the refractive index of the polymer or by displacing the microfluids along the air-holes to certain locations where overlap with the mode field is accessible. Devices such as tunable filters/attenuators and polarization-controllers, based on the dynamic position of fluids along the length of the fiber, are demonstrated. Birefringence and polarization in microstructured optical fibers can be also be created and tuned by introducing active materials in certain holes such as to break the symmetry of the waveguide and tune the asymmetry by changing the index of the material. Moreover, gratings formed by periodic structures introduced in the air-holes of the microstructured optical fiber are also described in the context of tunable filters.

4:30 PM J3.7
REALIZATION OF AIR TRENCH WAVEGUIDES FOR FUTURE MICROPHOTONICS. S. Akiyama, K. Wada, J. Michel, L.C. Kimerling, Dept of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA; M. Popovic and H.A. Haus, Dept of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA.

Silica optical bench (SiOB) technology is mature and widely used in integrated WDM applications, such as arrayed waveguide gratings (AWGs). The low-index-contrast waveguides permit low insertion loss at fiber coupling and low propagation loss. However, the major drawback is the large bending radii to keep radiation losses within acceptable bound, limiting the density of integration. We proposed a simple and CMOS compatible technology that allows sharp bends in silica allowing to a high density of integration by orders of magnitude[1]. Air trench waveguide realizes compact bending radius by introducing air or low index material at the bends and locally increasing index difference. This air trench waveguide realizes optical integration on chip using low index contrast material system. This means that this waveguide has good characteristics for the future microphotonics such as low transmission loss, low bending loss, low coupling loss between fiber and waveguide in addition to compact bending size. Simulations were done using the Finite Difference Time Domain (FDTD) method, primarily in two dimensions. They show that a waveguide bend designed to have a throughput efficiency of 98% can be reduced in size by a factor of 10-100 with the use of air trenches, with the bending radius itself reduced 30-500 times. For actual fabrication, we employed silicon oxynitride(SiON) for core and SiO_2 for cladding. The fundamental processes such as the optimization of SiON deposition and successive defect removal annealing process, film stress management, and precise deep oxide etch process are established. The comparison between and theoretical calculation and actual results will be shown. [1] M. Popovic, K. Wada, S. Akiyama, J. Michel, Journal of Lightwave Technology in Press.

4:45 PM J3.8
NONLINEAR OPTICAL POLYMER PHOTONIC CRYSTAL WAVEGUIDES. Shin-ichiro Inoue, Kotaro Kajikawa, Yoshinobu Aoyagi, Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama, JAPAN.

Studies and applications of nonlinear optical (NLO) processes in photonic crystals (PCs) are very exiting area. However, the main present study and development of PCs are carrying out in passive elements using the photonic band-gap. We consider that attractive characteristics of PCs in the NLO process open a door to realize new exiting active function and novel high-efficiency NLO applications. For example, an extremely low group velocity at a band edge provides the enhancement of the electromagnetic field of incident light, and the anomalous band dispersion of this region is very sensitive for small refractive index change. Moreover, simultaneously, it is possible to obtain phase matching by appropriate band-design. These features of PCs lead to an original high-efficiency optical switching and frequency conversion by the combination with the nonlinearity of host materials. However, these experimental realization and analysis of details in two-dimensional PCs slab waveguides formed by a high-nonlinear host material have scarcely been done yet, because of difficulty to obtain high-aspect and high-quality profiles of PCs for the best-known nonlinear inorganic crystals such as $LiNbO_3$. We propose a NLO polymer exhibits good processability to make PCs structure and comparable high-optical nonlinearity compared to inorganic crystals is one of the best candidate materials for the nonlinear PCs waveguides. In this work, we successfully obtained high-quality PCs waveguides using the NLO polymer which was fabricated by electron beam lithography and ICP etching. For these samples, the photonic band-structure was experimentally observed by angular dependent polarized reflectivity measurements, which is essentially important for exact band-design in NLO processes. The band-structure was in good agreement with calculated band dispersions and showed, for the first time, the phase matching conditions is achieved in SHG processes with the extremely low group velocity of the second harmonic wave. Further details will be reported in the presentation.

SESSION J4: POSTER SESSION
Chair: David J. Norris
Wednesday Evening, April 23, 2003
8:00 PM
Salon 1-7 (Marriott)

J4.1
STRESS EFFECTS ON THE PERFORMANCE OF OPTICAL WAVEGUIDES. M. Huang, Princeton University, Dept of Mechanical & Aerospace Engineering, Princeton, NJ.

Stresses can cause anisotropic and inhomogeneous distribution of the refractive index. Its effects on the performance of optical waveguides have been observed in photoelectric devices. In this paper, the photo-elastic relation and wave equations for inhomogeneous and anisotropic wavegudes are reviewed. The effective refractive indexes and mode shapes of a planar waveguide under different stress states are obtained analytically. It is found that stress can affect the optical performance; different stress states play different roles: high stress value can change the cutoff thickness, which may induce multimode; in-plane stress causes birefringence, which may induce Polarization Shift and Polarization Dependent Loss; stress concentration can change the mode shape, which may induced large transition loss; and pure shear stress has little effects on the effective refractive index.

J4.2
NANOPOROUS OPTICAL MATERIAL. Yujian You, Garo Khanarian, Robert Gore, Mike Talley, Scott Ibbitson, Angelo Lamola, Rohm and Haas Company, Spring House, PA; Mike Gallagher, Shipley Company, Marlborough, MA.

Porous media such as sol gel materials and porous silicon have been increasingly studied for optical applications because of their lowered refractive index, although the scattering effect from the pores is of concern. We approached this issue by applying nano-sized particles as templates to create porosity in organo-silicate matrices. These nanoparticles were compatible with the matrices and produced clear porous thin films. Micrographs showed discrete pores at low porosity, and SANS study have shown pores with size of about 3 nm. The resulting thin films have achieved substantial reduction of refractive index up to 0.2. The ability to create porosity in the thin film of matrix, and therefore to lower the refractive index, is closely related to the mechanical properties of the matrix material itself. Optical loss through the porous materials were measured using a waveguide approach. The loss due to porosity was determined to be less than 0.9 dB/cm at wavelength between 630 nm - 1550 nm. This material is applicable as cladding material in waveguide construction or in similar applications where low refractive index is desired.

J4.3
THE FORMATION MECHANISM OF PLASMA INDUCED SURFACE DAMAGE IN SILICATE GLASS DEEP ETCHING FOR OPTICAL WAVEGUIDES. Duk Yong Choi, Joo Hoon Lee, Dong Su Kim, Sun Tae Jung, Optical Communication Device Group, Fiber Optics Division, Samsung Electronics Co., Suwon, KOREA.

Ge-doped boron-phosphosilicate glass films are widely used as optical waveguides because of their low losses and inherent compatibility with silica optical fibers. These films were etched by ICP (inductively coupled plasma) with chrome etch masks, which were patterned by RIE (reactive ion etching) using chlorine-based gases. In some cases, the etched surfaces of silicate glass were very rough (root-mean square roughness greater than 100nm) and we call this phenomenon PISD (plasma induced surface damage). Rough surface can't be used as a platform for hybrid integration because of difficulty in alignment and bonding of active devices. PISD reduces etch rate of glass and it is very difficult to remove residues on a rough surface. The objective of this study is to elucidate the mechanism of PISD formation. To achieve this end, PISD formation during different etching conditions of chrome etch mask and silicate glass was investigated. In most cases, PISD sources were formed on glass surface after chrome etching, and residual chrome, metal chlorides were identified in theses sources. Water rinse after chrome etching reduced the PISD, due to the water solubility of metal chlorides. PISD was decreased or even disappeared at high power and/or low pressure in glass etching, even if PISD sources were present on glass surface. In conclusion, PISD sources come from the chrome etching process, and polymer deposition on these sources in silicate etching cause the PISD sources to grow. Etch rate on the area immediate of the PISD source would be increased due to increased ion flux, and this results in the formation of pits.

J4.4
Abstract Withdrawn.

J4.5
STUDY OF DIELECTRIC CONTRAST IN THE FABRICATION OF SEMICONDUCTOR OF LIGHT AND TUNING OF THE PHOTONIC BAND GAP. G.K. Johri, Akhilesh Tiwari, Manoj Johri, Department of Physics and Electronics, D.A-V. College, Kanpur, INDIA.

In this work we report a minimum dielectric constant contrast in the closed packed face centered cubic lattice using an alternative mechanism of scattering strength and minimum effective dielectric contrast. This gives an idea to search a material of dielectric constant less than silicon. The photonic band gap (PBG) arises a result of minimum density of states in addition to one proposed in this work for overlapping of PBG of all points of Brillouin zone. We have found that anisotropic behaviour may act as a shutter to tune the photonic band gap. The results obtained are fruitful to understand the mechanism of PBG and its tuning for understanding the practical applications for semiconductor of light in three dimension.

J4.6
PHOTONIC CRYSTAL MULTI-CHANNEL ADD/DROP FILTERS. Chul-Sik Kee, Dae-Hee Cho, Jong-Ho Jung, Ikmo Park, Sun-Gu Lee[a], Haewook Han[a], and H. Lim, Division of Electrical and Computer Engineering, Ajou University, Suwon, KOREA. [a]Dept. of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang, KOREA.

We propose the multi-channel add/drop filters based on photonic crystals. The filtering is performed by the coupling between cavity modes of point defects and guiding modes of line defects in a two-dimensional photonic crystal. The coupling between the cavities and the waveguide allows the cavities to trap photons from one waveguide and to emit them into another waveguide. The frequencies of photons trapped by the cavities can be selected by designing the point defects. The multi-channel add/drop filter implemented with the microstrip lines shows well the proposed characteristics in the microwave range.

J4.7
Abstract Withdrawn.

J4.8
SOFT CROSSLINKABLE AZOBENZENE POLYMER FOR RAPID SURFACE RELIEF FORMATION AND PERSISTENT FIXATION. Nobuyuki Zettsu, Chemical Resources Laboratory, Tokyo Institute of Technology, Yokohama, JAPAN; Takahiro Seki, Department of Applied Chemistry, Graduated School of Engineering, Nagoya University, Nagoya, JAPAN; Kunihiro Ichimura, Research Institute for Science and Technology, Science University of Tokyo, Chiba, JAPAN.

The photoinduced sinusoidal modulated surface relief structures on azobenzene functionalized (Az) polymer films, known as surface relief gratings (SRG), are formed via large-scale polymer chain migration. The all-optical single step fabrication of SRG (without development process) will lead to facile processing of periodic microstructures, which may find fascinating applications in photonic device systems. For conventional classes of SRG forming Az materials, however, the light dose required for SRG generation typically reaches the order of some tens J cm^{-2}. From a practical viewpoint, advancing the photosensitivity for the photoinduced mass transport and is a subject of great demand. Another important requirement for the SRG system is the shape stability in terms of long term storage and durability at higher temperature. The stability can be improved when one employs Az polymers with high Tg. However, such polymers seriously reduce segmental mobility for mass migration. In the above contexts, we propose herein a newly designed polymer material, a soft (fluid) crosslinkable Az polymers. The process involves two steps; rapid SRG inscription via light exposure followed by an on-demand post-fixation for persistent storage. Without fixation, the SRG structure is erased and regenerated many times. Based on this idea, we prepared new copolymers having an Az side chain and an oligo(ethylene oxide) (EO) unit. The flexible EO group is anticipated to increase the film fluidity, and the terminus hydroxyl group in this unit can be subsequently utilized for chemical crosslinking. The above copolymers show large mass transfer with extremely high photosensitivity. The typical exposure dose required is as low as 50 mJ cm^{-2}. The inscribed surface relief structure can be rapidly erased upon ultraviolet irradiation, which can be the result of the photochemical transition from the liquid crystalline to the isotropic phase. After the chemical crosslinking via the acetal reaction with a formaldehyde vapor, the surface relief structure became highly stable and durable at high temperatures up to 240°C. Interestingly, the trans/cis photoisomerization readily proceeded in the crosslinked film without changing the SRG structure.

J4.9
STRESS EFFECTS ON MULTILAYER OPTICAL WAVEGUIDES. Rui Huang and Yaoyu Pang, The University of Texas at Austin, Dept of Aerospace Engineering and Engineering Mechanics, Austin, TX.

Devices in integrated optic circuits and micro-optical electromechanical systems (MOEMS) often consist of dissimilar materials. Residual stresses in such devices result from both material deposition processes and thermal expansion mismatches between different materials. The presence of residual stresses then causes changes in refractive indices via photoelastic effects and affects the performance of the devices. In particular, stresses have significant effects on the confinement and the polarization of electromagnetic waves in optical waveguides. In this study, we consider planar optical waveguides with a periodic multilayer structure subject to biaxial stresses. General solutions are obtained for dispersion and mode shape of guided electromagnetic waves in both isotropic and anisotropic dielectric multilayers. Of particular interests are the stress effects on mode shapes, radiation loss, and birefringence for various thickness ratios and index contrasts between the core and the cladding layers. It is found that the TE and TM waves are coupled when one of the off-diagonal components of the dielectric tensor is non-zero. For materials with cubic structures, the dielectric tensor is diagonal and remains diagonal under biaxial stresses. For other materials such as fluorinated polyimide used in polymeric waveguides, however, the biaxial stresses induce off-diagonal components and thus cause coupling between TE and TM waves as well as large polarization dependent loss.

J4.10
PREPARATION AND PHOTONIC BANDGAP PROPERTIES OF (Pb,La)(Zr,Ti)O3 INVERSE OPALS. Bo Li, Ji Zhou, Lifeng Hao, Hu Wei, Ruilong Zong, Minmin Cai, Min Fu, Longtu Li and Zhilun Gui, State Key Lab of New Ceramics and Fine Processing, Department of Materials Science and Engineering, Tsinghua University, Beijing, P.R. CHINA; Qi Li, Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL.

(Pb,La)(Zr,Ti)O3 (PLZT) inverse opal photonic crystals were synthesized by a process of self-assembly in combination with sol-gel technique. In this process, PLZT precursors were infiltrated into the interstices of the opal template assembled by monodisperse submicron polystyrene spheres, and then gelled in a humidity environment. Polystyrene template were removed by calcining the specimen at a final temperature of 700°C accompanied with the crystallization of perovskite phase in PLZT inverse opal network. SEM images show that the inverse opal possesses a face-centered cubic (fcc) structure with a lattice constant of 300 nm. A very wide photnic bandgap in the visible range is observed from transmission spectra of the sample. Such wide photonic bandgap in photonic crystals should be of importance to in device applications.

J4.11
LASING CHARACTERISTICS OF SINGLE SPHERICAL MICRODROPLETS LEVITATED IN AN ION TRAP. Masahide Tona and Masahiro Kimura, Kochi Univ of Technology, Laboratory of Physics, Kochi, JAPAN.

We have investigated lsaing characteristics of single dye-doped microdroplets levitated in an ion trap. A single droplet in the ion trap is suspended electrodynamically without any materials and shaped into a nearly perfect sphere due to the surface tension. Such a droplet acts as a microcavity with extremely high quality values at the specific size parameters x ($= 2\pi a/\lambda$, where a is the radius of the microsphere and λ is the light wavelength). If light waves travel around the circumference of the droplet due to total internal reflection and round in phase, resonant standing waves are produced near the surface. Such resonances are called "morphology dependent resonances (MDRs)" because the resonance frequencies depend strongly on x's. The systems of a microsphere with MDRs are often called "photonic dots" by analogy with quantum dots. The photon confined in the microsphere is analogous to the electron bound in the quantum well. In order to obtain fundamental information on optical properties of photonic dots, we have carried out spectroscopic and microscopic observations of microdroplets composed of liquid glycerol doped with rhodamine 6G molecules. The droplets were generated by a method of electrospray ionization and injected into the ion trap. A pulsed green laser irradiated a dye-doped droplet. Both emission spectra and microscopic images were obtained from the direction perpendicular to the pump beam. We will present emission properties of photonic dots, including polarization characteristics of spectra and images, temporal properties and the dependence of lasing modes on dye concentration.

J4.12
MODAL ANALYSIS OF LIGHT TRANSMISSION BY SUBWAVELENGTH SQUARE COAXIAL APERTURE ARRAYS IN METTALIC FILMS. Gérard Granet, Antoine Moreau, Fadi Baida, Daniel Van Labeke.

Nowadays, opticians are greatly interested in structures that exhibit anomalous behavior because of their potential applications in novel photonic devices. The extraordinary enhanced transmission by subwavelength metallic hole arrays is one such phenomenon. Since the publication of Ebbesen et al., many experimental and theoretical studies have been carried out in order to determine the physical origin of the observed enhanced transmission. Several authors attributed it to the excitation of surface plasmons, others related the effect to cavity resonances. It is now established that both horizontal and vertical resonances play a role in the extraordinary transmission. It is then of importance to characterize and to understand the electromagnetic behavior of the channel through which the light propagates inside the metallic film. Recently, numerical simulations have shown that a transmission as high as 80% can be obtained with annular apertures. The aim of the present communication is to study the spectral response of metallic films with square coaxial aperture. Those structures resemble the above mentioned ones and indeed our results show that they present the very same electromagnetic behaviour as could be expected. Since the aperture dimensions are of the order of magnitude of the wavelength a rigorous electromagnetic treatment is necessary to analyze the behavior of such structures. Although the FDTD method allows to calculate rigorously the reflection and transmission of a plane wave by a periodical structure in the resonance domain, the Fourier Modal Method, together with the S matrix approach, gives a more physical insight in the present resonant phenomenon. The diffraction problem is reduced to the search of eigenvalues and eigenvectors of a particular matrice which allows to calculate the effective index of the mode of the coaxial aperture and the coupling of these modes with the reflected and transmitted order.

J4.13
Abstract Withdrawn.

J4.14
HIGH INTENSITY PHOTOLUMINESCENCE IN WAVEGUIDES OF SILICON-RICH SILICON DIOXIDE. R.T. Neal, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM; M.D.C. Charlton, Royal Society, Mesophotonics Ltd, UK, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM; C.E. Finlayson Department of Physics and Astronomy, University of Southampton, Southampton, UNITED KINGDOM; M.C. Netti, Mesophotonics Ltd; M.Josey, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM; G.J. Parker Mesophotonics Ltd, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM.

Following initial work by Iacona et al(1) on the growth of silicon nanocrystals, we have now succeeded in fabricating strongly luminescent planar optical waveguides based on nanocrystaline silicon material. Waveguides are fabricated from silicon-rich silicon dioxide through a combination of PECVD deposition and annealing, and display intense luminescence over the wavelength range 650-1200nm. Our process provides a new medium for the fabrication of silicon compatible LEDs and laser devices suitable for optical communications. In this paper luminescence and waveguiding properties will be discussed in detail. Waveguides are composed of an active silicon-rich silicon dioxide core layer deposited between silicon dioxide cladding and buffer layers on a standard silicon wafer. The effects of various anneal times upon the refractive index, luminescence spectrum, and transmittance of the waveguide were investigated. The active layer of the waveguide was pumped at normal incidence using an argon ion laser resulting in intense photoluminescence from 650-1200nm. Measurements were taken of light emitted from a sample facet. Broad band spectroscopic measurements were also performed on the waveguides, using a white light laser. Results show that a high-temperature activation anneal of the silicon-rich silicon dioxide, while necessary for the formation of photoluminescent centers, is itself detrimental to the transmission properties of the material in the visible range. In contrast with work done by M.L. Brongersma et al(2), the intensity of the photoluminescence increases with increased duration of anneal. Spectral measurements show that both annealed and unannealed material have excellent waveguiding properties and low loss in the 1.55μm communications window. 1 F. Iacona, G. Franzò, C. Spinella, Journal of Applied Physics, 87(3) p1295-1303 (2000) 2 M.L. Brongersma, A. Polman, K.S. Min, E. Boer, T. Tambo, Applied Physics Letters, 72(20) p2577-2579 (1998).

J4.15
SPECTRAL CHARACTERISTIC OF COLLOIDAL PHOTONIC CRYSTALS. Kai Dou, Zhusun Xu, and Thomas Collins.

The spectroscopic and microscopic investigation in polystyrene photonic crystals was performed. Colloidal crystalline layers were deposited on glass and quartz by vertical evaporation deposition. Emission, excitation and selected-excitation spectra were studied in both polystyrene powders and polystyrene photonic crystals. The experimental results indicated that spectral features were remarkably dependent on the particle properties of size, shape and arrangement. Blue emission at 420 nm was also found by using a 532-nm excitation due to multiphoton process and a dynamic model was proposed to explain the upconverted emission mechanism.

J4.16
TRANSMISSION OF ACOUSTIC WAVES THROUGH WAVEGUIDE STRUCTURES IN TWO-DIMENSIONAL PHONONIC CRYSTALS. J.O. Vasseur, M. Beaugeois, B. Djafari-Rouhani, LDSM, UMR CNRS 8024, Université de Lille I, FRANCE; Y. Pennec, LSPES, UMR 8008, Université de Lille I, FRANCE; A. Khelif, LPMO, UPR 3203, Université de Franche-Comte, FRANCE; P.A. Deymier, DMSE, University of Arizona, Tucson, AZ; J. Zemmouri, PhLAM, UMR 8523, Université de Lille I, FRANCE.

Phononic crystals are inhomogeneous materials made of periodic repetitions of inclusions in some different host material. They are the elastic analog of the so-called photonic crystals and physical phenomena similar to those observed in photonic crystals may occur in phononic crystals. In this work, we study theoretically and experimentally the transmission of acoustic waves through waveguide structures in a two-dimensional phononic crystal made of PVC cylinders arranged on a square array in air. We investigate the transmission through perfect rectilinear waveguides, waveguides containing a resonant cavity, or waveguides coupled with a side branch resonator such as a cavity or a stub. A rectilinear wave guide obtained by removing one row of cylinders in the perfect phononic crystal can support one or several modes falling in the absolute band gap of the phononic crystal. The transmission through a guide containing a cavity can be made very selective and reduced to narrow peaks associated with some of the eigenmodes of the cavity. The effect of a side branch resonator is to induce zeros of transmission in the spectrum of the perfect guide that appear as narrow dips with frequencies depending upon the shape of the resonator and its coupling with the guide. We find good correspondences between the peaks in the transmission spectrum of a waveguide containing a cavity and the dips in the transmission of a cavity side coupled waveguide. Most of these theoretical predictions are compared to experimental measurements made in the audible frequency range.

J4.17
Abstract Withdrawn.

J4.18
ENHANCED TRANSMISSION IN METAL-DIELECTRIC NANOSTRUCTURED THIN FILMS. A. Suarez-Garcia, R. del Coso, R. Serna, J. Solis, C.N. Afonso Instituto de Optica, CSIC, Madrid, SPAIN.

Nanostructures formed by Cu nanocrystals (NCs) embedded in amorphous Al_2O_3 have been shown to exhibit a high third order non linear optical response ($\chi^{(3)}$) together with a fast response time at wavelengths in the vicinity of the surface plasmon resonance (SPR) [1,2]. The figure of merit for non linear materials in waveguide devices is defined as $\chi^{(3)}/\alpha$ and in the case of metallic NCs principally limited by its linear absorption (α) which at the same time mainly depends on the content of metal in the film. It is desirable to be able to obtain a higher transmission independently on the NCs attributes. This can be possible in terms of optical band gap structures, where by mean of interferencial effects an enhancement of the transmission at a certain range of wavelengths is obtained. A nanostructured thin film has been grown by pulsed laser deposition (PLD) consisting of six layers of Cu NCs alternating with ~7 nm thick layers of amorphous Al_2O_3. The average diameter of the NCs is ~5 nm. The film absorption spectrum shows the surface plasmon resonance at about 600 nm that has been attributed to the presence of Cu nanocrystals. The optical properties of the nanostructured film has been analyzed by spectroscopic ellipsometry, assuming a multilayer structure (Al_2O_3)/(Al_2O_3:Cu NCs). The analysis of the results allows to determine the effective refractive index of the nanocomposite formed by the Cu NCs plus the Al_2O_3 that fills the space between them (Al_2O_3:Cu NCs). The optical constants of this complex material have been used to design photonic band gap structures that allow an enhancement of the transmission up to 30% at the SPR wavelength in respect to the reference sample, while keeping the same Cu total content and the same Cu nanocrystal features. Films with the best configurations have been synthesized by PLD, and the corresponding experimental absorption spectra will be shown. The agreement with the simulated design is excellent. The advantages of the different designs in terms of the optical response will be discussed. [1] J.M. Ballesteros, R. Serna, J. Solis, C.N. Afonso, A. Petford-Long, D.H. Osborne, R.F. Haglund, Appl. Phys. Lett, vol 71, No 17, pp 2445-2447 [2] R. de Nalda, R. del Coso, J. Requejo-Isidro, J. Olivares, A. Suarez-Garcia, J. Solis, C.N. Afonso. J. Opt. Am. B vol.19, n 2, pp 289-296.

J4.19
SELF-ASSEMBLED PHOTONIC CRYSTALS. K.C. Huie and A. Chandran, NanoSonic Inc., Blacksburg, VA; R. Claus, L. Supriya, J. Huie, College of Engineering, Virginia Tech, Blacksburg, VA.

This paper describes the application of electrostatic self-assembly (ESA) processing methods to the fabricatio of two-dimensional photonic crystals. The synthesis approach is an extension of conventional ESA deposition techniques in that photodegradable chemisorbed self-assembled monolayers (SAMs) are deposited as the initial layer of the ESA nanocomposite. SAMS are long chain alkane molecules, which can adsorb spontaneously onto substrates to form a very ordered monmolecular layer. The SAMs functionality here is to act as ultrathin resists, which establish regions on a substrate that can prevent the adsorption of ions, based on surface hydrophobicity. Upon UV-exposure, the aliphatic portions of the SAM molecule photolyze producting hyrdophilic regions having charged hydroxyl groups where subsequent ESA bilayers can selectively grow. We have investigated occtadecyltrichlorosilane (OTS) SAMs for the ESA patterning of 2D photonic crystals. Experimental measurements of photonic bandgap waveguide materials operating in the near infrared optical communications wavelength band are shown and discussed.

J4.20
COLLOIDAL CRYSTALS WITH WELL-CONTROLLED CRYSTALLOGRAPHIC ORIENTATIONS. Yadong Yin, Yu Lu, Younan Xia.

We have demonstrated a simple and convenient method that allowed for the fabrication of large colloidal crystals with their (100) planes oriented parallel to the surfaces of supporting substrates. The key components are templates on the surfaces of Si (100) wafers fabricated using anisotropic wet etching. The capability and feasibility of this template-directed self-assembly process have been demonstrated by crystallizing spherical colloids (>250 nm in diameter) into (100)-oriented crystals over areas as large as several square centimeters. Inverse opals with (100) crystallographic orientation could also be fabricated by templating liquid precursors (such as a UV-curable prepolymer) against these colloidal crystals. We believe that the ability to preciely control the crystallographic orientation of colloidal crystals will greatly enrich our studies on their properties.

J4.21
SYMMETRY REDUCTION AND DEFECT LAYERS IN MACROPOROUS SILICON 3D PHOTONIC CRYSTALS. J. Schilling, C. Jamois, R.B. Wehrspohn and Ulrich Goesele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY.

Macroporous silicon 2D photonic crystals which consist of straight air pores in silicon can be extended to 3D photonic crystals by a periodic modulation of the pore diameter with pore depth. Assuming a circular pore cross section this 3D crystal has hexagonal symmetry. Due to the modulation a stopband also opens in the direction along the pore axis. Moreover a 2D defect layer can be introduced in this 3D photonic crystal by etching a straight segment of the pores. Defect resonances at λ_0=6.8μm were experimentally determined. The Q value of the defect resonances depends on the number of modulation periods above and below the defect layer and reaches an experimentally observed maximum of Q=139 for 7 modulation periods. This corresponds to an attenuation of 4.4 dB per period for the modulated pore sections. For the investigated samples only a single defect resonance would be expected within the fundamental stopband. However a transmission measurement with polarized radiation shows that 2 defect resonances exist which couple to different polarization states. The reason for this is the actual shape of the pores. Due to the slight quadratic pore cross section the symmetry of the assumed 3D hexagonal lattice is reduced to an orthorhombic one in reality. This leads to splitting of photonic bands causing polarization dependent bandedge positions and the appearance of 2 closely spaced defect modes. The splitting of the bands connected with the reduced orthorhombic symmetry is also understood from crystal optics. A hexagonal crystal is uniaxial. There exist only 1 refractive index for light propagation along the c-axis (pore axis). An orthorhombic crystal is biaxial. Two polarization dependent refractive indices appear along the pore axis which correspond to the 2 different slopes of the split photonic bands in the long wavelength limit. As the birefringence along the pore axis is caused by the *shape* of the scatterers (pores), it represents a case of *formbirefringence*. The described effect can be used for polarization dependent interference filter in the mid infrared.

J4.22
SYNTHESIS OF DIELECTIC AND METALLO-DIELECTRIC PHOTONIC CRYSTALS BASED ON POROUS ALUMINA WITH ADJUSTABLE RATIOS OF RADIUS TO INTERPORE DISTANCE. Jinsub Choi, Yun Luo, Ralf B. Wehrspohn, Reinald Hillebrand, Jörg Schilling and Ulrich Gösele, Max Planck Institute of Microstructure Physics, Halle, GERMANY.

Perfect $2D$-photonic crystals were synthesized based on porous alumina template methods. To fabricate monodomain porous alumina template on a large scale, indentation by a master stamp consisting of Si_3N_4 pyramids with hexagonal patterns was carried out by a simple oil press before electrochemical anodization. The fabricated porous alumina photonic crystal has an interpore distance of 500 nm and an initial pore diameter of 180 nm, which can be increased by anisotropic chemical etching to create photonic crystals with different r/a. For fabrication of metallo-dielectric photonic crystals silver was infiltrated into the monodisperse templates with various r/a via electrochemical plating. The optical properties of the porous alumina photonic crystal were measured with an infrared microscope in $\Gamma - M$ direction. Reflectivity of the photonic crystals with different r/a shows bandgap positions, indicating the porous alumina is composed of two layers: an inner layer consisting of a high purity alumina having a refractive index of 1.6-1.7 and an outer layer of alumina incorporated with anions, for example, PO_4^{2-} having a non-uniform refractive index. We will discuss the index of the inner and the outer layer of porous alumina and compare the bandgaps observed by $FT - IR$ with band structure and reflectivity calculations.

J4.23
EXPERIMENTAL DEMONSTRATION OF HIGHLY DIRECTIONAL RADIATION SOURCES USING SYMMETRIC AND ASYMMETRIC PHOTONIC CRYSTALS. Humeyra Caglayan, Irfan Bulu and Ekmel Ozbay, Department of Physics, Bilkent University, Bilkent, Ankara, TURKEY.

Two features are of interest in the control of emission from radiation sources: the first one is to enhance the emitted power, and the second one is to confine the emitted power to a narrow angular region. In this context, modes near the band edges of photonic crystal (PC) are of interest. At the band edges, it is known that the density of states increases for certain directions. This feature of PCs can be used to confine the power emitted from a source to a narrow angular region. In this work, we experimentally and theoretically studied the angular distribution of power emitted from a radiation source located inside a perfect (PC) and an asymmetric PC (an asymmetric PC has different lattice constants along different lattice vectors). We demonstrated that for the band edge modes it is possible to confine the power emitted from a radiation source to a narrow angular region. Half-power beamwidths less than 11 degrees were measured for a source located inside a perfect PC. Experiments showed that the directivity of the source strongly depends on its location inside the PC. We implemented an asymmetric PC to improve the directivity furthermore. Our results showed improved angular confinement for the asymmetric PC when compared to the perfect PC.

J4.24
OPTICAL SIMULATION AND MICROWAVE FREQUENCY DEMONSTRATION OF A PLASMON SWITCH. Luke Sweatlock and Harry Atwater, Harvard University, Cambridge, MA; Stefan Maier, California Institute of Technology, Pasadena, CA.

Plasmonic structures confine light to a fraction of its free wavelength and could potentially enable optical devices with a scale of a few hundreds of nanometers. We explore the functionality of an all-optical plasmonic switch through simulation, and through construction of an analogous laboratory scale structure that operates in the microwave regime (λ = 3.7 cm). Periodic arrays of centimeter copper rods support propagating electromagnetic modes similar to the dipole modes in plasmonic waveguides. We assemble arrays of copper rods that have a diameter of 0.1 cm (0.03 λ) and length 1.4 cm (0.38 λ); and are spaced 0.2 cm (0.03 λ) apart orthogonal to the long axis. Our interferometric switch consists of two such linear arrays that meet at right angles to form a "T" structure. A center-fed dipole antenna drives the source arm from a klystron, while the gate arm is driven from an identical supply but with variable attenuation and phase. A probe dipole connected to an Agilent E4419B meter was used to monitor the power transmitted to the third arm. When the gate is in phase with the source, the signals add constructively and power is observed in transmission. This can be considered the on state of the switch. Conversely, with the gate out of phase, nulling occurs and the transmitted intensity is lowered. On/off ratios of over 25 dB have been observed. These results agree with simulations performed using finite difference time domain (FDTD) simulation of the system. We will also present FDTD simulation of a nanometer scale subwavelength "T" switch formed from silver nanoparticles with 3:1 ellipsoidal aspect ratio, which support propagating modes near their optical frequency surface plasmon resonance. Pulsed and CW operation of such a plasmonic switch, and its relationship to the radio frequency switch, will be discussed.

J4.25
TUNABLE COLOR ELECTROLUMINISCENCE FROM ARRAY OF QUANTUM DOT-POLYMER COMPOSITES. Sumit Chaudhary and Mihri Ozkan, University of California Riverside, Dept of Electrical Engineering, Riverside, CA; Cengiz Ozkan, University of California Riverside, Dept of Mechanical Engineering, Riverside, CA.

Arrays of quantum dot/polymer composites which can exhibit full color tunable electroluminescence have been investigated. For this purpose, different sized CdSe nanocrystals passivated with a wider band gap semiconductor (ZnS) were incorporated into thin films of Polyvinylcarbazole (PVK) and an oxadiazole derivative (t-Bu-PBD). The electroluminescence (EL) devices were formed by spin coating the composite solution on the Indium Tin Oxide (ITO) and vacuum evaporating the Al electrodes on the top. It is shown that (EL) spectra of the CdSe(ZNS)/polymer films are nearly identical to the photoluminescence spectra of the corresponding CdSe(ZnS) nanocrystals. As the size of quantum dots become smaller, their energy increases in accordance with uncertainty principle, band gaps open up and electron affinity decreases. Thus the threshold voltage increases and differently sized dots start electroluminescing at different threshold voltages. It was found that electroluminescence signal is almost exclusively generated within the nanocrystals, which act as recombination centers. Conducting polymers also showed luminescence at higher threshold voltages than quantum dots. Therefore, by changing the input voltage to the quantum dot/polymer mixture, emission wavelength was controlled and full visible spectrum electroluminescence was obtained, tunable by virtue of sizes of quantum dots and their different threshold voltages. The performance of these heterostructure devices was influenced by the thickness of films. This direct correlation between input voltage and output color leaves tunable pixel panel with immense importance for the development of next generation optical switches, biosensors, LEDs and other optoelectronic devices.

J4.26
Abstract Withdrawn.

J4.27
Abstract Withdrawn.

J4.28
LIGHT TRANSPORT THROUGH POROUS SILICON COUPLED MICROCAVITIES. M. Ghulinyan, C.J. Oton, Z. Gaburro, P. Bettotti, N. Daldosso, L. Dal Negro and L. Pavesi, INFM and Dept of Physics, University of Trento, ITALY; R. Sapienza and D.S. Wiersma, INFM and European Laboratory for Nonlinear Spectroscopy, Florence, ITALY.

We report the experimental characterization of porous silicon free-standing coupled microcavities with several $\lambda/2$ spacers separated by dielectric mirrors. Samples with up to 109 layers were successfully grown. Good quality air-porous silicon-air structures were obtained, which allowed us to carry out reflectance measurements from both sides of the samples. This gave us an opportunity to distinguish the microcavities which are closer to the illuminated side of the structure and, thus, to obtain information about the structural and optical inhomogenities along the growth axis. The blue shift of the microcavity resonant modes, which is observed in the backside reflection data, together with the SEM analysis, demonstrate clear decrease in the thickness for the deepest layers, which is due to the reduced etch rate in the deeper layers. Numerical calculations of reflectance and transmission spectra have been carried out to estimate the drifts in layer thickness and porosity. These drifts were successfully compensated by changing the etching parameters in a controlled way, which allowed us to obtain equal front- and backside reflectance spectra. In this way all the resonant modes of a 10 coupled microcavity structure are resolved in both transmission and reflection measurements. These structures present interesting light transport properties when ultrashort laser pulses are introduced and analyzed. We are performing time resolved transmission measurements in order to observe light confinement effects and interference beatings between modes.

J4.29
SELF-COLLIMATING PHENOMENA IN PLANAR SQUARE PHOTONIC CRYSTALS. L. Wu, M. Mazilu, J-F. Gallet and T. F. Krauss, The Ultrafast Photonics Collaboration, School of Physics & Astronomy, University of St. Andrews, St. Andrews, Fife, Scotland, UNITED KINGDOM.

To realize ultracompact photonic integrated circuits based on photonic crystals (PhCs), it is necessary to precisely control the spatial profile of the propagating light. Propagation without divergence is particularly desirable in such systems. After the first experimental demonstration of self-collimating phenomena in a hexagonal planar configuration [1], we have now extended the wavelength collimating range from 20nm to 40nm by changing the lattice from triangular to square.
Our material system is a GaAs/AlGaAs heterostructure perforated by a square photonic crystal lattice with an air-filling factor of 40-45%. The lattice constant is a=300 nm and the measurement is performed in the 1300 nm wavelength window. Fig.1 shows SEM (top view) of photonic crystals with input and output waveguides. The input waveguide is tilted 10° from normal to the crystal edge (the incident edge is Γ-M). Vidicon micrographs of the output facets as a function of wavelength are shown in Fig.2. Each spot represents one of the output waveguides that are spaced 10° apart and the micrographs obtained for each wavelength have been mounted together in order to show the evolution with wavelength. The corresponding transmission spectra are shown in Fig.3 with the scattered points representing the raw data and solid lines being given as a visual aid. Fig.2 and Fig.3 clearly indicate that the light propagates through the crystal along Γ-M direction, when the input is tilted at 10° to normal, which means that light beams with up to 20° divergence can be cleanly collimated. The useful wavelength range for 20° divergence is 40 nm (1260 nm to 1300). This range will be enough to control the input and output light spatial profile of photonic lattice based devices. Furthermore, we observe good agreement with FDTD calculations and wavevector diagrams based on plane-wave expansion. In conjunction with suitably designed interfaces and the superperprism phenomena in planar photonic crystals that we have already reported [1], the knowledge obtained here represents a further step towards realizing integrated circuits based on PhCs.

SESSION J5: 2D PHOTONIC DEVICES
Chairs: Masaya Notomi and Olav Solgaard
Thursday Morning, April 24, 2003
Golden Gate A3 (Marriott)

8:30 AM *J5.1
DESIGN AND CHARACTERIZATION OF OPTICAL NANOCAVITIES. A. Scherer, T. Yoshie, M. Loncar, J. Vuckovic[a], D. Deppe[b], K. Okamoto, Caltech, [a]Stanford University, [b]U.T. Austin.

(ABSTRACT NOT AVAILABLE)

9:00 AM *J5.2
LIGHT PROPAGATION CONTROL IN 2D PHOTONIC CRYSTALS. Masaya Notomi, NTT Basic Research Laboratories, Atsugi, JAPAN.

Wavelength and spatial dispersion of photonic crystals is one of interesting characters in terms of lightwave control using photonic crystals. In this presentation, we will demonstrate a variety of ways to utilize the exotic behavior of dispersion in 2D photonic crystals. First, strong wavelength dispersion of group velocity in photonic-bandgap waveguides will be discussed. Large reduction of group velocity for traveling light and large increase in group velocity dispersion are observed, and they are compared with theoretical calculations. Second, negative refractive property of photonic crystals which is a curious aspect of spatial dispersion in photonic crystals, will be discussed. We will show that effective index of refraction becomes meaningful in the vicinity of the photonic band gaps or edges, which leads to interesting negative refraction for some photonic bands. Finally, interesting lasing action at the photonic band edge will be discussed. Single-mode lasing action is possible at the photonic band edge, where both of wavelength and spatial modes for lasing action are simultaneously governed by the photonic band structure. We will show a variety of forms of lasing action in photonic crystals.

9:30 AM J5.3
PHOTONIC CRYSTAL PHOTOLUMINESCENCE MODIFICATION IN SILICON-RICH SILICON DIOXIDE WAVEGUIDES. R.T. Neal, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM; M.D.C. Charlton, Royal Society, Mesophotonics Ltd, UK, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM; G.J. Parker Mesophotonics Ltd, Dept of Electronics & Computer Science, University of Southampton, Southampton, UNITED KINGDOM; C.E. Finlayson, Department of Physics and Astronomy, University of Southampton, Southampton, UNITED KINGDOM; J.J. Baumberg, Mesophotonics Ltd, UK, Dept of Electronics & Computer Science, Department of Physics and Astronomy, University of Southampton, Southampton, UNITED KINGDOM; M.C. Netti and M.E. Zoorob, Mesophotonics Ltd.

Following the successful fabrication of strongly luminescent planar optical waveguides based on silicon-rich silicon dioxide material(1), we have now progressed to the incorporation of 2-dimensional photonic crystal structures within the active core layer of optimized waveguides. In this paper we present the first ever experimental measurements on photonic crystal structures incorporated within a luminescent silicon compatible material. Our results demonstrate clear modification of the luminescence spectra, for light guided through the patterned waveguide. Triangular photonic crystal lattices with various pitch sizes varying from 360-610nm were etched to a depth of $2\mu m$ into a planar waveguide structure composed of a 450nm thick silicon-rich silicon dioxide core, clad with 200nm silicon dioxide isolated from a silicon substrate by a $2.1\mu m$ silicon dioxide buffer layer. Structures were pumped at normal incidence using a 510nm Argon Ion laser resulting in intense luminescence over a broad spectrum from 650-1200nm. This luminescence was then used to probe the band-structure of the photonic crystal lattices. Our results demonstrate a clear shift in band gap position over the wavelength range as a function of pitch and filling fraction showing good agreement with plane wave theory. Our results demonstrate that photonic crystal structures can be used to modify the shape of the luminescence spectra generated by silicon nanocrystals embedded within the core layer. Our structures provide the basis for a controllable silicon light-emitting source in the red/near IR portion of the electromagnetic spectrum.

9:45 AM J5.4
NOVEL STRUCTURAL DESIGN AND FABRICATION OF THE AlGaAs-BASED OXIDE-CLADDING PHOTONIC-CRYSTAL SLAB WAVEGUIDES. Yu Tanaka, Yoshimasa Sugimoto, Naoki Ikeda, Tao Yang, and Kiyoshi Asakawa, The Femtosecond Technology Research Association (FESTA), Tsukuba, JAPAN; Kuon Inoue, Chitose Institute of Science and Technology, Chitose, JAPAN.

Two-dimensional (2D) photonic-crystal (PC) slab waveguides (WGs) have received much attention due to their potential application to ultra-small photonic devices. In particular, an oxide-cladding (OC) type 2D-PCWG is a promising structure for having a high refractive-index contrast in the vertical direction with larger mechanical stability than an air-hanging structure. Here, we report on the fabrication and characterization of an AlGaAs-based novel OC-PCWG. The OC layer is fabricated by a conversion of AlGaAs-cladding layer to AlGa-oxide. In general, oxidation performed over a broad area frequently induces significant strain. Therefore, we designed a new structure with the OC-PCWG, which was sandwiched between tapered ridge waveguides. Advantages of this structure are the following. First, a partial oxidation of the cladding region at the wide input/output ports of the ridge waveguide reduces the oxidation-induced strain significantly. Second, a gradual change of the average refractive-index in the tapered cladding layer eliminates the reflection loss that would appear at the otherwise abrupt boundary. Third, since the tapered ridge waveguide fabricated in this way functions as a spot size converter, the coupling efficiency with an optical fiber at the input/output end is expected to increase significantly. For achieving this structure, the oxidation process was precisely investigated by varying a fraction of Al content in the $Al_xGa_{1-x}As$ cladding layer and the oxidation temperature. The oxidation rates were estimated by measuring the oxidation depth on the sidewall with a scanning electron microscopy observation. It was found that the low-temperature oxidation process at less than 400°C was effective for the fabrication of the structure mentioned above. Subsequently, we compared the transmission measurements with the three-dimensional finite-difference time-domain (FDTD) calculations and obtained the good agreements, showing the excellent characteristics of the OC-PCWG.
This work was supported by NEDO within the framework of the Femtosecond Technology Project.

10:30 AM *J5.5
FABRICATION OF MICROOPTICAL PHASED ARRAYS FOR APPLICATIONS IN OPTICAL COMMUNICATION AND SENSING. Olav Solgaard, Department of Electrical Engineering, Stanford University, Stanford, CA.

Integrated Circuit (IC) manufacturing is continuously being improved to produce faster transistors and larger, more complex systems with smaller features and tighter dimensional control. As a consequence, IC technology is becoming increasingly better suited to fabrication of micro and nano-optical devices and systems. Not only does modern IC manufacturing provide efficient parallel processing of large arrays and allow integration of optics, electronics and mechanics, but its vertical and horizontal dimensions are smaller than optical wavelengths in the visible and near IR, thus enabling fabrication of high-quality, diffractive optical elements and photonic crystals. Combining such optical components with MicroElectroMechanical (MEMS) actuators creates tunable optical devices with functions that cannot practically be implemented using traditional fabrication technologies. In this paper we review the design and operation of microoptical devices based on IC fabrication and MEMS-actuator technology. Fiber switches, optical filters, diffractive spatial light modulators, and interferometric filters will be described. The optical and mechanical requirements of these systems are used as a basis to derive specifications on material properties and dimensional control in the fabrication process. Technological developments aimed at producing high-quality, highly functional optical MEMS structures are then discussed. First we describe the development of high-force, electrostatic combdrives based on self-aligned structures fabricated using Deep Reactive Ion Etching (DRIE) of crystalline silicon. This type of high-force microactuator has the potential to drastically improve the speed and optical quality of many important optical MEMS devices. We then discuss low-tempertaure wafer bonding for MEMS-on-IC integration. This technology will enable efficient and flexible design and operation of large, two-dimensional MEMS arrays for the most challenging applications.

11:00 AM *J5.6
SUBWAVELENGTH OPTICAL ELEMENTS (SOEs) AND NANOFABRICATIONS - A PATH TO INTEGRATE OPTICAL COMMUNICATION COMPONENTS ON A CHIP. Stephen Y. Chou, NanoStructure Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ.

Subwavelength optical elements (SOEs) are a special class of optical elements, where the feature size is less than the wavelength of light, hence having no non-zero order diffraction. SOEs behave fundamentally different from bulk (i.e. ray) optics or diffraction optics [1-4]. First, SOEs can create new optical functions that are unavailable in bulk or diffractive optical. Second, SOEs can perform an optical function with a size that is orders of magnitude smaller than that of a bulk optical element. And third, SOEs perform different optical functions by using different geometries (shape and size) of features but the same materials, rather than different materials in bulk optics. The second and the third properties of SOEs make them particularly suited for integrated communication optical elements on a chip and be manufactured at the wafer scale. Examples will be given where by changing the geometries of the sub-wavelength feature, while keeping the materials are the same, a SOE will be changed from a waveplate to an antireflection surface, to a polarizer, to a beam splitter, to a filter, and to a lens. It will also to be shown that each of the above functions has been achieved with a SOE layer of less than one micron thick. Examples on the integrations of these SOEs are also given.
The SOEs also can be integrated with active elements such as lasers or detectors. We will describe how SOEs can be used to (a) turn a multi-mode laser into a single mode, (b) tune the frequency or polarization of a laser, and (c) create a very high-frequency optical clock.
The promise of SOEs will not be realized, unless we have a low-cost, high-throughput nano-manufacturing technology. This is also the reason that it took so long for us to realize the importance of SOEs. Nanoimprint lithography (NIL) is one of the most promising nano-manufacturing technologies that can impact many different industries, including optical communications [5,6]. Fabrication of SOEs on wafer scale by NIL will be presented.
Using SOEs as optical elements and NIL as the manufacturing technology, our dream to have optical elements integrated on a chip - a revolution similar to the vacuum-tube-to-transistor revolution in electronics will be greatly accelerated.
References
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11:30 AM J5.7
DESIGN AND DEMONSTRATION OF WIDE BANDWIDTH 2-D PHOTONIC CRYSTAL WAVEGUIDES. Edmond Chow, Annette Grot, Laura Mirkarimi, Mihail Sigalas, Agilent Technologies, Palo Alto, CA.

We present the design, fabrication, and characterization of a 2-D slab photonic crystal waveguide with low propagation loss and wide spectral transmission. The waveguide is created by altering one row of holes in an hexagonal photonic crystal lattice. By increasing the diameter of the circle from 0.6a to 0.9a, one can create a waveguide with a spectral width of 10% the operating wavelength. However, such a photonic crystal waveguide is difficult to fabricate because the critical dimension, or smallest feature size, is only 40nm. We have found that elliptical rather than circular holes allow one to create wide spectral width waveguides without substantially reducing the critical dimension between holes. This is an important factor in the fabrication of these devices. We pattern our photonic crystal waveguides using a JEOL6000fs ebeam lithography tool. Our waveguide material is 0.26μm thick Si on oxide. The photonic crystal lattice period is typically 400nm, corresponding to a photonic crystal bandgap from 1286nm to 1632nm. The dimensions of the elliptical hole are dx=0.55a (220nm) and dy=1.29a (516nm), where x describes the direction of the waveguide. We use a thin SiO_2 layer as a hard mask during the RIE etching of the Si layer. We do not etch or remove the underlying 1 μm layer of SiO_2. Initial experimental results show propagation loss of 5db/mm from 1545nm-1585nm. Due to suboptimal control of the hole sizes during fabrication, the bandwidth is approximately 80 nm which is less than 5% of the operating wavelength. Using finite difference time domain modeling to simulate transmission through the waveguide, we are able to predict this narrow transmission spectrum and show that by using optimal dimensions (dx=0.72a and dy=1.66a) the transmission spectrum increases to 200nm.

11:45 AM J5.8
TUNING OF GaAs BASED 2D PHOTONIC CRYSTALS BY INFILTRATED LIQUID CRYSTALS. Ch. Schuller, F. Klopf, J.P. Reithmaier and A. Forchel, Technische Physik, Universitaet Wurzburg, Am Hubland, Wurzburg, GERMANY.

In photonic crystals (PC) the propagation of electromagnetic waves is strongly affected by the dielectric contrast. We are able to tune the photonic band gap by infiltrating liquid crystals into the voids of the 2D PC and controlling the refractive index of the liquid crystals.
To investigate the tuning of photonic crystals, planar microcavities with two PC mirrors with lattice constants of about 300 nm are used. They are fabricated on AlGaAs/GaAs-waveguides with a single InGaAs dot layer as internal light source. The crystal is defined for a wavelength of 1 μm by high resolution e-beam lithography in PMMA and transferred by RIE into the SiO_2-mask. The pattern is etched down into the semiconductor using ECR-RIE. In a final step the liquid crystals are filled into the evacuated voids.
The transmission experiments are done by optical pumping of the embedded dots. The emitted TE polarized light propagates in-plane through the microcavities and is detected by a CCD camera from a cleaved facet.
The microcavities are investigated with and without liquid crystals. After filling the voids with liquid crystal of type E7 the resonance shifts about 50 nm to longer wavelength while the linewidth and the transmittance slightly increases. By raising the temperature until the clearing point of the liquid crystal the refractive index slightly increases which can be observed by a continuous resonance shift of about 5 nm. Above 62°C the liquid crystals lose their nematic order which results in a step like jump of more than 4 nm of the resonance with no further change in the peak position for higher temperatures. Thus the first tunable photonic crystal could be fabricated on III/V-semiconductor waveguides. The experimental data are compared with finite difference time domain (FDTD) simulations. The simulated shift of the resonance fits well with the measured ones. Also the raise in transmittance and the asymmetric peak shape is reproduced.

SESSION J6: EMISSION IN PHOTONIC STRUCTURES
Chair: Michael J. Brett
Thursday Afternoon, April 24, 2003
Golden Gate A3 (Marriott)

1:30 PM *J6.1
QUANTUM DOT SINGLE PHOTON SOURCES: STATE OF THE ART AND FUTURE PROSPECTS. Jean-Michel Gerard, CEA/DRFMC/SP2M/ Nanophysics and Semiconductors Laboratory, Grenoble, FRANCE.

We will first review the recent development of the first single-mode solid-state single photon source, which is based on a single InAs QD in a GaAs/AlAs pillar microcavity. In this device, a true CQED effect, the Purcell effect, is implemented to collect a large fraction of the single photons (up to 40 per cent experimentally) and to obtain a single-mode emission. We discuss some intrinsic and extrinsic limitations of this single photon source, which apply to its efficiency (less than 70 per cent)and to its operating temperature (T less than 150K). Novel designs for improved QD-single photon sources based on photonic crystals, or high oscillator strength QDs are presented and discussed on the basis of some recent experimental data.

2:00 PM J6.2
PHOTONIC POLYMERS:THREE-DIMENSIONAL COUPLED RESONATORS FROM INTERSECTING POLYMER BLEND MICROSPHERES. Michael D. Barnes, Brian Hathorn, Shannon Mahurin, Bobby Sumpter, and Don Noid, Oak Ridge National Laboratory, Chemical Sciences Division; Keith Runge, University of Florida, Department of Physics and Quantum Theory Project.

Photonic molecules are mesoscopic heirachical structures, constructed from "monomer" units with typical dimensions of 1 - 5 μm, that function as coupled optical resonators. These structures are so named because they confine electromagnetic fields in modes that are closely analogous to bonding and antibonding electronic molecular orbitals in real molecules. Recently, we discovered an interesting material property of a simple water-soluble polymer-blend that allowed us to realize a new kind of polymer microsphere-based structure that we called photonic polymers. Using a linear quadrupole to manipulate the particles in space, we are able to take advantage of modified surface structure in the blend-particle to actively assemble particles in programmable two- or three-dimensional architectures. Strong resonance features in fluorescence are observed near the intersection between linked spheres that cannot be interpreted with a two-dimensional (equatorial plane) model. Three-dimensional ray optics calculations show long-lived periodic trajectories that propagate in great circles linked at an angle with respect to the plane containing the sphere centers. A number of interesting applications are anticipated for these structures including optical fan-outs, frequency manipulation (e.g. add-drop) devices, 3-D conductive vertical wires/supports, and new sensor technologies.

2:15 PM J6.3
PROBING THE LOCAL DENSITY OF STATES IN SILICON-INFILTRATED SILICA COLLOIDAL PHOTONIC CRYSTALS. J. Kalkman[a], E. de Bres[a], Y. Jun[b], D.J. Norris[b], A. van Blaaderen[a,c], and A. Polman[a]; [a]FOM-Institute AMOLF, Amsterdam, THE NETHERLANDS; [b]Dept. of Chemical Engineering and Materials Science, University of Minnesota, MN; [c]Debye Institute, Utrecht University, Utrecht, THE NETHERLANDS.

Silica colloidal crystals were fabricated on silicon substrates using self-assembly, and then infiltrated with silicon using low-pressure chemical vapor deposition, in order to fabricate three-dimensional photonic crystals with high index contrast. Dry etching was used to remove any remaining Si covering the crystal, leading to the formation of a well-defined planar photonic crystal surface. With the silica removed by a wet-chemical etch, these crystals have a full photonic bandgap in the near-infrared. To probe the photonic bandstructure and local optical density of states, erbium ions were incorporated into the (unetched) photonic crystal by 2 MeV ion implantation.
After annealing at 700°C, intense photoluminescence (PL) from Er in silica at 1.5 μm is observed under 488-nm pumping. A PL lifetime as long as 9 ms is observed, close to the radiative rate. At the same time, 1.5 μm PL from Er in silicon is also observed. The Stark splitting observed in the spectrum for Er in Si indicates a crystalline environment (expected for this anneal) and the lifetime in Si is around 900 μs, close to the expected radiative rate. PL signals from silicon and silica have distinctly different temperature quenching behavior and thus, by varying the temperature, their relative spectral contributions can be modified. For example, at room temperature, all PL from Er in Si is quenched and only PL from Er in silica is observed. Also, by varying the pump wavelength Er ions in Si and silica can be separately addressed: at 457 nm (outside the Er absorption bands) no excitation of Er in silica occurs, while a strong photocarrier-induced signal from Er in Si is observed.
We will present data on the spontaneous emission rate of Er in photonic crystals with different lattice spacings, and correlate these with the local optical density of states in the silica and silicon regions of the photonic crystal. Finally, data will be presented on crystals with the silica etched out (full bandgap).

2:30 PM J6.4
ENHANCEMENT OF RADIATION FROM SOURCES EMBEDDED IN PHOTONIC CRYSTALS. Irfan Bulu, Humeyra Caglayan and Ekmel Ozbay, Department of Physics, Bilkent University, Bilkent, Ankara, TURKEY.

Spontaneous emission from radiation sources can be altered by means of electromagnetic mode distributions different from that of free space mode distribution. In this sense, photonic crystals (PCs) are promising structures for the control of emission from radiation sources. The effect of PCs on the radiation of a localized source is encapsulated in local density of states, which depends on position and frequency. For a PC, local density of states is proportional to the amplitude of the electric field at the position where the source is located. On the other hand, it is inversely proportional to the group velocity of the mode at which the source radiates. In this work, we experimentally studied the radiation properties of a monopole source located inside a perfect PC and inside various defect structures created in a PC. We measured the transmission properties for a perfect PC, a single cavity structure and a coupled cavity structure. Reduced group velocities for the modes near the band edges, for the single cavity mode and for the coupled cavity modes were observed. We measured the enhancement factor, defined as the ratio of the intensity of the EM waves emitted from a source located inside a PC to the intensity of the EM waves emitted from a source in free space. The measurements showed that the emission of radiation near the band edges, at the single cavity mode and at the coupled cavity modes is enhanced compared to the emission of radiation in free space. We have also shown that the emission of radiation from a monopole source depends on the group velocity of the modes and on the intensity of the electric field at the source location.

2:45 PM J6.5
DEVELOPMENT OF A NANOSCALE SILICON LASER. Supriya Jaiswal, University of Virginia, Charlottesville, VA and Oak Ridge National Laboratory, Oak Ridge, TN; John Simpson, Steve Withrow, C.W. White, C. Rouleau, Oak Ridge National Laboratory, Oak Ridge, TN; Pamela Norris, University of Virginia, Charlottesville, VA.

Ever since the observation of optical gain in Silicon Nanocrystals, the race to develop a nano-scale silicon laser has begun. A silicon laser would enable a host of optical technologies, including optical interconnects, optical computing, integrated lasers with standard IC chip technology, and a variety of new types of optically based biological and chemical sensors. However, the challenge in such a task remains to design and develop laser architecture with simple, cheap, CMOS compatible materials. Preliminary calculations presented in this paper will show that such a laser could be constructed using the combination of photonic crystal architecture, and silicon nanocrystals dispersed in a silicon dioxide matrix. Two key material related issues determine the success of the laser: The characterization of the stimulated emission from the silicon nanocrystals in a silicon dioxide matrix, and the fabrication of a highly resonant laser cavity using sub-wavelength structures in silicon dioxide. The work presented here demonstrates the theoretical and experimental progress made thus far in producing a near infrared nano-scale silicon based laser, with two different laser designs: a Fabry Perot Cavity laser, and a Distributed Feedback laser.

SESSION J7: 3D PHOTONIC CRYSTALS
Chair: Jean-Michel Gerard
Thursday Afternoon, April 24, 2003
Golden Gate A3 (Marriott)

3:30 PM *J7.1
CHIRAL NANOSTRUCTURE AND SQUARE SPIRAL PHOTONIC CRYSTAL FABRICATION. Michael Brett, Dept. Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, CANADA.

The glancing angle deposition (GLAD) process has been demonstrated to be capable of fabricating sub-micrometer structures of posts, zig-zags, helices, and square spirals, utilizing substrate motion and glancing incidence of evaporative flux. With an appropriately designed periodic array of seeds or dots on the substrate, GLAD nanostructures grow only from the seed locations, enabling simple fabrication of arrays of helices or other structures. This process has recently been harnessed to grow arrays of tetragonal square spirals, which are proposed [O. Toader and S. John, Science 292, p1133 (2001)] as a large bandgap three dimensional photonic crystal material. The process is also capable of fabricating chiral or helical nanostructures which have been used in hybrid liquid crystal devices. A wide range of materials can be used for GLAD, manipulation of lattice constant and helix pitch ensures optical tunability, and the GLAD films are robust to micromachining and post-processing. The presentation will review the GLAD process and detail the characteristics of the seed array necessary to optimize fabrication of periodic nanostructures. Examples will be given of a variety of types of chiral and square spiral geometries, and of the effect of inclusion of defects in the arrays. Optical characterization of these chiral nanostructures and in particular of square spiral arrays of Si will be presented.

4:00 PM J7.2
TEMPERATURE INSENSITIVE PHOTONIC BANDGAP STRUCTURES IN SILICON. Sharon M. Weiss[a] and Philippe M. Fauchet[a,b]; [a]The Institute of Optics, University of Rochester, Rochester, NY, [b]Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY.

Silicon-based PBG structures have been fabricated with one, two, and three-dimensional periodicity. Defects incorporated into these structures spatially localize the light and narrow the spectral linewidth. Practical PBG devices need to operate over a range of temperatures and yet the refractive index of silicon is temperature dependent. For both active and passive defect-based PBG devices, even a small change of the refractive index may be sufficient to drastically alter the performance at the operating wavelength. The creation of temperature independent structures has practical implications for the technological use of PBG devices.
We have indeed observed significant thermal effects in porous silicon microcavities that exhibit a narrow resonance in the reflectance spectrum. In as-anodized microcavities, the resonance position redshifts by 3nm upon heating to 100°C. In oxidized microcavities, the resonance position blueshifts over the same temperature range. The maximum blueshift relates to the level of oxidation, possibly due to thermal expansion effects. For example, chemical oxidation in hydrogen peroxide causes a 7nm blueshift while oxidation at 900°C in oxygen for 3 minutes causes a 5nm blueshift. Through careful control of the thermal oxidation conditions, we have fabricated a temperature independent device. After oxidation at 700°C in nitrogen for 3 minutes, the resonance position moves by less than 0.5nm as the temperature is increased up to 100°C. A similar method should be applicable to two-dimensional and three-dimensional PBG structures.

4:15 PM J7.3
SENSING BY PHOTONIC CRYSTAL SUPERPRISMS. Tushar Prasad, Silvia Rubio Monzon, Vicki Colvin, Dept. of Chemistry; Rajesh Rengarajan, Daniel Mittleman, Electrical & Computer Engineering Dept., Rice University, Houston, TX.

The superprism phenomenon is the extremely large angular dispersion experienced by a light beam when entering a photonic crystal. This arises from the anisotropy of the photonic band structure. Strong anisotropy can be present even in the systems without a complete photonic band gap. We describe a theoretical investigation of the superprism effect in three-dimensional macroporous polymer photonic crystals formed from colloidal crystal templates. From the complete photonic band structure, an equal-energy surface (dispersion surface) is obtained. This dispersion surface is analogous to the index ellipsoid in conventional crystalline optics or to the Fermi surface in electronic crystals. The propagation direction inside the photonic crystal is determined by the gradient of this surface. Using this formalism, we explore the extreme sensitivity of the propagation direction to various input parameters, including the input angle, the light frequency, and the composition of the photonic lattice. The experimental data confirms the sensitivity of the beam propagation direction inside the macroporous polymer photonic crystal. Precise control over beam propagation allows carefully engineered photonic crystals to be used for waveguiding and filtering applications. Finally, we describe a new optical sensing technique based on the superprism effect. This method exploits the sensitivity of the diffraction angle to the refractive index contrast. The described sensor should provide an increase by as much as three orders of magnitude in the sensitivity to small changes in index contrast, in comparison with other sensing methods.

4:30 PM J7.4
NANOPARTICLE-MEDIATED ASSEMBLY OF COLLOIDAL CRYSTALS ON PATTERNED SUBSTRATES. Carlos J. Martinez, Michael Bevan[a], Wonmok Lee, Paul V. Braun, and Jennifer A. Lewis, University of Illinois, Urbana, IL. [a]Present address: Texas A&M, College Station, TX.

Through fundamental studies of the phase behavior and structure of binary mixtures of attractive colloidal microspheres and highly charged nanoparticles, we have discovered a new colloidal stabilization mechanism known as nanoparticle haloing. Colloidal microspheres were assembled onto (100) fcc patterned and non-patterned glass substrates from binary mixtures of varying nanoparticle concentration. Confocal images of such assemblies were acquired in both the wet and dry states, and the position of the particle centers, g(r), and local and global order parameters were obtained through image analysis. Through nanoparticle engineering, we have created robust colloidal crystals that can be harvested from solution without the introduction of drying related defects. Currently, we are developing an optimized drying process that can be used to regulate the point defect distribution within such assemblies.

4:45 PM J7.5

MESOSCOPICALLY PHOTO-PATTERENED COLLOIDAL PHOTONIC CRYSTALS. Gi-Ra Yi, Sarah Kim, Yong-Hak Park, Seung-Man Yang, Dept of Chemical and Biomolecular Engineering, Daejeon, KOREA; David J. Pine, Dept of Chemical Engineering, University of California, Santa Barbara, CA.

Mesoscopic hierarchical structures, which are constructed from monodisperse spherical colloids by self-assembly, have been focused on recently by a myriad of researchers for nanophotonics due to their potential uses as photonic crystal devices. Recent progress of such self-assembly approach has shown that defect-free regular array could be easily grown by several novel ways combining well-established techniques including precise rate-controlled dip-coating and epitaxial growth. One of remaining issues for self-assembled photonic crystals is to engineer the colloidal crystals for photonic devices such as photonic crystal based microdisplay, integrated photonic chips for guiding light beam, and resonant cavity for extracting or adding light of a specific frequency. Several research groups have proposed the innovative fabrication methods for colloidal crystals with designed functional defects including colloidal crystallization inside microchannels, two-photon-absorption polymerization, and surface-charge-induced colloidal crystallization. Here, we describe highly facile method for the fabrication of photonic-crystal array of pixels by selective photon-induced polymerization in self-assembled colloidal crystal film, which is of practical significance for photonic crystal based microdisplay.