SYMPOSIUM K

Microphotonics–Materials, Physics, and Applications

November 26 – 29, 2001

Chairs

Pierre Wiltzius
Beckman Inst for Advanced Sci & Tech
Univ of Illinois at Urbana-Champaign
Urbana, IL 61801
217-244-8373

Alfons van Blaaderen
Physics & Chem Condensed Matter Dept
Utrecht Univ
Ornstein Lab
Utrecht, 3584 CC NETHERLANDS
31-30-2532204

Claude Weisbuch
Laboratoire PMC
Ecole Polytechnique
Palaiseau cedex, 91128 FRANCE
33-1-69-333959

Symposium Support
Army Research Office

Proceedings to be published in both book form and online
(see *ONLINE PUBLICATIONS* at www.mrs.org)
as Volume 694
of the Materials Research Society
Symposium Proceedings Series

* Invited paper

SESSION K1/AA1: JOINT SESSION
COLLOIDAL SELF ASSEMBLY AND PHOTONIC CRYSTALS
Chair: Pierre Wiltzius
Monday Morning, November 26, 2001
Room 201 (Hynes)

8:30 AM *K1.1/AA1.1
TOWARDS MICROPHOTONIC CHIPS. Geoffrey A. Ozin, Materials Chemistry Research Group, Department of Chemistry, University of Toronto, Toronto, Ontario, CANADA.

The physical dimensions of contemporary optical circuits may profoundly shrink in size if microphotonic chips are reduced to practice. Such a development is envisioned to disrupt contemporary photonic technologies and revolutionize optical circuit miniaturization in a way analogous to the displacement of traditional electrical circuits by integrated silicon microelectronic chips. This is an on-going research goal of our photonics materials chemistry group using as platform materials silicon inverse opals (Ozin and co-workers, Nature 2000, 405, 437-440) and opal-patterned silicon chips (Ozin and Yang, ChemComm 2000, 2507-2508, Adv Funct Mat 2001, 11, 1-10).

9:00 AM K1.2/AA1.2
INVERSE OPALS SYNTHESIZED THROUGH A HIERARCHICAL SELF-ASSEMBLY APPROACH. Byron Gates, Younan Xia, Univ of Washington, Dept of Chemistry, Seattle, WA.

We have recently demonstrated a hierarchical self-assembly approach to the fabrication of inverse opals. In a typical process, building blocks with dimensions on two different scales – monodispersed spherical colloids with diameters in the range of 0.2 to 1.0 um and nanoparticles with sizes below 15 nm – were mixed with appropriate ratios and crystallized into opaline lattices that exhibit long-range order in all three dimensions of space. Subsequent removal of the template resulted in the formation of inverse opals made of various functional materials such as magnetite and titania. The optical properties of these inverse opals will also be discussed in this presentation.

9:15 AM K1.3/AA1.3
LIGHT PROPERGATION IN 3D PHOTONIC CRYSTAL. H. Kitano, F. Minami, Dept of Physics, Tokyo Institute of Technology, Tokyo, JAPAN; T. Sawada, National Institute for Material Science, Tsukuba, Ibaraki, JAPAN; S. Yamaguchi, K. Ohtaka, Center for Frontier Science, Chiba University, Chiba, JAPAN.

By using femtosecond optical pulses, we have studied light propagation near the stop band of a 3D photonic crystal. This crystal was fabricated from a colloidal suspension of polystyrene microspheres, having a diameter of 0.194 μm and monodisperse to within 3.4%. From Kossel line patterns, the crystal was found to have a fcc structure. The phase and amplitude of the transmitted optical pulses have been measured in the energy- and temporal domain with the Spectrally Resolved Cross-correlation technique. The transmission spectrum of the fcc crystal along the [111] direction showed a stop band centered around 800nm with a spectral width of 10 nm. The phase of the optical pulses changes drastically at the band edges, thus reflecting the enhanced variation of group velocity according to its frequency. The obtained dependence of group delay on frequency is in good agreement with that predicted by the dispersion (E versus k) curve along the [111] direction calculated from the photonic band calculation.

9:30 AM K1.4/AA1.4
FABRICATION OF COMPLEX STRUCTURES THROUGH SELF-ASEMBLY WITH SPHERICAL COLLOIDS AS THE BUILDING BLOCKS. Yadong Yin, Univ of Washington, Dept of Chemistry, Seattle, WA.

We have recently demonstrated a strategy that combines physical templating and capillary forces to assemble spherical colloids into uniform clusters with well-controlled sizes, shapes, and structures. We have illustrated the capability and feasibility of this approach by assembling polystyrene beads and silica colloids ($\geq$150 nm in diameter) into complex structures that include polygonal or polyhedral clusters; linear or zigzag chains; and circular rings. We have also generated hybrid aggregates in the shape of HF or H_2O molecules that are composed of polymer beads having different diameters; polymer beads labeled with different organic dyes; and a combination of polymeric and inorganic beads. In this talk, we will discuss the experimental procedure, and some applications of this procedure in fabricating microphotonic devices such as arrays of microlenses and photonic crystals.

9:45 AM K1.5/AA1.5
PHOTONS CONFINED IN 3D-MICROCAVITIES DOPED WITH QUANTUM DOTS. U. Woggon, M.V. Artemyev, B. Möller, W. Langbein, FB Physik, University Dortmund, GERMANY.

We present the concept of a three-dimensionally confined photonic dot (PD) doped with CdSe quantum dots (QDs) and report on the interplay of 3D-confined cavity modes of single microspheres (the photonic dot states) with photons emitted from quantized electronic levels of single semiconductor nanocrystals (the quantum dot states). We show how cavity modes of high cavity finesse are switched by single, blinking quantum dots. The QDs@PD-structures have been prepared using very small glass spheres covered with a thin polymeric shell containing CdSe QDs. With R<5 μm, the small size of the PD ensures a large mode spacing of a few tens of meV. For the cavity mode widths $\hbar\Delta\omega_{cav}$, values between 250 μeV and 1.5 meV were observed yielding maximum Q-factors $\leq$ 7500. Using imaging spectroscopy at the diffraction limit, the emission spectra are analyzed and intensity and polarisation are mapped accross a single microsphere with spatial resolution of 0.5 μm. Polarisation-selective detection schemes allow a spatial addressing of nanocrystals at the surface of the cavity exploiting the lifting of degeneracy of TM and TE-modes in a spherical cavity. At low temperatures and homogeneous linewidths of single quantum dots as narrow as the photonic dot modes, we observe an enhancement in the spontaneous emission rate, i.e. the Purcell effect is found for quantum dots inside a photonic dot. For these studies we use two special samples: one is a high-Q glass microsphere, the other a small piece of glass from a broken microsphere. Both are impregnated with CdSe QDs in the same process, thus eliminating all variations arising from chemical preparation. To avoid the influence of nonradiative recombination caused by trap processes we optimized before the preparation route and used only those nanocrystals which exhibit monoexponential decay curves with lifetimes in the range of nanoseconds. The PL-decay times have been studied spectrally resolved, in- and off-resonant to cavity modes. Enhancement factors of the spontaneous emission rate in the 3D-cavity compared to emission in free space varying between 2 and 6 have been obtained.

10:30 AM *K1.6/AA1.6
ON-CHIP ASSEMBLY OF SILICON PHOTONIC BAND GAP CRYSTALS. Yurii A. Vlasov, NEC Research Institute, Princeton, NJ; Xiang-Zheng Bo, James C. Sturm, Princeton University, Dept. of Electrical Engineering, Princeton, NJ; and David J. Norris, NEC Research Institute, Princeton, NJ.

Colloidal assembly can now achieve 3D semiconductor photonic crystals (inverted opals) that theory predicts should exhibit a complete photonic band gap. However, serious skepticism remains whether in practice these materials will 1) actually have a band gap and 2) be useful in any real device. Here, these issues will be addressed by exploring high-quality silicon inverted opals that are assembled directly "on-chip". These structures are useful both for understanding their photonic properties and potential applications.

11:00 AM *K1.7/AA1.7
PHOTONIC BAND GAP DEVICES. Vicki Colvin, Department of Chemistry, Rice University, Houston, TX.

The gemstone opal exhibits a brilliant visible iridescence due to the regular spacing of sub-micron colloids which comprise its structure. This natural motif can be replicated in the laboratory, and artificial opals can be cast as thin films of controlled thickness using colloidal assembly techniques. The opal motif can also be harnessed in the production of highly regular porous materials. Numerous solids, ranging from polymers to metals, can be cast around the colloidal network and the colloids subsequently removed. The macroporous materials that result have arrays of spherical cavities interconnected by smaller windows. The diffractive properties of these inside-out structures are even stronger than the host opal, making them suitable for many optical filtering applications. The highly monodisperse cavities of macroporous polymers are ideal environments for growing many types of uniform particles, including solid and hollow spheres, as well as elliptical particles. Finally, we have begun to build opto-electronic devices from conducting polymers prepared with strong photonic gaps.

11:30 AM K1.8/AA1.8
PHOTONIC CRYSTALS OF POLYSTYRENE-TITANIA CORE-SHELL COLLOIDS. Arnout Imhof, Condensed Matter Dept, Debye Institute, Utrecht University, THE NETHERLANDS.

Numerical calculations have shown that photonic crystals assembled from core-shell colloidal particles give rise to some interesting photonic properties such as a widening of the bandgap. A procedure was therefore developed to coat colloidal polystyrene spheres with a smooth and well-defined layer of titanium dioxide. The thickness of the coating can be easily varied from a few nanometers upward and can be increased further by seeded growth. The coated particles were characterized with electrophoresis, thermogravimetric analysis, X-ray diffraction, electron microscopy, and light scattering. The core-shell particles can also be turned into spherical hollow titania shells by dissolution of the polystyrene cores in suspension or by calcination of the dried particles in a furnace. Calcination results in spherical shells composed of a dense arrangement of TiO_2 (anatase) nanocrystals. The composite particles are very monodisperse and self-assemble into colloidal crystals. This way, photonic crystals of coated spheres as well as of hollow titania shells were obtained. We studied the photonic properties of these crystals by means of transmission measurements.

11:45 AM K1.9/AA1.9
METALLO-DIELECTRIC COLLOIDAL PARTICLES FOR PHOTONIC APPLICATIONS. Christina Graf[a], Alfons van Blaaderen[a,b], [a]Utrecht University, Physics and Chemistry of Condensed Matter, Debye Institute, Utrecht, THE NETHERLANDS; [b]FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS.

It was shown recently that metallo-dielectric colloidal (MDC) particles are promising candidates to construct photonic crystals with a complete band gap in the visible (Moroz, A. Phys. Rev. Lett. 1999, 83, 5274). Moreover, MDC spheres can also improve applications of photonic crystals, like ns optical switches, that do not rely on a strong index contrast. In addition, single MDC particles can enhance Raman scattering of dyes that are placed close to these particles with factors of 10^{15} or larger caused by strong local field enhancements that are due to plasmon resonances in the metal. In this contribution we will show how core-shell MDC particles can be made with tunable optical properties. The particles consist of a monodisperse silica core, a gold shell and an optional silica outer layer. The silica can be labeled with fluorescent dyes and/or nano-crystals. The silica outer shell allows for tuning of the interparticle interaction potential through a reduction in the Van-der-Waals forces and facilitates functionalization of the particle surface; the variable gold shell around an also variable silica core makes the plasmon resonance of the particles adjustable over the whole visible and infrared region of the spectrum. The properties of the particles can be further modulated by controlled anisotropic deformation with high energy ion irradiation. It is also possible to turn the MDC particles into hollow metal spheres. Particle characterization by SEM, TEM and extinction measurements will be discussed. Finally, results on crystallization of the MDC particles into colloidal crystals induced by an electric field (Dassanayake, U.; Fraden, S.; van Blaaderen, A.J. Chem. Phys. 2000, 112, 3851) and/or the charge on the particles and the first optical measurements of these crystals will be presented.

SESSION K2: 3D PHOTONIC STRUCTURES

Chair: Arnout Imhof
Monday Afternoon, November 26, 2001
Room 201 (Hynes)

1:30 PM *K2.1
OPTICAL PROBES INSIDE PHOTONIC CRYSTALS. M.J.A. de Dood, H. Isshiki, B. Berkhout, J. Kalkman, L.H. Slooff, S.Y. Lin, J.G. Fleming, A. Moroz, K.P. Velikov, A. van Blaaderen and A. Polman, FOM Institute-AMOLF, Amsterdam, THE NETHERLANDS, Sandia National Laboratories, Albuquerque NM, Utrecht University, THE NETHERLANDS.

One of the best ways to probe the properties of a photonic crystal is by studying the luminescence of optically active ions incorporated in the crystal. In this paper we present new data on the properties of rare earth doped colloidal crystals, as well as 2-D and 3-D Si photonic crystals.
Rare earth doped colloidal SiO_2 microspheres were prepared from tetra-ethoxy-silane by either a base-catalyzed wet chemical process in combination with Er ion implantation, or by an acid catalyzed reaction in which Eu, Tb or Er ions were incorporated during wet synthesis from their chloride salts. The colloids show long (ms) luminescence lifetimes which opens the possibility use them as optical probes in colloidal crystals. Preliminary data taken using confocal microscopy will be presented.
2-D Si photonic crystals were made using anisotropic etching to form regular arrays of 220-nm diameter Si pillars. Index guiding in the third dimension was achieved either by using the index contrast between amorphous and crystalline Si, or by using a SiO_2 substrate. A novel technique to dope these 2-D crystals with optically active Er ions will be discussed, in which a thin Er-rich oxide coating is grown on the pillar structures using a wet chemical process. The Er ions then serve as a sensitive probe of the local density of states.
Next, we present measurements of the optical properties of an Er-implanted 3-D Si photonic woodpile lattice with a bandgap centered around 1.5 μm. Er related luminescence is observed superimposed on a broad luminescence band due to defects in the polycrystalline Si host material. This broad luminescence intrinsic to the polycrystalline material can be used to study the optical properties of the woodpile lattice. A strong decrease in the luminescence intensity is observed in the spectral region above 1.3 μ in agreement with the calculated photonic bandgap of the woodpile structure. These data are compared to detailed measurements of the reflectivity as function of wavelength, incident angle and orientation of the woodpile lattice. The reflectivity measurements clearly reveal the effect of finite thickness and/or surface termination of the photonic crystal sample.

2:00 PM K2.2
EMISSION ENHANCEMENT OF EUROPIUM DOPED CALCIUM ALUMINOSILICATE GLASSES BY PHASE SEPARATION MICROSTRUCTURE. Atsuo Yasumori, Takahiro Kawaguchi, Yoshikazu Kameshima, Kiyoshi Okada, Tokyo Inst of Tech, Dept of Metallurgy and Ceramics Sci, Tokyo, JAPAN.

Luminescent materials with high emission efficiency and with thermal and physical stability are very important for the various display and laser materials. On the other hand, emission enhancement owing to light scattering accompanied with the microstructure of organic-inorganic composite materials has been investigated recently in order to fabricate novel laser materials. Thus, the luminescence from the glassy materials as host materials, which have inner microstructure due to phase separation, was examined in this study. The europium doped calcium aluminosilicate glasses with spinodal-type phase separation were prepared by melt-quenching method via two liquids stable immiscibility. With increase of alumina content in the glass, the microstructure of phase separation became small and fine, whereas the emission intensity of Eu3 ions at 612nm, which were excited by the illumination at 464nm, once increased and then decreased with the increase of the alumina content. Since the concentration of Eu3 ions in CaO rich phase of the phase separation structure was observed from the emission spectra in the micro-region of the glass using a scanning near-field optical microscope, the scattering of the excitation light due to the phase separation microstructure is considered to enhance the emission intensity. Also, the composition of the host glass matrix possibly affected the emission intensity.

2:15 PM K2.3
FABRICATION AND PROPERTIES OF 3-D METALLIC PHOTONIC LATTICES. J.G. Fleming, Shawn-Yu Lin, Sandia National Laboratories, Albuquerque, NM.

The photonic band structure results when light encounters a well-defined repeating arrangement of materials with differing refractive indexes. When correctly designed and fabricated, such structures can exhibit the property that photons with the band gap energy can not penetrate the lattice regardless of their angle of incidence. Recently, advances in silicon processing technology, especially chemical mechanical polishing, have enabled rapid progress in this area. We have now successfully extended our approach to the fabrication of metallic photonic lattices active in the infrared. This was done by fabricating our standard Silicon/silicon dioxide lattices, selectively removing the silicon using a KOH etch and backfilling the resulting silicon dioxide mold using the chemical vapor deposition of tungsten and then removing the excess tungsten from the surface of the wafers by chemical mechanical polishing. The silicon dioxide can then be removed using HF which does not attack tungsten. The structures fabricated exhibit lower wavelength band edges of ~5 microns and very large gaps. The degree of transmission of light through the structure is also much higher than would have been expected from simple models of reflectivity, based on the size of the holes in the structure and the effective thickness of the tungsten. However, the application of Finite-Difference-Time-Domain modeling yields results in good agreement with experiment. One potential application of such structures would be to thermal photovoltaics. The theoretical efficiency of scaled devices using these W photonic lattice structures is on the order of fifty percent, which is roughly 3 times that of a black body emitter and twice that of a textured metal emitter. This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

2:30 PM K2.4
INFLUENCE OF INTERFACE CORRUGATION ON THE PHOTOLUMINESCENCE POLARIZATION ANISOTROPY FROM (311)A GaAs/AlAs SHORT-PERIOD SUPERLATTICES: A GaAs LAYER THICKNESS OF LESS THAN 10.2Å. G.A. Lyubas, V.V. Bolotov, United Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, RUSSIA.

The corrugated and flat GaAs/AlAs short-period superlattices (SLs) were studied using polarization resolved-photoluminescence. The flat SLs were grown using molecular beam epitaxy technique on (311)B and (100) surfaces. The corrugated SLs (CSLs) were grown on faceted (311)A GaAs surfaces. The thickness of GaAs layers in the SLs was varied from 0.34 to 4.0 nm. The phenomenon of photoluminescence polarization anisotropy was observed [1,2]. The polarization nature of the 1ehh transitions is explained by valence band anisotropy in the case of a (311)A corrugated SLs with a GaAs layer thickness of more than 3.5 nm. For a thickness from 1.02 to 3.5 nm, the 1ehh polarization anisotropy is explained by both valence band anisotropy and anisotropy associated with interface corrugation. It was determined that the SLs grown on faceted (311)A GaAs substrates contain periodic corrugated GaAs and AlAs layers. The period of corrugation is 3.2 nm along the [01-1] direction, the height of corrugation is 1.02 nm. This correlates with the model [3] and contrasts with the model [4], where the height of corrugation is 0.34 nm. Latter the 1.02 nm interface corrugation of GaAs and AlAs layers in these (311)A SLs was directly observed by TEM. The CSLs with average GaAs layer thickness of less than 1.02 nm (height of corrugation) exhibited considerably lower polarization anisotropy. In this case quantum-well clusters (quantum dots) in process of self-assembly were formed. The clusters length is about 4-5 nm along the [01-1] direction. The formation of clusters reduce the polarization degree. These results are important for manufacturing CSL-based lasers, light-emitting diodes and photo-detectors sensitive to polarization [5]. This work was supported by the Zamaraev International Charitable Scientific Foundation.

1. G.A. Lyubas, V.V. Bolotov, JETP Lett., **72** (2000) 205.
2. G.A. Lyubas, Phys. Low-Dim Struct., 11/12 (2000) 161.
3. R. Nötzel, N.N. Ledentsov, L.A. Daweritz, *et al.*, Phys. Rev. Lett., **67** (1991) 3812.
4. M. Wassermeier, J. Sudijono, M.D. Johnson, *et al.*, J. Cryst. Growth **150** (1995) 425.
5. V.V. Bolotov, G.A. Lyubas, IEEE Elect. Devices and Materials 2000, No1 (2000) 36.

2:45 PM K2.5
EFFECT OF CRYSTALLIZATION ON PHOTOLUMINESCENCE OF Er_2O_3 THIN FILMS. Xiaoman Duan, Kevin Chen, Sajan Saini, Michal Lipson and L.C. Kimerling, MIT, Dept. of Materials Science and Engineering, Cambridge, MA.

The effect of microstructures on the room temperature photoluminescence of Er_2O_3 thin films has been systematically studied in this paper. The Er_2O_3 film was fabricated via reactive sputtering of Er metal in an Ar/O_2 atmosphere. The as-deposited thin film contained both amorphous and polycrystalline structures, which showed weak photoluminescence at 1.549 μm. Annealing at an elevated temperature from 600 to 1050°C in an O_2 ambient significantly incorporated oxygen into the lattice and greatly stimulated crystalline grain growth, which in turn dramatically induced the transaction of photoluminescence from 1.549 μm to 1.541 μm. The ideal large crystal Er_2O_3 structure was finally obtained by conducting a two-step annealing, 650°C for 5 hours followed by 1020°C for 2 hours, which produced a sharp photoluminescence peak at 1.541 μm.

3:30 PM *K2.6
ELECTROCHEMICALLY-PREPARED 2D AND 3D PHOTONIC CRYSTALS. R.B. Wehrspohn, A. Birner, J. Schilling, C. Jamois, K. Nielsch, J. Choi, R. Hillebrand, F. Müller and U. Gösele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY.

Recent progress on 2D photonic crystals based on macroporous silicon and alumina is reviewed [1] and future outlook on possible unique devices is given. Macroporous silicon can be obtained by a well controlled manner on up to 6" substrates with interpore distances in the range of 500 nm to a few tenth of microns. This process has been optimized in the last ten years starting from first demonstration by Lehmann and Föll in 1990. Pores with a depth of at least 100 μm and an adjustable r/a values from 0.25 to 0.5 can be obtained. 2D calculations show an excellent agreement with the experimental transmission measurements of bulk and finite photonic crystals. Therefore, these structures can be called fully 2D photonic crystals. One disadvantage of these structures to date is the lack of confinement of light in the third dimension. This in particular disturbs high-Q value defects and structures like waveguides and cavities. One possible solution is the variation of the pore diameter in the depth of the structures. This creates embedded, graded-index waveguides, a unique feature of the electrochemical process. First results on these structures are shown, in particular the ease to create multiple embedded waveguides. The continuous modulation of the pore diameter leads to extended 3D photonic crystals. These photonic crystals do not have a complete 3D photonic bandgap due to their hexagonal symmetry but exhibit a tunable dispersion relation in all three directions and omnidirectional reflectivity. Finally, possible new photonic crystal devices based on macroporous silicon structures are presented. This work has been done in close collaboration with the Universities of Halle, Konstanz and Toronto.

4:00 PM K2.7
PROPERTIES OF 2D AND 3D DIELECTRIC STRUCTURES FABRICATED BY ELECTROCHEMICAL DISSOLUTION OF III-V COMPOUNDS. I.M. Tiginyanu, S. Langa, V.V. Sergentu and E. Foca, Laboratory of Low-Dimensional Semiconductor Structures, Technical Univ of Moldova, Chisinau, MOLDOVA; J. Carstensen, M. Christophersen and H. Föll, Dept of Engineering, Christian-Albrechts-Univ, Kiel, GERMANY.

Electrochemistry proved to be a powerful tool for developing photonic crystals on crystalline silicon [1] and advanced nonlinear optical materials on III-V compounds [2]. In this work, electrochemical etching techniques were used for the purpose of manufacturing periodic and quasi-periodic dielectric structures on III-V compounds. Under certain etching conditions, self-arrangement of submicrometer parallel pores in two-dimensional hexagonal lattices was observed in GaP and InP crystalline substrates. We explored the possibility to fabricate three-dimensional photonic structures with pitting occurring on (100) surface and pores propagating along <111> crystallographic directions. When the pits are arranged in two-dimensional quadratic lattices with the lattice constant a, the material percolation proves to be broken at pore radius $r = 0.35a$. For the percolation limit, the volume of pores in the dielectric structures was found to be as high as 74 percent. Reflectance spectra for periodic and quasi-periodic dielectric structures prepared by anodic dissolution of GaP, InP and GaAs are presented. The impact of the deviation from periodicity on photonic properties of two-dimensional dielectric structures is studied both experimentally and analytically. [1] A. Birner et al, Adv. Mater. 13, 377 (2001); [2] I.M. Tiginyanu et al, Appl. Phys. Lett. 77, 2415 (2000).

4:15 PM K2.8
TRANSMISSION CHARACTERIZATION OF DRILLED ALTERNATING-LAYER THREE-DIMENSIONAL PHOTONIC CRYSTALS. E. Kuramochi, M. Notomi, I. Yokohama, NTT Basic Research Laboratories, Atsugi-shi, JAPAN; J. Takahashi, C. Takahashi, NTT Telecommunications Energy Laboratories, Atsugi-shi, JAPAN; T. Kawashima, S. Kawakami, NICHe, Tohoku University, Aoba-ku, Sendai, JAPAN.

We have developed a novel three-dimensional photonic crystal, or drilled alternating-layer photonic crystal (DALPC), which can be fabricated by a combination of the alternating-layer deposition of dielectric films and one-time dry etching. We have calculated the photonic band of the DALPC by the plane wave expansion method and have found that a large full photonic bandgap (PBG) can be obtained [1]. Here we report the fabrication of Si/SiO_2 DALPCs and describe their transmission characteristics. We set the lattice constant at (x/y/z = 0.7/0.5/0.32 μm) to give a PBG wavelength of 1.5 μm. We deposited four pairs of SiO_2/Si (0.15/0.16 μm) by *autocloning*, i.e., the rf-bias sputtering with enhancing the periodic corrugation introduced from a patterned substrate [2]. We then fabricated periodic air holes by electron beam lithography. We successfully drilled cylindrical air holes through an alternating SiO_2/Si multi-layer by using CF_4-SF_6 electron cyclotron resonance plasma etching [3]. We measured the light transmission spectra of the DALPC samples for two in-plane directions (Γ-X and Γ-Y) and a normal direction (Γ-Z). We obtained a clear dip at a wavelength of 1.4 μm in all directions and two light polarizations (TE/TM). The common dip suggests that a three-dimensional PBG may exist around 1.4 μm. The existence of satellite dips and an insufficiently large attenuation at the TM polarization dip are considered to result from imperfectly drilled air holes. The results support our belief that the DALPC will soon become a reality and prove to be a good platform for ultra-small integrated lightwave circuits. [1] M. Notomi, T. Tamamura, T. Kawashima, and S. Kawakami, Appl. Phys. Lett. **77**, 4256 (2000). [2] S. Kawakami, Electron. Lett. **33**, 1260 (1997). [3] E. Kuramochi, M. Notomi, T. Tamamura, T. Kawashima, S. Kawakami, J. Takahashi, and C. Takahashi, J. Vac. Sci. Technol. **B18**, 3510 (2000).

4:30 PM K2.9
3D PHOTONIC BANDGAP CRYSTALS FROM CHALCOGENIDE GLASSES MADE BY INTERFERENCE LITHOGRAPHY. A. Feigel, Z. Kotler and B. Sfez, Electro-Optics Division, NRC Soreq, Yavne, ISRAEL; A. Arsh, M. Klebanov and V. Lyubin, Physics Dept, Ben-Gurion University, Beer-Sheva, ISRAEL.

We present fabrication of 3D photonic band gap woodpile crystals from photosensitive chalcogenide glass with the help of interference lithography and layer by layer construction. The required alignment method is described, which is scalable to extremely small feature sizes required for photonic crystals in the visible region. Optical spectrum photonic band gap crystals require high refraction index materials and technology for 3D sub-micron structure fabrication. The most flexible approaches are based on semiconductor lithography processes. Most of them require sophisticated equipment and are confined by the current

state of the art feature size limit. Thus there is demand for scalable lithography technologies and new types of materials, offering easy treatment and high refractive index. Chalcogenide glasses are highly promising materials for photonic crystals. Their refractive index varies from 2.5 to 3, together with transparency from 800nm to 12 micron. They are photosensitive, and can be used as positive or negative photoresists. In addition they are amorphous materials that can be deposited on almost any other material by vacuum vapor deposition at low temperature. Maskless interference lithography can replace classical mask lithography in the case of photonic crystals due to their periodical structure. The required periodic pattern of illuminated and dark regions can be produced by interference of two or more coherent laser beams. The advantages of interference over mask lithography are higher resolution and deep focus.

SESSION K3: SOFT CONDENSED MATTER APPROACHES TO PHOTONIC CRYSTALS

Chair: Alfons van Blaaderen
Tuesday Morning, November 27, 2001
Room 201 (Hynes)

8:30 AM *K3.1
ELECTRO-OPTIC BEHAVIOR OF LIQUID CRYSTAL-FILLED SILICA OPAL PHOTONIC CRYSTALS: FABRICATION METHODS AND EFFECTS OF LIQUID CRYSTAL ALIGNMENT. Noel Clark, Daeseung Kang, University of Colorado Dept of Physics, Boulder, CO.

We will discuss the electro-optic behavior of photonic crystals made of nematic liquid crystal intercalated into the void space of close-packed silica spheres (synthetic porous opal). The effects of liquid crystal alignment condition on the sphere surfaces will be analyzed and data presented with the nematic director either parallel or normal to the sphere surfaces. A fast growth method for fabrication of ordered close-packed hard sphere colloidal crystal arrays will be presented. Work supported by NASA Grant NAG 3-2457 and NSF MRSEC Grant DMR 98-09555.

9:00 AM *K3.2
PHOTONIC CRYSTALS MADE BY HOLOGRAPHIC LITHOGRAPHY. Andrew Turberfield, Oxford University, Department of Physics, Oxford, UNITED KINGDOM.

Holographic lithography is a general and flexible technique for the fabrication of three-dimensional photonic crystals. Three-dimensional microstructure is generated when a laser interference pattern is used to expose a thick layer of photoresist. Highly exposed regions in the resulting intensity grating are rendered insoluble; unexposed areas are then dissolved away to produce a three-dimensional photonic crystal formed of cross-linked polymer with air-filled voids. The polymeric structure may be used as a template for the production of photonic crystals with higher refractive index contrast. This technique is particularly well adapted to the production of structures with the sub-micron periodicity required for applications in the visible optical spectrum. The properties of a photonic crystal produced by holographic lithography may be controlled by designing the interference pattern that determines its microstructure. Its translational symmetry is defined by the angles between the laser beams used to generate the interference pattern. With a four-beam interference pattern a single laser wavelength can be used to produce an infinite number of lattices, including high-symmetry lattices such as simple cubic, fcc and bcc with various lattice parameters. The basis of the interference pattern (the contents of a unit cell) are controlled by the overlap between the beam polarizations: for each lattice an infinite number of crystal structures can be created. Particularly significant are diamond-like structures which are believed to be optimal for the production of complete photonic band gaps.

9:30 AM K3.3
3-D FABRICATION WITHIN COLLOIDAL CRYSTALS BY 2-PHOTON PHOTOPOLYMERIZATION. Paul V. Braun, Wonmok Lee, Stephanie A. Pruzinsky, University of Illinois at Urbana-Champaign, Dept of MS&E, Urbana, IL.

The functionality of self-assembled photonic crystals will be greatly enhanced if complex features including wave guides and cavities are defined within the interior of the photonic crystal. Here we demonstrate one promising approach to create such features based on multiphoton polymerization of monomers contained within the interstitial space of colloidal crystals. Following assembly of the colloidal crystal and removal of solvent, the interstitial space was filled with an appropriate monomer photoactive dye system, such as trimethylolpropane triacrylate and Rose Bengal. The monomer was locally photopolymerized in a defined pattern via 2-photon excitation using a modified laser scanning confocal microscope and the near-infrared output of a Ti-Sapphire laser. After the desired pattern was polymerized, unpolymerized monomer was removed with solvent. The colloidal crystal matrix supports the polymerized features, thus no shrinkage or cracking was observed. This methodology enabled the fabrication of complex 3-D patterns within the colloidal crystal with a minimum feature size of 1 micrometer and is compatible with many techniques for creating high dielectric contrast photonic crystals including melt imbibing of chalcogenide glasses, electrodeposition of II-VI semiconductors, sol-gel, and nanoparticle deposition.

9:45 AM K3.4
DYNAMIC MECHANICAL SPECTROSCOPY OF PHOTONIC BANDGAP COMPOSITES. Stephen H. Foulger, Amanda C. Lattam, Clemson Univ, School of Materials Science and Engineering, Clemson, SC; Ping Jiang, Yurong Ying, Clemson Univ, Department of Chemistry, Clemson Univ, Clemson, SC.

Polymeric composites are presented that exhibit a photonic bandgap. These composites are fabricated in a two-step procedure which includes: (1) the stabilization of a self-assembled crystalline colloidal array composed of polystyrene spheres, with an average diameter of 109 nm, in a hydrogel through the free radical polymerization of a methacrylate functionalized PEG in the presence of the ordered arrays and (2) the replacement of water in the hydrogel with 2-methoxyethyl acrylate and its subsequent free radical polymerization. Dynamic mechanical spectroscopy of the composites indicated a low temperature shear modulus (G') of ca. 2x10^9 Pa that underwent a significant drop at an onset temperature of -35°C. At the rubbery plateau, the modulus of the composites exhibited a relatively constant value of ca. 3x10^5 Pa up to a temperature of 125°C. Optical studies on the composites indicated a stop band at a wavelength of 533 nm and an index of refraction of 1.473 at 633 nm. Assuming that the stop band corresponds to the d_{111} interplanar spacing of a FCC lattice, this periodicity translates into a 222 nm nearest neighbor distance of the particles, twice their diameter. Composite films which were mechanically strained exhibited a mechanochromic response, where a strain of 44% resulted in a 102 nm blue shift in the observed stop band.

10:30 AM *K3.5
ORDERED MACROPOROUS MATERIALS FORMED BY CRYSTALLIZATION OF BREATH FIGURES: IT IS NOT ALL HOT AIR. Mohan Srinivasarao, Georgia Institute of Technology, School of Textile and Fiber Engineering, School of Chemistry and Biochemistry, Atlanta, GA.

We report the formation of a three dimensionally ordered array of air bubbles of monodisperse pore size in a polymer film through a templating mechanism unlike most published in the literature. Dilute solutions of a simple, coil-like polymer in a volatile solvent are cast on a glass slide in the presence of moist air flowing across the surface. Evaporative cooling, and the generation of an ordered array of breath figures, forms multilayers of hexagonally packed water droplets that are preserved in the final, solid polymer film as spherical air bubbles. The dimensions of these bubbles can be simply controlled by changing the velocity of the airflow across the surface. Such three dimensionally ordered macroporous materials with dimensions comparable to visible light are predicted to have unique optical properties such as photonic bandgaps, and optical stop-bands.

11:00 AM K3.6
POLYMER DISPERSED LIQUID CRYSTALS AS MESOSCALE 2D AND 3D LATTICES. Michael J. Escuti, Gregory P. Crawford, Division of Engineering, Brown University, Providence, RI.

Here we introduce and explore 2D and 3D lattices formed using Polymer Dispersed Liquid Crystals (PDLCs), which exhibit an electrically controllable index modulation in multiple dimensions. As electro-optically active holograms, these materials exhibit fast switching (~100 microseconds), are fabricated with relative ease, and may prove useful in several photonic contexts. Periodic structures in polymer dispersions of LCs have been known for several years and proposed as reflective displays, color filters, and WDM diffractive components. Switchable Bragg and Raman-Nath gratings with high efficiencies and fast response times are possible with simple holographic methods. Equivalently known as Holographic-PDLCs (H-PDLCs) or Electrically Switchable Bragg Gratings (ESBGs), this material set is initially composed of a miscible mixture of liquid crystal, monomer, and photoinitiator that is exposed with spatially structured coherent light (visible or UV). Generally, polymerization occurs most rapidly in the bright fringes and leads to a phase separation of the LC into droplets within the dark regions. The resulting periodic array of LC within a polymer binder can exhibit an index modulation in the range of 0.001 to 0.2 depending on the choice of materials. The LC molecules within the droplets align parallel to an applied electric field, which leads to a change in (even the extinction of) the index modulation. While most development has focused on the improvement of one-dimensional index modulations, our preliminary work in this area has shown that superimposed multidirectional gratings with high fidelity are possible with H-PDLCs. Therefore, in this work we propose 2D and 3D lattices formed in these materials, characterize their optical properties (and possible band gap), and explore the utility of electrical control of the orientation of LC within the polymer binder.

11:15 AM K3.7
SELECTIVE DEPOSITION OF TWO-DIMENSIONAL COLLOIDAL ARRAYS ON PATTERNED POLYELECTROLYTE MULTILAYER TEMPLATES. Haipeng Zheng, Ilsoon Lee, Michael F. Rubner and Paula T. Hammond, Department of Chemical Engineering and Department of Materials Science and Engineering, The MIT Microphotonics Center, Massachusetts Institute of Technology, Cambridge, MA.

Fabrication of two- (2D) or three- (3D) dimensional colloidal crystals have been attractive because of their versatile applications in photonic crystal devices, functional templates or catalysts, novel optoelectronic devices and sensor arrays. In recent work, we have demonstrated that patterned micro-level polyelectrolyte multilayer structures with high selectivity are achieved by adjusting the ionic strength, pH and polyelectrolyte chemical structures. Then colloidal particles can selectively deposit on such patterned surfaces. Furthermore, the resulting patterns are used as functionalized templates to fabricate the complex 2D colloidal arrays through electrostatic, hydrophobic, and hydrogen-bonding interactions, and metallic-polystyrene complex colloidal arrays using electroless nickel-plating process.

11:30 AM K3.8
2D COLLOIDAL ARRAYS ON TOP OF CIRCLE PATTERNED POLYELECTROLYTE TEMPLATES: CONTROLLING AND SELECTIVE METAL COATINGS OF COLLOIDAL CLUSTERS. Ilsoon Lee, Haipeng Zheng, Tom C. Wang, Xueping Jiang, Michael F. Rubner, Lionel C. Kimerling, Paula T. Hammond, Massachusetts Institute of Technology, Dept of Chemical Engineering and Dept of Materials Science and Engineering, Cambridge, MA.

The precise positioning of colloidal particles in complex two- and three-dimensional structures has attracted a great attention for the potential applications, such as opto-electric devices, photonic band gap materials, and biochip devices and sensors. We have demonstrated that long-range 2-D arrays of single colloidal particles, and group of particles on circle patterned polyelectrolyte templates can be controlled by adjusting the ratio of diameters of colloid and circle pattern on surfaces. Unlike the previous work, we deposited colloidal particles on top of cylindrical patterns, using electrostatic and capillary forces, where the height of cylindrical pattern can be linearly controlled by the number of polymeric bilayers. Due to the underlying polymeric layers, the prepared colloidal arrays remained stable even after a lot of other processings, such as selective metal coatings in severe conditions, which will also be presented. These combined microstructures of colloids, patterned polyelectrolyte, and metal nanoparticles or coatings lay the foundation for producing complex devices, such as 2-D photonic wave-guide materials due to the well-defined point or line defects that are critical in photonic chip design.

11:45 AM K3.9
ALL-OPTICAL SWITCHES FROM A MICROSPHERE RESONATOR COATED BY A CONJUGATED POLYMER. Charles Tapalian, Juha-Peka Laine, Paul A. Lane, Charles Stark Draper Laboratory, Cambridge, MA.

We report on the development of an all-optical switch consisting of a high quality-factor silica microsphere optical resonator coated by a conjugated polymer. A 250 micron diameter silica microsphere was coated by dipping into a solution of poly(2,5-dioctyloxy-1,4-phenylenevinylene) (DOO-PPV) in toluene. The resonator properties were measured by evanescently coupling light at 1.5 microns from a Stripline-Pedestal Anti-Resonant Reflecting Optical Waveguide (SPARROW) into whispering gallery modes of the microsphere. Optically pumping the polymer coating alters its refractive index resulting in a shift of the resonator mode frequencies. Absorption of pump light at 405 nm at power density of 100 mW/cm^2 shifts the microsphere resonances by 3.185 GHz. The time constant of the frequency shift is approximately 0.165 seconds, leading us to attribute the frequency shift to thermal effects. As microsphere resonators with 2 MHz linewidths (corresponding to cavity $Q > 10^8$) can be easily fabricated, such a system would therefore be capable of switching speeds on the order of 100 microseconds.

SESSION K4: PHOTONIC CRYSTAL CHANNELS AND FIBER

Chair: Pierre Wiltzius
Tuesday Afternoon, November 27, 2001
Room 201 (Hynes)

1:30 PM *K4.1
PHOTONIC CRYSTAL FIBERS: USING HOLES TO KEEP LIGHT IN. J.C. Knight, T.A. Birks, P. St.J. Russell, Department of Physics, University of Bath, Bath, UNITED KINGDOM; B.J. Mangan, Blazephotonics, c/o University of Bath, Bath, UNITED KINGDOM.

Conventional optical fibers are made using two homogeneous glassy materials with different refractive indices to form a core and a cladding structure. Over the past few years we have demonstrated new forms of optical fiber which rely on the unusual optical response of microstructured glass to create the waveguiding structure. The fibers are made of silica, and have a 2-dimensional array of air holes running down their length. The presence of these air holes completely alters the optical properties of the material: the holey silica constitutes a new optical material which can be used to form several different types of fiber waveguide. This new class of fibers, which we have termed photonic crystal fibers, exhibits a range of remarkable optical properties which are turning accepted optical fiber technology on its head. Our fibers are drawn from a preform made by carefully stacking silica capillaries and rods. The preform is formed by hand on a macroscopic scale, and can incorporate complex patterning by including different rods and tubes in different locations. The fiber drawn from this preform contains a regular 2-dimensional pattern of air holes, which defines the waveguiding structure. The regular nature of the air-hole array can lead to the development of photonic bandgaps in the material, and we have used these bandgaps to demonstrate an optical fiber in which light is truly guided with low loss down a larger air hole which forms the fiber core. Alternatively, the holeymaterial can be used as a cladding material with a refractive index below that of silica. In this case, waveguides formed by surrounding a silica core with air holes guided light in the core due to modified total internal reflection from the silica/air cladding. Each of these forms of waveguide possesses unique features which are generally unattainable using conventional fiber optics.

2:00 PM *K4.2
AIR-SILICA MICROSTRUCTURED OPTICAL FIBERS ENABLE NOVEL DEVICE STRUCTURES. B.J. Eggleton, Specialty Fiber Devices, Research Department, Lucent Technologies, Somerset, NJ.

Air-silica microstructured fibers incorporate air holes within the cladding region that run along the length of the fiber. Recently there has been renewed interest in such fibers because the microstructured region provides extra degrees of freedom in manipulating mode propagation, which can be exploited in a range of different applications. To date, research has primarily focused on understanding the guidance properties of fundamental modes localized in the core region, for example, bend loss, cutoff wavelength, mode field diameter, and dispersion. A broader class of applications for these fibers, which we consider in this paper, is in the design of optical components, such as grating-based filters, tunable fiber devices and novel tapered fiber devices. In these applications, core mode guidance can be associated with total internal reflection in a high-index doped region (e.g. germanium doped core). The microstructure cladding, region is exploited to manipulate the propagation of higher order cladding modes. Because of the short interaction lengths involved in these device application modes that are inherently leaky can be exploited. And, in the context of tapered fiber devices, ensures a mechanically robust device that can be spliced to standard fiber with low insertion loss enabling dramatic efficient nonlinear process including widely tunable Raman soliton generation.

2:30 PM K4.3
PREPARATION OF HIGHLY ORDERED METAL-NANOWIRE-ARRAYS: CHARACTERIZATION AND POSSIBLE APPLICATIONS. Guido Sauer, Georg Brehm, and Siegfried Schneider, Institute of Physical und Theoretical Chemistry, University of Erlangen, GERMANY; Kornelius Nielsch, Jinsub Choi, Ralf B. Wehrspohn, and Ulrich Gösele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY.

During recent years, nanoparticles of various shape and size have become one of the main research topics in physics and materials science due to various possible applications. For example, metal nanowire arrays are excellent substrates for Surface Enhanced Raman Spectroscopy (SERS) [Pure Appl. Chem. 2000, *72*, 221]. Furthermore, it has been theoretically predicted that 2D silver nanowire arrays are one possible structure for the application as photonic crystal in the visible and near-UV region [J. Opt. A: Pure Appl. Opt. 2000, *2*, 395]. Both, the systematic investigation of size-dependent properties of metal nanoparticles and the application of the particles as photonic crystal require the preparation of highly monodisperse particles. Highly ordered alumina pore structures, which are based on an approach by Masuda [Science 1995, *268*, 1466], are a very suitable matrix for the synthesis of anisotropic nanoparticles with well defined diameter and aspect ratio. Filling of the alumina templates by (electro)deposition with metals like Co, Ni, Ag or Au yields nanowire

arrays with (wire) diameters adjustable between 15 - 80 nm and lengths up to several microns. The nanowire arrays prepared according to our procedure show a nearly perfect hexagonally ordered pattern, and - in contrast to most publications in this field - a degree of pore filling of almost 100%. Furthermore, when using highly ordered templates for nanowire array preparation the distribution in the particle dimensions is much narrower than in samples prepared with non-ordered alumina structures. This monodispersity allows accurate investigations on the size-dependent properties of the nanowires and nanowire arrays. In our contribution we describe different strategies for the preparation of ordered nanowire arrays and the characterization of the obtained structures with (high resolution) electron microscopy. Finally, various possible applications of these substrates are discussed, including the field of SERS.

2:45 PM K4.4

OPTICAL BISTABILITY IN NON-LINEAR PHOTONIC CRYSTAL FIBERS. E. Centeno, D. Felbacq[a], M. Le Vassor d'Yerville, D. Cassagne, and J.P. Albert, Groupe d'Etude des Semiconducteurs, Université Montpellier II, Montpellier, FRANCE; [a]LASMEA, Aubière, FRANCE.

Numerous studies have been devoted to photonic crystals (PCs) made of linear materials. But the development of the future optical data processing systems will not be possible without new active optical components. Non-linear effects in PCs may lead to design logical gates and active filters for integrated optical systems. We numerically and theoretically study the behavior of localised modes inside 2D PCs made of dielectric fibers with Kerr type index. The 2D PC is constituted by a finite number of dielectric fibers. The crystal is doped by a central microcavity and the Kerr type permittivity of the fibers is $\varepsilon_r(x,y) = \varepsilon_r^0(x,y) + \chi^{(3)}|\mathbf{E}(x,y)|^2$ All computations are done using a linear multi-scattering theory of diffraction and an iterative scheme [1]. In case of a very weak incident field, the crystal is in the linear regime, and it presents a localised mode inside the last gap. For stronger intensities, the distribution of the optical index inside the crystal may change and consequently the value of the resonant wavelength may vary. Numerical computations show that the shift of the resonant wavelength is directly given by the sign of the susceptibility tensor $\chi^{(3)}$. These results show that the transmission ratio vs. the amplitude of the incident field describes a hysteresis loop characteristic of the optical bistability. The behavior of localised modes inside a non-linear medium allows the switch of PCs from a non-passing state to a transmitting state. Such a bistability associated to localised modes may be explained by an analytical study [1]. Our mathematical analysis gives the essential parameters as well as the threshold intensity or the minimal detunning of wavelength allowing the bistability. [1] E. Centeno, D. Felbacq, Optical bistability in finite-size non-linear bidimensional photonic crystals doped by a microcavity, Phys. Rev. B. 62, R7683-R7686, 2000.

SESSION K5: POSTER SESSION
Chair: Alfons van Blaaderen
Tuesday Evening, November 27, 2001
8:00 PM
Exhibition Hall D (Hynes)

K5.1

PHOTONIC CRYSTALS OF CORE-SHELL COLLOIDAL PARTICLES. Krassimir P. Velikov[a], Alexander Moroz[a], and Alfons van Blaaderen[a,b]; [a]Chemistry and Physics of Condensed Matter, Debye Institute, Utrecht University, Utrecht, THE NETHERLANDS; [b]FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS.

We report on the fabrication and optical transmission studies of thin three-dimensional (3D) photonic crystals of high-dielectric ZnS-core and low-dielectric SiO_2-shell colloidal particles. These samples were fabricated using a vertical controlled drying method. The spectral position and width of a stopgap depend on the core-to-shell ratio, in a manner consistent with numerical calculations. Both experiments and calculations show that the relative L-stopgap width in the case of high-index core low-index shell particles can be larger in comparison to the case of homogeneous particles of either material. The core-shell morphology gives additional control over the photonic stopgap characteristics.

K5.2

L-ARGININE SALTS ARE PROMISING MATERIALS FOR NON-LINEAR OPTICS. Aram M. Petrosyan, Ruzan P. Sukiasyan, Yerevan State Univ, Dept of Physics, Yerevan, Armenia; Harutyun A. Karapetyan, Molecular Structure Research Center, Yerevan, Armenia; Robert S. Feigelson, Geballe Lab for Advanced Materials, Stanford Univ, CA; Eric W. Van Stryland, Univ of Central Florida, CREOL, Orlando, FL.

The semiorganic non-linear optical crystalline salts of protonated amino acids, particularly, L-arginine (L-Arg), combine the positive features of both inorganic (easy to grow, good mechanical and thermal properties etc.) and organic crystals (possibility of engineering the chemical composition for reaching high nonlinearities). L-arginine forms two series of salts with single-charged (Arg^{+}) and double-charged (Arg^{++}) arginine cations [1]. Salts with composition L-Arg.HX are formed as a rule due to protonation of arginine L-$Arg^{+}.X^{-}$, and salts with composition L-Arg.2HX are formed by the formation of double-charged cation L-Arg^{++}. $2X^{-}$. However, it is possible that the formation of salts with composition 1.2 can take place according to L-Arg^{+}. $(XHX)^{-}$ mechanism and with composition 1.1 with double-charged cation which can occur when interacting with dibasic acids (L-Arg.H_2Y i.e. L-$Arg^{++}.Y^{--}$).
In this paper we report the results of a study of the crystallisation conditions for growing seven arginine salt crystals grown previously by us [1] as well as two new crystals (L-Arg.$HClO_3$, L-Arg.$HBrO_3$). In addition, we report a scientific and practically interesting study of the interaction of L-arginine with oxalic acid $(COOH)_2$ as the simplest dicarboxylic acid. In the system L-Arg + $(COOH)_2$ + aq we find the formation of different crystal phases: 2(L-Arg).$(COOH)_2$, L-Arg.$(COOH)_2$ (three different phases), and L-Arg.2$(COOH)_2$. All the L-arginine-based crystals grown show optical activity with non-centrosymmetric structures and give second harmonic generation (SHG) of a Nd:YAG laser. Crystals are also characterised by X-ray diffraction, spectral (UV, VIS, IR) and thermal analysis methods. The possibility of growing large crystals of good quality from aqueous solution and the detection of strong phase-matched SHG in most of them, point out that crystals of this family are promising for further study and applications in non-linear optics.
[1] Petrosyan A.M., Sukiasyan R.P., Karapetyan H.A., Terzyan S.S., Feigelson R.S., J. Crystal Growth, 213, 103 -111 (2000).

K5.3

SPATIALLY CONTROLLING SURFACE PLASMONS IN LITHOGRAPHICALLY PATTERNED SELF-ASSEMBLED MONOLAYERS OF GOLD NANOCRYSTAL. S. Egusa, X.-M. Lin, Y.-H. Liau, H.M. Jaeger, and N.F. Scherer, Departments of Physics and Chemistry, The James Franck Institute, and MRSEC, The University of Chicago, Chicago, IL.

We examine the surface plasmon field distribution in monolayer films of 5.5 nm Au nanocrystal, self-assembled in close packed lattice, with micron-scale shapes defined by electron beam lithography. Direct measurements are performed by near-field optical microscopy (NSOM). Monochromatic light is injected into a single-mode optical fiber irradiating the lattice of Au nanocrystals through a tip with 100 nm aperture. The light from the aperture excites, in the optical near-field, the surface plasmon depending on the degree of organization of the individual nanocrystals and the micron-scale boundary conditions of the lithographic pattern. Under proper circumastances, a standing wave pattern is observed in the optical far-field transmission image. Furthermore, the images show standing wave patterns outside the Au monolayer structures in classically forbidden regions reflecting the penetration of the plasmon field beyond the boundary. We present the results of measurements performed on structures such as rectangles, circles, and rings.

K5.4

PHOTONIC CRYSTALS FOR TEMPERATURE MAPPING OF MICRON-SIZED OBJECTS. Durdu Guney, Senol Isci, Yasar Gurbuz, M. Naci Inci, Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul, TURKEY.

A two-dimensional photonic crystal structure is proposed to study temperature mapping of micron-sized objects; such as temperature profiling of biological tissues and micro-machines. The structure consists of triangular array of air holes etched into InGaAsP with linear and various point defects. The trunsduction mechanism of the photonic band-gap device is based on guiding and filtering out of specifically selected multiple optical frequencies emitted from the object in concern. Optical intensities which correspond to such specifically selected frequencies are scaled in accordance with black-body radiation curve characteristics. In contrast to conventional black-body detection systems, our proposed device does not require the detailed knowledge of emissivity, transmission loss and the distance of the radiation source to detector parameters.

K5.5

A KIND OF WIDE BANDGAP PHOTONIC CRYSTAL. Zhengbiao Ouyang, Jun Zhu, Jingzhen Li, Solid State Photonics Laboratory, College of Scientific Researches, Shenzhen University, Shenzhen, CHINA.

In many applications of photonic crystals, it is important to provide a wide photonic band gap. It is known that the largest photonic band gap is usually less that 30% of the center frequency in the band gap. So, it is necessary to do researches on obtaining large photonic bandgaps. In this paper, we investigated a structure, which is made of many unit cells. There are two kinds of dielectric layers in each unit. The inside structures of adjacent cells are slightly different. However, we keep the optical length of each cell being the same. Surprisingly, we find that the width of the photonic bandgap of such a structure is very large. It is over 2 times larger than that of ordinary photonic crystals, although the optical length of each cell is the same. Such a wide photonic bandgap may find application in controlling light, in wide stop-band filtering, in solar energy utilization and in heat energy engineering. Keywords: wide band gap, photonic band gaps, photonic crystals

K5.6
SIMULATIONS OF REALIZABLE PHOTONIC BANDGAP STRUCTURES WITH HIGH CONTRAST. Bonnie Gersten, Jennifer Synowczynski, Weapons and Materials Research Directorate, Army Research Laboratory, Aberdeen Proving Grounds, MD.

Finite difference time domain (FDTD) software was used to evaluate the photonic bandgap (PBG) properties of periodic arrangements of high permittivity ferroelectric composites ($BaSrTiO_3$/MgO: e_r 85, tanδ 0.004 at 10 GHz) in a Styrofoam matrix (e_r 1). The periodic structures that were investigated included a 1D Bragg stack and a 3D FCC lattice structure. For each structure, the effect of the filling factor on the transmission versus frequency and wave vector was evaluated. To explore the application of these structures for microwave waveguides, filters, and delay lines, the effect of various defects on the transmission and dispersion was also investigated. The $BaSrTiO_3$/MgO composite is a special material not only because of its high permittivity but also because of its ferroelectric nature. Ferroelectrics have the unique capability to reverse their polarization and thereby change their permittivity under an applied electric field. This makes it possible to electronically tune the bandgap properties for many microwave applications. Therefore, the PBG structure was modeled with this capability in mind.

K5.7
Er-O COMPLEXES DOPED IN SILICON PHOTONIC CRYSTALS BY WET-CHEMICAL METHOD AND THE INDIRECT EXCITATION EMISSIONS. Hideo Isshiki, Michiel J.A. de Dood, Albert Polman, FOM Institute for Atomic and Molecular Physics (AMOLF), Amsterdam, THE NETHERLANDS; Tadamasa Kimura, The University of Electro-Communications, Tokyo, JAPAN.

We present a simple and successful process to form luminescent Er-O complexes in silicon photonic crystals, which uses the combined process with rapid thermal oxidation and anneal (RTOA) after dip coating of $ErCl_3$/ethanol solution. Striking results of room temperature photoluminescence (PL) measurements for the Er-O complexes are shown. Si photonic crystals are prepared by electron beam lithography and ECR etching techniques. Si pillars with 2 μm diameter and 1μm tall are formed on a SiO_2 layer by etching a SOI substrate. The configuration is square arrangement as a two dimensional photonic crystal, and the pitch between each pillars are 4, 8, and 16 μm respectively. After the dipping into the $ErCl_3$/ethanol solution, RTOA process was performed continuously with a short interval by using a rapid thermal annealing system using a halogen lump, and by switching of the ambient flow gases between oxygen (RTO) and argon (RTA) with atmospheric pressure. RTO and RTA processes were carried out at 900°C for 4 min and at 1200°C for 3 min respectively. An intense PL emission peak at 1.53 μm with an FWHM of 10meV from Er/O complexes formed in a Si photonic crystal was observed under the e-h pairs mediated indirect excitation at room temperature. In this sample, any clear effect as a photonic crystal does not have been observed yet, but we can expect that the Er-O complexes become one of the certain light sources for the Si photonic crystals. In addition, note that this novel process is simple, productive and easy to join the silicon LSI technologies and microphotonics.

K5.8
ELECTROMAGNETIC WAVES THROUGH DISORDERED SYSTEMS: COMPARISON OF INTENSITY, TRANSMISSION AND CONDUCTANCE. Gabriel Cwilich, Fredy R. Zypman, Yeshiva University, New York, NY.

There has been great interest recently in studying the different regimes (ballistic, diffusive, localized) in which a wave can propagate in a random medium, and determine if the statistical properties of the distribution of the transmittance quantitites can be used as signatures of the different propagating regimes. We introduce a model consisting of scalar waves incident on a system of randomly distributed scatterers which act as sources of secondary radiation. We considered both the case of point scatterers and extended objects, for different degrees of disorder. We have determined the distributions of the propagating intensity (one incident mode - one collected mode), the transmission (one incident mode- all outgoing modes) and the conductance (all incident modes- all outgoing modes) by numerically evaluating these quantities for different configurations of the disorder, and we compared the moments of their distributions with theoretical predictions. To calculate intensity, we set an incoming plane wave from a fixed direction. Each particle of the sample then scatters radiation from the incoming wave and from secondary radiation from the other particles. The outgoing wave is then collected at one point in space. That is the intensity for that particular sample. At that point we generate another sample, belonging to the same ensemble and calculate the intensity again. By repeating the process a large number of times, we construct the probability distribution of the intensity. We find that the momenta of the distribution present an asymptotic exponential behavior. Similar studies were performed for Transmission and Conductance. In the case of Conductance we considered the incoming wave from different directions to have random phase, to mimic the realistic situation of incoherent waves incident on the sample. **This work is supported by Yeshiva University**.

K5.9
OPTICAL STUDIES OF THE PHOTONIC BANDS OF INVERTED OPALS. Alvaro Blanco, Marta Ibisate, Florencio Garcia-Santamaria, Beatriz Hernandez, Cefe Lopez, Instituto de Ciencia de Materiales de Madrid (CSIC), Madrid, SPAIN; Silvia Rubio, Francisco Meseguer, Unidad Asociada CSIC-UPV, Universidad Politecnica de Valenica, Valencia, SPAIN; Hernan Miguez, Department of Chemistry, University of Toronto, Ontario, CANADA; Fernando Lopez-Tejeira, Jose Sanchez-Dehesa, Departamento de Fisica Teorica de la Materia Condensada, Universidad Autonoma de Madrid, Madrid, SPAIN.

Inverted opals have proved to be suitable systems for the exploitation of their photonic band gap properties. The opening of a full gap, although not their only potentiality, is viewed as the most important one. Some applications (such as spontaneous emission inhibition) rely on that property but some (such as super refractive effects) do not require this stringent condition. Fabrication, optical characterization and Photonic band structure calculation of Resin, CdS and Sb2S3 composites and inverse opals are studied. Resins are highly transparent in the visible and very manageable, producing perfect replicas and serving well as model systems. The silica is removed from the composite material by means of a 1 wt % HF aqueous solution. The good connectivity provided by the sintering allows the etchant to reach the whole structure and fully dissolve the silica skeleton. For CdS a control on the degree of infiltration, from 0 to 100%, is attained. The band gap at L is studied finding that the width decreases and then recovers as a function of CdS infilling (from bare opal to fully loaded structure). Stibnite, Sb2S3,is a luminescent material that has a refractive index (3.2 in the amorphous and 3.8 in the crystalline forms) capable of producing a full gap. The electronic gap allows its use in the visible. The synthesis can be done by chemical bath deposition like other sulphides and nearly 100% infiltration can be achieved. The high refractive index of this material produces huge shifts of the Bragg peaks. Inversion has been attained in highly infiltrated samples.

SESSION K6: 2D FABRICATED PHOTONIC CRYSTALS
Chair: Albert Polman
Wednesday Morning, November 28, 2001
Room 201 (Hynes)

8:30 AM *K6.1
TOWARDS THE INTEGRATION OF PHOTONIC CRYSTAL STRUCTURES WITH OPTICAL FIBER. Yuri Suzuki, Lu Chen, Department of Materials Science and Engineering, Cornell University, Ithaca, NY; Glenn E. Kohnke, Sullivan Park Research Center, Corning, Inc., Corning, NY.

Advances in optical communications have been enabled by developments in optical fiber for information transmission and in fiber-based optical devices. Recently devices based on photonic crystal structures have been the focus of research since they are a potential building block for an all optical circuitry. In particular, photonic crystals centered at near-infrared wavelengths have been fabricated in a range of materials from Si and GaAs to self-assembled block coploymers. However in order for these structures to be incorporated into an all-optical circuitry, insertions losses from coupling light between fiber and photonic crystals need to be addressed. We have developed a novel silicon platform where light from optical fiber is coupled directly into and out of silicon-based photonic crystal structures with over 30dB suppression of transmission from 1400nm to 1700nm and defect energy levels tuned to within 2nm in the bandgap. Insertion losses as low as 3.5dB have been achieved. The optical spectra of our one-dimensional silicon-based photonic crystals can be quantitatively described by a simple model of light incident on a series of dielectric interfaces. The agreement between experiment and simulation and the low insertion losses are promising for the future integration of photonic crystals into optical communications.

9:00 AM ***K6.2**

PHOTONIC WAVEGUIDES ON AN SOI SUBSTRATE.

Toshihiko Baba, Atsushi Sakai and Ayumu Motegi, Yokohama National Univ, Dept of Electrical and Computer Engineering, Yokohama, JAPAN.

Line defect waveguides in a photonic crystal (PC) slab are attracting much attention due to the strong optical confinement by photonic bandgap (PBG) and index confinements and the potential of various devices synthesized by positioning defects[1]. Such waveguides were first demonstrated at lightwave frequencies by a GaInAsP film bonded on a SiO_2 cladding[2]. However, the use of an SOI substrate significantly simplifies the process. Now, the single line defect channel is possible by employing the airbridge structure and properly designing triangular lattice airholes to achieve the pure guided mode with a large group velocity[3]. The typical propagation loss of ~10 dB/mm is dominated by the process imperfection, i.e., size fluctuation and distortion of airholes. In the same wafer, conventional index-confinement waveguides are also fabricated with smaller imperfection[4]. However, the propagation loss is still 5 – 10 dB/mm. This not only indicates the necessity of the reduction and/or control of the imperfection, but also the possibility of a lower scattering loss of PC waveguides. The perturbation theory suggests that, if the scattering of guided mode into radiation modes is suppressed by the PBG, loss of PC waveguides can be of 1 – 2 order lower than that of index waveguides. In the index waveguides, a large group index of >5 by a large structural dispersion and 90°-bend-loss of <1 dB for bend radius of 1 μm are observed. For PC waveguides, more peculiar dispersion characteristics and lower bend loss should be investigated for clarifying advantages of PC waveguides. [1] J. Yonekura, et al., J. Lightwave Technol. 17 (1999) 1500. [2] T. Baba, et al., Electron. Lett. 35 (1999) 654. [3] T. Baba, et al., Electron. Lett. 39 (2001, in press). [4] A. Sakai, et al., Jpn. J. Appl. Phys. 40 (2001) L383.

9:30 AM **K6.3**

OPTICAL STUDY OF TWO-DIMENSIONAL PHOTONIC CRYSTALS IN A InP/InGaAsP SLAB WAVEGUIDE STRUCTURE.

Rolando Ferrini, David Leuenberger, Romuald Houdré, Ecole Polytechnique Fédérale de Lausanne, Institut de Micro et Opto-électronique, Lausanne, SWITZERLAND; Mikael Mulot, Min Qiu, Anand Srinivasan, Royal Institute of Technology, Dept of Microelectronics and Information Technology, Kista, SWEDEN; Jürgen Moosburger, Thomas Happ, Martin Kamp, Alfred Forchel, Univ of Würzburg, Technische Physik, Würzburg, GERMANY.

In the last few years it has been proved that, although an omni directional band gap is only possible in a three-dimensional (3D) photonic crystal (PC), a two-dimensional (2D) PC with a step-index waveguide in the vertical direction offers enough light control for integrated optics (IO) applications. Up to now the potentials of this approach have been successfully demonstrated in GaAs-based structures in the 1000-1100 nm spectral range (1), showing remarkable advantages, such as the possibility of leaving out many complex problems that arise in the fabrication of ideal 3D PCs. Moreover, the vertical guiding structure combined to the embedding of an internal light source allows the optical characterization of PC samples by using the photoluminescence emission excited inside the heterostructure through which the PC is etched and then guided towards the PC itself (2). In this communication we will present the first optical characterization of PC structures consisting of a triangular array of air cylinders deeply etched through a InP/InGaAsP waveguide. The internal light source consists in a double quantum well heterostructure whose emission peaks are centered around 1550 nm, which is the spectral range of interest for IO applications. We will show the absolute transmission (T) spectra of simple PC slabs, obtained by normalising the PC T spectrum with respect to the spectrum collected in a non-patterned region of the sample. The experimental T data were analysed by means of a supercell-planewave expansion method in order to get important structural information such as the effective mean filling factor (f) of the PC structure. A more accurate analysis performed in the framework of a 2D FDTD model will be presented in order to assess the exact amount of losses (due to in-plane or out-of-plane diffraction, and to absorption). These results will be compared to the corresponding results obtained by means of standard techniques such as scanning electron microscopy (SEM). Simple PC slabs were then used to build up passive building blocks for IO. In-plane Fabry-Perot (FP) cavities formed between two PC slabs were fabricated: they exhibit interest both as a further characterization tool (3) and as a basic structure for filtering applications. Absolute T was measured in order to investigate the FP-like peaks appearing in the spectra. Experimental data will be compared to 2D FDTD simulations in order to get a feed-back on structural parameters (f, cavity widths) and losses of the PC structures. Quality factors and peak transmissions of these features were calculated and the absolute reflection (R) of the PC mirrors was deduced, thus completing the optical characterization of the PC slabs. By omitting a well-defined selection of holes in a perfectly periodic crystal, a line defect can be introduced and a defect state can be opened-up inside the gap allowing the propagation of guided modes. T spectra of these PC-based waveguides will be presented for different guide widths: the so-called ministopband (MSB) dips appear in the T spectra. Finally, the problem of sharp bending has been considered. The measured T spectra of different 60° bend designs will be compared with the T spectra of the corresponding straight waveguides. (1) H. Benisty et al., IEEE J. Lightwave Technol., Vol. 17, pp. 2063-2067 (1999). (2) D. Labilloy et al., Physical Review Letters Vol. 79, pp. 4147-4150 (1997). (3) M. Rattier et al., IEEE J. Quantum Electron. Vol. 37, pp. 237-243 (2001).

9:45 AM **K6.4**

NONDEGENERATE MONOPOLE MODE TWO-DIMENSIONAL PHOTONIC BAND GAP LASER.

Hong-Gyu Park, Jeong-Ki Hwang, Joon-Huh, Han-Youl Ryu, Yong-Hee Lee, Department of Physics, Korea Advanced Institute of Science and Technology, Taejon, KOREA; Jung-Soo Kim, Telecommunication Basic Research Laboratory, Electronics and Telecommunications Research Institute, Taejon, KOREA.

The photonic crystal is a novel artificial material whose optical properties can be engineered to the taste of the designer. In this paper, as a strong candidate for a zero-threshold laser, we propose and demonstrate the novel nondegenerate monopole mode two-dimensional (2D) photonic band gap (PBG) laser having a high quality factor (Q factor), emitting at 1540 nm at room temperature. For our PBG lasers, freestanding 2D single defect triangular photonic crystal slab structures are employed. The normal single defect cavity of the slab structure supports only dipole modes that are doubly degenerate. On the other hand, by reducing and pushing away the nearest neighbor holes around the defect, the other mode, monopole mode can be generated. This truly nondegenerate monopole mode remains single mode even under asymmetric structural perturbation and is expected to have a large spontaneous emission factor. By the three-dimensional (3D) finite difference time domain (FDTD) method, the monopole mode is proved to have a high Q factor. The monopole mode laser is experimentally realized in InGaAsP active material system. The lasing and unique properties of the monopole mode are measured by optical pulsed pumping at room temperature. The hexagonal symmetric mode shape, no preferred polarization direction, and a high Q factor above ~1900 of the monopole mode are experimentally confirmed. The pump spot size is ~2.7 um and the threshold pump power is ~0.5 mW. Finally, because the monopole mode has an intensity minimum at the center, the introduction of a post of small radius at the central node hardly affects the characteristics of it and this fact can be used preferably for electrical current pumping.

10:30 AM ***K6.5**

FUNCTIONAL PHOTONIC CRYSTAL DEVICES: PHOTONIC CRYSTAL LASER AND CHANNEL DROP DEFECT FILTER.

Susumu Noda, Kyoto Univ, Dept of Electronic Science and Engineering, Kyoto, JAPAN.

Much interest has been drawing in photonic crystals in which the refractive index changes periodically. A photonic bandgap is formed in the crystals, and the propagation of electromagnetic waves is prohibited for all wave vectors. Various important scientific and engineering applications such as control of spontaneous emission, zero-threshold lasing, very sharp bending of light, trapping of photons, and so on, are expected by utilizing the photonic bandgap and the artificially introduced defect states and/or light-emitters. Thus far, we have investigated novel functional devices utilizing 2D photonic crystals as well as the realization of full 3D photonic bandgap crystals [1]. In this symposium, I would like to describe two unique devices utilizing 2D photonic crystal. One is a 2D photonic crystal laser. The device utilizes a multi-directional distributed feedback effect and can work as a surface-emitting laser [2], which oscillates in a very large area with single longitudinal and lateral modes. It will be also shown that the polarization mode can be well controlled by engineering photonic atom structure, which indicates that unprecedented type of lasers with excellent features such as perfect single-mode over a large area, high output-power, and surface-emission with a very narrow divergence angle would be realized. Next, I would like to describe a device utilizing a single defect in 2D photonic bandgap structure [3]. The defect traps the photons which propagate through a waveguide formed in 2D photonic crystal slab and emits them to free-space. This phenomenon is very promising for the actual application to an ultra-small optical device with a function of dropping (or adding) photons with various energies from (or into) optical communication traffic (fiber). The detailed properties of the device will be described here including various trials of defect engineering. [1] S. Noda, K. Tomoda, N. Yamamoto, and A. Chutinan, "Full Three-Dimensional

Photonic Bandgap Crystals at Near-infrared Wavelengths", Science, 289, 604-606 (2000). [2] M. Imada, S. Noda, et al, "Coherent Two-Dimensional Lasing Action in Surface-Emitting Laser with Triangular-Lattice Photonic Crystal Structure", Appl. Phys. Lett., 75, 316-318 (1999). [3] S. Noda, A. Chutinan, and M. Imada, "Trapping and Emission of Photons by a Single Defect in a Photonic Bandgap Structure", Nature, 407, 608-610 (2000).

11:00 AM K6.6
PHOTONIC BANDS OF A WAVEGUIDE-EMBEDDED GaAs PHOTONIC CRYSTAL WITH TWO-DIMENSIONAL TILTED SQUARE LATTICE. M. Galli, M. Agio, L.C. Andreani, D. Bajoni, G. Guizzetti, M. Patrini, INFM and Dipartimento di Fisica "A. Volta", Universitá di Pavia, ITALY; E. Di Fabrizio, F. Romanato, L. Vaccari, D. Cojoc, L. Businaro, TASC-INFM at ELETTRA Sincrotrone Trieste, ITALY; A. Passaseo, M. De Vittorio, INFM and Dipartimento di Ingegneria dell'Innovazione, Universitá di Lecce, ITALY.

Two-dimensional (2D) photonic crystals are fabricated on $Al_xGa_{1-x}As$ epitaxial layers using high-resolution electron-beam lithography for the direct writing and X-ray mask fabrication, followed by reactive ion etching. Sub-micrometer photonic structures in the near-infrared and visible spectrum are patterned deeply into a air/GaAs/Al(0.25)Ga(0.75)As slab waveguide, with a square lattice with tilted square dielectric columns. Reflectance spectra taken at different angles of incidence allow to measure the dispersion of 2D photonic bands due to grating-induced coupling of the external beam to the waveguide modes. The photonic bands in a waveguide are calculated by expanding the electromagnetic field in the basis of waveguide modes coupled by the dielectric tensor; reflectivity spectra are also calculated by a scattering matrix method. The measured dispersion of photonic bands is found to be in good agreement with the theoretical results.

11:15 AM K6.7
PLASMON WAVEGUIDES FOR ELECTROMAGNETIC ENERGY BELOW THE DIFFRACTION LIMIT USING ORDERED ARRAYS OF METAL NANOPARTICLES. Stefan Maier, Mark Brongersma, Pieter Kik, Harry Atwater, California Institute of Technology, Pasadena, CA; Sheffer Melzer, Ari Requicha, Bruce Koel, University of Southern California, Los Angeles, CA.

The miniaturization of optical devices towards densely integrated optical chips akin to their electronic counterparts will require structures that guide electromagnetic (EM) energy below the diffraction limit of light. We investigate the possibility of using structures consisting of ordered arrays of closely spaced metal nanoparticles for this purpose. We have developed a theory that predicts that energy transport in these arrays occurs via resonant near-field coupling between metal nanoparticles that sets up plasmon modes. This coupling leads to coherent propagation of energy along nanoparticle arrays with group velocities of about 0.1c and energy can be guided around 90 degree corners and split via tee structures with high efficiency. We confirmed our theoretical predictions in a macroscopic analogue operating in the microwave regime both via experiment and full field electrodynamic simulations. In order to verify the guiding properties at the nanoscale, we fabricated ordered arrays of closely spaced 30-50 nm gold particles in a variety of geometries such as straight lines, corners and tee structures using electron beam lithography on ITO coated glass substrates and assembly using atomic force microscope manipulation. We are currently working on the optical characterization of these structures using an illumination mode near field scanning optical microscope (NSOM) as a local excitation source at 514 nm close to the surface plasmon frequency of gold nanoparticles. The propagation of energy along the nanoparticle structures is tested using carefully aligned 60 nm dye-filled polymer spheres which fluoresce at 580 nm upon excitation. Results of power transmission measurements will be presented. If the guiding of electromagnetic energy at optical frequencies on the nanoscale proves to be of the same efficiency as it is in the macroscopic microwave analogue, then ordered arrays of metal nanoparticles could become building blocks of nanoscale integrated optical devices.

11:30 AM K6.8
SINGLE LINE PHOTONIC CRYSTAL WAVEGUIDES ON SUSPENDED MEMBRANES. Marine Le Vassor d'Yerville, David Cassagne, Emmanuel Centeno, Jean Paul Albert, Université Montpellier II, Groupe d'Etude des Semiconducteurs, UMR 5650 du CNRS, Montpellier, FRANCE; Xavier Letartre, Christian Seassal, Christian Grillet, Pedro Rojo-Romeo, Pierre Viktorovitch, Ecole Centrale de Lyon, Laboratoire d'Electronique, Optoélectronique et Microsystèmes, UMR CNRS 5512, Ecully, FRANCE.

Recently an increased interest has been devoted to 2D photonic crystals (PCs) slabs for their applications in microphotonics. We present here a modelling of waveguides in such structures. Using a 3D plane wave expansion method and a supercell approach, we study a single line PC waveguide embedded in a InP membrane suspended in air. The waveguide consists in a row of missing holes in a triangular lattice of air holes drilled through the membrane. Due to the index contrast between the membrane and the surrounding air, a good in-plane confinement of light is obtained. The modelling of such a structure requires 3D calculations to take into account the finite height of the membrane and the occurrence of vertical losses. With the supercell approach we show the possibility to obtain the dispersion curves not only below the light line where modes are perfectly guided, but also above the light line where they can suffer losses. The comparison with the experimental characterization of a waveguide on an InP membrane presents an excellent agreement [1]. We demonstrate that thanks to the high vertical index contrast the waveguide exhibits 4 modes with no losses below the light line. We also show the existence of a large monomode frequency region due to a wide gap opening between the other modes. Finally we perform a detailed comparison between 3D and 2D calculations, in order to establish quantitatively the range of validity of 2D effective index approximations in such PC slabs structures. [1] X. Letartre, C. Seassal, C. Grillet, P. Rojo-Romeo, P. Viktorovitch, M. Le Vassor d'Yerville, D. Cassagne, and C. Jouanin, Group velocity and propagation losses measurement in a single line photonic crystal waveguide on InP membranes, to appear in Appl. Phys. Lett.

11:45 AM K6.9
NEAR INFRARED PHOTONIC CRYSTAL DEVICES BASED ON A NOVEL SILICON PLATFORM. Lu Chen, Y. Suzuki, Department of Materials Science and Engineering, Cornell University, Ithac, NY; Glenn E. Kohnke, Sullivan Park Research Center, Corning, Inc.

We have developed one and two dimensional silicon based photonic crystal devices coupled directly to optical fiber with insertion losses as low as 3.5dB. The novel silicon platform that we have developed enables us to effectively couple light from fiber to microphotonic structures without planar waveguides. One-dimensional photonic crystals, fabricated by electron beam lithography, exhibit a higher order photonic bandgap with over 30dB suppression of transmission from 1400nm to 1700nm, that is consistent with simulation. By introducing defects, we are able to place localized modes at 1550nm. We will also present results on two-dimensional hexagonal structures coupled to optical fiber with a photonic bandgap around 1550nm. These results may lead to the true integration of photonic crystals into optical fiber communication systems as optical switches and routers.

SESSION K7/AA7: JOINT SESSION
COLLOIDS AND PHOTONIC CRYSTALS
Chair: Willem L. Vos
Wednesday Afternoon, November 28, 2001
Room 201 (Hynes)

1:30 PM *K7.1/AA7.1
TYPE IV SEMICONDUCTOR INVERSE OPALS. F. Meseguer, Unidad Asociada CSIC-UPV Edificio de Institutos II. Universidad Politècnica de Valencia, Valencia, SPAIN, also Instituto de Ciencia de Materiales de Madrid (CSIC) Campus de Cantoblanco, Madrid, SPAIN.

Inverse opals has proven to be an easy an cheap route in the fabrication of Photonic Crystals with an omnidirectional photonic gap along the three directions of the space. Here, we show results on the synthesis of germanium and silicon based inverse opals. To guarantee that full gap appears below the semiconductor absorption edge, large periodicity opals should be employed. In the case of silicon (germanium) we have used templates with particle size of 0.87 (1.2) microns. Through the sintering process we can vary the opal void volume. It constitutes an additional parameter to control the photonic gap. We have used Chemical Vapour Deposition method that allows a layer by layer semiconductor infiltration up to a full loading of the opal void. Therefore, one can tailor gap widths of the composites. By comparing optical data with theory we can find evidences of the opening of a full photonic gap in both inverted structures in the near infrared region, around 1.5 microns (for silicon) and 2 microns (for germanium). The gap to mid gap value for the silicon inverse opal is 5%, and 7% for the germanium case.

2:00 PM K7.2/AA7.2
ANISOTROPIC DEFORMATION OF PHOTONIC CRYSTALS OF SPHERICAL INORGANIC COLLOIDAL PARTICLES. Krassimir P. Velikov[a], Teun van Dillen[b], Albert Polman[b] and Alfons van Blaaderen[a,b]; [a]Physics and Chemistry of Condensed Matter, Debye Institute, Utrecht University, Utrecht, THE NETHERLANDS; [b]FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS.

Spherical SiO_2, ZnS, and core-shell particles of these materials show a dramatic anisotropic plastic deformation under ion irradiation [1].

Individual particles can be turned into oblate and prolate ellipsoids with exact control over the aspect ratio. Here, we report on the fabrication and optical characterization of thin three-dimensional (3D) photonic crystals of spherical particles that were anisotropically deformed by means of ion irradiation [1]. As a result of the now collective deformation process both the unite cell symmetry and the particle form factor were changed. In this manner, the spectral position of a stopgap can be tuned. Colloidal crystals of anisotropically shaped spheres have a reduced symmetry of the Brillouin zone compare to face-cubic-centered, giving rise to a birefringence at long wavelengths, and can also be used as a template to grow inverse structures. [1] E. Snoeks, A. van Blaaderen, T. van Dillen et al., Adv. Mater. **12**, 1511 (2000).

2:15 PM K7.3/AA7.3

OPTICAL PROPERTIES OF Sn AND Pb INFILTRATED OPALS. Gugang Chen, G.U. Sumanasekera, V.H. Crespi, and Peter Eklund, Pennsylvania State University, University Park, PA.

Opals (70 nm and 300 nm) were infiltrated with Sn and Pb by the high-pressure melt injection method. The near normal incidence reflectance of polished surfaces of these photonic materials and the bulk solid was measured at 10 K and 300 K. A Kramers-Kronig (KK) analysis was carried out to determine the effective dielectric function. Shifts in the frequencies of intra- and interband absorption are observed for the infiltrated opal relative to those in the bulk metal. These shifts will be discussed in connection with theoretical model calculations on these systems. This work was supported by NSF MRSEC(PSU).

2:30 PM K7.4/AA7.4

METALLO-DIELECTRIC PHOTONIC CRYSTALS AND GLASSES OF SILVER COLLLOIDAL PARTICLES. Krassimir P. Velikov[a], Gabby E. Zegers[a], Willem L. Vos[b], Alexander Moroz[a], and Alfons van Blaaderen[a,c]; [a]Physics and Chemistry of Condensed Matter, Debye Institute, Utrecht University, Utrecht, THE NETHERLANDS; [b]Van der Waals-Zeeman Institute, University van Amsterdam, Amsterdam, THE NETHERLANDS; [c]FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS.

Colloidal crystals of metallic and metallo-dielectric spheres in a dielectric host are suitable candidates to achieve tunable photonic bandgaps for optical wavelengths [1, 2]. Photonic gaps exist in many periodic structures and are robust against disorder caused by stacking faults and particle polydispersity. Here we report on the fabrication and characterization of metallo-dielectric photonic crystals and glasses of large (100 - 500 nm in radius) silver (Ag) colloidal particles. The experimental method to create Ag colloidal particles and their characterization by electron microscopy will be discussed. The optical properties on a single particle level are studied by means of light scattering and compared to Mie scattering theory. Silver particles in water tend to self-organize in a charge stabilized colloidal crystal, which displays strong Bragg reflection colors. Optical properties of colloidal crystals and glasses of Ag particles will be discussed and compared to theoretical calculations. [1] A. Moroz, Phys. Rev. Lett. **83**, 5274 (1999); Europhys. Lett. **50**, 466 (2000). [2] W.Y. Zhang, X.Y. Lei, Z.L. Wang et al., Phys. Rev. Lett. **84**, 2853 (2000).

2:45 PM K7.5/AA7.5

PHOTONIC CRYSTALS AT NEAR INFRARED AND OPTICAL WAVELENGTHS. Alexander Moroz, Physics and Chemistry of Condensed Matter, Debye Institute, Utrecht University, TA Utrecht, THE NETHERLANDS.

Photonic-band-gap properties of binary colloidal mixtures (both dielectric and metallo-dielectric) of homogeneous and core-shell spherical particles and of two-dimensional (2D) metallo-dielectric structures of (infinitely long) cylinders are discussed. Results are presented on reflection and absorption, as a function of crystal thickness, in the region of a complete photonic bandgap of 2D and three-dimensional (3D) metallo-dielectric photonic crystals. The stability of optical properties of a photonic crystal with respect to a stacking disorder is investigated.

3:30 PM *K7.6/AA7.6

INVERSE OPAL PHOTONIC CRYSTALS MODIFY THE EMISSION AND THE PROPAGATION OF LIGHT. A. Femius Koenderink, Juan F. Galisteo, Lydia Bechger, Patrick M. Johnson, and Willem L. Vos, Van der Waals-Zeeman Instituut, Universiteit van Amsterdam, Amsterdam, THE NETHERLANDS.

Periodic dielectric composites with length scales of the order of the wavelength of light are known as *photonic crystals*. These complex systems are under intense scrutiny because of the possibility to completely control spontaneous emission and the propagation of light. Self-assembly methods such as those involving colloids, are attractive complements to nano-engineering methods that borrow techniques from the semiconductor industry. Through self-assembly, extended samples can be made in all 3 dimensions simultaneously. A particularly strongly interacting and well-ordered kind of crystal, pioneered in our lab, are inverse opals. These consist of ordered arrays of macropores, or air spheres, contained in a backbone of a material with a high refractive index. We discuss methods to improve crystal quality, and novel x-ray probes [1] to confirm the excellent long-range order of the crystals [2]. Photonic crystals are developed from semiconductors with high refractive indices in the range where band gaps are anticipated [3] and doped with light sources. Optical experiments are performed to study emission and the propagation of light in the crystals. We discuss the modification of spontaneous emission due to the (local) density of states and multiple Bragg diffraction. Multiple Bragg diffraction appears to be essential to understand the formation of band gaps [4]. [1] D.O. Riese, G.H. Wegdam, W.L. Vos, R. Sprik, D. Fenistein, J.H.H. Bongaerts, and G. Grübel, *Phys. Rev. Lett.* **85** 5460 (2000). [2] M. Megens and W.L. Vos, *Phys. Rev. Lett.* **86** 4855 (2001). [3] With the groups of J.J. Kelly (Utrecht) and W.E. Buhro (St. Louis). [4] H.P. Schriemer, H.M. van Driel, A.F. Koenderink, and W.L. Vos, *Phys. Rev. A* **63** (2001) no. 011801 (Rapid Comm.).

4:00 PM K7.7/AA7.7

TUNABLE OPTICAL PROPERTIES OF LARGE GOLD NANOPARTICLE ARRAYS. Beomseok Kim, Steven L. Tripp, Alexander Wei, Purdue University, Department of Chemistry, West Lafayette, IN.

The self-organization of large (16-170 nm) gold nanoparticles into 2D arrays is described. Transmission electron microscopy indicates a trend toward decreasing interparticle spacings with increasing unit particle diameters. The nanostructured arrays exhibit periodicity-dependent plasmon resonances and surface-enhanced Raman scattering (SERS), the latter with empirical signal enhancement factors ranging from 10^4 to over 10^7. These enhancements are reproducible and correlate strongly with periodic structure and excitation frequency. The arrays are sufficiently robust to support cell growth and attachment, and are being investigated as chemical and biomolecular sensors.

4:15 PM K7.8/AA7.8

AMPLIFICATION OF SPONTANEOUS EMISSION IN INCOMPLETE OPALINE PHOTONIC CRYSTALS. S.G. Romanov, D.N. Chigrin, C.M. Sotomayor Torres, Institute of Materials Science and Dept. of Electrical and Information Engineering, University of Wuppertal, Wuppertal, GERMANY; N. Gaponik, A. Rogach, A. Eychmüller, Institute of Physical Chemistry, University of Hamburg, Hamburg, GERMANY.

The manipulation of the spontaneous emission (SE) is among the most exciting prospects of photonic crystals (PhCs). While no omnidirectional 3D PhCs have been demonstrated in the visible, studies of emission in incomplete photonic bandgap materials, e.g. opals, provide novel information about light-matter interaction. The angular resolved photoluminescence (PL) of CdTe nanoparticles embedded in thin latex opaline films have been studied. Relative spectra obtained by comparison of PL spectra from the PhC and the similar unstructured sample demonstrate the stop-band in emission. Alternatively, ratio spectra obtained by comparison of PL spectra at different levels of excitation power reveal changes of the emission rate. Both relative and ratio PL spectra show spectral features centered at the Bragg resonance. The minimum in the ratio spectrum, which can be interpreted as a decrease of the emission rate, was observed at low gain. In the case of a higher gain, the minimum in the ratio spectrum is replaced with the maximum, moreover, its magnitude is increased with the gain thus demonstrating the SE amplification. Photons with frequencies in the stop-band can either leave the crystal or come back to the emitter, i.e. the emission intensity acquires an angular pattern. SE in localized modes is prohibited. The number of localized modes is constant for a given sample and, subsequently, the depth of the ratio spectrum minimum is gain-insensitive. In contrast, detailed calculations of 3D vector diagrams reveal in the stop-band a certain density of slow propagating eigenmodes, which appear due to the super-prism effect. Their group velocity is about 5 times lower as compared with modes propagating in allowed directions. SE coupled to slow modes can be enhanced when PhC has a sufficient gain. This competition of localization and enhancement of SE was detected by the analysis of ratio spectra. This effect opens the possibility of lasing on eigenmodes of an incomplete PhC.

4:30 PM K7.9/AA7.9

GERMANIUM NANOCRYSTALS IN SILICA FORMED BY HYDROGEN REDUCTION OF SILICON-GERMANIUM MIXED-OXIDES: PROCESS MODELING AND OPTICAL PROPERTIES. Gianni Taraschi, Wendy W. Fan, Eugene A. Fitzgerald, Massachusetts Institute of Technology, Dept of Materials Science and Engineering, Cambridge, MA.

Ge nanocrystals in a silica matrix show potential for the fabrication of high index contrast, non-linear, integrated optical devices. Ge nanocrystals in a SiO_2 matrix were synthesized using H_2 reduction of $Si_{1-x}Ge_xO_2$ at temperatures between 700°C and 800°C. Experiments were conducted for both $Si_{1-x}Ge_xO_2$ on $Si_{1-x}Ge_x$, and $Si_{1-x}Ge_xO_2$ on SiO_2 to explore the kinetics of the reduction process. Under specific annealing conditions, in particular for a temperature of 800°C and using a 6% H_2/ 94% N_2 annealing atmosphere, the reduction experiments for the $Si_{1-x}Ge_xO_2$ on $Si_{1-x}Ge_x$ samples showed that Ge can be highly mobile. Under such conditions, all the Ge formed diamond-shaped oriented crystals at the $Si_{1-x}Ge_x$ interface, with no Ge nanocrystals in the oxide, implying a solid state growth process akin to vapor phase growth on crystal surfaces. Similar experiments at 700°C, reveal a significantly slower Ge mobility, leading to the formation of Ge nanocrystals throughout the oxide. The mobility of the Ge is possibly due to the diffusivity of GeO gas, as opposed to the motion of elemental Ge in oxide, which is expected to be very slow, and hence cannot account for the 800°C data. A model incorporating both the thermodynamics of the reduction reaction, and the diffusion of reactants and products was developed to explain the data. Diffusion of water vapor from the reduction is an important rate limiting step incorporated in the model. Based on calculations, an optimized annealing sequence was designed to improve the size uniformity of the Ge nanocrystals, and hence reduce the inhomogeneous broadening of the optical spectra. Slab waveguides consisting of Ge dots in the core region were fabricated to measure optical transmission properties and explore potential integrated optics applications.

SESSION K8: PHOTONIC STRUCTURES AND DEVICES I

Chair: Claude Weisbuch
Thursday Morning, November 29, 2001
Room 201 (Hynes)

8:30 AM *K8.1
POROUS GALLIUM PHOSPIDE, A CAGE FOR VISIBLE LIGHT.
A. Lagendijk, J. Gomez Rivas, P.M. Johnson, van der Waals-Zeeman Instituut, Universiteit van Amsterdam, THE NETHERLANDS; R.W. Tjerkstra, D. Vanmaekelbergh, J.J. Kelly, Debye Instituut, Universiteit van Utrecht, THE NETHERLANDS.

Electrochemical etching of semiconductors has been widely investigated in recent years. Most of this work has been focused on silicon (Si). Recently, we have shown that many of the Si etching features can also be realized in gallium phosphide (GaP). Gallium phosphide has a very high refractive index (n=3.3) at sub-band gap wavelengths and a band gap of 2.24 eV, corresponding to a wavelength of 0.55 microns. This makes GaP transparent for light in the red part of the visible spectrum, in contrast to Si, which has the band gap at a wavelength of 1.1 microns. Therefore, GaP is a very interesting material for optical applications at wavelengths where Si presents strong absorption. In spite of this advantage there are only a few studies based on porous GaP. We present a detailed investigation of pore formation and the scattering strength as a function of the doping concentration and the etching potential. Bigger and more widely spaced pores can be formed in low-doped GaP. At low potential the pore diameter is reduced. The scattering strength in a heterogeneous material depends on the refractive index contrast between the scatterers and the surrounding medium, the size of the scatterers relative to the radiation wavelength and the density of scatterers. Therefore, it is easy to tune the scattering strength of porous GaP in a wide range. Enhanced backscattering and transmission measurements are used to quantify the scattering strength of porous GaP. The most strongly scattering sample of visible light reported to date is low-doped porous GaP.

9:00 AM *K8.2
HARNESSING LOSSES OF REAL-WORLD 2D PHOTONIC CRYSTALS.
C. Weisbuch, H. Benisty, S. Olivier, Laboratoire de Physique de la Matiére Condensée, Ecole Polytechnique, Palaiseau, FRANCE.

2D photonic crystals are emerging as a novel system for ultra-compact implementation of integrated optics functions. To provide full 3D control of optical waves, confinement in the third dimension rests on total internal reflection (TIR) in a waveguide structure. Combining such a vertical confinement with horizontal channeling of light in photonic crystal patterns is liable to introduce losses, which have to be assessed for applications. We discuss first low-loss schemes, comparing the membrane approach and the conventional semiconductor substrate approach. For the latter, our approach to radiation losses relies on the departure from variable separability of the propagation equation for etched structure. It is versatile and it provides a relationship between the 3D etch parameters and a phenomenological imaginary constant introduced into a 2D model, a much desirable way to tackle modeling of large systems, unaffordable in 3D calculations. The existence of truly lossless guided modes, with k below the cladding light line, is allowed by membrane-type systems, albeit in the very restricted (k,omega) region. However, bends and couplers will unavoidably break translational invariance, and with it the light-line picture. Therefore, photonic crystals in 2D will have to live with nonzero radiation loss, for both types of implementation. From there, we will discuss strategies to validate these approaches through adequate experiments, and we will in particular discuss some of our loss measurements. We have observed that a PC waveguide compares favorably with a ridge waveguide, and can provide a quantitative assessment of losses. Perspectives from both experiments and theory suggest that values of 1dB/mm could be reached in an optimized system. The physics of radiation losses may also offer interesting opportunities, however. The same phenomena also leads, if properly harnessed, to coupling light to or from the outside, especially in fibers located somewhere around the planar photonic crystals.

9:30 AM K8.3
THE Q-FACTOR OF A DEFECT MODE RESONANT CAVITY IN A PHOTONIC CRYSTAL WITH MODERATE DISORDER.
Evgenii Narimanov, Electrical Engineering Department, Princeton University, Princeton, NJ.

A defect mode introduced in the bandgap of a photonic crystal, can be used to create a high-Q resonant cavity. The lifetime of the corresponding resonance is then determined by the deviations of the surraunding media from perfect periodicity due to various imperfections (e.g. small variations of the diameters of the holes created in a regular pattern in a solid block of dielectric). Using the perturbative technique initially developed to treat the surface scattering of electrons in thin films, we evaluate the resonant cavity Q-factor in the limit of moderate effective disorder.

9:45 AM K8.4
FABRICATION OF MICROSTRUCTURES FOR MICRO-PHOTONIC CIRCUIT.
Subhasish Chakraborty, Robert J. Mears, Photonics and Sensors Group, Department of Engineering; David G. Hasko, Microelectronics Research Centre, Department of Physics; University of Cambridge, UNITED KINGDOM.

Use of Silicon as a material on top of Silicon dioxide is an exciting choice. It provides a high refractive index contrast at λ=1.54μm and is process compatible with standard integrated circuit fabrication methods. We will describe modeling and fabrication of Silicon strip waveguide with periodic/quasiperiodic arrangement of circular air holes in the waveguide which will manipulate the guided photonic dispersion and hence one can exploit that to realize useful photonic devices such as channel add/drop filter for WDM communication system around λ=1.54μm. Two commercially available softwares have been tested to model the devices and to predict the results. PBG effect devices of around 100nm feature size have been made using high-resolution lithographic and pattern transfer processes. The wafer consisted of 260nm crystalline Si core on 1.0μm SiO_2 cladding layer on Si substrate. Direct-write electron-beam lithography is used to generate the pattern in polymethylmethacrylate (PMMA), which follows a subsequent lift-off metalisation process and reactive-ion-etching. STS RIE has been used for Fluorine based plasma etching. Various gas combinations including CF_4/O_2, $CF_4/O_2/CHF_3$, $SiCl_4/CF_4$ have been investigated to etch Si and SiO_2. CF_4/O_2 mixtures have a fast etch rate but poor directionality. The $CF_4/O_2/CHF_3$ plasma is of particular interest, each gas has a known specific function and influence, so the etched profile is easily controlled just by changing the flow rate of one of these gases. $SiCl_4/CF_4$ is highly directional but has poor etch rate for SiO_2. Optical probing at λ=1.54μm of the first structure, which has a periodicity of 2μm is made. The guided mode at λ=1.54μm in the waveguide is translated into the radiation modes of the periodic PBG structure. The PBG structure thus acts as an output coupler. Optical probing of the second structure, which has a periodicity of 0.5μm, is under progress.

10:30 AM *K8.5
TWO-DIMENSIONAL PHOTONIC CRYSTAL MODES AND RESONANCES IN THREE-DIMENSIONAL STRUCTURES.
Shanhui Fan, Stanford University, Department of Electrical Engineering, Stanford, CA; J.D. Joannopoulos, MIT, Department of Physics, Cambridge, MA.

In this talk, I will present computational studies on two-dimensional photonic crystal modes in photonic crystal slab structures, and in a new three-dimensional photonic crystal structures. These are modes that retain two-dimensional symmetry properties, and yet are confined in the third dimension. I will discuss the applications of these modes in LED's, lasers, and integrated photonic circuits.

11:00 AM K8.6
SILICON ON INSULATOR BASED PHOTONIC BAND GAP

DEVICES FOR ROOM TEMPERATURE LIGHT EMISSION.
E. Hadji, D. Sotta, M. Zelsmann, T. Charvolin, E. Picard, N. Magnea, CEA/Grenoble, DRFMC/SP2M, FRANCE; M. Assous, N. Bouzaida, B. Dal Zotto, H. Moriceau, CEA/Grenoble, LETI/DTS, FRANCE; X. Letartre, P. Rojo Romeo, C. Seassal, LEOM/UMR CNRS 5512, Ecole Centrale de Lyon, FRANCE.

Recent progress showed the possibility of strong light emission from doped silicon material at room temperature. These results open the route to practical Si based microphotonic devices which might be integrated within microelectronic chips. We present here the fabrication and characterization of Si based photonic band gap (PBG) structures designed with the aim to improve Si intrinsic light emission properties at room temperature. We have developed a process on 8" SOI wafers which is compatible with standard microelectronic technology. Silicon on insulator (SOI) provides effective in plane light guiding due to the high optical index of Si, while SiO_2 forms a very efficient barrier against diffusion of carriers injected or photogenerated in the Si layer. Furthermore, oxide resistance to silicon etching process allow us to use the top oxide as a hard mask and buried oxide as etch stop layer. In a first step, we made B and P implantation of SOI films to obtain room temperature light emission. In a second step, we have designed and fabricated test structures for operation in the 1.1 - 1.5 microns range. These test structures consist of one-dimensional (1D) planar microcavities defined by 1D or 2D PBG reflectors etched in optical waveguides. Optical characterizations including transmission, through injection and collection of light by cleaved edges, and photoluminescence are performed at room temperature. Theses preliminary results show the possibility to study Si based micro emitters confined within PBG structures. This work has been carried out with CEA-LETI/PLATO facilities

11:15 AM K8.7
LUMINESCENCE AND OPTICAL AMPLIFICATION STUDY OF Er_2O_3. S. Saini, K. Chen, M. Lipson, J. Michel, L.C. Kimerling, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA.

A detailed spectroscopic study of erbium oxide is presented, as a new materials candidate for optical amplification of 1.55 μm light. Reactively sputtered films of Er_2O_3 were analyzed; we conclude that long-temperature anneals for high crystallinity are not requisite to strong PL performance, and that optical activation can be effectively achieved by rapid thermal anneals of less than 30 s in a nitrogen gas ambient. Integrated luminescence intensity reduces by a factor of 9 between 4 K and room temperature, indicating a coupling of optical centers to defect states. A model to explain this temperature-quenching will be presented from X-ray photoelectron spectroscopy atomic bonding, ellipsometry and spectral absorption measurements. It is observed that the energy difference between the first excited state and ground state can be quantitatively controlled by annealing time or annealing temperature, allowing tailoring of the luminescence and gain peak over a range of wavelengths. Room temperature versus 4 K studies indicate the presence of two competing atomic states, whose relative content can be controlled by deposition technology and deposition growth parameters. Excited-state lifetime decrease with pump power indicates the presence of weak upconversion; comparison is made between upconversion luminescence from sputtered thin films and the oxidized films of Kasuya et al.[1] Comparison with Erbium Doped Fiber Amplifier core material indicates comparable upconversion, suggesting the possibility of utilizing this new material system for a high gain coefficient optical amplifier. Preliminary optical amplification measurement results will be presented. [1] A. Kasuya and M. Suezawa, Appl. Phys. Lett. 71, 2728 (1997).

11:30 AM K8.8
EXPERIMENTAL CHARACTERIZATION OF THE DISPERSION PROPERTIES OF THE LEAKY MODES IN THE PLANAR PHOTONIC CRYSTAL WAVEGUIDES. Marko Loncar, California Institute of Technology, Electrical Engineering, Pasadena, CA; Dusan Nedeljkovic, Thomas P. Pearsall, Centre Europeen de Recherche de Fontainebleau, Corning, Avon, FRANCE; Jelena Vuckovic, Axel Scherer, California Institute of Technology, Electrical Engineering, Pasadena, CA; Sergey Kuchinsky, Corning Scientific Center, St. Petersburg, RUSSIA; Doug Allan, Corning Incorporated, Corning, NY.

We have experimentally characterized dispersion properties of the leaky modes supported in a triangular lattice planar photonic crystal waveguide. Single line defect waveguides, with different types of discontinuities (sharp bends, micro-cavities), were fabricated in the silicon-on-insulator wafer. Standard e-beam lithography procedure and chemically assisted ion beam etching were used to define patterns in silicon. Samples then received an additional HF etch to remove SiO_2 layer underneath the waveguide in order to form free-standing membrane. Butt-coupling of a single-mode fiber was used to introduce the light from the tunable semiconductor diode laser (wavelength range: 1440nm to 1590nm) into the photonic crystal waveguide. Waveguiding performance was observed using an infrared television camera positioned in the plane perpendicular to the sample. In the experiment, light coupled into the waveguide formed clear standing wave pattern that could be detected by infrared camera. The spatial periodicity of this intensity modulation grows shorter as the difference between the wavelength of light and 1500nm grows larger, in *either direction of the wavelength*. We have attributed this pattern to the interference of two counter-propagating (leaky) modes of the structure: forward propagating light excited with the external light source, and backward propagating light reflected from the waveguide discontinuity. We have used a fast Fourier transform to extract information on the spatial periodicity of the standing wave pattern. In that way we could experimentally map the dispersion diagram of the leaky mode supported in the waveguide. This experimental result is in an excellent agreement with dispersion diagram obtained using three dimensional finite difference time domain (3D FDTD) calculations. For the wavelengths in the range (1495nm, 1505nm) modulation intensity detected by the infrared camera has disappeared. This can be attributed to the presence of the mini stop band around 1500nm wavelength as predicted by 3D FDTD calculations.

SESSION K9: PHOTONIC STRUCTURES AND DEVICES II
Chair: Alexander Moroz
Thursday Afternoon, November 29, 2001
Room 201 (Hynes)

1:30 PM *K9.1
MODELLING PHOTONIC CRYSTAL DEVICES : WHAT IS LEARNT FROM THE PLANE WAVE METHOD? Philippe Lalanne, Jean-Paul Hugonin, Institut d Optique, Orsay, FRANCE.

In recent years, there has been reawakened interest in the modelling of the propagation and the diffraction of light in materials structured at a subwavelength scale. For photonic crystals, the possibility of opening band gaps and of favouring new types of localized states are some of the phenomena that retained the attention of researchers. Photonic crystal devices are based on a periodic structure, where some local defects are introduced to provide some basic functionalities like filtering, dispersing or guiding. Many numerical tools are now available to model these devices. We will first revisit the plane-wave method, a widely method used for computing the energy bands of periodic structures. We will report on a drastic improvement in terms of convergence rate. This improvement is achieved by the use of correct factorization rules to express the product of two discontinuous functions in Fourier space. The plane wave method is not limited to the analysis of periodic structures. In fact, with only a few modifications, it can be used for aperiodic structures like photonic crystal waveguides. In this context, the losses due to out-of-plane scattering in the non-perfectly confined waveguide will be emphasized. The physics and the implementation of tapers based on artificial materials and acting as mode converters to reduce the losses will be discussed. Finally, a platform to modelize photonic crystal circuits will be suggested. It may rely on many numerical tools but all these tools have to share a common root to describe the electromagnetic field quantities. This root could be a complete modal basis as it is usually the case for commercial software modelling classical photonic integrated circuits.

2:00 PM K9.2
FEMTOSECOND LASER-MACHINED PHOTONIC CRYSTAL AND ITS TRANSMISSION MEASUREMENT. Ming Li, Makoto Ishizuka and Xinbing Liu, Panasonic Technologies, Boston Laboratory, Cambridge, MA; Y. Sugimoto, N. Ikeda and K. Asakawa, The Femtosecond Technology Research Association, Tsukuba, JAPAN.

In 1999 and early 2000, we demonstrated the capability of femtosecond laser with a UV wavelength of 387 nm to drill 200-250 nm holes in Si-on-SiO_2 substrate [1]. It met the spacing requirement for 1D waveguide photonic crystal [2]. We then took our next step to study drilling small holes on actual waveguides (prepared with e-beam lithography; Si waveguide width: 500-700 nm; waveguide material: Si-on-SiO_2, 200 nm thick single crystal Si on 1000 nm thick SiO_2). Promising drilling results on waveguides were achieved, and a forbidden transmission zone or photonic band gap was discovered from the laser-machined waveguides during our preliminary measurement. We believe this is the first photonic band gap crystal fabricated by a laser.
On 600-nm-wide waveguides, we drilled 8 holes (diameter $\sim$200 nm) with pitch size of 400 nm using our femtosecond laser pulses. Reasonable uniformity in hole-size and hole-shape was obtained. Holes were pretty well positioned. Our measured transmission spectrum of these waveguides indicates a rapid increase of transmission from 1350 nm to 1410 nm and a decrease towards 1500 nm. In addition, the

transmission rate is very low after 1500 nm. This measured spectrum agrees with the theoretical simulation reasonably well. We concluded from our data that there is a prohibited band created by the series of holes, and we captured the bandedge on the short wavelength side and a portion of the band gap.

This work was performed under FESTA, which is supported by the New Energy and Industrial Technology Development Organization (NEDO).

References:
[1] M. Li and X. Liu, Japanese Journal of Applied Physics, 40, 3476 (2001). [2] J.S. Foresi et al., Nature, 390, 143 (1997).

2:15 PM K9.3
PIEZOELECTRIC STRAIN-TUNABLE PHOTONIC BANDGAP CRYSTALS FOR HIGH SPEED OPTICAL SWITCHING. Sungwon Kim, Thomas Dilazaro, Venkatraman Gopalan, Pennsylvania State University, Materials Research Laboratory, University Park, PA.

We propose a new class of strain tunable photonic crystals, whose bandgap can be strongly tuned by application of strain transduced through a piezoelectric, electrostrictive or magnetostrictive substrates. In particular, we have designed two-dimensional strain-tunable photonic bandgap crystals by distorting the symmetry of the crystal from a regular hexagonal to a quasi-hexagonal lattice by means of field driven strain using a piezoelectric material. Calculations predict that the original high symmetry energy bands split up into several strained energy bands depending on the magnitude and direction of the strain. In the proposed structures, we show that 2% (3%) shear strain can be used to tune ~52% (73%) of the original undistorted absolute bandgap of a two-dimensional photonic bandgap crystal. We also present a systematic study of changing the lattice basis and its influence on the bandgap tunablility. For small resonantly driven structures, these devices can be used for optical switching and modulation at frequencies approaching megahertz.

2:30 PM K9.4
PHOTONIC CRYSTAL NARROW PASS BAND FILTERS.
Zhengbiao Ouyang, Haishan Liu, Jingzhen Li, Solid State Photonics Laboratory, College of Scientific Researches, Shenzhen University, Shenzhen, CHINA.

We present a photonic crystal narrow pass band optical filter, which is made of two pieces of photonic crystals with different photonic band gaps. The principle for the system is to arrange properly the band gaps of the two photonic crystals so that a small narrow pass band appears in the combined photonic band gap region. Our numerical investigations show that this kind of structure is feasible for narrow band optical filtering. The pass band may be less than 0.5nm in the infrared communication frequency band. In idea cases, the optical transmission in the pass band is higher than 99.99%. This means a very low insert energy loss. It is greatly superior to other kind of narrow band optical filters. This kind of photonic crystal narrow band optical filter may find applications in dense wavelength division multiplexing (WDM) for optical communications and in remote sense and measurement. Keywords: optical narrow pass band filters, photonic crystals, photonic band gaps.

2:45 PM K9.5
SECOND ORDER NON-LINEARITY IN PHOTONIC CRYSTALS COMPOSED FROM CENTRO-SYMMETRIC MATERIALS.
A. Feigel, Z. Kotler and B. Sfez, Electro-Optics Division, NRC Soreq, Yavne, ISRAEL.

We describe a technique for obtaining effective second order non-linearity in non centro-symmetric Photonic Crystal (PC) made from centro-symmetric materials (e.g. glass, Ge or Si). The effect is based on the electric quadrupole transition, strong electromagnetic mode deformation and different contributions to the volume polarization from different parts of the photonic crystal. A local second order polarization exists even in centro-symmetric materials due to the higher than dipole electromagnetic transitions. The asymmetry of the electromagnetic field spatial mode leads to quadrupole transition, while dipole transition is based on the asymmetry of the electron wave function. Generally the volume contribution of such polarization vanishes, due to periodicity of electromagnetic mode and gradient dependence of quadrupole transition polarization. However the result in properly designed photonic crystals can be quite different. Volume contribution of the local quadrupole polarization in dielectric/air PC can be different from zero. The reason is unequal contributions to the polarization from different parts of the media. The polarization of the air regions can be totally neglected due to low electron density. Constructing PC in such a way that in dielectric part the quadrupole polarization has one sign and in the air the opposite, effective structural volume polarization can be obtained. From the previous experiments on the surface non-linear effects in Si and Ge, it is possible to estimate that structural second order susceptibility in photonic crystals made from these substrates can be comparable with second order susceptibilities of ordinary non-linear materials.

3:30 PM *K9.6
ULTRA-COMPACT PASSIVE FUNCTIONS FROM 2D PHOTONIC CRYSTALS: EXPERIMENTAL CLUES TO DESIGN. H. Benisty, C. Weisbuch, S. Olivier, Laboratoire de Physique de la Matiere Condensee, Ecole Polytechnique, Palaiseau, FRANCE; C.J.M. Smith, Univ of Glasgow, Optoelectronics Research Group, Glasgow, SCOTLAND, UK; T.F. Krauss, Univ of St. Andrews, School of Physics and Astronomy, St. Andrews, SCOTLAND, UK.

Guiding light as a copper wire guides electrons is one of the dreams that could be achieved by means of photonic crystal (PC) waveguides. One preferred realization of such PCs consists of holes etched at nodes of a triangular lattice through a planar structure, in which confinement rests on refraction (Total Internal Reflection). Such systems have already demonstrated many of their promises for basic crystals properties and also for confining elements such as cavities. The next step towards device functions is to connect, e.g., the cavities or some electro-active parts through channel guides, straight or adequately bent. Even if one sticks to the simplest scheme, whereby each of these elements is defined by removing some “atoms” of the PC lattice, the optics problem remains complex in many respects. Taking the most basic case, a free wave at a bandgap frequency impinging from an unpatterned region onto a PC, the wave is not just reflected but also diffracted. The same phenomenon occurs in straight waveguides and cavities, leading to complex mode shapes which are delicate to handle with former integrated optics concepts. To illustrate the pro’s and con’s of this complexity, we will present experiments showing the basic properties of straight micron-size waveguides of 2 to 5 missing rows, in which a mode coupling phenomenon, now well understood, gives rise to a “Mini-Stopband”. We will next discuss the measured properties of 60° waveguide bends defined in PCs. Finally, we will examine various structures in which cavities are connected to straight guides sections. One of these structure is the “photon gun”, which can be viewed as a first step towards high-brightness in-plane spontaneous emission source. Another structure of interest has a cavity inserted along a waveguide, or at a bend, showing resonant transmissions. From these data, we will suggest some rules for better coupling and for improved performances of these passive elements.

4:00 PM K9.7
Er-DOPED BARIUM TITANATE THIN FILM WAVEGUIDES FOR INTEGRATED OPTICAL AMPLIFIERS. A.R. Teren and B.W. Wessels, Northwestern University, Dept. of Materials Science and Engineering, Evanston, IL; S.-S. Kim and S.T. Ho, Northwestern University, Dept. of Electrical and Computer Engineering, Evanston, IL.

Thin film epitaxial $BaTiO_3$ waveguides were investigated for potential use as integrated optical amplifiers for microphotonic applications. Er doped $BaTiO_3$ with dopant concentrations of 0.1-1 atomic per cent was deposited by metal-organic chemical vapor deposition. Ridge waveguides were fabricated via photolithography and wet chemical etching. Stimulated emission from the waveguides was studied using the pump-probe technique over the spectral range of 1510-1560 nm. A maximum differential gain of 3 dB/cm was measured at 1540 nm.

4:15 PM K9.8
SUBMICRON-SCALE FREQUENCY SELECTIVE SURFACES FOR THERMOPHOTOVOLTAIC SPECTRAL CONTROL.
James E. Raynolds, Lockheed Martin, Schenectady, NY.

Frequency Selective Surfaces (periodic arrays) containing sub-micron scattering elements for use in Thermophotovoltaic spectral control applications have been designed, fabricated, and analyzed. These filters are promising because of their simplicity (few layers vs. many-layered dielectric stacks) and low sensitivity to angle of incidence effects. The demands of maximum efficiency and power density result in stringent requirements on high transmission in the pass band, high reflectivity in the stop band, a sharp transition from low to high transmission, and low overall absorption. This poses a challenging design problem via trade-offs between desirable pass band transmission, stop band reflection and absorption. Detailed comparisions between theory and measurements will be presented.

4:30 PM K9.9
EVANESCENT WAVEGUIDE CHARACTERIZATION AND PHOTOISOMERIZATION OF ALL -AZOBENZENE FUNCTIONALIZED DENDRIMERS ON ULTRATHIN FILMS: AGGREGATION BEHAVIOR AND MATRIX EFFECTS.
Derek Patton, Mi-kyoung Park, Shuangxi Wang, and Rigoberto Advincula, University of Alabama, Birmingham, AL.

We have used evanescent wave-guide techniques to characterize ultrathin films of azobenzene dendrimers in polymer matrices.

Dendrimers are a new class of macromolecules characterized by their tree-like generational structure. Azobenzene dyes adds photochromic behavior to these macromolecules allowing light induced structural and refractive index changes. This study also focuses on the use of linear polarized photoisomerization (LPP) to control the shape anisotropy of the dendrimer at various concentrations within a polymer matrix. We are interested in the "globular" shape (or conformation) and functionality of the dendrimer and how the matrix material affects these properties. Typically, systems involving small molecule azo-dyes are well understood. In contrast, macromolecular systems, while abundant and widely studied, are typically ill defined and the photochemical properties are difficult to predict. In an ATR experiment, we are able to define the real and complex properties of the material three-dimensionally to correlate with the polarization of irradiated light. Interesting differences in the behavior of these systems may play an important role in distinguishing applications and phenomena of azobenzene materials for linear and nonlinear photonics applications.