SYMPOSIUM W

W: Engineered Porosity for Microphotonics and Plasmonics

December 2 - 4, 2003

Chairs

Ralf Wehrspohn
Dept. of Physics
Paderborn University
Warburger Str. 100
Paderborn, 33098 GERMANY
49-5251-60-2748

Francisco Garcial-Vidal
Dept Fisica Teorica Materia Condensada
Universidad Autonoma de Madrid
Madrid, 28049 SPAIN
34-91-397-8515

Masaya Notomi
NTT Basic Research Laboratories
Morinosato-Wakamiya
Atsugi, 243-0198 JAPAN
81-46-240-3553

Axel Scherer
California Institute of Technology
MS 200-36
1200 California Blvd.
Pasadena, CA 91125
626-395-4691

Proceedings to be published in both book form and online
(see *ONLINE PUBLICATIONS* at www. mrs.org)
as Volume 797
of the Materials Research Society
Proceedings Series

* Invited paper

SESSION W1: Porous Silicon
Chair: Ralf Wehrspohn
Tuesday Morning, December 2, 2003
Room 204 (Hynes)

8:30 AM *W1.1
Porous Silicon – a relaxed view of the status quo.
Frederick Koch, Physik Department, Technical University Munich, Garching, Germany.

Remember the hot debates on what makes porous Si luminesce only a few years ago? It is remarkably quiet now as dedicated research has provided some of the answers. It is also that some vociferous advocates have capitulated in view of the controversial results. We review central facts on the photoluminescence, including the status of the essential oxidized porous Si dilemma. There is now a plausible resolution of the controversy based on an unexpected discovery [Phys. Rev. Lett. 89, 137401 (2002)] showing how energy is drained out of Si nanoparticles to surface oxygen. The well established nonlinear increase of PL intensity with pump power because of Auger damping has impaired the prospects of achieving actively light emitting devices. Only incorrigibles are pursuing the concept of the Si nanoparticle-based laser. There is all the more effort under way to develop porosity-engineered microstructures with unique optical properties. In particular, those based anisotropically etched nanoparticles with their giant birefringence [Opt. Lett. 26, 1265 (2001)].

9:00 AM W1.2
Photoluminescent porous silicon patterns of sub-micron dimension by metal-assisted electroless etching.
Soma Chattopadhyay[1,2,3] and Paul W Bohn[1,2,3]; [1]Department of Chemistry, University of Illinois at Urbana-Champaign, Urbana, Illinois; [2]Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, Illinois; [3]Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Photoluminescent porous silicon (PSi) pixels of sub-micron dimensions are produced by patterning sub-micron diameter Pt areas onto Si before subjecting it to etching. Porous silicon (PSi) can be produced by metal-assisted electroless, i.e. non-electrochemical, etching of Si (100) in a solution of methanol, HF and H_2O_2. A thin layer of Pt (d $\sim$ 30 $\AA$) is patterned onto Si prior to immersion in the etching solution. Unlike conventional fabrication methods, PSi formation takes place in a few seconds without use of electrical bias or illumination. Exciting the PSi thus produced with UV light causes photoluminescence and the emission wavelength can be tuned simply by varying the etch conditions. The Pt pattern deposited on Si prior to etching spatially directs the formation of PSi which in turn makes it possible to control the luminescence spatially. In order to achieve sub-micron resolution of patterning, focused ion beam assisted deposition of Pt on Si has been employed. Characterization of the morphology and the optical characteristics of the sub-micron scale luminescent PSi is necessary to develop a better understanding of the process. Scanning Electron Microscopy and Atomic Force Microscopy have been employed for high resolution surface investigations. Moreover these techniques when coupled with photoluminescence spectroscopy and microscopy are used to correlate surface morphology of the etched structures with the optical properties of emission. Investigation of the optical characteristics of photoluminescent pixels of about 100 nm dimension is limited by the resolution achievable by conventional optical microscopes. To overcome this, Near-field Scanning Optical Microscopy will be used to obtain spatial information of the emission characteristics of the photoluminescent pixels.

9:15 AM W1.3
Fabrication of Flexible One-Dimensional Porous Silicon Photonic Band-Gap Structures. Natalya Tokranova, Andrew Stollenwerk, Bai Xu and James Castracane; School of NanoSciences and NanoEngineering, University at Albany (SUNY), Albany, New York.

Photonic crystals are periodic dielectric structures that have a photonic band gap to control the propagation of light in a certain wavelength range. This property offers a means to manipulate photons in the same way as electrons can be controlled in an atomic lattice. Porous silicon is an ideal candidate for the fabrication of photonic crystals because of the availability of a variety of silicon micromachining techniques. One-dimensional photonic crystals with customized parameters can be economically fabricated using porous silicon multilayer structures with periodically modulated porosity. Despite the structural non-homogeneities, porous silicon fabricated on a p-type Si substrate has optical properties similar to a dielectric material with a single effective refractive index. The exact value of the refractive index for each layer depends on its porosity. An engineered porosity can be obtained by changing the etching currents during the anodization process. This results in a modulation of the refractive index. A stack of alternating layers with high and low porosity produces a distributed Bragg reflector (DBR). Various designs incorporating multilayer porous silicon structures with an optical Fabry-Perot resonator and coupled microcavities are under development and can serve as an optical filter. Prototypes of such free-standing structures with 21-200 stacked layers to be used as DBRs, Fabry-Perot resonators or coupled microcavities are being fabricated. These structures are coated with polystyrenesulfonate on their backsides to increase mechanical strength and at the same time maintain flexibility. In this work, reflection spectra of these porous silicon multilayers with and without polymer on the backside were measured. Simulations of the multilayer one-dimensional photonic crystals were performed to predict the reflection spectra and optimize their structures before the fabrication and to compare to experimental data.

10:00 AM *W1.4
Active and passive photonic bandgap structures with porous silicon. Philippe M Fauchet, ECE, University of Rochester, Rochester, New York.

Photonic bandgap (PBG) structures made in silicon appear promising for integrating electrical and optical functionalities on the same chip. This presentation will start with a survey of the possible applications of such structures, for example as MOEMS replacement or for optical interconnects. Then, several passive PBG structures and active PBG structures (i.e., those whose optical properties are controlled by external stimuli) made of meso- and macro-porous silicon will be discussed in detail. Finally, the systems engineering implications of the present and anticipated performance of these structures will be briefly mentioned. This work is supported by the National Science Foundation, the Air Force Office of Scientific Research, and the Semiconductor Research Corporation.

10:30 AM W1.5
Enhanced luminescence properties of pulsed laser deposited europium activated yttrium oxide thin films on porous silicon surfaces. Jaeyoung Choi and Rajiv K. Singh; Materials Sci. & Eng., Univ. of Florida, Gainesville, Florida.

The surface roughness of thin film phosphors in one of the factors that affect the brightness of photoluminescence and cathodoluminescence properties. Tailoring the surface roughness of thin film phosphors using various methods can enhance the relatively low brightness of the thin film phosphors. One approach to modifying the surface roughness can be the formation of a porous silicon layer as a template to be applied to silicon surfaces prior to deposition of thin film phosphors. The porous silicon layer is inherently rough, and thus varying the roughness of the porous silicon layer can suitably conrtol the roughness of the thin film phosphors. This approach has several advantages of lower cost, rapidity and simplicity in wet chemical process. Therefore, the objective of this study is to establish the optimum processing conditions to fabricate thin films of Eu:Y2O3 red phosphors with various roughness values on porous silicon surfaces to obtain enhanced cathodoluminescence efficiency using the formation of porous silicon layer. The thin films were grown on bare and porous silicon surfaces at various roughness conditions by pulsed laser deposition. The deposited films were characterized using x-ray diffraction, field emission scanning electron microscopy, optical profilometry, atomic force microscopy, photoluminescence and cathodoluminescence. Measurements of photoluminescence and cathodoluminescence properties of Eu:Y2O3 films showed that the films grown on porous silicon surfaces were brighter than the films of bare silicon surfaces under identical deposition conditions. Furthermore, this brightness increased with increasing the roughness of substrate surface. Since brightness losses are attributed to internal reflection from smooth interfaces, the increased substrate roughness allows increased brightness from the phosphor films by reducing internal reflections.

10:45 AM W1.6
Laterally Graded Rugate Filters in Porous Silicon.
Sean Erik Foss and Terje G Finstad; Department of Physics, University of Oslo, Oslo, Norway.

Rugate optical reflectance filters with a position dependent reflectance peak in the vis-NIR were realized in porous silicon (PS). Optical filters in PS produced by anodic etching of bulk silicon wafers offers a cheap, flexible way of combining (micro-)optics/optronics and silicon technology. By varying the current density continuously and periodically, the refractive index into the PS layer will vary accordingly. With this approach we obtained reflectance rugate filters which have narrow reflection peaks, no detectable higher order harmonics and suppressed sidebands compared to discrete layer filters. As a starting point for the graded filters we designed and made a rugate filter with a peak reflection at 636 nm at 19 deg. incidence.

The full width at half maximum was 16 nm and the maximum reflectance was 55%. In a graded version of this filter with a relatively small gradient, we observed a shift of the reflection peak from 614 nm to 680 nm across the 1 cm wide filter area. To obtain this graded filter a lateral voltage-drop was applied during the anodic etching. This leads to a lateral change in both the porosity and the periodicity of the optical thickness into the PS thin film. SEM analysis of the resulting pore structure will be discussed. The effect of this gradient on the filter characteristics is studied by varying the gradient, comparing measurements at different positions with measurements on non-graded filters. We have observed extra features in the reflectance spectrum of these graded filters compared with reflectance from non-graded filters. A possible connection between the gradient and the extra features will be discussed as well as strategies for obtaining graded rugate filters with the designed reflection spectrum.

11:00 AM W1.7
Strong light confinement in microporous Si photonic structures. Gilles Lerondel[2], Peter Reece[1], Aurelien Bruyant[2] and Mike Gal[1]; [1]School of Physics, University of New South Wales, Sydney, New South Wales, Australia; [2]Laboratoire de Nanotechnologie et Instrumentation Optique, UTT, Troyes, France.

We recently reported the fabrication of Si based subnanometer linewidth microcavities and "perfect" mirrors. The structures are made of microporous silicon by electrochemical anodisation. The resonant structure high quality (Q > 5000) and the observation of omnidirectionnal stop bands have been made possible by the optimisation of the starting material, etching conditions and structure design. We shall in this paper discuss in more details the choice of these parametres considering the material intrinsic limitations.

11:15 AM W1.8
Optical devices based on anisotropic nanostructured Silicon. Joachim Diener, Nicolai Kuenzner, Egon Gross and Dmitri Kovalev; Physik Department E16, Technische Universitaet Muenchen, Garching, Germany.

Over recent years, nanostructuring of semiconductors has been considered as an alternative way to the search for new materials. Material properties, especially optical ones can be modified by reducing the dimensions or by proper engineering of macroscopic structures on the nanometer scale. A key idea is the introduction of optical anisotropy by the reduction of the symmetry of bulk crystals via ordered nanostructuring. The simplest approach based on "drilling" holes in semiconductors is proved to be an effective strategy for a variety of optical applications. However, not all photonic applications require a strictly ordered distribution of holes. A quasiuniform distribution is sufficient for specific applications where the dimensions of both, holes and skeleton fragments are much smaller than the wavelength of the propagating light. Under these conditions the binary material can be considered as an optically homogeneous medium where light propagates without internal scattering. An optical anisotropy requires the reduction of a cubic lattice symmetry. Thus, in-plane optical anisotropy in cubic crystals can be realized by in-plane perturbation of the crystal symmetry for instance via crystalline direction sensitive pore propagation. Such selective pore alignment along [100] directions has been demonstrated for electrochemically etched Silicon (porous Si). Recently it has been shown that etching of low symmetry (110) Si wafers results in highly anisotropic alignment of the pores and nanocrystals in the [1-10] crystalline direction [1,2]. Another important property of porous Si is the simplicity of controlling the mean dielectric constant of the porous Si layers and their thickness via a variation of the etching current density and the time of etching. For instance, by alternative varying the etching time and the current densities porous semiconductor superlattices can be formed. This concept is the basis of a wide variety of dielectric, porous Si based, optical devices: retarders [3], dichroic Bragg-Reflectors [4], dichroic microcavities [5,6] and polarizers. [1] D. Kovalev, G. Polisski, J. Diener, H. Heckler, N. Kuenzner, V. Yu. Timoshenko, F. Koch, Appl. Phys. Lett. 78 (2001) 916 [2] N. Kuenzner, D. Kovalev, J. Diener, E. Gross, V. Yu. Timoshenko, G.Polisski, F. Koch and M. Fujii, Optics Lett. 26 (2001) 1265 [3] D. Kovalev, G. Polisski, J. Diener, H. Heckler, N. Kuenzner, F. Koch Phys. Stat. Sol.(a) 180 (2000) r8-r11 [4] J. Diener, N. Kuenzner, D. Kovalev, E. Gross, V. Yu. Timoshenko, G.Polisski and F. Koch, Appl. Phys. Lett. 78 (2001) 3887 [5] J. Diener, N. Kuenzner, D. Kovalev, E. Gross, F. Koch J. Appl. Phys. 91 (2002) 6704 [6] J. Diener, N. Kuenzner, D. Kovalev, E. Gross, F. Koch, M. Fujii Phys. Stat. Sol. (a) 197 (2003) 582

11:30 AM W1.9
Silicon micro-photonic structure for ultra-sensitive biosensing. Bradley Steven Schmidt, Vilson Rosa Almeida and Michal Lipson; Electrical and Computer Engineering, Cornell University, Ithaca, New York.

We propose a micron-size silicon photonic structure for discrete detection of metal nano-particles for single bio-molecule sensing. The structure is based on a defect (sensing volume) inside a silicon micro-cavity defined within a one-dimensional photonic crystal embedded in a high-index-contrast waveguide. By using Finite-Difference Time-Domain (FDTD) simulations we show that due to the field enhancement in the sensing volume, the absorption cross section of the nano-particle embedded in the defect is strongly enhanced. This enhancement enables the distinguishing of single particles down to 5 nm diameter within the sensing volume. The presence of an analyte labeled with metal nano-particles is then detected by observing a decrease in optical transmission due to the absorption by the particles. Structures were fabricated using e-beam lithography and RIE etch on Silicon-On-Insulator (SOI) wafers. The one-dimensional photonic crystal is embedded in a high index contrast silicon oxide clad silicon waveguides with height and width of 250 nm and 450 nm, respectively. The entire structure is less than 5 μm in length. By measuring the transmission spectra of the structure at λ = 1.5 μm, we demonstrate a strong field enhancement inside a sensing volume as small as $10^{-3}\mu m^3$, corresponding to three orders of magnitude enhancement of the absorption cross section of the embedded metal nanoparticles.

11:45 AM W1.10
Second- and third-harmonic generation spectroscopy of coupled microcavities formed from all-silicon photonic crystals. Denis G. Gusev, Irina V. Soboleva, Mikhail G. Martemyanov, Tatyana V. Dolgova, Andrey A. Fedyanin and Oleg A. Aktsipetrov; Physics Department, Moscow State University, Moscow, Russian Federation.

The possibility to control the light localization and to fulfill the phase-matching conditions makes photonic-crystal microcavities perspective for nonlinear optoelectronic applications. In the microcavities coupling through additional photonic crystal, the optical response is controlled by variation of parameters of this Bragg reflector. The modes of coupled microcavities (CMC) are split with spectral (angular) gap between them determining by intermediate Bragg reflector transmittance. This paper presents the observations of second- and third-harmonic generation (SHG and THG) resonant enhancement in all-silicon CMC's formed from mesoporous silicon photonic crystals when the fundamental radiation is in resonance with modes. The CMC's are made by the electrochemical etching of heavily doped Si(001) wafers. The pore size is controlled by the variation of the current flowing through the wafer perpendicular to its surface. Two identical half-wavelength-thick cavity spacers are surrounded by Bragg reflectors. External photonic crystal consists of 4 periods of porous silicon bilayers with quarter-wavelength-thickness each layer. The thickness of intermediate Bragg reflector is varied from 0.5 to 4.5 bilayers. The centers of photonic band gap coupled MC's are 1200 nm. The SHG and THG spectroscopies are performed in the wave vector domain by changing the angle of incidence of fundamental radiation. Angular positions of split CMC modes are defined by the electromagnetic coupling between two identical microcavity spacers, which is controlled by the reflectivity of the intermediate Bragg reflector. The SHG intensity and THG intensity enhancement is observed at the resonance of the fundamental radiation with the CMC modes. Angular splitting of the peaks in the SHG and THG spectra shows monotonous dependence on magnitude of coupling between microcavity spacers. The basic mechanism of the SHG and THG enhancement is localization of the fundamental field inside the microcavity spacers, which results in the increase of the amplitudes of the SH and TH fields generated inside spacers. The second mechanism is constructive interference of the outgoing SH and TH fields from the various layers of CMC, which results in redistribution of amplitudes of SHG and THG resonances and their shift from the angular positions corresponding to the maximal localization of the fundamental field. For strong coupling, maxima of the SHG resonances are located on the external sides of dips of linear reflection spectrum. Reduction of coupling leads to the splitting of the right SHG resonance on two peaks. The fit of the experimental spectra shows the small deviation of parameters of CMC samples with the depth that can be used for updating a technique of preparation of photonic crystals and microcavities based in porous silicon.

SESSION W2: Plasmonics I
Chair: Francisco Garcia-Vidal
Tuesday Afternoon, December 2, 2003
Room 204 (Hynes)

2:00 PM W2.1
Fabrication and Properties of Metallic Photonic Crystals Thermally Emiting in the Near Infrared. James Fleming and Shawn-Yu Lin; Sandia Nat Labs, Albuquerque, New Mexico.

Three-dimensional photonic crystals are complex structures with submicron minimum feature sizes when active in the infrared. These structures can now be fabricated using modifications of standard silicon processing techniques. These engineered devices have truly unique properties. In particular, we have experimentally demonstrated that tungsten photonic crystals with full 3-D bandgaps can exhibit thermal emission well in excess of that of a blackbody, cavity emitter over a range of wavelengths near the band edge. Unlike earlier work, which demonstrated thermal emission in excess of Planck's law, the light emitted from the metallic photonic crystal is propagating rather than evanescent. We believe that there are many technologies that could benefit from this effect such as highly efficient lighting, efficient, high energy density power supplies, and high efficiency IR sources. We attribute the effect to a suppression of the density of states in the bandgap, combined with an enhancement in density of states at the band edge. It is also necessary that the material making up the crystal have a significant emissivity. Due to the complex nature of the dielectric constant and the relative complexity of the structures, modeling of the emission behavior is difficult. In this presentation we will consider the optical and emissive properties of 3-D metallic photonic crystals and their fabrication by lithographic techniques. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL 85000.

2:15 PM W2.2

Control of Surface Plasmons Emitted from Arrays of Subwavelength Apertures. Girsh Blumberg[1], Brian S Dennis[1] and Dima Egorov[1,2]; [1]Bell Labs, Lucent Technologies, Murray Hill, New Jersey; [2]Physics, Harvard University, Cambridge, Massachusetts.

Recent works on extraordinary optical transmission [1] and light beaming [2] in sub-wavelength periodically structured metal films suggest a direction for fabricating optical devices that operate below the diffraction limit and utilize the coherent fluctuations of surface plasmons (SP). Significant advances in this area may be possible if SPs can be controllably converted to and from free-space photons, and if their surface propagation can be intentionally directed. In this work, we demonstrate that SPs can be emitted in the form of long and coherent jets whose intensity and propagation direction can be manipulated by varying the wavelength, incidence angle, and polarization of the excitation light as well as through adjustment periodicity of 2D structures and dielectric properties of the interfaces. We also demonstrate the reverse conversion of SPs back into free propagating light and observe controllable and highly directional beaming. We use for sample gold films on a fused silica substrates with fabricated arrays of subwavelength apertures illuminated by a tunable laser. We image coherent SP modes by a near-field scanning optical microscope (NSOM) and demonstrate emission of SP jets in controlled propagation direction. Distribution of fields in the SP jets has been recently reproduced by FDTD simulations with remarkable agreement between the simulation and experiment down to the details of the jet propagation [3]. By adding mirrors and lenses we demonstrate SP standing waves and focusing which concentrates extremely high local density of electromagnetic energy on the gold-air interface. By performing NSOM scans as a function of distance from the gold-air interface we map out the volume distribution of light intensity above the array and confirm highly directional nature of light emitted from periodic 2D structure of subwavelength apertures down to a few microns away from the surface. The method presented for controlling propagation directions and intensities of the SP jets is a step towards complex plasmon-based photonic devices. Combining it with other methods of adjusting light-plasmon coupling, such as coating the surface with a variable layer of dielectric, liquid crystals, or non-linear optical material may allow additional degrees of control of jet propagation using electronic and optical methods. Placing additional arrays on lines of jet propagation may allow localized, directional out-coupling of light at points away from the excitation spot; thus fast and complex micro-scale optical routers and switches may be constructed using simple focused-ion beam or lithographic fabrication techniques. 1. T. W. Ebbesen et. al., Nature 391, 667 (1998). 2. H. J. Lezec et. al., Science 297, 820 (2002). 3. M. I. Haftel, Abstract, this meeting.

3:00 PM *W2.3

Waveguiding Components Utilizing Surface Plasmon Polariton Band Gap Structures. Sergey I Bozhevolnyi, Institute of Physics, Aalborg University, Aalborg East, Denmark.

Conventional photonic crystals (PCs) represent composite materials with periodic modulation of refractive index that do not allow the propagation of electromagnetic waves in a certain interval of wavelengths, i.e., that influence the propagation of photons in the same way as electronic crystals forbid or allow the flow of electrons. Line defects in photonic crystals can be used for light guiding around sharp corners similarly to directing electrical currents in integrated circuits. The idea is to confine the radiation in one dimension (e.g., by using a planar waveguide) and to control its propagation by two-dimensional (2D) periodic modulation of refractive index. However, such a configuration is only quasi-2D, and there exists a formidable problem of keeping the radiation in the waveguide plane, especially when dealing with bent PC-waveguides. Recently, we have suggested the usage of special interface waves, viz., surface plasmon polaritons (SPPs), for the same purpose [1]. Surface plasmon polaritons (SPPs) are surface electro-magnetic waves propagating along a metal-dielectric interface and exponentially decaying in neighbour media. SPPs are thereby suited for PC-based waveguides and circuits provided that one can periodically influence the SPP propagation in the surface plane. It turned out that the efficient periodic modulation of the SPP propagation constant can be achieved by arranging nanometer-sized metal bumps in a periodic pattern on the metal film surface [1-3]. Here the results of our investigations concerning the SPP guiding along (straight, bent and Y-splitting) line defects in periodically corrugated surfaces of gold films are reviewed together with recent results on the SPP guiding along channels in random surface nanostructures [4]. Finally, our latest studies of guiding of long-range SPPs (at telecommunication wavelengths [5]) in periodic gold structures are presented. References: [1] S. I. Bozhevolnyi, J. Erland, K. Leosson, P. M. W. Skovgaard, and J. M. Hvam, *Waveguiding in surface plasmon polariton band gap structures*, Phys. Rev. Lett. **86**, 3008 (2001). [2] S. I. Bozhevolnyi, V. S. Volkov, K. Leosson, and J. Erland, *Observation of propagation of surface plasmon polaritons along line defects in a periodically corrugated metal surface*, Opt. Lett. **26**, 734 (2001). [3] S. I. Bozhevolnyi, V. S. Volkov, K. Leosson, and A. Boltasseva, *Bend loss in surface plasmon polariton band-gap structures*, Appl. Phys. Lett. **79**, 1076 (2001). [4] S. I. Bozhevolnyi, V. S. Volkov, and K. Leosson, *Localization and waveguiding of surface plasmon polaritons in random nanostructures*, Phys. Rev. Lett. **89**, 186801 (2002). [5] T. Nikolajsen, K. Leosson, I. Salakhutdinov, and S. I. Bozhevolnyi, *Polymer-based surface-plasmon-polariton stripe waveguides at telecommunication wavelengths*, Appl. Phys. Lett. **82**, 668 (2003).

3:30 PM W2.4

Modeling of a Surface Plasmon Polariton Interferometer. Victor Coello[1] and Sergey Bozhevolnyi[2]; [1]Unidad Monterrey, CICESE, San Nicolas de Los Garza, Nuevo Leon, Mexico; [2]Physics Institute, Aalborg University, Aalborg, Denmark.

Surface plasmon polaritons (SPPs), i.e., collective oscillations of surface charge density, represent (quasi) two-dimensional waves [1]. Associated with SPPs, there exist electromagnetic fields propagating along the (metal-dielectric) interface and exponentially decaying perpendicular to it. Therefore, these modes are strongly confined to the metal surface and exhibit an extremely high sensitivity to surface properties such as roughness and surface adsorbates. Due to their electromagnetic nature, SPPs propagating along the surface can diffract and reflect by surface features and interfere. These properties are clearly exhibited in the course of elastic (in the plane) SPP scattering. Usually, elastic scattering of SPPs and related phenomena [1] have been generated because of randomly situated defects. Nevertheless, several studies of a two-dimensional optics of SPPs based on artificially fabricated micro-components have already been reported. Thus, first examples of SPP micro-lens, micro-mirrors [2] and photonic band gap structures [3] were demonstrated. This new direction of SPP investigations has revealed several features, such as wavelength dispersion and stability (with respect to geometric parameters) of the micro-components, that have to be elucidated. One could gain more understanding in this context investigating several configurations (e.g. varying the number of single scatterers, and orientation) of a particular micro-component. This task seems to be more reliable and less time demanding when carried it out by means of numerical simulations. Here we report the results of numerical simulation of an SPP beam splitter and interferometer. The numerical approach is developed employing a vectorial model for multiple scattering by surface nanoparticles via surface polariton-to-polariton interactions [4]. We investigate in detail the overall sensitivity of the SPP beam splitter to different incidence angles of the beam, sizes (radii) of the particles, and inter-particle distances. Based on the best configuration for a 3dB SPP beam splitter, the feasibility of fabricating an interferometer was corroborated. The results obtained are in good agreement with experimental data available in the literature [5]. The combination of several SPP micro-optical elements could lead, in principle, to two-dimensional SPP optical circuits with (in general) high potential benefits for nanotechnology and nanoscience. References [1] H. Raether, Surface Plasmons, Springer Tracts in Modern Physics Vol. 111. [2] I. I. Smolanyinov, et al, Phys. Rev. Lett. 77, 3877 (1996). S.I. Bozhevolnyi and V. Coello, Phys. Rev. B. 58, 10899 (1998). [3] S.I. Bozhevolnyi, et el, Phys. Rev. Lett. 86, 3008 (2001). [4] T. Sondergaard and S.I. Bozheveolnyi, Phys. Rev. B. 67, 165405 (2003). [5] H. Dittlbacher, et al, Appl. Phys. Lett. 81, 1762 (2002).

3:45 PM *W2.5
Subwavelength Structured Optical Elements and Resonant Grating Filters. Hisao Kikuta[1], Kochi Iwata[1], Akio Mizutani[2], Hiroshi Toyota[2] and Wanji Yu[2]; [1]College of Engineering, Osaka Prefecture University, Sakai, Osaka, Japan; [2]Osaka Science and Technology Center, Izumi, Osaka, Japan.

Subwavelength structured (SWS) surfaces are attractive for new optical elements. The subwavelength structure has the following optical features: artificial refractive index, form birefringence, resonance and band-gap effects. In this presentation, after introducing some SWS elements we describe guided-mode resonant grating filters with different structures. Antireflective structured (ARS) surfaces were fabricated on a fused silica lens. To obtain a high aspect structure, a micro-disk array of chromium thin film was used as an etching mask for a high-density plasma. Because the Cr disks are etched not only from the top surface but also from the disk edges, the resultant surface profile becomes a micro-cone array with a smooth taper. We also fabricated an achromatic form-birefringent wave-plate and an array of form-birefringent wave plates. This wave plate array is used for imaging polarimetry. A guided-mode resonant grating filter is a narrow band reflection filter based on the resonance of light waves in the grating structure. We developed (1) a non-polarization filter for oblique incidence, (2) a low sideband filter with ARS surface, and (3) narrow-band filters operating in a small area. The non-polarization grating filter was realized by a two-dimensional rhombic lattice structure. The low sideband filter consists of a high-index film deposited on the ARS surface. The ARS effect suppresses the reflection of non-resonant light waves for broad spectral bandwidths. The narrow-band filter operating in a small area can be realized by a doubly periodic grating structure. A finite-width grating structure with distributed Bragg reflectors at both ends also acts as the narrow band filter. These filters will be used as non-linear optical elements because the field energy is accumulated in the finite small area.

4:15 PM W2.6
Multiband Far-Infrared Metallodielectric Photonic Crystals. Robert P. Drupp[1], Jeremy Bossard[1], Yong-Hong Ye[2], Douglas H. Werner[1] and Theresa S. Mayer[1]; [1]Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania; [2]Physics, The Pennsylvania State University, University Park, Pennsylvania.

Metallodielectric photonic crystals (MDPCs) are being investigated for use as band-reject and band-pass filters at infrared (IR) wavelengths. Traditionally, these MDPCs have been fabricated by stacking three or more layers of micron-scale metal elements with intermediate dielectric spacers to achieve resonant stop-bands with strong band rejection (> 10 dB). In this talk, we present results showing that single- and dual-band Far-IR MDPCs can be designed and fabricated with excellent rejection (>10 dB) in one or both transmission bands by patterning a single layer of fractal metallic patch elements on a thin, flexible polyimide substrate. The MDPCs that we investigated consist of arrays of single or second-stage fractal cross dipole and square metallic elements. In each case, the design dimensions were optimized using a periodic method of moments (PMM) model that incorporates dielectric and metallic loss. Single-layer arrays fabricated with second-stage fractal elements result in MDPCs with a dual-band rejection behavior, where the element dimensions and spacing determine the band-rejection frequencies and their relative attenuation. Moreover, the radial symmetry of these elements gives rise to a response that is relatively insensitive to wave polarization and angle of incidence. Single layer MDPCs with aluminum cross-dipole elements having 17 and 7 μm long primary and secondary stages were characterized using a Fourier Transform Infrared Spectroscopy. Attenuation greater than 10 dB was measured in both bands, which were centered at 46 and 17 μm. Similar results were obtained using square patch fractal metallic elements having 10 and 7 μm primary and secondary stages. These experimental results correspond well with those predicted by the PMM model that includes dielectric loss. We are currently optimizing the design of the square patch MDPC to yield stopbands in the mid-IR. We are also investigating complementary MDPC structures with band-pass response in the transmission spectrum.

4:30 PM W2.7
Thermal Conductivity by Phonon-Polaritons in Photonic Crystals and Nanoporous Media. Vitor Rafael Coluci[1,2], Anvar A. Zakhidov[2] and Vladimir M. Agranovich[3]; [1]IFGW-DFA, Universidade Estadual de Campinas, Campinas, SP, Brazil; [2]NanoTech Institute and Department of Chemistry, University of Texas, Richardson, Texas; [3]Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, Russian Federation.

It is well-known that the contribution of radiative transport by photons to thermal conductivity of majority of solids becomes important only at rather high temperatures of the order of a few 1000 K. The situation changes if the dependence of dielectric constant on frequency is accounted, which might be strong due to resonance with dipole allowed excitations of solids. In this region of spectrum the interaction of dipole active quasi-particles (such as optical phonons) with transverse photons (retardation effect) is responsible for the appearance of quasi-particles known as phonon-polaritons. Polaritons play an important role in many processes, since their mean free path and density of states are quite different from that of free photons. The emissivity of SiC (which has polaritonic gap of Δ=180 cm^{-1}) has been recently found experimentally to increase significantly, compared to that of black body radiation due to contribution of surface polaritons. In this presentation we show that bulk phonon-polaritons can significantly change the thermal conductivity temperature dependence K(T) both for diffusive and ballistic propagation of polaritons. At low-T a peak appears in the thermal conductance compared to bulk photon contribution, due to increased density of states below polaritonic gap Δ. On the other hand, for thermal transport at high T, the T-dependence becomes much stronger than T^3 of free photons, due to dependence of mean free path on frequency. Moreover if the polariton is propagating in nanoporous media, like photonic crystal the thermal conductivity may have even more pronounced changes in so called "Braggariton" bands, where polariton gap coincides with photonic band gap (PBG) due to periodicity. The calculations of K(T) for SiC and MgO nanostructured solids demonstrate how K(T) can be engineered by the width and relative positions of Δ and PBG.

4:45 PM W2.8
Hexagonal lattice photonic crystal in active metallic microcavity. Hoi Lam Tam[1], Rupert Huber[3], King Fai Li[1], Polis W H Wong[2], Yue-Bun Pun[2], Shu Kong So[1], Jian Bai Xia[1] and Kok Wai Cheah[1]; [1]Physics, Hong Kong Baptist University, Hong Kong, Nil, China; [2]Electronic Engineering, City University of Hong Kong, Hong Kong, Nil, China; [3]Physics, Munich James-Franck-Strasse, Munich, Nil, Germany.

A hexagonal lattice photonic crystal was fabricated inside the metallic microcavity. And a thin film of Alq3 was incorporated inside the textured cavity as a active medium. The microcavity is designed such that the modified photonic modes due to the textured structure can couple to the excited electronic states of Alq3. This leads to changes in the emission characteristics of Alq3. From the angular transmission results, the photonic bandgap was observed at all angles from normal incident to 60°. The presence of surface plasmon was observed in both TM and TE modes of the transmission. Compare to the bulk Alq3 photoluminescence spectrum, significant modification of the photoluminescence spectrum was observed in the angle-resolved photoluminescence. The photoluminescence spectra showed clear suppression in luminescence intenisity for the range inside the photonic bandgap. We use decouple approximation for the standing wave modes and derive the photonic waveguide characteristics for two-dimensional textured metallic microcavities. The theoretical result is in good agreement to the experimental result.

SESSION W3: Photonic Crystals I
Chair: Jean-Michel Lourtioz
Wednesday Morning, December 3, 2003
Room 204 (Hynes)

8:30 AM *W3.1
3D photonic crystals based on macroporous silicon. Joerg Schilling[1], Axel Scherer[1], Gary W Stupian[2], Reinald Hillebrand[3], Ulrich Goesele[3], Ralf B Wehrspohn[4] and Stephen W Leonard[5]; [1]California Institute of Technology, Pasadena, California; [2]The Aerospace Corporation, Los Angeles, California; [3]Max-Planck-Institute of Microstructure Physics, Halle, Germany; [4]Department Physik, Universitaet Paderborn, Paderborn, Germany; [5]NovX Systems Inc., Markham, Ontario, Canada.

The high aspect ratio and the large refractive index contrast of macroporous silicon make this material a perfect candidate for the fabrication of 3D photonic crystals if a periodic refractive index change along the direction of the pore axis is additionally introduced. One way to achieve this is by periodic modulation of the pore diameter. Combined with a 2D triangular pore pattern, the resulting structure represents a 3D photonic crystal and the pore diameter modulation leads to a bandgap along the pore axis in the mid infrared. Introducing a straight section of the pores represents a defect layer and causes defect resonances in transmission within the gap. For a thorough understanding of the shown polarization dependence of the bandgap and the defect mode positions, the specific pore shape has to be considered. The slight quadratic pore cross section reduces the symmetry of the 3D lattice to an orthorhombic one and degeneracies are therefore lifted. A complete 3D-bandgap was predicted for overlapping air spheres in silicon which are arranged in a simple cubic lattice. Such a structure can be obtained when the modulated pores are arranged in a 2D quadratic lattice and the pores are later chemically widened to obtain the interconnected network of air spheres. Bandstructure calculations show a complete 3D gap with a maximum width of 3.8%. Recently a totally new structure was proposed consisting of the original electrochemically etched hexagonal arranged straight pores and a second hexagonal pore set orthogonal to it. The resulting interpenetrating 3D network of air pores in silicon represents a 3D photonic crystal with tetragonal unit cell. A gapmap for different porosities was determined and revealed a maximum gapsize of 25% . The structure can be realized by drilling the second pore set with a focused ion beam. First experimental results are shown and demonstrate the obtained highly regular 3D structure. The structure parameters fulfill the requirements for the mentioned large photonic gap in the near infrared region around a wavelength of $1.3\mu m$ wavelength.

9:00 AM W3.2
Periodically Arranged Point Defects in a Twodimensonal Photonic Crystal - The Photonic Analogue to a Doped Semiconductor. Stefan Richter, Stefan L. Schweizer, Cecile Jamois, Ralf Boris Wehrspohn, Margit Zacharias and Ulrich Goesele; Exp. Dept. 2, Max Planck Institute of Microstructurephysics, Halle, Germany.

The concept of a photonic crystal is the optical analogue to a semiconductor. The generated dispersion relation for photons corresponds to the bandstructure for electrons and determines the existence of photonic states within the photonic crystal. The introduction of defects to the photonic crystal therefore creates additional states within the photonic bandgap. These defect states allow spatial confinement and guiding of light. We present studies on hexagonal point defects in a twodimensional photonic crystal consisting of macroporous silicon. These point defects are prepatterned periodically by lithography and form a superstructure within the photonic crystal. Optical investigations related to their morphological properties (like pore radius and defect concentration) are compared to bandstructure and local density of states (LDOS) calculations. The confined defect states were identified and their quality factors were also estimated to evaluate the interaction between adjacent point defects. To investigate the influence of the cavity on internal light emitters, colloidal HgTe quantum dots were infiltrated into single cavities and their emission was measured by photoluminescence spectroscopy.

9:15 AM W3.3
Jahn-Teller Effect in Two-Dimensional Photonic Crystals. Natalia Malkova, Sungwon Kim and Venkatraman Gopalan; The Pennsylvania State University, Materials Research Institute, University Park, Pennsylvania.

The Jahn-Teller effect in photonic crystals as a prototype of photon-phonon interactions is studied. We are interested in removing the degeneracy of a defect state due to coupling with vibronic mode. Two-dimensional square photonic lattice of the dielectric rods in vacuum doped by the defect rod, giving the doubly degenerate E state in the first TM band gap is studied. We showed that coming from the Jahn-Teller theorem, the lattice vibration with the symmetry of B_1 and B_2 modes should result in splitting the degeneracy of the E photon state, the lattice vibration being frozen. The stable configuration in the presence of the Jahn-Teller effect is determined from the dependence of the energy as a function of the rod displacement. Using the value of the vibronic constants, obtained from the suppercell plane wave calculations and the Finite Difference Time Domain simulations, we find the stable configuration of the lattice. We discuss the conditions to observe the effect.

10:00 AM W3.4
New Si-based Waveguide with Photonic Band Gap Dielectric Cladding Layers. Yasha Yi, Shoji Akiyama, Kazumi Wada, Jurgen Michel, Xiaoman Duan and L. C. Kimerling; Massachusetts Institute of Technology, Cambridge, Massachusetts.

A new type of silicon waveguide- PBG cladding waveguide is developed based on Photonic Band Gap (PBG) principle. The light in the core of the waveguide is confined by PBG mechanism, in contrast to the total internal reflection (TIR) mechanism, which requires higher index materials in the core of the waveguide. The refractive index in the new PBG cladding waveguide core, therefore has a large flexibility. Low index core (e.g. SiO2) or hollow core waveguide can be realized with our PBG cladding waveguide structure. Sharp bend of this kind of waveguide is possible due to the PBG confining mechanism. The PBG waveguide can be designed as slab waveguide, ridge waveguide, and channel waveguide with low index core (SiO2 or air), which is surrounded by high index contrast dielectric cladding pairs (Si/SiO2 or Si/Si3N4). The waveguide is compatible to CMOS process. Potential applications include optical amplifier when doped with optical active materials (e.g. Er) for SiO2 core, optical switching or optical modulator when electro-optic or thermo-optical fluids are injected to the hollow core, integrated optics, as well as new physics based on PBG cladding waveguide.

10:15 AM *W3.5
Functinal Optical Devices Based on Highly Ordered Anodic Porous Alumina. Hideki Masuda, [1]Applied Chemistry, Tokyo Metropolitan University, Tokyo, Japan; [2]Kanagawa Academy of Science and Technology, Kanagawa, Japan.

Optical properties of ordered structures with a two-dimensionally (2D) periodic index of refraction have recently attracted growing interests, because such periodic structures display a stop band in their electromagnetic transmission properties, and have potential applications for the design of novel optoelectronic devices. We describe here the results of the fabrication of highly ordered anodic porous alumina and its application to optical devices. Anodic porous alumina, which is formed by anodization of Al in acidic solution, consists of ordered triangular array of holes with high aspect ratios in alumina matrix [1]. The combined process of a pretexturing treatment of Al and an appropriate anodizing condition generates the ideally arranged configuration of the hole-array in alumina matrix [2]. Anodic porous alumina with ideally ordered hole arrays is a promising candidate for two-dimensional (2D) photonic band-gap materials, due to the highly ordered periodic structure. Anodic porous alumina with an ideally ordered air-hole array with a 200 nm to 250 nm lattice constant exhibits a 2D photonic band gap in the visible wavelength region [3,4]. Anodic porous alumina with highly ordered hole-array architectures can also be used as a starting material for nanofabrication. Examples of replication processes for metal and semiconductor hole arrays using ordered anodic porous alumina as a starting structure will be also reported. [1] H.Masuda and K.Fukuda, Science, 268, 146 (1995). [2] H.Masuda et al., Appl. Phys. Lett., 71, 2770 (1997) . [3]H.Masuda et al., Jpn. J. Appl. Phys. 38 , L1403 (1999). [4]H.Masuda et al., Jpn. J. Appl. Phys. 40, L1217 (2001).

10:45 AM W3.6
Three-Dimensional Lithography for Rutile TiO2 Single Crystals using Swift Heavy Ions. Koichi Awazu[1], Makoto Fujimaki[2], Nagasawa Yoshihiro[2] and Yoshimichi Ohki[2]; [1]CAN-FOR, AIST, Tsukuba, Ibaraki, Japan; [2]Waseda University, Waseda University, Shinjyuku, Tokyo, Japan.

Recently, many researchers have studied photonic crystals using conventional semiconductor manufacturing. One of the most conventional methods to obtain micro-structures must be the reactive ion etching (RIE), however, roughness and ripple pattern on the side wall of micro-structures, RIE-lag, and etch stop have been frequently observed. We have examined the structure of latent track introduced in solids by the swift heavy ion. [1] In the present paper, we have developed a nano-micro structure fabrication method in rutile TiO2 single crystal by use of swift heavy-ion irradiation. In the method, we have utilized a good etching selectivity induced by the ion irradiation. The area where ions heavier than Cl ion accelerated with MeV-order high energy were irradiated was well etched by hydrofluoric acid, by comparison etching was not observed in the pristine TiO2 single crystal. Noticed that the irradiated area could be etched to a depth at which the electronic stopping power of the ion decayed to a value of 6.2keV/nm. In other words, etching was not observed in TiO2 single crystal received the electronic stopping power below the threshold value of 6.2keV/nm. We also found that the value of the electronic stopping power was increased, eventually decreased against depth in TiO2 single crystal with, e.g. 84.5MeV Ca ion. Using such a beam, inside of TiO2 single crystal was selectively etched with hydrofluoric acid, while the top surface of TiO2 single crystal subjected to irradiation was not etched. At a glance, air gap was created in the region of 4-8micron from the top surface subjected to irradiation of 84.5MeV Ca ion followed by etching. Roughness of the new surface created in the single crystal was within 7nm with the atomic forth microscopy measurement. The X-ray diffraction and high-resolution electron microscope analyses indicated that the irradiated area was composed from amorphous and the stressed rutile phases, both phases were well dissolved in 20% hydrofluoric acid. In conclusion, it was successful to fabricate 3-dimensional structure with nano-order smooth surface by use of this technique. This methods also makes it possible to fabricate rutile TiO2 plates thinner than a few micron with nano order flatness, which has been difficult by the conventional methods. Our method will be available for the processing of solar cells, photonic catalysts, or photonic crystals, which require nano-fabrication technique.[2] *Corresponding author: k.awazu@aist.go.jp [1] K. Awazu, S. Ishii, K. Shima, S. Roorda, and J. L. Brebner, Phys. Rev. B 62, 3689 (2000). [2] K.Nomura, T.Nakanishi, Y.Ohki, K.Awazu, M.Fujimaki, Phys. Rev. B (in press).

11:00 AM W3.7
Abstract Withdrawn

11:15 AM W3.8
Thermal Conductivity of Inverse Opal Photonic Crystals.
Ali E. Aliev, S. B. Lee, P. London, A. A. Zakhidov and R. H. Baughman; NanoTech Institute, The University of Texas at Dallas, Richardson, Texas.

The thermal conductivity of various inverse opal photonic crystals (PC) has been measured in the temperature range of 10-400 K using transient pulse method and compared with that of homogeneous bulk parent materials. Inverted opal PCs with lattice constants of 200, 300, 450 and 800 nm with different filing factors have been fabricated by templating of porous silica opals with different materials: CVD graphite, pyrolitic amorphous carbon, epoxy resin, bismuth and other metals. The suppression of thermal conductivity in periodic nanostructures of empty spheric shells of inverted opals is compared with analogous effect in the periodic arrays of spheres, i.e. in direct opal PCs. The case of surface templated PC is analyzed separately. So in case of graphitic thin wall PC the thermal current flow through 100-angstrom-thick layers of graphite sheets tiled on spherical surfaces of empty overlapping spheres arrayed in face-centered-cubic lattices has been analyzed in terms of the anisotropy factor. Taking into account high anisotropy factor in graphite, $\gamma = 175$, we found that the thermal conductivity of inverse opal is limited by heat flow across the graphitic layers in bottleneck, ~5.8 W/mK. The electronic contribution to the thermal conductivity, $\lambda_{e(300K)} = 3.7{\cdot}10\text{-}3$ W/mK is found to be negligibly small compared to the measured value of total thermal conductivity, $\lambda_{(300K)} = 0.38$ W/mK. The effect of filling the porous matrix of inverted opals with various liquids on their thermal conductivity and diffusivity is also studied.

11:30 AM W3.9
Optical and Crystallographic Properties of Inverse Opal Photonic Crystals Grown by Atomic Layer Deposition.
Jeffrey Stapleton King[1], C Neff[1], D Heineman[1], S Blomquist[2], E Forsythe[2], D Morton[2], E Graugnard[1] and C Summers[1]; [1]Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Army Research Laboratory, Adelphi, Maryland.

We report a new technique for the formation of inverse opal structures that produces high quality, low porosity conformal material structures. Monodispersed silica spheres of sizes 150 - 460 nm were used to make (111)-oriented 20 mm thick opal films by settling the spheres in a modified confinement cell[1], followed by sintering. High index material was deposited within the void space of the opal lattice by atomic layer deposition. Infiltrations of ZnS:Mn, ZnS, and TiO^2 were studied, with conventional precursors used for the deposition. Growth temperature and pulse cycle lengths were modified for improved infiltration. The resulting structures were etched using HF to remove the silica spheres, forming an inverted opal. Following deposition, both the infiltrated and inverse opals were characterized by SEM, XRD, photoluminescence and transmission/reflection spectroscopy. The reflectance spectra exhibited features corresponding to strong low and high order photonic band gaps in the (111) direction (G-L). For ZnS:Mn, average filling fractions of the interstitial volumes were found to be > 90%, calculated from the (111) band gap positions using Bragg's law. In addition, partial ZnS infiltrations of 27% and 57% have been performed, corresponding to 2 nm and 5 nm films, respectively. TiO^2 films deposited at 100° C were amorphous and films deposited at 500° C were primarily anatase as confirmed from X-ray studies. The effectiveness of a post-deposition heat treatment for converting these films to rutile was studied, since the rutile phase exhibits a higher refractive index than anatase. Multi-layered infiltrations are currently being studied, as well as angular dependent photoluminescence of the ZnS:Mn structures. 1. B.Gates, Y.Yin, Y.Xia, Chem. Mater. 1999, 11, 2827-2836.

11:45 AM W3.10
Ionic Colloidal Crystals: Attractive Ordered Binary Colloidal Assemblies through Controlled Heterocoagulation.
Garry R Maskaly[1], R. Edwin Garcia[2], W. Craig Carter[1] and Yet-Ming Chiang[1]; [1]Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts; [2]Materials Science and Engineering Laboratory Office, National Institute of Standards and Technology, Gaithersburg, Maryland.

Ionic colloidal crystals (ICCs) are here defined as ordered multicomponent colloids formed by attractive electrostatic interactions. Compared to previous approaches to colloidal crystallization, the ICC approach holds the potential for the rapid self-assembly of a wide range of structures similar to that seen in ionic compounds naturally. These structures are difficult or impossible to produce by other methods. Of particular interest is the zincblende structure, which has been theorized to have a complete photonic band gap. In this work, the conditions under which ICCs are stable have been theoretically predicted. A model is presented in which dimensionless parameters are found to fully characterize the thermodynamics of an ICC system. We calculate the Madelung constant for ICCs of several classical ionic crystal structures as a function of these two parameters, and discuss the parallels between the Madelung constants of ICCs and classical ionic crystals. Experimentally accessible regions of surface charge, particle sizes, ionic strength, and temperature where ionic colloidal crystallization is possible are identified. Furthermore, we believe we have produced the first binary ICCs through the ordered heterocoagulation of colloidal mixtures of silica (negative surface charge) and polystyrene functionalized with amidine (positive surface charge) suspended in 2-propanol. Experimental conditions predicted by the theory have been implemented to obtain heterocoagulation of these particles into the rocksalt structure. To our knowledge, this is the first experimental demonstration of an ICC. The importance of various experimental parameters to ICC formation is illustrated through particle dynamics simulations and experimental results.

SESSION W4: Plasmonics II
Chair: Sergey Bozhevolnyi
Wednesday Afternoon, December 3, 2003
Room 204 (Hynes)

1:30 PM *W4.1
New Lenses for Imaging the Near Field. John Pendry, Physics, Imperial College London, London, United Kingdom.

Recently it has been shown how a slab of negatively refracting material can focus sub wavelength images. This result can be extended to a much wider class of structures including cylinders, spheres, and intersecting planes. We introduce the powerful technique of coordinate transformation to map a known system into an equivalent system.

2:00 PM W4.2
Experimental Study of Near-Field Imaging Using Planar Silver Films. Pieter G Kik, Stefan A Maier and Harry A Atwater; Thomas J. Watson Laboratory of Applied Physics, Caltech, Pasadena, California.

It has been predicted that thin metal films may be used to generate images with a spatial resolution better than the diffraction limit. We present near-field scanning optical microscopy (NSOM) experiments that study near-field focusing with planar metal films. Our previous finite-difference simulation studies suggest that near-field focusing with planar metal films can be experimentally achieved using a 60 nm thick Ag-Si_3N_4 bilayer. In particular, we have shown that placing a finite-linewidth oscillating point dipole source near the nitride surface of such a bilayer can induce a coherent superposition of surface plasmons at the silver/nitride interface, resulting in a narrowed electric field distribution in the image plane directly behind the bilayer. The electric field distribution was found to be narrowed by a factor 2 when the interface was excited at the surface plasmon resonance. To experimentally verify these predictions we have deposited 30 nm thick silver films onto freestanding 30 nm-thick silicon nitride films. Silver depositions were performed at liquid nitrogen temperature to prevent dewetting of the silver. The resulting freestanding Ag-Si_3N_4 bilayers support localized surface plasmons at the silver-nitride interface when excited at a frequency of 4.73×10^{15} rad/s, corresponding to a free-space wavelength of ~400 nm. To generate an oscillating local dipole source near the surface, we couple 400 nm laser light into the fiber (coupled power ~10 mW) and bring the tip in contact with the nitride film. The tip can excite surface plasmons at the Ag-Si_3N_4 interface which in turn results in the formation of an image of the tip behind the Ag film. To detect the presence of the image, we have deposited 40 nm diameter Ag nanoparticles on the silver film. These particles act as local scatterers in the image plane. By monitoring the transmitted intensity as a function of tip position, we are able to evaluate the image resolution. In this way we have been able to detect Ag nanoparticles located at a distance of ~80 nm from the NSOM tip aperture with a resolution better than 60 nm. We believe that this is the first direct experimental evidence of near-field imaging using planar metal films.

2:15 PM W4.3
Near and Far Field Diffuse Scattering From Imperfect Periodic Dielectric/Conducting Media. Ricky Lamar Moore, [1]STL, Georgia Tech Research Institute, Atlanta, Georgia; [2]GTRI, University, Atlanta, Georgia.

Composition and geometry in periodic, dielectric and conducting structures, yields spectral control of the specular transmission and reflection coefficient of a composite. Two measurements of specular reflection and/or transmission are used to predict the effective permittivity and permeability of the composite and such analysis leads to anomalous index (e.g. negative) values. In this paper, we present analysis of changes in the near and far zone scattered field which arise due to constitutive or geometric errors within a unit cell of a periodic composite. Photonic crystals, fractured/patterned conducting films, and 3d arrays of conducting elements display intense electromagnetic field localization. Thus small formulation errors may have abnormally large impact on the transmitted and or reflected fields. Simulations apply two methodologies. First a variational model is presented where small perturbations in the unit cell are represented by perturbation in the electromagnetic near field that then lead to diffuse scattering and modified specular transmission and reflection. A second analysis presents exact computational finite difference time domain and method of moment calculations for diffuse and specular reflection and transmission of finite dimension and planar periodic crystals (both dielectric and conducting) that have small constitutive and/or geometric errors in the unit cell. Variations in local and far field transmissions are applied to infer expected error bars in measurement of similar materials. We conclude the article with comparisons of near field probe and far field diffuse and specular reflection for periodic structures in the RF spectrum and compare those measurements of prediction. Research Supported by the Office of Naval Research, N00014-01-1-0303 and the MetaMaterials Program through AFRL/ MLBP Contract F33615-01-C-5023.

3:00 PM *W4.4

Local Investigation of Light Propagation in Photonic Crystals. Laurens Kuipers, Nanophotonics group, FOM Institute for Atomic and Molecular Physics, Amsterdam, Netherlands.

Photonic crystals are a class of artificial composite dielectric materials that enable a huge control over light. One of the powerful aspects of photonic crystals is the strong dependence of their optical properties on (local) geometry. It is this property that can be exploited to generate integrated optical circuits based on carefully engineered defects in the overall perfectly periodic structure. It is immediately obvious that small variations in the geometry, intended or not, can have large consequences. A tool that can investigate both the flow of light and the geometry simultaneously is therefore highly desireable. A near-field optical microscope can do exactly that. Here, we will present local measurements of light in photonic crystals. A unique pulse tracking photon scanning tunneling microscope is used to study the phase evolution and pulse propagation of light inside planar photonic crystals. In addition, it will be shown for the first time that the coupling of light in the so-called near-field from a pointlike light source to a photonic crystal is spatially dependent and also depends on the normalized frequency of the coupled light.

3:30 PM W4.5

Photonic crystal nanocavity modes probed by near-field scanning optical microscopy. Koichi Okamoto, Marko Loncar, Tomoyuki Yoshie and Axel Scherer; Electrical Engineering, California Institute of Technolog, Pasadena, California.

Near-field scanning optical microscopy (NSOM) is a powerful alternative method to observe the optical intensity distributions in fabricated nanophotonic structures. Several groups have obtained NSOM images of planar photonic crystal (PPC). However, high spatially resolved near-field images of the field distribution inside the PPC nanocavity have not so far been reported. Here, we show the smallest optical mode profiles obtained by NSOM on high-quality (Q) factor PPC nanocavities. The PPC nanocavities were fabricated in active InGaAsP quantum well materials. High-Q cavity modes are defined by fractional-edge dislocations in triangular lattice PPC structures with different defect air hole sizes (r'), at the position of maximum field intensity. The r'/a parameters were changes from 0 to 0.18 (a: periodicity of the lattice). We have measured Q factors of Q=2,000 and realized laser action with low threshold of 220 microWatt in the design with r'/a=0.18. On the other hand, Q factors, for the designs of no central defect hole (r'/a=0), are limited to about 1000, according to our theoretical predictions. For the NSOM measurement, we used the metal-coated fiber tip with small aperture size (150nm) to distinguish between localized cavity modes and propagating far-field modes, and to obtain more precise mode profiles. A He-Ne laser (633nm) and a diode laser (780nm) were used as cw excitation laser sources. Photoluminescence (PL) signals were filtered out to suppress pumping laser signals, and were detected with a high-sensitivity (fW) InGaAs photo-detector. We confirmed that the PPC nanocavities have only high-Q localized modes in the QW emission range by micro-photoluminescence. This way, we could observe NSOM-PL images of localized defect modes in these PPC nanocavities. The bright spots were found in NSOM-PL images located at the center of the PPC structures, matching the positions of the defect cavities. The small spots indicate that, indeed, the modes have small mode volumes as expected from our modeling. The size of the bright spot, probed from the nanocavity with r'/a=0, was roughly four by three lattice spacing. On the other hand, spot size in nanocavity with r'/a=0.18 was as small as center hole size and exhibited the high spatially resolved optical mode profile around the center hole. The NSOM images were very similar with mode profiles obtained by our three-dimensional finite difference time domain (FDTD) modeling. To the best of our knowledge, this is the first experimental observation of the smallest optical mode profiles in PPC nanocavities.

3:45 PM W4.6

Very large plasmon band shift in strongly coupled metal nanoparticle chain arrays. Luke A. Sweatlock[1], Stefan A. Maier[1], Joan J. Penninkhof[2], Albert Polman[1,2] and Harry A. Atwater[1]; [1]Thomas J. Watson Laboratories of Applied Physics, California Institute of Technology, Pasadena, California; [2]FOM Institute for Atomic and Molecular Physics, Amsterdam, Netherlands.

Noble metal nanoparticles interact strongly with light at the resonance frequency of a coherent electron oscillation, or plasmon, within the particle. When arranged in closely spaced arrays, in which the spacing d is smaller than the wavelength λ, such particles couple to one another via electromagnetic near-field interaction. These coupled arrays exhibit collective plasmon modes, which may vary significantly from that of a single particle. A promising application is the construction of waveguides and other optical devices for visible or near-infrared frequencies. Previously we have investigated sub-diffraction limit energy confinement and pulse propagation in relatively large linear arrays of, e.g., 50 nm diameter particles with center-to-center spacing of 75 nm. In this arrangement, the dipole component of the near field dominates particle interactions. Practically, the distance for power transfer in these structures is limited by an $1/e$ energy attenuation length on the order of a few particle spacings. To address the challenge of realizing energy transfer over a larger number of particle spacings, we consider increasing the interaction strength between neighboring particles by reducing the particle size and spacing. Here, we discuss the optical properties of very closely spaced arrays of 10 nm silver particles with 12 nm center-to-center distance. In this regime higher order multipole mode excitation plays an important role. We determine via finite difference time domain (FDTD) simulation the plasmon mode spectrum as a function of incident polarization and of the particle array length. These FDTD results are compared to experimental far field extinction of semi-ordered nanoparticle arrays of similar dimension, which we have fabricated by high energy ion irradiation of silver doped glass. A red shift of the plasmon extinction peak of greater than 1 eV is observed experimentally in these samples, which is about 5 times greater than observed arrays of 50 nm particles fabricated by electron beam lithography. Such strong coupling is expected to improve plasmon waveguiding performance by reducing the energy attenuation per particle. Furthermore the very small interparticle spacing leads to an increase in local subwavelength field enhancement, an important parameter for the design of active devices. Strategies for well-controlled fabrication of very small particles in isolated chain arrays will be presented.

4:00 PM W4.7

Angular Roll-Off Dependence Of Spectral Emission From A Metallodielectric Photonic Crystal. Irina Puscasu[1], Martin U. Pralle[1], Mark P. McNeal[1], Nicholas Moelders[1], Anton C. Greenwald[1], Alan Ludwiszewski[1], James T. Daly[1], Edward A. Johnson[1] and William L. Schaich[2]; [1]Ion Optics Inc., Waltham, Massachusetts; [2]Indiana University, Bloomington, Indiana.

We are reporting on the analysis of a new design for a thermal source exploiting Si-based suspended micro-bridge structures. A device consists of a metal film perforated by a periodic array of apertures extending into the Si substrate and each of size on order of the wavelength of the light. This perforated film permits resonant coupling of the incident radiation from the underlying silicon photonic crystal with surface plasmons at the metal surface. The coupling provides for unusually high optical emission efficiencies when the structure is thermally excited. The radiation emitted exhibits an enhancement over a narrow wavelength range in the infrared and its spectral response is highly dependent on the direction of observation. The positions of the main resonances, for both reflection and emission from our structures, scale linearly with the periodicity of the metallodielectric structure. As one moves off normal incidence, a single main resonance splits into several smaller resonances whose locations scale roughly linearly with observation angle. Theoretical analysis of the spectral response using the finite-difference time-domain method (FDTD)shows good agreement with the experimental data and gives insight into the physical mechanisms responsible. These structures have been used as emitter/detector sensor chips to selectively detect industrial pollutants like carbon dioxide. Control of the wavelength of resonance, bandwidth and direction of emission play an important role in improving the sensitivity and selectivity of these gas sensors.

4:15 PM W4.8

Standing Wave Reflectivity in Photonic Structures Using a Scattering Type Optical Near-Field Optical Microscope. Aurelien Bruyant[1], Sebastien Aubert[1], Gilles Lerondel[1], Sylvain

Blaize[1], Renaud Bachelot[1], Pascal Royer[1] and Vincent Minier[2]; [1]Laboratoire de Nanotechnologie et Instrumentation Optique, TROYES, France; [2]Groupement Electromagnetisme Experimental et Optoelectronique, Meylan, France.

We report a new method for directly measuring the complex reflection coefficient spectrum in photonic structures. The latter is obtained by imaging the standing wave pattern upstream of the structure. We performed this study on a corrugated integrated waveguide using a scattering type optical near-field microscope. Thanks to an interferometric effect between guided modes and losses, the scanning near-field optical microscope allows an absolute measurement of the reflection coefficient by simple fourier analysis.

4:30 PM W4.9
Near-field photoluminescence spectroscopy of microcavities and coupled microcavities. Oleg Vadimovich Lebedev, Anton Igorevich Maidykovski, Irina Soboleva and Oleg Andreevich Aktsipetrov; Physics, MSU, Moscow, Russian Federation.

Photoluminescence spectroscopy of porous silicon photonic crystal microcavities and coupled microcavities is studied by the far-field and near-field probes using the apertureless scanning near-field optical microscope. Narrow microcavity mode with the spectral width of 10nm in far-field spectra and broad photoluminescence peak with the spectral width of 50nm in near-field spectra of microcavity samples is observed. Near-field spectra of coupled microcavities are consisted of two microcavity mode. To increase the photoluminescence signal photonic crystal microcavities and coupled microcavities are doped by fluorescence dye. The enhancement of photoluminescence at microcavity mode wavelength of doped samples is observed using near- and far-field spectroscopy. Dye molecules of Rhodamin B, Rhodamin 6G, Nile Blue with different concentrations are used. Maximum of photoluminescence response for microcavity with the mode of 580 nm is obtained for Rhodamin 6G molecules. Photoluminescence signal of doped microcavity structures is enhanced by two orders of magnitude with respect to dye free microcavity structures. The embedded dye molecules shift microcavity modes to red range of optical spectra on 40 nm. Porous silicon shifts maximum of fluorescence of dye molecules to blue range of optical spectra on 50 nm. Homogeneous distribution of dye in the bulk of the sample is achieved, as the molecule size is essentially smaller than the size of pores. Near-field and far-field spectra of microcavity doped by dye are substantially different: strong and broad with the spectral width of 40nm photoluminescence peak in near-field spectra corresponding to the photoluminescence peak of dye resonantly enhanced by microcavity doped by dye is observed.

SESSION W5: Poster Session
Chair: Joerg Schilling
Wednesday Evening, December 3, 2003
8:00 PM
Exhibition Hall D (Hynes)

W5.1
Monodispersed Spherical Colloids of Titania: Synthesis, Characterization and Crystallization. Xuchuan Jiang and Younan Xia; Chemistry, Univ. of Washington, Seattle, Washington.

We have demonstrated a simple and convenient process for the large-scale synthesis of monosized spherical colloids of titania with a controllable diameter ranging from 200 to 500 nm. These monodispersed colloidal spheres were successfully prepared without any assistance of surface modifiers by controlling the hydrolysis of titanium glycolates in acetone at room temperature. These uniform spheres could self-assemble into 3D crystals with interesting optical properties. After calcinating these monodispersed colloids at elevated temperatures, different phases of titania (amorphous, anatase and rutile) were obtained without changing their original morphologies. As one of the most important ceramics and oxide semiconductors, titania has found many applications as catalysts, photoconductors, and nonlinear optical materials. In this paper, we will present the synthesis and characterization (using spectroscopic and electron microscopic techniques) of these monodispersed colloids, as well as their self-assembly into photonic crystals.

W5.2
Photonic Quasiperiodic Multilayers of Porous Silicon. Rocio Nava[1], J. Antonio Del Rio[2], Chumin Wang[1] and Vivechana Agarwal[3]; [1]Instituto de Investigaciones en Materiales, UNAM, Mexico, D. F., Mexico; [2]Centro de Investigacion en Energia, UNAM, Temixco, Morelos, Mexico; [3]Centro de Investigacion en Ingenieria y Ciencias Aplicadas, UAEM, Cuernavaca, Morelos, Mexico.

Porous silicon is an efficient photo- and electro-luminescence material and represents a promising candidate for opto-electronic applications. Furthermore, a high enough refractive index contrast in porous silicon multilayers can be obtained and it could be used to design ultra narrow band pass filters when a quasiperiodic sequence is introduced. In this work, we study the light transmission in Fibonacci multilayers made of porous silicon. The theoretical reflectance spectra are compared with experimental data, observing a good agreement, even though they are extremely sensitive to the preparation conditions when the number of quasiperiodic layers increases. Changes in the optical path length through the multilayers and the wave length dependence of the refractive index affect mainly the high frequency region of the spectra. Finally, the effects of the quasiperiodic structures on the photoluminescence spectra are also analyzed.

W5.3
Optical Properties of Dielectric and Magnetic Photonic Crystals in the Low-Frequency Limit. Arkady Krokhin[1,2], Jesus Arriaga[1] and Reyes Edgar[1]; [1]Instituto de Fisica, Universidad Autonoma de Puebla, Puebla, Pue., Mexico; [2]Center for Nonlinear Science, University of North Texas, Denton, Texas.

Periodic composites, photonic crystals, behave like homogeneous medium if the wavelength exceeds the period of the structure. The problem of calculation of the effective parameters (e.g. speed of sound) of an inhomogeneous medium has a long history, starting from the pioneering work of Maxwell-Garnett (1904). Exact analytical results are very rare and most of the works use different approximations. In a series of papers [1-4] we demonstrate that the problem of homogenization of a two-dimensional dielectric photonic crystal can be solved exactly and obtain explicit formulas for the effective dielectric constants. These formulas are valid for arbitrary cross-section of the cylindrical inclusions, Bravias lattice, and filling fraction. We introduce the index ellipsoid for 2D photonic crystals and demonstrate that the conventional classification of natural crystals (uniaxial and biaxial) is applicable for dielectric photonic crystals as well. However, recently we have obtained that it is not the case for the magnetic photonic crystals, i.e. for the structures possessing magnetic permeability. Natural crystals are characterized by three principal dielectric constants only since their atoms are magnetically isotropic with respect to the electromagnetic field of the propagating wave ($\mu_{ik} = \delta_{ik}$). Magnetic photonic crystals possess magnetic anisotropy and we calculated the effective index of refraction that depends on the direction of propagation, electric susceptibility and magnetic permeability of the constituents. Both eigenmodes with TM- and TE- polarizations turn out to be extraordinary even in a geometry of the unit cell that would correspond to uniaxial natural crystal. Magnetic photonic crystals exhibit unusual optical properties that do not exist for natural crystals. In particular, magnetic photonic crystal may be a crystal without optical axis at all and exhibit an unusual form of birefringence. This work is supported by CONACyT, grant No. 42136-F. 1. P. Halevi, A.A. Krokhin, and J. Arriaga, Phys. Rev. Lett. 82, 719 (1999). 2. P. Halevi, A.A. Krokhin, and J. Arriaga, Appl. Phys. Lett. 75, 2725 (1999). 3. P. Halevi, A.A. Krokhin, and J. Arriaga, Phys. Rev. Lett. 86, 3211 (2001). 4. A.A. Krokhin, P. Halevi, and J. Arriaga, Phys. Rev. B 65, 115208 (2002).

W5.4
Ferroelectric Based Photonic Crystals: New Route to Electrically Tunable Photonic Band Gap. Ji Zhou and Bo Li; Department of Material Science & Engineering, Tsinghua University, Beijing, China.

A scheme for tuning the photonic band gap (PBG) by an external electric field in a ferroelectric inverse opal structure was proposed and presented. Inverse opals consisting of ferroelectric (Pb,La)(Zr,Ti)O3 (PLZT) ceramics were synthesized by sol-gel process using synthetic opals as template. Optical reflection spectra show that the PBG of the PLZT inverse opals shifts continuously with the change in the applied electric field. The mechanism is based on the electric field dependence of refractive index associated with the electro-optic effect in the PLZT ferroelectrics. The tunable PBG in PLZT inverse opals—as an "all solid" structure — should be of high interest in device applications.

W5.5
FDTD Modeling of The Emission of Surface Plasmon Jets. Michael I Haftel, Center for Computational Materials Science, Naval Research Laboratory, Washington, District of Columbia.

Recently Blumberg et al. [1] directly observed, in near-field scanning optical microscopy experiments, the emission of surface plasmon (SP) jets when light of the appropriate frequency and incidence angle interacts with an aperture nanoarray on a gold film. This work demonstrated the ability to manipulate the direction and intensity of the SP jets by varying the experimental conditions (wavelength, incidence angle, etc.), as well as the reconversion of surface plasmons to freely propagating light. We employ the NRL HASP (FDTD) code to simulate the electromagnetic fields produced in this experiment. Surface plasmons are evidenced in the simulation as regions of enhanced electromagnetic field intensity confined to the surface region and propagating in specified directions in the plane as well as in the characteristic directions of propagating radiation. The fields produced in the simulation closely match the experimental observations of the SP jets and the re-radiation. The (0,-2) and (-1,0) SP modes are examined. When the apertures are 200 nm in diameter the former mode, exhibits two subjets that converge about 10 mm past the end of the nanoarray, precisely matching the experimental observations [1]. The latter mode exhibits two separate jets, but when the sample is rotated 5 degrees, one of these is largely extinguished, and the single emitted jet matches the experimental observation. We further employ the FDTD method to examine the dependence of the SP intensity on the hole diameter. This dependence, which is nonmonotonic, will be discussed. [1] G.Blumberg, B.S. Dennis, and D. Egorov, abstract, this meeting.

W5.6

Modification of Optical Transmission through Micro-scale Periodical Capacitive Metallic Grids. Yonghong Ye, Center for Nanoscience Devices, The Pennsylvanis State University, University Park, Pennsylvania.

There has been considerable interest in the optical properties of structured metallic films due to their potential applications in novel photonic devices. We report here the modification of the transmission of capacitive metallic grids in the visible regions. The micro-scale silver grids on a glass (or sapphire) substrate are obtained by the natural lithography. The silver grids consist of periodical triangular metallic islands, whose transmission spectrum exhibits a band-stop behavior. The longer the periodicity is, the higher the refractive index of the substrate material is, the more red-shift the peak of the stop-band is. The feature of the transmission spectrum is related to the coupling of incident radiation to surface plasmons.

W5.7

Nonlinear-optical properties of anisotropically nanostructured porous silicon. Victor Yurevich Timoshenko[1], Dmitri Kovalev[2], Leonid Golovan[1], Alexei Zheltikov[1] and Pavel Konstantinovich Kashkarov[1]; [1]Physics Department, Moscow State M.V.Lomonosov University, Moscow, Russian Federation; [2]Physik Department E16, Munich Technical University, Garching, Germany.

Nanostructuring of semiconductors via electrochemical etching is a promising way for fabricating new artificial photonic media. We report on linear and nonlinear-optical properties of the electrochemically prepared porous Si (PSi) layers. These layers are assembled from Si nanocrystals and nanopores whose dimensions can be tuned in the range 1-50 nm. The absence of a large volume fraction of Si results in a reduced value of the refractive index of PSi, which is easily controlled by porosity variations. Because of an anisotropy of the pore propagation the symmetry of the optical susceptibility of PSi is drastically reduced in comparison to the isotropic optical properties of bulk Si. This finding results in a variety of new photonic applications of PSi. For instance, structures of PSi multilayers with alternating refractivr indices show tunable 1D photonic band gap. Additionally, our experiments demonstrate possibility to reach phase matching conditions for polarization-dependent second-harmonic generation in PSi multilayers. Optically homogeneous PSi layers formed from low symmetry Si wafers (e.g. (110) oriented) are found to exhibit optical properties of a birefringent crystal due to the form anisotropy of Si nanocrystals. The optical axis direction and birefringence value depend on the substrate parameters and porosity of the PSi layer. The in-plane birefringence of a (110) PSi layer can be strong enough to compensate for the normal dispersion of material in the visible and middle IR ranges. This remarkable fact allows phase-matched nonlinear optical wave interactions in the birefringent PSi to be achieved. Additionally, an increase of the nonlinear-optical susceptibility and modifications of its anisotropy parameter are possible for the birefringent PSi because of local electric field fluctuations in quasiordered ensembles of anisotropically shaped Si nanocrystals. Both effects are confirmed by our experiments on second and third harmonic generation in anisotropic PSi layers.

W5.8

Photonic Crystal Tapers For Coupling Large Ridge Waveguides To Planar Photonic Crystal Waveguides. Francis Ndi and Jean Toulouse; Physics, Lehigh University, Bethlehem, Pennsylvania.

We present a study of various photonic crystal taper structures each characterized by the taper angle and roughness for coupling light into planar photonic crystal waveguides from large ridge waveguides. The photonic crystal waveguide is made of a triangular lattice of holes in a dielectric. The objective is to find a taper structure that offers the best coupling efficiency over a range of widths of the ridge waveguide while leaving a small footprint. We show that such a structure indeed exists and can be further optimized as the width of the ridge waveguide gets even larger leading to more than 90% increase in coupling efficiency in some cases.

W5.9

Phonon-Polariton Propagation, Guidance, and Control in Bulk and Patterned Thin Film Ferroelectric Crystals. David W Ward, Eric R Statz, Jaime D Beers, Nikolay Stoyanov, Thomas Feurer and Keith A Nelson; Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts.

We have characterized the propagation and dispersion relation of phonon-polaritons, admixtures of electromagnetic radiation and lattice vibrations, in ferroelectric thin films– specifically, $LiNbO_3$ and $LiTaO_3$ of 10-250 micron thickness. We demonstrate that a ferroelectric crystal in this thickness range behaves as a slab waveguide for phonon-polaritons. Further, we show that ferroelectric crystals in this size regime are amenable to processing by ultrafast laser machining. This form of controlled laser ablation allows for the milling of user-defined patterns designed for guidance and control of phonon-polariton propagation. We demonstrate several functional structures including THz rectangular waveguides, resonators, splitter/couplers, interferometers, focusing reflectors, and diffractive elements. Confinement and amplification of electromagnetic and mechanical energy within a THz resonator cavity have been attained through the use of femtosecond pulse shaping for generation of optical pulse sequences whose repetition rate can be tuned through the resonance frequency. Phonon-polariton amplification or suppression is demonstrated and is characterized by the cavity Q.

W5.10

Fabrication of Two-dimensional Nonlinear Photonic Crystal by Electron Beam Lithography. Chiang Huen Kang, Ze Xiang Shen and Sing Hai Tang; Physics, National University of Singapore, Singapore, Singapore.

In this paper, we present a study on quasi-phase matched (QPM) two-dimensional $\chi^{(2)}$ lithium niobate (LN) nonlinear photonic crystals (NPC) for frequency doubling at λ=1064nm. The NPCs are fabricated by electron beam lithography (EBL) through periodic polarization inversion of the ferroelectric domains and characterized with electrostatic force microscopy (EFM), atomic force microscopy and optical microscopy. Domain inversion occurred through the entire wafer thickness of 0.5mm as EFM images on the +c face of the z-cut wafer showed uniform domain structures throughout the corresponding electron beam irradiated regions of the -c face. In addition, the intended periodicity was observed. Moreover, domain inversion was also seen to have taken place in bulk from the optical images of the chemically etched samples. The EBL technique offers great flexibility in superlattice design and relative ease of fabrication as compared to the conventional poling techniques as pattern transfer is direct without the need for a mask and/or a coating of resist. Besides, micro- or sub-micro scale superlattices corresponding to wavelengths in the visible and into the ultraviolet are highly feasible, restricted only by the transparency of the crystals.

W5.11

Creation and Optical Property of Microphotonic Crystals by Electrophoretic Deposition Method Using Micro-counter Electrode. Kiyoshi Kanamura, Jun-ichi Hamagami and Kazuhiro Hasegawa; Department of Applied Chemistry, Tokyo Metropolitan University, Hachioji, Tokyo, Japan.

In order to create micrometer-scale functional materials or devices we have been investigated on development of a novel electrophoretic deposition (EPD) method using a microelectrode as a counter electrode in the EPD system. This method is so-called μ-EPD method. The μ-EPD method was applied to prepare micro colloidal crystals consisting of monodisperse polystyrene (PS) particles for microphotonic materials and/or devices. Scanning electron micrographs of the as-prepared specimens under the optimized μ-EPD process parameters showed a formation of microdot consisting of three-dimensionally close-packed ordering of the PS microspheres in planes parallel to an indium-tin oxide-coated glass substrate. In order to accurately characterize the optical properties of the microdot, an optical microscope combined with a photonic multi-channel analyzer was used in this work. In this optical measurement system the measuring area depends on pin-hole size and the magnification of the objective lens. For example, the measuring spot size was 2 μm in diameter when the pin-hole size and the magnification of the objective was 100 μm and 50 times, respectively. The microscopic spectrum of the microdot exhibited a narrow absorption peak rather than the macroscopic spectrum. The absorption peak was detected at 460 nm of wavelength in the transmittance spectrum in visible region for the three-dimensional crystal consisting of 204 nm PS particles. This experimental result is in good agreement with calculated value from Bragg/s law. From these results, it can be said the microphotonic crystals with defect-free sphere arrangement has been prepared by this μ-EPD method.

W5.12

Colloidal Photonic Crystals with Graded-Index Distribution.

Jeong-Ho Park and Dong-Yu Kim; Material Science & Engineering department, Kwangju Institute of Science and Technology (KJIST), Kwang-ju, South Korea.

Photonic crystals or photonic band gap materials (PBG) have been the subjects of intensive theoretical and experimental researches. Their periodic dielectric structures that are designed to control the propagation of electromagnetic (EM) waves by defining allowed and forbidden energy gaps in the photon dispersion spectrum. The absence of propagation EM modes inside the structures gives rise to distinct optical phenomena such as inhibition of spontaneous emission.[1] Synthetic opals have been studied as pseudo photonic crystals to establish the growth techniques for the three-dimensional periodic structure. Previously, there have been many demonstrations that various materials can be infiltrated into interconnected nanosize voids of opals. Based on this fabrication technique, the concept of tunable photonic crystals is proposed, in which the photonic bandgap can be tuned as desired by controlling parameters such as the refractive index, periodicity, or space-filling factor.[2-3] In this presentation, we proposed a novel photonic crystal in which the background index of colloidal opal crystal is gradually changed to specific direction of the crystal. This was achieved by infiltrating polymers using the interfacial-gel polymerization with relatively high refractive-index organic dopants.[4] This method results in a novel infiltrated colloidal crystal that has graded refractive index distribution. Therefore, this device has gradually varying stop band on the different position of the crystal. This could be a kind of tunable optical filter based on the positional variations. The optical properties and potentials for other optical applications were investigated. [1] E. Yablonovitch. Phys. Rev. Lett. 1987, 58, 2059 [2] Y. Iwayama, J.Yamanaka et al. Langmuir 2003, 19, 977 [3] M. Ozaki, Y. Shimoda, M. Kasano, K, Yoshino. Adv. Mater. 2002, 14, 514 [4] Y. Koike, T. Ishgure, E. Nihei. J. Lightwave Technol. 1995, 137, 1475

W5.13

Narrow Two-Dimensional Photonic Band Gaps for SBA-15 Structure But With High Index Contrast. Changsong Liu[1], Yun Ying Wu[1], Osamu Takai[1] and Yoshitake Masuda[2]; [1]Takai Lab, Center for Integrated Research in Science and Engineering, Nagoya University, Nagoya 464-8603, Japan; [2]Department of Applied Chemistry, Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan.

Generally photonic band gap (PBG) materials with high dielectric contrast could give rise to widths about 150 nm, which can block almost half the relatively narrow visible spectrum. Thus, photonic crystals with much narrower PBG, widths below 10 nm (full width at half-maximum), are likely to be more suitable for technological purposes; these can be usually achieved by maintaining a small index contrast. However, we found a narrow PBG for a structure with high dielectric contrast when we calculated the spectral response of SBA-15 ordered mesoporous materials. The structure with a narrow PBG is similar with SBA-15 "geometric" structure but with back ground dielectrics (dielectric constant ϵ more than 12.0) instead of silica (ϵ around 4.0). The position and the width of the gap are dependent on the filling fraction (f, defined as the sum of the cross-sectional areas of the air cylinders over total area), polarization, incident angle (β) and the dielectric constant (ϵ). The gap locates at 0.313 (fN,$\omega a/2\pi c$) for f= 50%, E-polarization, ϵ=16.0 and β=10° in the out-of-plane (i.e., waves with k having a component parallel to the axis of the cylinders). We get the lattice constant (for SBA-15) a=12 nm, the corresponding PBG wavelength is about 38.3 nm ($\lambda=c/f=2\pi c/\omega=a/fN=12/0.313=38.3$ nm, in the soft X-ray region) and the width (full width at half-maximum) is 0.5 nm (around single frequency). Noting that fN is a non-dimensionalized frequency, if a=200 nm, then the corresponding PBG wavelength is about 639 nm (in the visible spectral region) and the width is only about 8 nm. This work is supported by JSPS - RFTF99R13101 and the 21st Century COE Program "Nature-Guided Materials Processing".

W5.14

Penrose Quasicrystal Pattern on Metallic Microcavity.

Jia Yi Zhang[1], Hoi Lam Tam[1], W.H. Wong[2], Y.B. Pun[2] and Kok Wai Cheah[1]; [1]Department of Physics, Hong Kong Baptist University, Kowloon Tong, Hong Kong; [2]Department of Electronic Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong.

Most photonic crystal structures currently used on microcavity are cubic or hexagonal, whose folding symmetry is less than six and those photonic band gaps depend on the azimuthal angle of the microcavity. In this work, we fabricated metallic microcavity with Penrose quasicrystal pattern that exhibits 10-fold symmetry. A complete photonic band gap was observed in the transmission spectrum in both TE and TM modes. Moreover, the photonic band structure is independent of incident angles of incoming light beam. With luminescence material such as tris(8-hydroxyquinoline) Aluminum (Alq_3) embedded in the microcavity, coupling of photonic mode to photoluminescence can be observed. Clear photonic bandgap exists in the photoluminescence spectrum, and the integrity of the gap is equally robust, as demonstrated in the transmission experiment. It is believed that by modifying the geometries of the cavity such as the cavity width and the corrugations of the pattern, one can be able to engineer the photoluminescence properties of luminescence materials. Theoretical calculation on the band structure of the photonic microcavity with Penrose pattern was also performed . It is found that the photonic band gap can be accomplished with a minimum number of 15 reciprocal lattice points. In other words, the optical properties of the photonic microcavity can be characterized by at least 15 lattice points in the Penrose quasicrystal pattern.

W5.15

All-optical Tuning of the Extinction Spectra of Metal Nanoparticle Arrays Using Highly Birefringent Photoaddressable Polymer Films. Beth Lachut[1], S. A. Maier[1], E. Kelsic[1], M. J. A. de Dood[2], R. Hagen[3], S. Kostromine[3], A. Polman[2,1] and Harry A. Atwater[1]; [1]Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California; [2]FOM Institute for Atomic and Molecular Physics, Amsterdam, Netherlands; [3]Bayer Polymers, Leverkusen, Germany.

Highly birefringent polymers are a powerful means for improving the capacity of data storage media and are also potentially useful as waveguides and active device materials in integrated photonic devices. Photoaddressable polymers (PAPs) show considerable potential for these applications. Unusually large birefringences of Δn = 0.6 at 660 nm can be optically written in ambient conditions, and the films have the capacity to undergo more than 3000 read/write cycles. The optical contrast of writable media can potentially be enhanced by embedding a dense array of metallic nanoparticles within birefringent PAP films. Thin PAP films have been well characterized at various write wavelengths and intensities, and the effect of thermal treatment during and after writing has also been explored. Writing is performed by applying a polarized EM field at absorbing wavelengths of the polymer below 630 nm. This induces photoisomerization cycles of the azobenzene moieties, resulting in a strong in-plane birefringence and preferentially aligning the side-chains perpendicular to the polarization direction. Polarized transmission measurements show that a very large birefringence is maintained over the entire nonabsorbing range of 650 - 1700 nm, with Δn values greater than 0.35 at 1500 nm. As a potential application, we will present initial results of the splitting and shifting of plasmon modes when ordered arrays of small Au spheres are embedded in the PAP. Mie theory predicts that the dipole plasmon absorption resonance wavelengths can be shifted from 570 to 650 nm depending on whether the side chains are perpendicular or parallel to the monitored direction. The limits of nanoscale writing using near-field scanning optical microscopy will also be noted, as this has important implications to data storage applications. The effect of PAP birefringence on the extinction spectra of metallic nanoparticle arrays embedded in the polymer will be presented.

W5.16

Electromagnetic Energy Transport in Nanostructured Media: Application to Nanoparticle Plasmon Waveguide.

Yongqiang Xue and Mark A. Ratner; Chemistry Department and Materials Research Center, Northwestern University, Evanston, Illinois.

Nanophotonics, by utilizing local electromagnetic interaction between a few nanostructured elements, provides a promising route of circumventing the diffraction limit to the further miniaturization of integrated photonic devices. In particular, metallic nanoparticles, due to their capability of sustaining strong coupling with the electromagnetic field in the visible spectrum through resonant collective surface plasmon excitations, have opened up numerous opportunities for developing novel plasmon-based nanophotonic devices. Since both the dimension and spacing of the nanostructured components are much smaller than the wavelength of visible light, concepts and methods from macroscopic electrodynamics are no longer valid and careful analysis of the local-field effect is essential to understand electromagnetic wave propagation through nanophotonic structures. In this talk we present a Lagrangian approach to the microscopic electrodynamics of nanostructured media which establishes rigorously the connection between the wave propagation phenomena and the underlying electronic processes. We apply the theory to electromagnetic energy transport through plasmon waveguide consisting of closely spaced metal nanoparticle chains. We give the microscopic definition of energy transport velocity and demonstrate the inadequacy of group velocity in characterizing energy transport through nanostructures coupled by optical near-field. Both simple model calculations and possible extension to microscopic models will be discussed.

W5.17

Optical and Mechanical Properties of Photo Assisted, Self Assembled Nano Particle Films. Ricky Lamar Moore[1], G. A. Gaddy[2], Edward P. Locke[2] and Diane M. Stoakley[2]; [1]STL, Georgi Tech Research Institute, Atlanta, Georgia; [2]NASA Langley Research Center, Hampton, Virginia.

This paper presents research funded under the DARPA MetaMaterial program for design and development of nanoparticle based, mesoscale electromagnetic and optical materials. Specifically we present results of formulation and near infrared measurement-model validation for photo assisted self assembled multi layer metallic nanoparticles films. The multi layer films may be used as optical filters and absorbers. We demonstrate that nanoparticles can be made into composites that can exhibit new electromagnetic constitutive properties. Nanoparticle dispersions are made with a single-stage self-metallizing protocol. Metal nanoparticles films evolve from a single homogeneous resin solution containing a metal precursor that is exposed to UV radiation and a controlled thermal environment. The combination of thermal curing and UV exposure creates a multiphase material composted of low volume fractions of dispersed metallic clusters (10 to 20 nm in size) and high concentrations of nanoparticles which form layered embedded films. Examples of the composite have separated inner-layers of increased volume fraction of metal and layer separation is controlled by UV exposure. These materials show significant absorption in the optical and near IR region. Further they exhibit mechanical properties similar to bi-metallic layers. They display reversible bending with exposure to light and resulting rapid temperature increase. The presentation will present examples of formulation process, optical-mechanical measurements and measurement model comparison.

W5.18

Compact Tunable Photonic Crystal Mach Zehnder. Stefan Francis Preble, Carlos Angulo Barrios, Roberto Ricardo Panepucci and Michal Lipson; Electrical and Computer Engineering, Cornell University, Ithaca, New York.

We demonstrate an ultra-compact photonic crystal (PC) interferometer on silicon-on-insulator (SOI). The device is based on a balanced Mach-Zehnder (MZ) interferometer with arm lengths of $20\mu m$ or less. The MZ consists of coupled resonator optical waveguides (CROWs), which significantly slow the group velocity of light, in turn enhancing the phase sensitivity of the device. This increased sensitivity enables larger phase changes in shorter distances. Structures were fabricated using e-beam lithography and etched by RIE on Silicon-On-Insulator wafers. The interferometer is formed using silicon waveguides with height and width of 250 nm and 450 nm, respectively. The entire structure is less than $25\mu m$ in length. The refractive index is changed in only one arm of the MZ, inducing a phase mismatch at the output. We show that with a refractive index change of only 0.1% complete switching of the output can be achieved. Such a device could open the door to ultra compact switches, sensors, and modulators.

W5.19

Characterization By Variable Angle Spectroscopic Ellipsometry of Dielectric Columnar Thin Films Produced by Glancing Angle Deposition. James Gospodyn, Michael Brett and Jeremy Sit; Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada.

The growth of thin films by using glancing angle deposition [1] (GLAD) produces films with engineered micro- and nano-structure. In this technique, the incoming physical vapor flux arrives at the substrate at highly oblique angles, typically between 80^o and 90^o with respect to the substrate normal, resulting in a highly porous thin film composed of slanted, isolated columns. Several researchers have examined means for tailoring the microstructure of GLAD produced films, including substrate rotation and variation of the angle at which the incoming flux arrives at the substrate. However, few detailed studies of the optical properties of the basic columnar GLAD film structures have been performed to date. In this study, we examine the optical properties of porous, dielectric GLAD thin films such as MgF_2 and TiO_2 using variable angle spectroscopic ellipsometry, a particularly effective technique for characterizing these films, since it enables measurement of the dispersion relation of the index of refraction. The tilted columnar film structures resulting from GLAD are shown to be biaxial, where one of the principal indices is oriented in the direction of the columns. We further discuss the effects of film material, deposition angle, and film thickness on the three principal refractive indices and the birefringence. As the tilted columnar films form the basis for more complex micro- and nano-engineered GLAD structures, this study of the optical properties forms the foundation for study of these porous engineered films in applications such as integrated optics [2] and photonic crystal structures [3]. [1] K. Robbie et al., J. Vac. Sci. Technol. B 16, 1115 (1998). [2] J. C. Sit et al., Liquid Crystals 27, 387 (2000). [3] S. R. Kennedy et al., Photonics & Nanostructures in press (2003).

W5.20

Anodization Time Dependent Photolumination Intensity Of Porous Silicon. Nazrul Islam, ISRO, Ahmedabad, Gujarat, India.

Visible photoluminescence (PL) at room temperature from electrochemically etched porous silicon (PS) has been a strong motivating factor to study nanocrystalline silicon (nc-Si) for their possible applications in optoelectronic integration[,]. PL intensity is normally increases with anodization time (ta) for shorter ta. However, PL intensity was found to decrease after a maximum for a longer ta in photochemical etching. It is due to the fact that after a certain ta, PS layer thickness starts decreasing due to photochemical dissolution of PS layer. In this article, we present the effect of longer ta on PL from PS formed by electrochemical anodization. The PL intensity first increases with ta and then decreases at very large ta. It was found that both the PL peak and integrated (total) intensities go to a maximum and then decrease. The increase in PL intensity with ta may be understood if we take the PL intensity to be proportional to the effective volume of PS layer under the probe laser beam. The effective volume of PS layer will be proportional to its thickness and reciprocal to the porosity. For a fixed anodization condition, the thickness and porosity both increase with ta. The increase in thickness increases the effective PS volume, while the increase in porosity causes the effective volume to decrease. Therefore the intensity variation is governed by these two parameters: thickness and porosity. The observed results suggest that the thickness dominates the PL intensity initially and then the porosity becomes more important for very long ta. The PS layers prepared under ambient light illumination also exhibited the similar behaviour. The intensity variation with ta was explained as the interplay of thickness and porosity variations with ta.

W5.21

Tuneable Fabry-Perot Fibres. Gilles Benoit[1], Shandon D Hart[1], Burak Temelkuran[1], John D. Joannopoulos[2] and Yoel Fink[1]; [1]DMSE, MIT, Cambridge, Massachusetts; [2]Physics, MIT, Cambridge, Massachusetts.

The fabrication of tuneable optical devices is of fundamental importance in the areas of communications and sensing. Here we demonstrate the design, fabrication and characterization of a mechanically tuneable dielectric mirror fibre. The fibres consist of a drawn nearly-cylindrical multilayer structure exhibiting a large photonic bandgap and containing a single-mode Fabry-Perot cavity whose resonant wavelength is shifted under applied strain. Broadband spectroscopic ellipsometry is used to accurately measure the refractive indices of the materials comprising the fibres, which in turn allows for the simulation of the opto-mechanical characteristics of the Fabry-Perot fibres. These were found to be in good agreement with experiment. A normalized shift of 0.347% of the resonant mode towards lower wavelengths has been measured under 0.9% applied axial strain. As these fibres exhibit large photonic bandgaps they may be used for a variety of passive and active applications requiring high quality factors and small modal volume. Furthermore, their inherent flexibility allows for the incorporation of these fibres into fabrics.

W5.22

Resonance enhanced fluorescence in photonic crystals studied by near field technique. anton Igorevich Maidykivski, Oleg Lebedev, oleg Aktsipetrov and Irina Soboleva; Physics, Moscow State University, Moscow, Russian Federation.

The spatial distribution of the local optical field in the photonic crystal microcavities formed of porous silicon is studied by apertureless scanning near-field optical microscope. Samples of one-dimensional photonic crystals and microcavities are prepared from highly doped Si (001) wafer by electrochemical etching. The structure consists of microcavity layer and two Bragg reflectors. The image of the spatial distribution of optical field at the cleaved edge of microcavity is observed in near-field scattering and near-field fluorescence. Sample is illuminated through external single-mode fiber perpendicularly to the planar microcavity surface. The localization of the resonant optical field in microcavity is observed in near-field scattering. To increase fluorescence up to 100 times photonic crystals are doped by fluorescence dye Rhodamin 6G. The wavelengths of the microcavity modes are optimized for maximum of dyes spectra. The fluorescence characteristics of the microcavities are obtained by far- and near-field probes. The spatial distribution of the local optical field in near-field fluorescence at the wavelength of local optical maximum of fluorescence spectra is essentially different. There is localization of radiation only in microcavity layer. We obtain resonance enhanced fluorescence in microcavity layer up to 100 times comparing with nonresonance case.

W5.23
Negative Refraction and Nonlinearities at Optical Frequencies by Exciton-Polaritons in Molecular Meta-Materials. Anvar A Zakhidov[1], Vladimir M Agranovich[1,3], Ron Y Shen[2] and Ray H Baughman[1]; [1]Physics, University of Texas at Dallas, Richardson, Texas; [2]Physics, University of California, berkeley, California; [3]Institute of Spectroscopy, Academy of Sciences, Moscow, Russian Federation.

The negative refraction (NR), has attracted a great interest after its experimental verification in microwave frequencies using arrays of split ring resonators (SRR). NR is presently associated with two classes of materials: 1) so called left handed meta-materials (LHM), which have simultaneously negative *epsilon*—(ω) < 0 and *mu*—(ω)<0 at certain frequency range.2) Photonic crystals in the region of flat energy bands, e.g. close to photonic band gaps. In this presentation we discuss the physical concepts, which will allow to extend the phenomena of negative refraction to optical frequencies and suggest several types of meta-materials in which this concepts can be realized. First of all we demonstrate that the negative refraction is a result of a negative group velocity and therefore it is not limited to magnetic media with a negative magnetic permeability, but could exist in any dielectric media with a sufficiently strong and proper spatial dispersion. We have investigated the origin and validity of LH M taking into account on equal footing not only the magnetic-dipole but also the electric quadrupole contribution. We have found no fundamental restrictions that may prohibit existence of LHM at optical frequencies. Dipole electric and magnetic polarization as well as quadrupole polarization strongly contribute to spatial dispersion near exciton resonances being responsible for the appearance of additional electromagnetic waves which can have a negative refractive index and a negative group velocity of exciton-polaritons. An unusual character of nonlinear optical processes such as harmonic generation, stimulated Raman scattering and short pulse propagation in the negative refraction materials is found, so the harmonics generated by NRM carry major part of the intensity in a reflected direction, opposite to the propagation direction of incident beam and not in transmitted direction as in conventional matter. Search of organic and gyrotropic (organic and inorganic) materials with narrow exciton resonances and investigation of additional electromagnetic wave propagation near resonances with negative group velocity is discussed in detail.

W5.24
A Novel Approach to Two-dimensional Photonic Crystals Using Engineered Arrays of Vertical Nanowires.
Thomas Martensson, B J Ohlsson, M Borgstrom, W Seifert and L Samuelson; Solid State Physics, Lund, Sweden.

A bottom-up approach for fabrication of a two-dimensional photonic crystal structure consisting of high-refractive-index columns in air is demonstrated, using vertical nanowires as building blocks. Being a bottom-up method it avoids many of the difficulties present in top-down etching of bulk material that is the currently dominating fabrication method. An electron beam lithography (EBL) technique is used to pattern (111)B substrates with gold particles catalyzing the growth of nanowires. Vertical <111>B nanowires are then grown via vapor-liquid-solid (VLS) using metal-organic vapor phase epitaxy (MOVPE). The lithographic nature of the technique provides considerable freedom in design, which can be utilized in photonic crystals and defect engineering for wave-guiding structures. Tailor-made high-quality nanowire arrays are shown and a tentative wave-guiding structure, consisting of an InP<111>B nanowire array grown on InP(111)B substrate is presented. For this material system the growth temperature is 400C and trimethylindium (TMI) and phosphine are used as source gases. Other material systems will be discussed. Since, for a certain set of growth parameters there is a one-to-one relation between the diameter of the EBL-defined gold disks and the wire diameter after growth, the lateral dimension can be controlled well within a few nanometers. The length of the wires is controlled by the growth time. In addition, being one-dimensional structures nanowires inherently have a high aspect ratio. A prerequisite for high quality wire arrays is knowledge of the correct growth parameters for different materials. Source pressures and temperature strongly affect properties such as growth rate and aspect ratio (tapering) of the wires, as well as defect formation. Results from such fundamental studies are presented and optimal growth conditions are concluded. Furthermore, III-V low-dimensional structures have been shown to have interesting optical, as well as electrical properties in numerous studies. This makes them highly interesting for device integration and suggests promising future applications.

W5.25
Effects of Dielectric Interface Roughness on Photonic Crystal Properties. Karlene Rosera Maskaly, Martin Maldovan and W. Craig Carter; Materials Science and Engineering, MIT, Cambridge, Massachusetts.

Incorporation of the useful properties of photonic crystals, such as complete photonic band gaps, into devices will occur only if those properties can be retained in large-scale production. In this talk we will address various aspects of optical sensitivity to architectural and meso-geometrical dielectric structure. To investigate one aspect of processing sensitivity, we model the the effect of interface roughness and waviness on the optical properties of a one-dimensional photonic crystal. We demonstrate the use of a two-dimensional finite element code applied to lamellar dielectric composites with specifiable interfacial roughness. The results of these simulations characterize the effect of roughness on optical properties. Other processing sensitivities will be identified and, if time allows, will be presented.

W5.26
Minimizing and Exploiting the Effects of Disorder in Photonic Crystals. Walter Frei and H. T. Johnson; Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois.

The study of disorder in photonic crystal structures is of great importance because photonic structures must be as resistant to manufacturing defects as possible. This paper examines the effects of disorder in two-dimensional rod structure photonic systems. It is shown that certain points within the band gap are more resistant to disorder than other points. These points can be found by examining the band gap map for the points which are best at inhibiting transmission. At these points, the structure is not only resistant to disorder, but the strength of the band gap can even be increased by introducing random variation in the position of the rod structures. This anomalous increase in band gap strength can be explained in terms of distributions of line defects within the photonic crystal structure. Certain line defects act as imperfect waveguides and inhibit transmission better than a perfect photonic crystal structure. This effect is shown for several different geometries. Further calculations examine the effects of disorder on waveguide structures and show that while the photonic band gap effect may be enhanced by disorder, waveguide quality always decreases due to variations in feature position. Band gap maps for perfect structures are generated here using the transmission matrix method (TMM) and disorder calculations are done using the finite element method (FEM) to solve 2D Maxwell's Equations in the frequency domain.

SESSION W6: Photonic Crystal II
Chair: Axel Scherer
Thursday Morning, December 4, 2003
Room 204 (Hynes)

8:30 AM *W6.1
Room temperature 1.3-1.55 micron laser-like emission from Ge/Si self-assembled islands in Si-based photonic crystals.
Jean-Michel Lourtioz, Sylvain David, Moustapha El Kurdi, Cecile Kammerer, Sebastien Sauvage, X. Li, Philippe Boucaud and Alexis Tchelnokov; Institut Electronique Fondamentale, CNRS Universite Paris Sud, ORSAY, 91405, France.

Getting light efficiently out of silicon has always been a long standing goal for many researchers. The combination of optical functionalities integrated on a silicon chip should allow the development of devices at low cost for multimedia markets and address some key issues for the inter- and intrachip optical interconnections. The increase of the quantum efficiency of a silicon integrated source requires specific approaches in order to bypass the expected inefficiency associated with an indirect gap semiconductor. In this invited talk, we will discuss the approach which consists in combining silicon-based photonic crystal cavities and emitters. After recalling the different techniques of silicon-based photonic crystals (microporous silicon, inductively-coupled-plasma (ICP) etching of burried SiGe/Si waveguides and reactive ion etching of silicon-on-insulator (SOI) substrates), we will focus on the combination of Ge/Si self-assembled quantum islands and SOI photonic crystals. We show that the room temperature 1.3-1.55 micron emission from Ge/Si self-assembled islands can be significantly enhanced in photonic crystal microcavities. The investigated structures are obtained as follows. The Ge/Si island layers are first deposited on a SOI substrate which is further processed to get a two-dimensional photonic crystal with defect microcavities. A laser-like emission is observed under optical pumping at room temperature in these devices. This emission is characterized by a threshold and a slope which depend on the size of the microcavities. This effect is enhanced in the case of cavities surrounded by wide pores (i.e. micropillar-like cavities). The non linear behavior is accompanied by a drastic enhancement of the room temperature 1.3-1.55 micron Ge island emission, the latter being more than two orders of magnitude larger than that of the unprocessed sample. In the experiments, the room temperature luminescence amplitude is also compared to that of a single InGaAs quantum well. The silicon-based system then appears as a promising alternative for micro sources on silicon at telecommunication wavelengths that are fully compatible with silicon micro- and nano-technologies.

9:00 AM W6.2

High Speed Photonic Crystal Nanolasers. Tomoyuki Yoshie[1], Marko Loncar[1], Yueming Qiu[2], Oleg B. Shchekin[3], Hao Chen[3], Dennis G. Deppe[3] and Axel Scherer[1]; [1]Electrical Engineering, California Institute of Technology, Pasadena, California; [2]In Situ Technology and Experiments Systems Section, Jet Propulsion Laboratory, California Institute of technology, Pasadena, California; [3]Electrical and Computer Engineering, the University of Texas at Austin, Austin, Texas.

We have investigated the miniaturization of photonic devices for photon localization, and have demonstrated two-dimensional photonic crystal nanolasers with quantum well (QWs) and quantum dot (QDs) gain material. The photonic crystal lasers showed very low thresholds - as low as 0.12mW and 0.22mW for QD-photonic crystal lasers and QW- photonic crystal lasers, respectively. These low threshold values could be obtained by three-dimensional cavity designs and careful nanofabrication. Research efforts on photonic crystal lasers have so far focused on static properties such as low thresholds and frequency tenability. However, nanolasers have also been known to offer the possibility of high modulation speeds due to microcavity effect. Indeed, microcavities are helpful in that these increase photon densities by tight three-dimensional optical confinement. In addition, microcavity effects enhance a rate of energy transfer between the carriers and the photon population. In order to determine the operable frequencies from our samples, we conducted non-static measurements and identified dynamic properties of photonic crystal nanolasers. High frequency modulation was observed from such measurements of QW-photonic crystal nanolasers. We used square lattice and triangular lattice photonic crystals to produce localized modes. We know that the laser designs have small mode volume of 0.4-1.2 cubic wavelengths with high quality factors ranging from 10,000 to 100,000, predicted by our three-dimensional finite difference time domain modeling. The QW- photonic crystal nanolasers showed the highest frequency of up to 130 GHz compared to conventional lasers, which to our knowledge can be modulated at frequency of up to 40 GHz. The measured oscillations are at least three times higher than those of conventional lasers. This improvement is obtained because of decreased photon lifetime and increased photon density in nanocavities. Miniaturized lasers can be operated with surprisingly small absorption power of sub-mW for high frequency laser operation while conventional lasers need more than 100mW for 40GHz operation. The output power was several tens of nano Watts. Therefore, photonic crystal nanolasers can be compact and efficient light sources for high speed signal processing. Here we report on how to construct the highest frequency and the lowest threshold photonic crystal nanolasers.

9:15 AM W6.3

Biochemical sensors based on photonic crystal nano-lasers. Marko Loncar[1], Mark Adams[1], Yueming Qiu[3], Stephen Quake[2] and Axel Scherer[1]; [1]Electrical Engineering, California Institute of Technology, Pasadena, California; [2]Applied Physics, California Institute of Technology, Pasadena, California; [3]In Situ Technology and Experiments Systems Section, Jet Propulsion Laboratory, Pasadena, California.

We have developed photonic crystal lasers (InGaAsP material) that permit the introduction of analyte within the peak of the optical field of the lasing mode. One interesting feature of our design is presence of an air hole at the center of the structure, which is the position of maximum field intensity. Therefore the structure can be used for chemical sensing and for exploration of interaction between light and matter on a nanoscale level. We have explored the design compromises for developing such sensitive low-threshold spectroscopy sources, and have demonstrated the operation of photonic crystal lasers in different solutions. Through 3D FDTD methods, we have studied the influence of the ambient refractive index on the quality factors (Q) and frequencies of the resonant modes of the cavity. We observed that the Q of our cavity is almost an order of magnitude smaller when refractive index of the ambient is increased from 1 to 1.4. Also, we observed that the frequency of the resonant mode depend linearly on the refractive index of the analyte, and we predict that the wavelength shift of the resonance should be approximately $\Delta\lambda \approx 266\Delta n$, where Δn is the change in refractive index. The simplest method of optically sensing ambient material uses wavelength shifts in the laser spectrum when the laser is immersed into a solution to measure its refractive index. If we assume that our cavity is embedded in a typical polymer (n=1.4) a wavelength shift that is still observable from passive cavity (Q=1,000) is $\Delta\lambda \approx 1.55$nm, what corresponds to change in refractive index of $\Delta n \approx 0.0056$. On the other hand, once we introduce optical gain into the cavity, as in the case of the proposed laser spectrometer, the linewidth of emission is significantly narrowed (0.12nm in our case), and therefore much higher sensitivities of $\Delta n < 0.001$ can be measured even in cavities with modest Q. In order to explore the sensitivity of our lasers on the changes in the refractive index of environment we used fluids with known refractive index in the range (1.295, 1.335) with step $\Delta n = 0.005$. We found that frequency shifts depend linearly on n, as predicted by numerical analysis. The experimentally measured sensitivity of our lasers is $\Delta\lambda = 1.26$nm when $\Delta n = 0.005$. We have integrated lasers with lithographically predetermined spectra into large arrays, within the same photonic crystal platform. These devices are particularly interesting as compact multi-wavelength light sources, but are also useful if several analytes have to be monitored at the same time. We were able to achieve simultaneous emission from two adjacent nano-lasers, at two different wavelengths, with comparable output powers. We have also integrated our sensors with microfluidic systems that can deliver picoliter volumes of analyte. This can lead towards compact and versatile "laboratory on a chip" devices, in which many analytical functions can be monolithically combined.

10:00 AM *W6.4

Ultra-Small Light Emitting Devices. Toshihiko Baba, Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan.

The recent progress on semiconductor ultra-small light emitting devices based on photonic crystal slabs, microdisks, microgears, photonic molecules, etc., will be presented. For photonic crystals, unique localized modes in modified point defects, line defects and point and line composite defects were theoretically calculated by the finite difference time domain method. The room temperature lasing by pulsed photopumping was experimentally demonstrated for these defects fabricated into a GaInAsP slab by inductively coupled plasma etching. In these photonic crystal microlasers, a 0.1 MK/W order large thermal resistance, large carrier diffusion inside the slab, and fast surface recombination at hardly processed sidewalls of holes have disturbed the cw lasing. Some candidate structures that could improve the problems were studied, e.g., a slit structure for the suppression of carrier diffusion, and a post structure for efficient heat sinking. In GaInAsP microdisks and microgears, the room temperature cw lasing was obtained with a 10 microwatt order threshold. Such an ultralow threshold is partly owing to the strain relaxation effect in compressively-strained quantum wells. This effect can improve the carrier confinement near the disk edge where the whispering gallery mode is localized. The lasing was also investigated for GaAs system, InAs quantum-dot system, etc. For microgears, the dependence of modal characteristics on the depth and shape of the microgear were theoretically calculated and the correspondence between the theory and experiment was well confirmed. The fusion of a microgear and a quasi-periodic photonic crystal was proposed and its modal characteristics were calculated for realizing a novel high Q cavity with a small modal volume, which is difficult to achieve in a simple microgear. The optical coupling of multiple microdisks forms a photonic molecule. It is expected to exhibit some nonlinear switching functions due to the coupling. The room temperature cw lasing and unique modal characteristics were also obtained for various photonic molecules. Lasing modes of the photonic molecule exhibited anti-crossing characteristics and the mini-band formation of coupled modes. The spontaneous emission factor and the Purcell factor are important for estimating the potential of an ultimate high efficiency and high speed light emitter. They can be evaluated by the fitting of theoretical results with experimental lasing and carrier lifetime characteristics. These characteristics were measured for microdisks at a wavelength range of around 1.55 microns using phase- and time-resolved spectroscopy. The result indicated a Purcell factor of nearly 6. This is the first clear demonstration of Purcell effect at room temperature.

10:30 AM W6.5

Tuning Microcavity Resonant wavelength by modification of cavity geometry in a 2D photonic crystal. Ganapathi Subramania, Shawn-Yu Lin, Joel Wendt and Jonathan Rivera; Sandia National Laboratories, Albuquerque, New Mexico.

High quality factor microcavities in two dimensional photonic crystals at optical frequencies are of great interest and importance due to their potential technological applications in optical switching, cavity QED, filtering and wavelenth multiplexing. For such applications a simple approach to tuning the microcavity resonant wavelength would prove quite useful. We propose a new microcavity design consisting of superdefect of smaller diameter holes embedded in a 2D photonic crystal lattice . We will show that we can tune the cavity resonant wavelength "coarsely" or "finely" by appropriately changing the geometry of the superdefect while still obtaining a high quality factor.

10:45 AM W6.6
Growth and Optical Properties of 2D Photonic Crystals Based on Hexagonal GaAs/AlGaAs Pillar Arrays by Selective-Area Metalorganic Vapor Phase Epitaxy. Junichi Motohisa, Junichiro Takeda and Takashi Fukui; Research Center for Integrated Quantum Electronics, Hokkaido University, Sapporo, Japan.

We report on the fabrication and optical properties of GaAs-based two-dimensional photonic crystals (2D PhCs) by using selective area metalorganic vapor phase epitaxial (SA-MOVPE) growth. The 2D PhCs consisting of a hexagonal pillar array in the triangular lattice were selectively grown on SiO masked GaAs (111)B substrates with circular mask openings. Because of the evolution of the facets during the growth, hexagonal pillars with {110} sidewalls vertical to the (111)B plane were formed in the opening area of the masked substrate at appropriate growth conditions. The pillars had extremely high aspect ratio exceeding 10. We observed a strong emission in the room-temperature PL measurement, attributable to a GaAs quantum well formed on the top of the GaAs/AlGaAs pillar structures. This emission is surprising considering the small diameter of the pillars (around 100 to 150 nm) and the significance of non-radiative recombination at the surface in GaAs based materials. Moreover, it was found the emission was dependent on the lattice constant a of 2D PhCs and became maximum for a=0.5 μm. The result suggests few non-radiative centers in the epitaxially grown pillar arrays and enhanced light extraction efficiency in 2D PhCs.

11:00 AM W6.7
Waveguiding in SOI-Based Photonic Crystals Slabs. Cecile Jamois[1], Ralf B Wehrspohn[1,2], Christian Hermann[3], Lucio Claudio Andreani[4], Ortwin Hess[3,5] and Ulrich Goesele[1]; [1]MPI Halle, Halle, Germany; [2]Department of Physics, University of Paderborn, Paderborn, Germany; [3]Institute of technnical physics, DLR Stuttgart, Stuttgart, Germany; [4]INFM and dipartimento di Fisica A. Volta, Universit{a} di Pavia, Pavia, Italy; [5]Advanced Technology Institute, School of Electronics and Physical Sciences, University of Surrey, Guildford, Surrey, United Kingdom.

We discuss theoretically and experimentally some basic properties of two-dimensional (2D) planar photonic crystals (PhCs) in thin silicon slabs for waveguiding purposes. The study includes the computation of band structures and field distributions of bulk PhCs modes, using a 3D FDTD code and two different plane-wave methods. A comparison with the two limiting cases of infinite 2D PhCs and planar waveguides is made, in particular to highlight the decisive role of the light line and of the higher-order modes. In a second step a straight waveguide is introduced into the PhC lattice and the waveguiding properties of the defect modes are studied. Again, the band structures and field distributions are considered and compared to the two limiting cases of waveguides in infinite 2D PhCs and ridge-waveguides. To confirm our argument transmission and losses calculations are presented as well. In the case of the lowest W1 waveguide mode, intrinsic radiation losses on average are around 100 dB/mm above the light line, whereas they are negligible below the light line. However, to obtain low losses, the structuring of an underlying oxide layer of at least 1 μm thickness in SOI-based PhC slabs is necessary. Experimentally, the structures are fabricated using inductively-coupled plasma (ICP) etching with a hard chromium mask to structure deeply the oxide. First experimental characterization are compared to the numerical results.

11:15 AM W6.8
Dispersion Engineering of Photonic Bandgap Devices. David M Pustai, Caihua Chen, Ahmed Sharkawy, Shouyuan Shi, Janusz Murakowski and Dennis W Prather; Electrical and Computer Engineering, University of Delaware, Newark, Delaware.

In this paper, we present the guiding and routing of light within a two-dimensional photonic crystal slab by engineering the dispersion properties of the lattice such that wave propagation is controlled by the shape of the equi-frequency dispersion contour (EFC). Waveguiding structures, such as line defects, are not contained in the lattice; rather, guiding is achieved by introducing a wave that has a frequency outside of the photonic band gap. In this case, the EFC corresponding to this frequency resembles the shape of a square, which indicates two primary directions of propagation. As such, light incident on the lattice, within a given angular range, propagates normal to the EFC along an allowed crystalline axis. Consequently, light is laterally confined as it propagates through the lattice, due to the engineered dispersive properties of the photonic crystal. These structures distinguish themselves as we have measured propagation loss for fabricated devices as low as 2.17 dB/mm as well as a high misalignment tolerance of $\pm 30°$ if used as coupling elements. Techniques for routing the light within these dispersion guiding photonic crystals will also be discussed. Additionally, the analysis and experimental validation of other dispersion-engineered devices, such as photonic crystal lenses, will be presented.

11:30 AM W6.9
Improving the efficiency of polymer LEDs with Bragg gratings. Michael David McGehee and Jonathan Ziebarth; Materials Science and Engineering, Stanford University, Stanford, California.

The external efficiency of normal polymer LEDs is reduced by total internal reflection, which typically causes fifty to eighty percent of the emitted photons to be trapped in guided modes. We have doubled the external efficiency by using a Bragg grating to scatter light out of the polymer film. The gratings are made either by using holographic lithography and reactive ion etching to pattern grooves in an indium tin oxide electrode, or by using soft lithography to stamp a grating of a conducting polymer onto the substrates. In order to optimize the outcoupling efficiency of the grating, we have empirically varied the thickness, grating depth and optical properties of the semiconducting layers and electrodes. We have also modeled the structures to determine the waveguide modeshape and absorption loss. We find that it is important to use an LED structure that is slightly different from that of conventional polymer LEDs in order to minimize waveguide losses. One of the key issues is using a low loss metal (e.g. silver) over a very thin layer of calcium, which is needed because of its ability to efficiently inject electrons into the polymer. The angular distribution and polarization of the scattered light is in good agreement with the waveguide model. In addition to showing that the efficiency of LEDs can be significantly improved with a built-in Bragg grating, we have demonstrated that directional emission can be obtained by transferring energy to rare earth complexes, which only emit over a very narrow range of wavelengths.

11:45 AM W6.10
Light Guiding in Low Index Materials using High-Index-Contrast Waveguides. Vilson Rosa Almeida, Qianfan Xu, Roberto Ricardo Panepucci, Carlos Angulo Barrios and Michal Lipson; Electrical and Computer Engineering, Cornell University, Ithaca, New York.

We propose a novel high-index-contrast waveguide structure capable of light confinement and guiding in low-refractive-index materials. The structure, hereafter named slot-waveguide, consists of two parallel high-index contrast single mode waveguides separated by a nanometer-sized low-refractive-index slot. Analyzing the slot-waveguide eigenmode we observe that the major component of the electrical field profile is perpendicular to the slot walls. Since the electrical flux density is continuous at the interface, the electric field profile experiences a discontinuity equal to the ratio between the dielectric constants in the high and low refractive materials, being higher inside the slot. For high-index-contrast materials this intensity discontinuity can reach large values, such as 6 and 12 for Si/SiO2 and Si/air systems, respectively. Therefore, as a consequence of the close proximity of the high-refractive-index waveguides on both sides of the slot, the field intensity is strongly concentrated in the nanometer-sized low-refractive-index slot. Waveguides and resonator devices employing slot-waveguides were fabricated on Silicon-On-Insulator (SOI) substrate using e-beam lithography and RIE etching. Theoretical analysis through semi-analytical and numerical methods and experimental results of such devices are presented. The degree of light confinement in the low-refractive-index material can be tailored by conveniently adjusting the geometry of the slot-waveguide cross-section. We show that for Si/Air slot-waveguides, approximately 60% of the optical power can be confined and guided through air for a slot width of the order of 100 nm. The slot-waveguide approach is entirely compatible with high-index-contrast planar optical waveguide technology, retaining most of its important properties such as nanometer-sized cross-section dimensions and small minimum bend radius. For the quasi-TE eigenmode the slot is obtained by lithographic patterning, whereas for the quasi-TM counterpart the slot is achieved by appropriate multilayer design. Potential applications for the slot-waveguide include host for active materials, sensing, non-linear optics, near-field optical microscopy, and efficient coupling to nanometer-sized waveguides and structures.

SESSION W7: Photonic Fibres and Theory
Thursday Afternoon, December 4, 2003
Room 204 (Hynes)

1:30 PM *W7.1
Dispersion Properties of Photonic Crystal Fibers - Issues and Opportunities. Jesper Laegsgaard[1], Stig E. Barkou Libori[1], Kristian Hougaard[1], Jesper Riishede[1], Thomas Tanggaard Larsen[1], Thorkild Soerensen[1], Theis Peter Hansen[1,2], Kim Per Hansen[1,2], Martin Dybendal Nielsen[1,2], Jesper Bo Jensen[1] and Anders Overgaard Bjarklev[1]; [1]Research center COM, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark; [2]Crystal Fibre A/S, 3460

Birkeroed, Denmark.

The dispersion, which expresses the variation with wavelength of the guided-mode group velocity, is one of the most important properties of optical fibers. Photonic crystal fibers (PCFs) offer much larger flexibility than conventional fibers with respect to tailoring of the dispersion curve. This is partly due to the large refractive-index contrast available in silica/air microstructures, and partly due to the possibility of making complex refractive-index structures over the fiber cross section. We discuss the fundamental physical mechanisms determining the dispersion properties of PCFs guiding by either total internal reflection or photonic bandgap effects, and use these insights to outline design principles and generic behaviours of various types of PCFs. A number of examples from recent modeling and experimental work serve to illustrate our general conclusions.

2:00 PM *W7.2
Design and fabrication of dispersion controlled and polarization maintaining photonic crystal fibers for optical communications systems. Satoki Kawanishi, NTT Network Innovation Laboratories, Yokosuka, Japan.

A PCF has an array of air holes surrounding a silica core region. Light is confined to the core by the refractive index difference between the core and the array of air holes. The optical properties, for example dispersion characteristics, are determined by selecting the appropriate combination of air hole diameter and air hole pitch. Since the initial demonstration of a photonic crystal fiber (PCF), research has concentrated on the analysis and fabrication of PCF. The PCF has special characteristics compared with conventional single mode fibers. Theoretical analyses and measurements show that the zero dispersion wavelength of PCF is shorter than 1280 nm that is suitable for dispersion compensation at 1550 nm. PCFs with zero dispersion in the 1550 nm region were recently proposed. This type of PCF enables us to realize the nonlinear optical devices that will enhance communication performance. In addition, low dispersion slope (i.e. dispersion flattened) PCF is attracting interest because it offers nonlinearity over a wide wavelength range. Another noteworthy characteristic of PCFs is their strong birefringence, which is induced by the size and arrangement of the air holes. A theoretical analysis and experiments showed high birefringence, three times larger than that of conventional polarization maintaining fibers. Therefore, optical components with better polarization maintaining characteristics are expected. The loss of initial PCFs was 80 dB/km, but recent developments in fabrication technology have drastically reduced the loss to 0.37 dB/km, comparable to conventional single mode fibers. PCFs are expected to become key optical devices. This talk describes the characteristics of dispersion controlled PCFs and polarization maintaining PCFs. It describes theoretical analyses and experimental results of fabricated PCFs that have short wavelength zero dispersion at 810 nm, polarization maintaining with birefringence of 1 x 10-3, absolutely single polarization with polarization dependent loss of 1 dB/m at 1550 nm, and polarization maintaining dispersion flattened functions. A supercontinuum generation experiment with PM-PCF in the 1550 nm region is shown with symmetrical spectral broadening to over 40 nm. The potential of PCFs will be discussed with reference to the next generation high performance networks.

2:30 PM W7.3
Optical gain media incorporated into cylindrical photonic bandgap fibers. Ken Kuriki, Shandon Hart, Gilles Benoit and Yoel Fink; Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

We have recently reported the design and fabrication of omnidirectional dielectric mirror fibers consisting of multiple alternating submicron-thick layers of a high-refractive-index glass and a low-refractive index polymer. These fibers have large photonic bandgaps and high reflection efficiencies, enabling specialized applications such as high transmission through a hollow-core fiber. Here, we will describe a new kind of optical fiber based on the presence of optical gain media in the core of omnidirectional dielectric mirror fibers, where light is confined by the large photonic bandgap. We also present a novel dielectric mirror fiber which incorporates optical gain media in a single-mode Fabry-Perot cavity that provides high quality factors and small modal volume.

3:15 PM W7.4
Fabrication of Polymer Microstructured Fibers. H. H. Chien[1], K. J. Ma[1], Z. P. Zheng[1], Y. P. Yeh[1], M. A. Chu[2], C. L. Chao[3] and C. C. Young[4]; [1]Dept of Mechanical Engineering, Chung-Hua University, Hsing Chua, Taiwan; [2]Dept of Mechanical Engineering, Chung Cheng Institute of Technology, Tahsi Taoyuan, Taiwan; [3]Dept of Mechanical & Electro-Mechanical Engineering, Tam-Kang University, Taipei, Taiwan; [4]Dept of Electrical Engineering, National Taiwan University, Taipei, Taiwan.

The polymer based photonic crystal fibers or microstructured fibers with low-cost manufacturability, and the mechanical and chemical flexibility offer key advantages over conventional silica based photonic crystal fibers. The polymer photonic crystal fiber is fabricated by careful stacking an array of PMMA capillaries to form a preform, and followed by fusing and drawing into fiber on a fiber-drawing tower. Temperature is the most crucial parameter for the fabrication of polymer microstructured fibers. At a relatively low temperature (<175 _), the ratio of air hole size to the pitch between the hole nearly remains the same. The air hole diameter is in a range between 3.5 and 4.5 _m, the pitch between the hole is between 12 and 14 _m. The fraction of air present in the samples is in a range up to around 30%. Increasing the furnace temperature to over 175 _, the hole size can be significantly reduced. due to the effect of strong surface tension forces. The light (_ = 1280 nm and 632nm) coupled into the polymer microstructured fibers with the air hole fraction larger than 25% does indeed travel along long lengths of fiber and remain a single guided mode

3:30 PM W7.5
Materials Selection Criteria in Composite Photonic Bandgap Optical Fiber Fabrication. Shandon Hart[1,2], Gilles Benoit[1,2], Ken Kuriki[1,2], Mehmet Bayindir[1,2] and Yoel Fink[1,2]; [1]Materials Science, Massachusetts Institute of Technology, Cambridge, Massachusetts; [2]Research Lab of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Composite photonic bandgap optical fibers rely on an ordered arrangement of at least two different materials in a photonic crystal structure for efficient light reflection or confinement. In general, the materials must have very different optical properties (high refractive index contrast) while maintaining similar thermal and mechanical properties over a broad temperature range. These unusual requirements stem from the combination of photonic crystal design principles and the selected fiber preform / drawing fabrication method. Here we will analyze chalcogenide glass / polymer materials systems that have been successfully used in bandgap fiber processing as case studies for materials selection criteria. We will discuss compatibility tests that may be employed to identify and predict which materials are good candidates for composite photonic bandgap fiber production. Greater understanding of these phenomena may enable new classes of microstructured fibers which employ a broad range of materials optimized for unique applications, wavelength ranges, or device functions.

3:45 PM *W7.6
Wannier Function Approach to Photonic Crystal Circuits. Kurt Busch[1], Sergei F. Mingaleev[1,2], Antonio Garcia-Martin[1,3], Matthias Schillinger[1] and Daniel Hermann[1]; [1]Institute for Theory of Condensed Matter, University of Karlsuhe, Karlsruhe, Germany; [2]Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine; [3]Consejo Superior de Investigaciones Cientificas, Instituto de Microelectronica de Madrid, Madrid, Spain.

We introduce a novel approach [1,2] to the accurate and efficient calculation of the optical properties of defect structures embedded in Photonic Crystals. This approach is based on an expansion of the electromagnetic field into optimally adapted photonic Wannier functions, which leads to effective lattice models of the Photonic Crystal structures. Calculations for eigenmode frequencies of simple and complex cavities as well as the dispersion relations for straight waveguides agree extremely well with the results from numerically exact supercell calculations. Similarly, transmission calculations through various waveguiding structures agree very well with the results of corresponding FDTD simulations. Besides being substantially more efficient than standard simulation tools, the Wannier function approach offers considerable insight into the nature of defect modes in Photonic Crystals. With this approach, design studies and accurate simulation of optical anisotropic and nonlinear defects as well as detailed investigations of disorder effects in higher dimensional Photonic Crystals come into reach. [1] S.F. Mingaleev and K. Busch, Opt. Lett. **28**, 619 (2003). [2] K. Busch, S.F. Mingaleev, A. Garcia-Martin, M. Schillinger, D. Hermann, J. Phys. Cond Mat., in press

4:15 PM W7.7
Efficient Coupling into Photonic Crystal Waveguides in Silicon-On-Insulator. N. Moll and G.-L. Bona; IBM Research, Zurich Research Laboratory, Rueschlikon, Switzerland.

The coupling into photonic crystal waveguides can be split into two parts: coupling from a fiber into a conventional ridge waveguide and then coupling from that waveguide into the photonic crystal waveguide. We computationally investigate the latter coupling problem for a three-dimensional photonic crystal slab and a two-dimensional photonic crystal. The particular system we study is the butt-coupling into a waveguide in a photonic crystal slab where the slab consists of a silicon-on-insulator (SOI) substrate with a triangular array of holes. The slab system only supports a small range of frequencies in which a guided mode exist. In this frequency range, the coupling efficiency is comparable to that of the two-dimensional system, and its value is around 0.8. For the other frequencies, where for the slab system only resonances exist, the transmission is much lower as that of the two-dimensional system. We conclude that complete three-dimensional computations have to be performed to obtain quantitative results for photonic crystal slab systems.

4:30 PM W7.8
Aperiodic lattices in a high refractive index contrast system for Photonic bandgap engineering. Subhasish Chakraborty[1], David G Hasko[2] and Robert J Mears[1,3]; [1]Engineering, Cambridge University, Cambridge, United Kingdom; [2]Physics, Cambridge University, Cambridge, United Kingdom; [3]Nanovis LLC, 189 Wells Ave., Newton, Massachusetts.

Engineering of the photonic band gap to study localization of the electromagnetic field has become an active field of research in the past few years. Most work has been done on periodic photonic lattices with single defects. In this paper we demonstrate that aperiodic photonic lattices are the best platform for the field localization study. It is highly unlikely, however, that a randomly chosen aperiodic lattice will have any useful transmission characteristics, either in terms of its use for WDM systems or for photonic integrated circuits. In particular, as the number of scattering sites is increased, it is computationally difficult to identify /useful/ aperiodic lattices. Using discrete Fourier Transform methods, which are more common in the area of signal processing, we have developed a technique to generate /useful/ aperiodic lattices for photonic applications. We have used a high refractive index contrast system (i.e. silicon on insulator, for which $\Delta n \approx 2$) to realize such aperiodic lattices for photonic application. A wide variety of structures have been designed and fabricated using high-resolution electron beam lithography and pattern transfer techniques. In particular an optimal etch strategy is devised for the fabrication of high quality optically smooth photonic microstructures. Propagation characteristics of such waveguides in the 1550nm wavelength region have been evaluated using the Fabry-Perot resonance method, demonstrating low-loss [better than 5 cm^{-1}] and the potential for large engineered dispersion. Transmission characteristics of these novel aperiodic structures have also been evaluated using state-of-the-art simulation tools, which demonstrate the huge potential of these structures for a wide variety of applications in photonic integrated circuits and for novel photonic devices.

4:45 PM W7.9
Abstract Withdrawn