SYMPOSIUM W

W: Engineered Porosity for Microphotonics and Plasmonics

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*Invited paper
Porous Silicon – a relaxed view of the status quo.

Frederick Kohl,* Wink Department, Technical University Munich, Garching, Germany.

Remember the hot debates on what makes porous Si luminesce only a few years ago? It’s remarkable, given how 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 parameter Porous Si lifetime. 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 becomes coherent Auger damping has impaired the prospects of achieving actively light emitting devices. Only incorrigibles are pursuing the concept of the Si nanoparticles-based laser. There is all the more effort under way to develop porosity-engineered microstructures with unique optical properties. In particular, those based microscopically etched nanoparticles with their giant birefringence [Opt. Lett. 26, 1265 (2001)].

Photoluminescent porous silicon (PS) pixels of sub-micron dimensions are produced by patterning sub-micron diameter Pt lines onto Si before subjecting it to etching. Porous silicon (PS) can be produced by metal-assisted electroless etching, i.e., non-electrochemical, etching of Si (100) in a solution of methanol, HF and H2O2. A thin layer of Pt (d ~ 30 Å) is patterned onto the surface prior to immersion in the etching solution. Unlike conventional fabrication methods, PS formation takes place in a few seconds without use of electrical bias or illumination. Exciting the PS 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 PS 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. The resolution 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 photoluminescent pixels.

Phonon Band-Gap Structures, Natalia Tokmakov, Andrew Stolkewek, Bai Xu and James Castracane; School of NanoScience and NanoEngineering, University at Albany (SUNY), Albany, New York.

Phononic 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 phononic crystals because of the availability of a variety of silicon microstructures and thin films. One-dimensional phononic 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 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 freestanding structures with 50-200 nm thick layers must be used as DBRs, Fabry-Perot resonators or coupled microcavities being fabricated. These structures are coated with photoresist on their back sides to increase mechanical strength and at the same time maintain flexibility. In this work reflection spectra of reflection spectra of 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.

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 functionality 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 performance and anticipated 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.


The surface roughness of thin film phosphors in one of the factors that affect the brightness of phosphor-ceramic 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 is 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 control the roughness of the thin film phosphor. 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 fabrication of porous silicon layer. The thin films were grown on bare and porous silicon surfaces at various roughness values, following 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.

Laterally Graded Rugate Filters in Porous Silicon, Erik Ros and Terje G. Fronland; Department of Physics, University of Oslo, Oslo, Norway.

Rugate optical reflectance filters with a position dependent reflectance peak in the vis-NIR were realized on porous silicon (PS) using laterally graded rugate filters in PS produced by indirect 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 sidelobes compared to discrete layer filters. As starting point for the graded filters we designed and made a rugate filter with a peak reflection at 636 nm at 19 deg. incidence.
11:00 AM W1.7
Strong light-matter interaction in microporous Si photonic structures: Gilles Lecercle, Peter Reece, Aurélien Bruyère and Mike Gnil. School of Physics, University of New South Wales, Sydney, New South Wales, Australia; Laboratoire de Nanotechnologie et Instrumentation Optique, UT2, Troyes, France.

We recently reported the fabrication of Si based sub-wavelength linewidth microwindows and perfect mirrors. The structures are made of microporous silicon by electrochemical etching. The resonant structure high quality (Q > 5000) and the observation of omnidirectional stop bands have been made possible by the optimization of the starting material, etching conditions and structure design. We shall in this paper discuss in more details the choice of these parameters considering the material intrinsic limitations.

11:15 AM W1.8
Optical device based on anisotropic nanostructured Silicon: Joachim Diener, Nicolas Kuenzler, Egon Gross and Dmitri Kovalev. Physik Department El 6, Technische Universität 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 nanostructures 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 quasistatic distribution is sufficient for specific applications where the dimensions of both, holes and skeleton structures 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. Anisotropic optical nanostructuring is particularly useful 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. 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 microwindows [5,6] and polarizers [7]: Physical characterization of the anisotropy requires the reduction of a cubic lattice symmetry. In-plain 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 propagation 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. 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 microwindows [5,6] and polarizers [7].

11:30 AM W1.9

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 thin film (scattering 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 additional metal nano-particle 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 processes. An InAs quantum dot (QD) wafer is used. A 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 μm, we demonstrate a strong field enhancement in the sensing volume as small as 100x, 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 microwindows formed from Al-silicon photonic crystals: Denis G. Gusev, Irina V. Shchukina, Mikhail G. Martemyanov, Tatiana V. Dolgova, Andrei A. Fedyanin and Oleg A. Aktsipetjans. 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 microwindows coupling through additional photonic crystal, the optical response is controlled by variation of parameters of this Bragg reflector. The modes of coupled microwindows (CMC) are split with spectral (angular) gap between them determining by interaction Bragg reflector transmittance. This paper presents the observations of second and third-harmonic generation (SHG and THG) resonant enhancement in Al-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 (100) wafers. The core size is controlled by the variation of the current flowing through the wafer perpendicular to its surface. Two identical half-wavelength-thick cavity microwindows 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 MCG’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 split microwindows, which is controlled by the reflectivity of the intermediate Bragg reflector. The SHG intensity and THG intensity enhancement is observed at the resonance of SMC and CMC modes. Angular splitting of the peaks in the SHG and THG spectra show monotonous dependence on magnitude of coupling between microwindows. The basic mechanism of the SHG and THG enhancement is localization of the fundamental field inside the microwindows, which results in the increase of the amplitudes of the SH and TH fields generated inside microwindows. 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, maximum 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.
Three-dimensional photonic crystals are complex structures with submicron minimum feature sizes when active in the infrared. These structures utilize light at wavelengths on the order of nanometers, and their properties are controlled by surface-based or planar fabrication processes. These engineered devices have truly unique features. In particular, we have experimentally demonstrated that optically active photonic crystals can exhibit photonic bandgap behavior and generate critical electronic interferences, such as laser lights or the use of photonic crystals in the semiconductor fabrication lines. They are used for the manipulation of light at the nanoscale level and can be used for a wide range of applications, including optical communications, data storage, and sensing.

### 2:15 PM W2.2 Control of Surface Plasmons Emitted from Arrays of Subwavelength Apertures, Gohar Zbib, Brian S Dennis and Dimas Egorov. This work was sponsored by the Department of Energy under contract DE-AC04-94AL85000.

Conventional metallic nanostructures can strongly scatter light in a broad spectral range. The use of subwavelength metallic nanostructures can lead to enhanced light-matter interactions, which can be exploited for various applications. Using a sophisticated approach, it has been shown that the coupling of surface plasmons with the photonic crystals allows for the control of the emission of light from these structures. This work was motivated by the need for improved light-matter interactions in photonic crystal devices, which can lead to enhanced functionalities.

### 3:00 PM W2.3 Waveguiding Components Utilizing Surface Plasmon Polariton Band Gap Structures, Sergey I Bozhevolnyi. 1 Unived Montereoy, 2 CISESE, San Nicolas de Los Garza, Nuevo Leon, Mexico; 3Physics Institute, Aalborg University, Aalborg, Denmark.

Surface plasmon polaritons (SPPs), i.e., collective oscillations of surface charge density, represent quasitwo-dimensional waves. Associated with SPPs, there exist electromagnetic fields propagating along the metal-dielectric interface and exponentially decaying perpendicularly 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 a periodically corrugated metal film can diffract and reflect by surface features and interfere. These properties are closely exhibited in the case of elastic (in the plane) SPP scattering. Usually, elastic scattering of SPPs and related phenomena have been measured because of randomly distributed roughnesses. 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-lenses, micro-mirrors, and electronic band gap structures were demonstrated. Furthermore, the 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 can gain more understand of this context involving 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 out by means of numerical simulations. Here we report the results of numerical simulation of SPP beam splitter and interferometer. The numerical approach is developed employing a vectorial model for multiple scattering by surface nanoparticles via surface plasmon-polariton interactions. We investigated in detail the overall process 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 2D SPP beam splitter, the feasibility of fabricating an interferometer was correlated. The results obtained are in good agreement with experimental data available in the literature. 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.
Subwavelength Structured Optical Elements and Resonant Grating Filters. K. Nakatani, T. Komine, A. M. Rappe, H. Toyoda, Y. Wu, 1 College of Engineering, Osaka Prefecture University, Sakai, Osaka, Japan; 2Osaka Science and Technology Center, Izumi, Osaka, Japan.

Subwavelength structured (SW) surfaces are attractive for new optical elements. The subwavelength structure has the following optical features: artificial refractive index, form birefringence, resonant gratings, and mode interference. In this presentation, we introduce some SW elements that describe guided-mode resonant grating filters with different structures. Antireflective structured (ARS) surfaces were fabricated on a fused silicon lens. To obtain a high aspect structure, a micro-corrugated array 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 side edges, the resultant surface profile becomes a micro-corrugated array with a smooth top. We also fabricated an achromatic form-birefringe waveplate and an array of form-birefringe waveplates. This waveplate array is used for imaging polarimeter. 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) narrowband 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 double periodic 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.

Multiband Far-Infrared Metallodielectric Photonic Crystals. Fisher P. Ma, 1, 2Kim-Bong Hong, 3Hong-Joon Yoo, 3Donovan H. Werner, 1 and Theresa S. Mayer 1.

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 double-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 polymer substrate. The MDPCs that we investigated consist of arrays of single- or double-layer fractal cross-dipole 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 fractural 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 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 and metallic loss, as well as 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.

Thermal Conductivity by Phonon-Polaritons in Photonic Crystals and Nanoporous Media. Vitor Rafael Coluccio 1,2, Anshu A. Zakharov 3,4, and Vladimir M. Agalov 4,5

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 excitons. In this region, a broadening of some SW elements we describe guided-mode resonant grating filters with different structures. Antireflective structured (ARS) surfaces were fabricated on a fused silicon lens. To obtain a high aspect ratio structure, a micro-corrugated array 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 side edges, the resultant surface profile becomes a micro-corrugated array with a smooth top. We also fabricated an achromatic form birefringe waveplate and an array of form birefringe waveplates. This waveplate array is used for imaging polarimeter. 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) narrowband 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 double periodic 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.

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simple cubic lattice. Such a structure can be obtained when the modulated pores are arranged in a 3D quadratic lattice and the pores are arranged hexagonally arranged to obtain the interconnected network of air spheres. Bandstructure calculations show a complete 3D gap with a maximum width of 3.5 eV. Recently a totally new structure was proposed consisting of the originally electronically etched hexagonal arranged straight pores and a second hexagonal pore set orthogonal to it. The resulting interpenetrating 3D network of air pores in siliccon represents a 3D photonic crystal with tetragonal unit cell. A groupmap for different porosities was determined and revealed a maximum gap of 200 nm. This 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 nm wavelength.

9:60 AM W3.2 Periodically Arranged Point Defects in a Twodimensional Photonic Crystal - The Photonic Analogue to a Doped Semiconductor. Stefan Richter, Stefan L. Schweizer, Cecile Jamin, Ralf Boris Wehrspohn, Merge Zeljkovic and Ulrich Gossele, Exp. Dept. 2, Max Planck Institute of Microstructure Physics, Halle, Germany.

The concept of a photonic crystal is the optical analog to a semiconductor. The generated dispersion relation for photon 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, the photonic band gap. These defect states allow spatial confinement and guiding of light. We present studies on hexagonal point defects in a twodimensional photonic crystal consisting of microcavities. These point defects are prepared periodically by lithography and form a superlattice 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.


The Jahn-Teller effect in photonic crystals as a prototype of photon-photon interactions is studied. We are interested in removing the degenerate electronic state due to vibronic coupling. The wavefunction of a photonic crystal is determined by the symmetry of the B1 and B2 modes. Using the value of the vibronic constants, 50 nm above the well lattice 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 Core. Xin Wan, Shaowei Li, Zhiyi Shao, Jing-Wei Micke, Xinman 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 material in the core of the waveguide. The high index core material is SiO2 or air, while the index of the cladding is still Si. The PBG waveguide is suitable for CMOS technology. Potential applications include optical amplifier when doped with optical active materials (e.g. Er) for SO2 core, optical switching or optical modulator when electro-optic or thermo-optical effects are induced to the hollow core cavity.
The thermal conductivity of various inverse opal photonic crystals (PC) has been measured in the temperature range of 10-100 K using transient pulse method and compared with that of homogeneous bulk parent materials. The thermal conductivity of PC is dependent on the formation of porous silicon, with different fillers having been fabricated by templating of porous silicon on different materials: CVD graphite, pyrolytic amorphous carbon, epoxy resin, biomaterials, and other metals. The suppression of thermal conductivity in periodic nanostructures of surface silicon 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 far, as in case of glass fiber wall PC thermal current flow through 100-nanometer-thick layers of graphite sheets is observed on spherical surfaces of empty overlapping spheres. Arrays in face-centered cubic lattices have been analyzed to allow for the nonuniform effect in the periodic array of spheres, i.e., in direct opal PCs.

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It has been found that the thermal conductivity of inverse opal is limited by heat flow across the by-sintered gap, with the total value of thermal conductivity, $\lambda_{\text{total}}$, ranging from 0.38 W/mK. The effect of heating the porous matrix of inverted opals with various liquids on their thermal conductivity is also studied.

11:30 AM W3.9
Optical and Crystallographic Properties of Inverse Opal Photonic Crystal Paper, Absorbed Layer Deposition
Authors: Jeffrey Steenleton King, C. Neff, D. Heineman, S. Bokumstek, E. Forsythe, D. Morton, E. Graugnard, and C. Summers
Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; Army Research Laboratory, Adelphi, Maryland.

We report a new technique for the formation of inverse opal structures that produce high quality, low porosity conformal material structures. Monodispersed silica spheres of sizes 150-400 nm were used to make monodispersed 30 nm-thick opal films by depositing the spheres in a modified confinement cell, followed by sintering. High-index material was deposited into the void space of the opal lattice by atomic layer deposition. Infiltration of ZnS:Mn, ZnS, and TiO$_2$ were studied, with conventional spectrophotometry 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. ZnS:Mn, ZnS, and TiO$_2$ infiltrations revealed photoluminescence from the opal film. The colloidal ZnS:Mn, amorphous and films deposited at 500°C were primarily amorphous as confirmed from X-ray studies. The effectiveness of a post-deposition heat treatment in recovering the photoluminescence from the opal film was studied, since the rutile phase exhibits a higher refractive index than amorphous material. Multilayered infiltrations are currently under study, as well as other materials.

11:45 AM W3.10
Ionic Colloidal Crystals: Attractive Ordered Binary Colloidal Assemblies Controlled Heterocoagulation
Garry R. Maksak, R. Edwin Garcia, W. Craig Carter, and Yet-Ming Chiang
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Ionic colloidal crystals (ICCs) are here defined as ordered multicomponent colloids formed by attractive electrostatic interactions. In contrast to previous approaches to colloidal coagulation, the ICC approach holds the potential for the rapid self-assembly of a wide range of structures similar to that seen in ionic colloids naturally. These structures are difficult or impossible to produce by other methods. Of particular interest is the zinblende 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 size, 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 amine (positive surface charge) suspended in 2-propanol. Experimental results and structure of 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 Bozhkovshy
Wednesday, December 3, 2013
Room 204 (Hyne)

1:30 PM W4.1
New Lensless Imaging of 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 fundamental 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. Peter G. Kil, Stefan A Maier and Harry A Ateawa; 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$_x$Si$_{2-x}$N$_4$ bilayer. In particular, we have shown that placing a finite width oscillating point dipole source near the surface of such a bilayer can induce a coherent superposition of surface plasmons on 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 of 2 when the interface was excited at the surface plasmon resonance. To experimentally verify these predictions we have deposited 30 nm-thick silver/GaAs$_{2-x}$N$_x$ bilayers onto free-standing 30 nm-thick silver/nitride films. Silver depositions were performed at liquid nitrogen temperature to prevent dewetting of the silver. The resulting freestanding Ag$_x$Si$_{2-x}$N$_4$ bilayers support localized surface plasmons at the silver/nitride interface when excited at a frequency of 4.75 x 10$^{10}$ rad/s, corresponding to a free-space wavelength of 480 nm. To generate an oscillating dipole source near the surface, we couple 480 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$_x$Si$_{2-x}$N$_4$ 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 scatters in the image plane. By monitoring the transmitted intensity in a fixed 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 8 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 Lamer Moore, STC, Georgia Tech Research Institute, Atlanta, Georgia; 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 for transmission are used to predict the effective permittivity and permeability of the composite and such analysis lends 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, fracture/periodated conductive filaments, and Si arrays of conducting elements display intense electromagnetic field localization. Such 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 diffusion scattering and modulated spectral transmission and reflection. A second analysis presents exact computational finite difference time domain and numerical simulation calculation. The incident field reflection and transmission of finite dimension and plane periodic crystals (both dielectric and conducting) that have small constitutive and/or geometric errors. The simulations in linear and far field transmissions are applied to infer expected error 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 with non-periodic materials. Recipient of the Office of Naval Research, N00014-01-1-0318 and the MetXmations Program through AFRL / MLIB Contract F33615-01-C-0023.

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) defects. 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 be used to trace the flow of light and the geometry simultaneously is therefore highly desirable. 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 point-like 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, Koshi Amano, Marko Loncar, Tomoyuki Yoshih and Axel Scherer, Electrical Engineering, California Institute of Technology, Pasadena, California.

Near-field scanning optical microscopy (NSOM) is a powerful alternative method to observe the optical intensity distribution in fabricated nanometre scale structures. Some papers have reported NSOM images of plane photonic crystal (PPC) structures. However, high spatially resolved near-field images of the field distribution inside the PPC nanocavities have not so far been reported. Here, we show the smallest optical modes obtained by NSOM on high-quality (Q) factor PPC nanocavities. The PPC nanocavities were fabricated in active InGaAs quantum well materials. High-Q cavity modes are defined by fractional edge diodes in triangular lattice PPC structures with different defect air hole sizes (r), at the position of maximum field intensity. The r/a parameters were changed from 0 to 0.18 (a periodicity of the lattice). We have measured Q factors of Q=3,600 and realized lasing 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 measurements, we used the metal-coated fiber tip with small aperture and miniaturized lenses. The NSOM images of plane photonic crystal (PPC) structures. 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 nanocavities have small mode volumes as expected from our modeling. The size of the bright spot, probed from the nanocavity with r/a=0.18, was roughly four by three lattice spacing. On the other hand, spot size in nanocavities with central hole size was as small as expected 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. Swenlock1, Stefan A. Maier2, Jean J. Penninkhof2, Albert Polman3,4 and Harry A. Atwater1; 1Thomas J. Watson Laboratories of Applied Physics, California Institute of Technology, 2FOM Institute for Atomic and Molecular Physics, Amsterdam, Netherlands.

Noble metal nanoparticles interact strongly with light at the resonant 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 A, such particles couple to one another via electromagnetic near-field interaction. These coupled arrays exhibit collective modes, whose frequency is significantly smaller than 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 Si/Al 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 multiple 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. We obtain a red shift of the plasmon extinction peak of greater than 1 eV is observed experimentally in these samples, which is ~2.5 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 FlipOff Dependence Of Spectral Emission From A Multilayer Porous Geometric Photonic Crystal, Iman Lee1, Pralle3,2, Mark P. McNeel1, Nicholas Moeller2, Anton C. Greenwald1, Alan Ludwicewski1, James T. Daly1, Edward A. Johnson1 and William L. Schneider2; 1Ion Optics Inc., Waltham, Massachusetts; 2Ion 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 performed by a periodic arrangement of thin metal strip extending into the Si substrate and each side of series on the wavelength of the light. This performed 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 spatial response is highly dependent on the design of the radiation. The positions of the main resonances, for both reflection and emission from our structures, scale linearly with the periodicity of the metakdielectric structure. As one moves off normal incidence, a simple model resonance splits into a number of smaller resonances. The 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 insights into the physical mechanisms that control the radiation pattern. 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 Microscopy, Aurelien Bruyant1, Sebastien Aubert2, Gilles Lerondel3, Sylvain
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 P.M. Wd4.9 Near-field photoluminescence spectroscopy of microcavities and coupled microcavities, Oleg Vladimirovich Ledobor, Anton Iogrech Madykowska, Irina Shchelyn and Oleg Andreevich Aktsipetrov, Physics, MSU, Moscow, Russia Federation.

Photoluminescence spectroscopy of porous silicon photonic crystal microcavities and coupled microcavities is studied by the far-field and near-field techniques using the scanning near-field optical microscope. Nearfield 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. Nearfield spectra of coupled microcavities are consisted of two microcavity modes. To increase the photoluminescence signal photonic crystal microcavities and coupled microcavities are doped by fluorescein 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 signal for microcavity with the mode of 380nm 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 the resonance modes to the red of optical spectra on 40nm. Porous silicon shifts maximum of fluorescence of dye molecules to blue range of optical spectra on 50nm. Homogenous 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 10nm 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 (Hyne)


We have demonstrated a simple and convenient process for the large-scale synthesis of monodisperse colloidal titania with an controllable diameter ranging from 200 to 500 nm. These monodisperse colloidal spheres were successfully prepared without any assistance of surface modifiers by controlling the hydrolysis of titanium glycolates in methanol at room temperature. These uniform spheres could assemble into 3D crystals with interesting optical properties. After calcining these monodisperse colloidal titania at elevated temperature, different phases of titania (anatase, rutile and mixed) 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 microscopy techniques) of these monodisperse colloids, as well as self-assembly into photonic crystals.
enhanced electromagnetic field intensity confined to the surface region and propagating in specified directions in the plane as well as the characteristic manifestations of propagating radiation of microcavities of nanoscale dimensions. The field reduces in the simulation closely match the experimental observations in the SP modes 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 a distinct ring that coincides with the end of the nanowire, precisely matching the experimental observation [1]. The latter mode exhibits two separate jets, but when the sample is rotated 5 degrees, one of these is largely extinguished, and the spot size increases with the experimental observation. We further employ the FDTD method to examine the dependence of the SP intensity on the high density. This dependence, which is nonmonotonic, will be discussed. [1] G Blumberg, B.S. Dennis, and D. Eigerman, abstract this meeting.

W5.6 Optical Transmission through Micro-scale Periodically Capacitive Metallic Grids, Yonghong Ye, Center for Nanoscience Devices, The Pennsylvania 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 Catanato nanolithography. 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 Timofeevski, Dmitri Kostylev, Leonid Golovan, Alexei Brikov, and Pavel Konstantinovich Krasnov. Physicists Department, Moscow State University, Moscow, Russian Federation; Physics 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 line-by-line and non-linear optical properties of the electrochemically prepared porous Si (PSi) layers. These layers are assembled from Si nanocrystals and nanoparticles 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 the anisotropy of the pore propagation the symmetry of the optical susceptibility of Si is drastically reduced in comparison to the isotropic optical properties of bulk Si. This finding results in a variety of novel photonic applications of PSi. For instance, structures of PSi multilayers with alternating regions show high electric field in the PSi layer. Additionally, our experiments demonstrate possibility to reach phase matching conditions for polarization-dependent second-harmonic generation in PSi layers. Optically anisotropic 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 angle 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 immunoselected ensembles of anisotropically formed 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 Nij and Jean Teouve. 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 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 the cladding intact. 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, Donald W. Ward, Eric D. Beers, Nikolai Noskov, Thomas Feuerer 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, LiNiO3 and LiTiO3 of 1-2.50 micron thickness. We demonstrate that a ferroelectric crystal in this thickness range behaves as a slab waveguide for phonon-polaritons. Further, we show that the ferroelectric crystals in this size regime are amenable to processing by ultrashort 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 Ti-Re 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 better than 50 GHz. 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, Ching Huen Kong, Ze Xiang Shen and Sing Hau 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 \( \lambda = 1.064 \mu m \). 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 4-c face of the 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 to use any photoresist. 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 crystal.

W5.11 Creation and Optical Property of Microphotonic Crystals by Electrodepositional Method Using Micro-counter Electrode, Kiyoshi Katsurara, Jun-Ichi Hamagami and Kazushiro Hasegawa; Department of Applied Chemistry, Tokyo Metropolitan University, Hachioji, Tokyo, Japan.

In order to create micrometer-scale functional materials or devices we have been investigating on development of a novel electrodepositional deposition (EPD) method using a microelectrode as a counter electrode in the EPD system. This method is so-called eµ-PED method. The eµ-PED method was applied to prepare micro colloidal crystals consisting of monodisperse polystyrene (PS) particles for photonic microtens for microphotonic materials and/or devices. Scanning electron micrographs of the prepared specimens under the optimized eµ-PED preparation parameters showed a fibrous structure of microtens 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 microtens, 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 microtens exhibited a narrow absorption peak rather than the microscopic spectrum. The absorption peak at 600 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 this results, it can be said the microphotonic crystals with defect-free sphere arrangement has been prepared by
Photonics or photonic band gap materials [PBG] have been the subjects of intensive theoretical and experimental researches. The photonic crystals and microcavities are used in 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 microcavities can be infiltrated into interconnected nanocavities formed from 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. [23] 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 scales at the direction of the crystal. This could be a kind of tunable optical filter based on the position variation. The optical properties and potentials for other optical applications were investigated. [1] E. Yablonovich, Phys. Rev. Lett. 58, 2020 (1987); Y. Arakawa et al. J. Lightwave Technol. 18, 977 (2000) M. Orlita, Y. Shioda, M. Kameo, K. Yoshino. Adv. Mater. 2002, 14, 514 [Y. Koike, T. Ishigake, E. Nishi, J. Lightwave Technol. 1995, 137, 1475

W5.13

Narrow Two-Dimensional Photonic Band Gaps for SBA-15 Structure But With High Index Contrast. Chongzhu Liu1, Yun Ying Wu1, Osamu Tkaki2 and Yoshitsune Masuda1. 1Tkaki Lab, Center for Integrated Research in Science and Engineering, Nagoya University, Nagoya 464-8603, Japan; 2Department 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 of 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 in which we calculate and observe a few-nanometer PBG in SBA-15 ordered mesoporous materials. The structure with a narrow PBG is similar with SBA-15 "geometric" structure but with back ground dielectricity (dielectric constant ε more than 12.0) instead of siliceous (ε near 2.5) surroundings. The width of the gap is 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 (θ) and the dielectric constant (ε). The gap locates at f = 0.313 (at λ = 520 nm, for f = 0.5), f = 0.30 (at f = 0.383 nm, in the visible X-ray region) and the width (full width at half-maximum) is 0.5 nm (around single frequency). Noting that f is a non-dimensionalized frequency, if f = 200 nm, then the corresponding PBG wavelength is about 630 nm (in the visible spectral region) and the width is only about 8 nm. This work is supported by JSPS - RFTPF99R13101 and the 21st Century COE Program "Nature-Guided Materials Processing".

W5.14

Penrose Quasicrystal Pattern on Metallic Microcavity. Jen Yi Yang1, Hai Lam Tran2, W.H. Wong3, Y.B. Pun1 and Kok Wai Cheah4. 1Department of Physics, Hong Kong Baptist University, Kowloon Tong, Hong Kong; 2Department of Electronic Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong.

Most photonic crystal structures currently used on microcavities are cubic or hexagonal, where folding symmetry is less than six and these photonic band gaps are generally weak and insensitive to the microcavity parameter. In this work, we fabricated metallic microcavity with Penrose quasicrystal pattern that exhibits 15-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 angle of incoming light beam. Luminescence material such as triethylsilane, (Alq3) embedded in the microcavity, coupling of photonic mode to luminescence can be observed. Clear photonic bandgap exists in the emission luminescence spectrum, and the intensity 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 of nanodot assemblies to different 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 quasiperiodic pattern.

W5.15

All-Optical Tuning of the Extinction Spectra of Metal Nanoparticle Arrays Using Highly Birefringent Photoaddressable Polymers. S. Mien1, E. Kehs2, M. S. Deardorff3, J. E. Hugan3, S. Kurotmine3, A. Polman3, 4 and Harry K. Awater. 1Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California; 2FOM Institute for Atomic and Molecular Physics, Amsterdam, Netherlands; 3Huygens 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 delay elements in integrated optical devices. Photoaddressable polymers (PAPs) show considerable potential for these applications. Unusually large birefringences of Δn = 0.6 at 600 nm can be optically written in amorphous conditions, and PAP films have the potential to undergo more than 8000 optical 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 850 nm. This induces photoreorientation cycles of the nematic mesoects, 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 non-absorbing range of 650 - 1700 nm, with Δn values greater than 0.25 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. Micromachining 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 optical microscopy will also be discussed. 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


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 propagating 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 dimensional scaling and the nanostructured components are much smaller than the wavelength of visible light, concepts and methods from microscale electronics 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 microelectronics of nanostructured media which establishes rigorously the connection between the wave propagation phenomena and the underlying electronic processes. We span the theory to electromagnetic energy transport through plasmon waveguide consisting of closely spaced metal nanoparticle chains. We give the microscopical 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, Rodney Lorimer Moore, G. A. Grady3, Edward P. Looke3, Diane M. Stankiewicz3,** STL, Georgia Tech Research Institute, Atlanta, Georgia, 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 a photo assisted self-assembled multi-layer polyelectrolyte array containing metal nanospheres. The multilayer 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-assembling protocol. Metal nanoparticle 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 multi-phase material composed of low volume fractions of dispersed metallic clasts (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 bimetallic 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 Franz Preble, Carlos Angelo Barrios, Roberto Ricardo Pappone2, Michael Lipson1, 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 260um or less. The MZ consists of coupled resonator optical waveguides (CROWs), which significantly lower 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 320 nm and 450 nm, respectively. The entire structure is less than 250um in length. The refractive index is shifted in only one arm of the MZ, inducing a phase mismatch at the output. We show that with a refractive index change of 0.3% the shift of the first order output wavelength is 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**, I. Neohag, Michael Brett and Jeremy Sir, 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 nanostructure. In this technique, the incoming physical vapor flux arrives at the substrate at highly oblique angles, typically between 80° and 90° with respect to the substrate normal, resulting in a highly porous thin film composed of well-separated, isolated columns. Several research groups have examined means for tailoring the microstructure of GLAD produced films, including substrate rotation and variation of the angle of the incoming flux 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 MgF2 and TiO2 using variable angle spectroscopic ellipsometry, a particularly unique technique for this study, since it enables measurement of the dispersion relation of the index of refraction. The tilted columnar film structures resulting from GLAD are shown to have three principal refractive indices and the birefringence. As the tilted columnar films form the basis for many 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].

**W5.20**

**Anodization Time Dependent Photoluminescence Intensity Of Porous Silicon, I. R. Islam, ISRO, Ahmedabad, Gujarat, India.**

Visible photoluminescence (PL) is 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 photovoltaic and electronics [1]. 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 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 under anodization may be measured by the refractive indices 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 increase in the intensity 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. PS layers prepared under ambient light illumination exhibit the similar behaviour. The intensity variation with ta was explained as the interplay of thickness and porosity variations with ta.

**W5.21**

**Tunable Fabry-Perot Fibres, Gilles Benoist1, Shandon D Hart1, Burak Temelkuran1, John D. Joannopoulos2 and Yoel Fink1,** 1DSME, MIT, Cambridge, Massachusetts; 2Physics, MIT, Cambridge, Massachusetts.

The fabrication of tunable optical devices is of fundamental importance in the areas of communications and sensing. Here we demonstrate the design, fabrication and characterization of a mechanically tunable dielectric Fabry-Perot fibre cavity. The fabrication of these devices relies on the use of a variety of passive and active applications requiring high quality factors and small modal volume. Furthermore, their intrinsic flexibility allows for the incorporation of these devices into fabrics.

**W5.22**

**Resonance enhanced fluorescence in photonic crystals studies by near field technique**, Anton Igorevich Malykivski, Oleg Lebedev, oleg Aktsipetrov and Trina Scholven, Physics, Moscow State University, Moscow, Russian Federation.

The spatial distribution of the local optical field in the photonic crystal microwaves formed by porous silicon is studied by apertureless scanning near-field optical microscope. Samples of one-dimensional photonic crystal and micron-size array fabricated from highly doped Si (001) wafer by electrochemical etching. The structure of microwaves layer and two Bragg reflectors. The image of the spatial distribution of optical field at the center of the electric dipole is observed in near-field scattering. To increase fluorescence density these photonic crystal are doped by fluorescence dye Rhodamin 6G. The wavelengths of the microwaves color are optimized for maximum of dyes spectra. The fluorescence characterizations of the microwaves 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 microwave layer. The generated fluorescence in microwave layer up to 100 times increasing with
Nonresonance case.

W5.23

Negative Refraction and Nonlinearities at Optical Frequencies by Exciton-Polaritons in Molecular Meta-Materials. Arvex Zakhidov, Vladimir M. Agranovich, Ron Y. Shen.

The negative refraction (NR) has attracted great interest after its experimental verification in microwave frequencies using arrays of split ring resonators (SRR). NR is presently associated with two classes of nonlinear metamaterials (LHM), which have simultaneously negative ϵ = ω_1 and μ = ω_2. This paper presents NR in the region of the energy bands, e.g., close to photonic band gaps. In this presentation, we will review the physical concepts that allow us to extend the phenomena of negative refraction to optical frequencies and suggest several types of metamaterials 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 also exist in 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 would prohibit existence of LH at optical frequencies. Dipole electric and magnetic polarization as well as quadrupole polarization strongly contribute to spatial dispersions near exciton resonances being responsible for the appearance of additional electromagnetic waves which can have a negative refractive index and a negative group velocity. The evidence for this is given in an experimental and theoretical presentation of new electromagnetic 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 every 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 inorganic (organic and inorganic) materials with high exciton resonances and investigation of additional electromagnetic wave propagation near resonances with negative electromagnetic wave velocity is discussed in detail.

W5.24


A bottom-up approach for fabrication of a two-dimensional photonic crystal structure consisting of high-refractive-index columns in air is demonstrated. Conventional methods of building blocks. By using a bottom-up method it avoids many of the difficulties present in top-down etching of bulk materials that is the currently dominating fabrication method. An electron beam lithography (EBL) technique is used to pattern the III-V nanowires with ion beam etching of the growth of III-V nanowires. Vertical <111>-oriented nanowires are grown on silicon substrates using metal-organic vapor phase epitaxy (MOVPE).

W5.30


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 resilient to disorder than others. These points can be found by examining the band gap map for the points which are least likely to be transmitted. Some points, the structure is not only more 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. These random changes in band gap strength can be explained in terms of distribution 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.

SESSION W6: Photonic Crystal II

Chair: Axel Scherer
Thursday Morning, December 4, 2003
Room 204 (Hyers)

8:30 AM W6.1


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 reviewing the different techniques of silicon-based photonic crystals (microcavities, microcavities, inductively-coupled-plasma (ICP) etching of buried Si/Ge/Si waveguides and reactive ion etching of silicon-on-insulator (SOI) substrates), we will focus on the combination of Ge/Sl self-assembled quantum islands and SOI photonic crystals. We show that the room temperature 1.3-1.55 micron emission from Ge/Sl self-assembled islands can be significantly enhanced in photonic crystal microcavities. The investigated structures are obtained as follows. The Ge/Sl island layers are first deposited on a SOI substrate which is then processed to get a two-dimensional photonic crystal. We also present the defect microcavities. A laser-like emission is observed under optical pumping at room temperature in these devices. This emission is characterized by a threshold as 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. microcavity-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
High Speed Photonic Crystal Nanolasers, Temoyuki Yoshie, Marko Loncze, Yueming Qin, Oleg B. Shchekin, Hao Chen, Dennis G. Deppe and Axel Scherer
Electrical Engineering, California Institute of Technology, Pasadena, California
In situ Technology and Experiments Systems Section, Jet Propulsion Laboratory, California Institute of technology, Pasadena, California
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 (QW) and quantum dot (QD) gain material. The photonic crystal lasers showed very low thresholds - as low as 0.12mW and 0.22mW for QD-photonic crystal laser 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 tunability. However, nanolasers have also been known to offer the possibility of high modulation speeds due to low microcavity effects. 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 available frequencies from our samples, we conducted non-stationary measurements and identified dynamic properties of photonic crystal nanolasers. High frequency modulation was observed from such measurements of QW-photonic crystal lasers with lattice constants and temperatures. We used surface photovoltage to excite lattice photonic crystal lasers 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 fitting 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 achieved only by means of our measurements. The measured oscillations are at least twice that of those of conventional lasers. This improvement is obtained because of increased photon lifetime and increased photon density in microcavities.

Biochemical sensors based on photonic crystal nanolasers, Marko Loncz, Mark Adams, Yueming Qin, Stephen Quake and Axel Scherer
Electrical Engineering, California Institute of Technology, Pasadena, California
Applied Physics, California Institute of Technology, Pasadena, California
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 laser mode. One interesting feature of our design is presence of an air hole at the cavity center, which is the structuring window. This 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 low-threshold lasers. Electroabsorption spectroscopy sources, we have demonstrated the operation of photonic crystal lasers in different solvents. Through 3D FDTD methods, we have studied the influence of the ambient refractive index on the quality factors (Q) and frequencies of the cavity modes. The Q we observed at the cavity 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 fluid. The results show that the cavity resonant wavelength is shifted by 1.2 nm when the fluid is changed from air to water. This change in the wavelength of the resonance should be approximately

Δλ ≈ 200 A/N, where N is the change of refractive index.

The simplest method of optically sensing ambient material uses wavelength shifts in the laser spectrum when the laser is immersed in 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 Δλ ≈ 1.5 nm, which corresponds to change in refractive index of ΔN ≈ 0.005. On the other hand, once we introduce optical gain into the cavity, this effect can be significantly enhanced for example with InGaAsP material, where a linewidth of emission is significantly narrower (0.01 nm) and so the cavity Q is much higher. In particular, measurements of ΔN ≈ 0.001 can be measured even in cavities with modal quality factor of 100,000. We have found that the frequency shifts depend linearly on n, as predicted by numerical analysis. The experimentally measured sensitivity of our lasers is Δλ = 1 nm when ΔN = 0.005. We have integrated lasers with lithographically predetermined sizes into large arrays of the same photonic crystal platform. These devices are particularly interesting compact multi-wavelength light sources, but we also use them for several analytes have since then time. We were able to achieve simultaneous emission from two adjacent nanolasers, at two different wavelengths, with comparable output powers. We have also integrated our sensors with microfluidic systems that can deliver pulsed volumes of analyte. This can lead towards compact and versatile "lab-on-a-chip" devices, in which many functional can be monolithically combined.

Ultra-Small Light Emitting Devices, Yoshiki Nishimura, Koichi Hayashi, and Satoshi Nakata, Electrical and Computer Engineering, the University of Texas at Austin.

The recent progress on semiconductor ultrasmall light emitting devices based on photonic crystal slabs, microdisks, microdisks, photonic molecule, etc, will be presented. Photonic crystals, uniformized modes in modified point defects, linear and nonlinear defects were theoretically calculated by the finite difference time domain method. The room temperature laser with pulsed pumping was experimentally demonstrated for these defects that have as a GaAsSb material. The room temperature cw laser was obtained with a 10 micron laser threshold. This ultrasonic threshold is partly owing to the strain relaxation effect in compressively-strained quantum wells. This effect can improve the cavity confinement near the dark edge where the whispering gallery mode is located. The beam was also investigated for GaAs system. InAs quantum-dot system, etc. For microdisks, the dependence of modal characteristics on the depth and shape of the microcavity were theoretically calculated and the correspondence between the theory and experiment was well confirmed. The fabrication of a microcavity 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 single microcavity. The optical coupling of multiple cavities with the same photonic molecule. It is expected to exhibit various selective coupling functions due to the coupling. The room temperature cw lasing and uniformized characteristics were also obtained at room temperature for 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 emission. They can be evaluated using the experimental data and 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.

Tuning Microcavity Resonant Wavelength by modification of cavity geometry in a 2D photonic crystal, Gunawidjaja Subramanian, Shyan Lin, Jonathan River, 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 wavelength multiplexing. For such applications a simple approach to tuning the microcavity resonant wavelength would prove to be very useful. We propose a new technique for tuning the microcavity resonant wavelength by modifying the geometry of the superlattice 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 superlattice while still obtaining a high quality factor.
Growth and Optical Properties of 2D Photonic Crystals Based on Hexagonal GaAs/AlGaAs Pillar Arrays by Selective-Area Metalorganic Vapor Phase Epitaxy.

Junichi Motodani, Junicho 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 epitaxy (MOVPE) grown GaAs/AlGaAs quantum wells. Square PhCs consisting of a hexagonal pillar array in the triangular lattice were selectively grown on SiO2 masked GaAs [111]B substrates with circular mask openings. Because of the evolution of the faces during the growth, hexagonal pillars with [110] sidewall 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 near-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 unit a of 5.5 μm. The result suggests few non-radiative recombination in the pillar arrays and enhanced light extraction efficiency in 2D PhCs.

Waveguiding in SOI-Based Photonic Crystals Slabs.

Cecile Janicot, Ralf B Weihrauch1,2, Christian Herrmann, Lucio Claudia Andreani3, Ortwin Hess4,5, and Ulrich Goesele1

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 structure and corresponding light distribution of bulk PhCs modes, using 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. A second study of 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 300 dB/cm above the light line, whereas they are negligible below 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 oxide layer as etch mask. First experimental characterization are compared to the numerical results.

Dispersion Engineering of Photonic Bandgaps Devices.

David M Psaltis, Cihhun Chen, Ahmed Sharkawy, Shouyun Shi, Jianusz 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 PhC photonic bandgaps 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 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 slab, that is, along an allowed group velocity of the PhC light. This 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/cm as well as a high mishandling tolerance of 9208° 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 dispersive-engineered devices, such as photonic crystal lenses, will be presented.

SESSION W7: Photonic Fibres and Theory
Thursday, December 4, 2003
Room 201 (Hynes)

1:30 PM W7.1 Dispersion Properties of Photonic Crystal Fibers - Issues and Opportunities. Zill, J., Zazo, P., Sig E. Brakke, Libor, Kristinn HÓFFI1, Jesper B Riedes1, Thomas Blom, Lars1,2, Martin Sorensen1, Thia Per Hansen1,2, Kim Per Hansen1,2, Martin Dyhendal Nielsen1,2, Jesper Bo Jensen1 and Anders Overgaard Bjarklev1.

Research center COM, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark.

1:30 AM W6.9 Improving the Efficiency of Polymer LEDs with Bragg gratings. Michael David McGeehan and Jonathan Ziebarsch, 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 holographic lithography and reactive ion etching to pattern grooves in an indium tin oxide electrode, or by using light that is vertically going through 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 collected data to determine the magnitude of the waveguide mode size 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 bulk-in Bragg grating, we have demonstrated that directional emission can be obtained by transferring energy to rare earth complexes, which emit over a very narrow range of wavelengths.
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 effective 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 that control the dispersion properties of PCFs, guided by either total internal reflection or photonic bandgap effects, and use these insights to outline design principles and generic behaviors 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. Sioshi Kawasaki, 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 1200 nm that is suitable for dispersion compensation at 1550 nm. PCFs with zero dispersion in the 1550 nm band have recently presented. 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 0.275 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/km at 1550 nm, and polarization maintaining dispersion flattened fiber. Demonstration 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 Kurki, Saundan 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, K. J. Ma, Z. P. Zheng, Y. P. Yeh, M. A. Chu, C. L. Chao and C. C. Young, 1Dept of Mechanical Engineering, Chung-Hua University, Hsin Chuen, Taiwan; 2Dept of Mechanical Engineering, Chang Cheng Institute of Technology, Taich Thatun, Taiwan; 3Dept of Mechanical & Electro Mechanical Engineering, Tam-Kang University, Taipei, Taiwan; 4Dept 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 (\( T \approx 175^\circ \)), 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 \( \mu \)m, and the air hole pitch between 12 and 14 \( \mu \)m. The fraction of air present in the samples is in a range up to around 30%. Increasing the furnace temperature over 175 \( ^\circ \), the hole size can be significantly reduced, due to the effect of strong surface tension forces. The light (\( \lambda = 1380 \) 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 Kurki1,2, Mehmet Buyindik1,3 and Yoel Fink1,2; 1Materials Science, Massachusetts Institute of Technology, Cambridge, Massachusetts; 2Research Lab of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts; 3Research Lab of Electronics, Philadelphia, Pennsylvania.

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 [highly 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 the use of glass 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,1,2 Sergei F. Mingaleev1,2, Antonio Garcia-Martin3,4, Matthias Schullinger4 and Daniel Hermann1,5; 1Institute for Theoretical Condensed Matter, University of Karlsruhe, Karlsruhe, Germany; 2H. N. Feshbach Inst. for Theoretical Physics, Kiev, Ukraine; 3Consejo Superior de Investigaciones Científicas, Instituto de Microelectronic de Madrid, Madrid, Spain.

We introduce a novel approach 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 efficient 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 nonlinearity and nonlinear effects as well as detailed investigation of various two-dimensional Photonic Crystal slabs have been undertaken. The two-dimensional Photonic Crystal slabs have been investigated and the results are presented in this talk. S.F. Mingaleev and K. Busch, Opt. Lett. 28, 619 [2003]. K. Busch, S.F. Mingaleev, A. Garcia-Martin, M. Schullinger, D. Hermann, J. Phys. Cond. Mat., in press.

4:15 PM W7.7
Efficient Coupling into Photonic Crystal Waveguides in SiO2-On-Insulator. N. Mell7 and G. L. Birkl1; 1Research, Zurich Research Laboratory, Riehen, Switzerland.

The coupling into photonic crystal waveguides can be split into two parts, coupling from a fiber to 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 P.M. W7.8

Aperiodic Lattices in a High Refractive Index Contrast System for Photonic Bandgap Engineering, Subhamish Chakraborty*1, David G. Hasko*2 and Robert J. Mears*1,2; *Engineering, Cambridge University, Cambridge, United Kingdom; *Physics, Cambridge University, Cambridge, United Kingdom; *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 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 P.M. W7.9

Abstract Withdrawn