SYMPOSIUM J

Microphotonics, Nanophotonics, and Photonic Crystals

April 22 – 24, 2003

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SESSION 1/P2Q1 / JOINT SESSION SELF-ASSEMBLY
Chair: Dr. J. Norris
Tuesday Afternoon, April 22, 2003
Metropolitan II (Argent)

130 P.M. **P2.1/Q4.1**
MULTICOMPOSITIONAL ASSEMBLY AND FUNCTION IN THREE DIMENSIONS. G. D. Stucky, University of California, Dept. of Chemistry & Biochemistry and Materials Dept.

Numerous examples exist, both biological and synthetic, of composite materials that are structurally organized on multiple length scales and dimensions. The 3-d organized molecular assembly of components that are both functionally and compositionally unique into an integrated system requires understanding of unique biological sequences in this area that are being made, as evidenced by presentations in this symposium. In biogenesis the components of the system are created via non-linear parallel self-assembly and processing. On the other hand, a new approach is to use a 3-d "living polymer" approach with distinctly defined chemical potential domains in which specific molecular assembly processes can be carried out on specified time scales. The overall system organization is then determined by the molecular definition of the interfaces between the domains. This talk will review some selected recent observations made on the 3-d molecular assembly of two or more inorganic species with distinct functionalities. The a priori simple configuration of homogeneous solutions made possible by possible electro-optical or magnetooptical composite arrays that are otherwise not easily accessible. An alternative is to carry out the molecular assembly of species with different compositions and functionalities in a fixed set of spatially extended domains. An example of this is the use of block polypeptides to coassemble capped CdSe (CdS) quantum dots and silicon nanoparticles into a microcavity configuration. In this case the electronic states of the three-dimensional confined semiconductor microcavities are coupled to the photonic states of the spherical microcavity to give single mode lasing.

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

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

2:30 P.M. **P2.3/Q4.3**
FORMATION OF 3D COLLOIDAL MONOLAYERS AT LIQUID SURFACES UNDER THE ACTION OF LONG-RANGE ELECTOSTATIC AND CAPILLARY INTERACTIONS. V. V. Puisumas, Department of Chemistry, University of Hull, Hull, UNITED KINGDOM

Recent progress in the preparation of 3D structured micro-particle monolayers has demonstrated the potential application of non-specific colloidal interactions between particles trapped at liquid interfaces or into liquid layers for fabrication of high technology coatings and materials. The characterization of the long-range colloidal forces operating between particles at liquid surfaces is a major step towards understanding and controlling the behavior of the particle monolayers by fine-tuning of the interparticle interactions. This presentation summarizes our findings on the long-range lateral capillary interactions between particles in several different configurations including freely floating and particles trapped in a liquid film. We reveal the formal analogy between the lateral capillary interaction between particles at a liquid-solid interface and the DLVOtype of electrostatic interaction between charged surfaces in electrolyte solution. We also analyze the super long-ranged electrostatic repulsion between charged micron-sized latex particles adsorbed at an oil-water interface. It was found that latex particle monolayers at octane-water interface remain highly ordered as a result of long-ranged electrostatic forces even in concentrated electrolyte solution. In the case of air-water interfaces, the lateral electrostatic repulsion between the particles was found to be sensitive to the electrolyte concentration and also to the ionic strength. Using a Monte Carlo approach in a reduced dimension, we have determined the long-range repulsive force as a function of separation between two charged polystyrene microspheres trapped at the oil-water interface. At large separations, the force is found to decay with distance to the power -4 and is insensitive to the ionic strength of the aqueous phase. The results are consistent with a model in which the repulsion arises primarily from the presence of very small residual electric charges at the particle interface. We discuss how super-structured 3D mixed monolayers of different particles can be assembled by using such long-range interactions.

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

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

4:00 P.M. **P2.5/Q4.5**
COLLOIDAL CRYSTAL TEMPLATING OF POROUS SOLIDS FOR APPLICATIONS BEYOND PHOTONICS. Andreas Stein, Hongwei Yan, Sergey Sokolov, Justin C. Lytle, Mohamed Alemany, University of Minnesota, Department of Chemistry, Minneapolis, MN.

A variety of colloidal crystal templating methods have been developed to produce three-dimensionally ordered macroporous (3DOM) or "inverse opal" structures. Many studies have focused on photonic crystals as target materials, with interesting projected applications involving confinement and control of electromagnetic waves. Structural requirements on such photonic crystals are rigorous, and strict control of defects is necessary to obtain photonic bandgaps. A number of other applications of 3DOM materials pose less rigorous requirements on structural periodicity, but benefit from the 3D arrays of relatively large interconnected pores, highly accessible surfaces, and compositional flexibility of the synthesis. Such applications include optical sensing, catalysis, battery materials, and biocatalytic materials. This presentation will provide a general overview of relevant issues of structural control in these applications and will then focus on 3DOM materials for nanostructured electrodes (V2O5, LiNO3, LiCoO2, LiMn2O4, and SnO2) and biocatalytic materials (SOx/Cnx).
SESSION J2: ANOMALOUS PHENOMENA IN PHOTONICS

Chairs: Thomas W. Ebbesen and Francisco J. García-Vidal

Wednesday Morning, April 23, 2003
Golden Gate A3 (Marriott)

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

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

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

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

9:30 AM #J2.3
A METALLIC MESH BASED ANTENNA: S. Enoki, G. Tagh, P. Sabouroux, N. Guefr, and P. Vincent, Institut Pluridisciplinaire, Faculté des Sciences et Techniques de St. Jérôme, Marseille, FRANCE.

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

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

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

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

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

11:00 AM #J2.6
EXTRAORDINARY OPTICAL PROPERTIES OF NANO-STRUCTURED METALS. F.J. García-Vidal, Universidad Autonoma de Madrid, Dpto. Física Teórica de la Materia Condensada, Madrid, SPAIN, L. Martín-Moreno, Universidad de Zaragoza, Dpto. de Física de la Materia Condensada, Zaragoza, SPAIN.

The dielectric response of a metal is completely governed by the free
electron plasma. Associated to this is the existence of
emergent electromagnetic resonances localized in the vicinity of its surface
(surface plasmons). These modes have an extremely high density and
can couple to external radiation. First we will illustrate how these
surface plasmons can be exploited for two opposite purposes: localize
light in very small volumes [1, 2] or to transmit light through arrays
of subwavelength slits [3] or holes [4, 5] periodically located in a metal
film. Then we will show how these two capabilities can be implemented
in single optical transducers (PLUTON). Moreover, we will demonstrate
how by creating a periodic texture on the exit side of a metal film, the shape
of the emerging radiation pattern can be tailored [6, 7, 1]. F.J. García-Vidal and J.B.


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

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

11:45 AM 12.8
DIFFRACTION CONTROL AND ENHANCED TRANSMISSION THROUGH SUBWAVELENGTH APERTURES
Thomas W. Ebbesen, Henri Lezec, Oleg G. Davaux, A. Yafet, University Louis Pasteur, Strasbourg, FRANCE.

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

SESSION 13: PLASMONICS AND PHOTONIC CRYSTAL FIBERS
Chair: James A. West
Wednesday Afternoon, April 23, 2003
Golden Gate III (Marriott)

1:30 PM 13.1
BESSEL BEAMS OF THE SECOND KIND AND SURFACE PLASMONS. J.D. Board, The Blackett Laboratory, Imperial College, London, UNITED KINGDOM.

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

2:00 PM 13.2
OXIDE AND METAL NANOSTRUCTURES FOR CONTROLLING OPTICAL PROPERTIES AT THE SUBWAVELENGTH SCALE
A. Deveurs, V. Lecoutre, R. Guider, J.C. Wecker, Submicron Optics Lab., University of Burgundy, Dijon, FRANCE.

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

2:30 PM 13.3
SUB-DIFFRACTION-LIMIT FOCUSING AND IMAGING IN THE NEAR FIELD WITH REAL MATERIALS
Peter G. Kik, Stefan A. Maier, and Harry A. Atwater, California Institute of Technology, Thomas J. Watson Laboratory of Applied Physics, Pasadena, CA.

We present calculations and experiments on sub-diffraction-limit focusing and imaging using thin (10-50 nm) metal films. While conventional optical imaging relies on applying phase corrections to propagating optical waves, near-field imaging requires the reproduction of non-radiating (evanescent) electromagnetic fields. It has been shown theoretically by Pendry that thin metal films can in fact partially reconstruct evanescent waves, allowing for imaging at sub-wavelength scale. To assess the feasibility of near-field imaging using real materials, we have performed Finite Difference Time Domain (FDTD) simulations. The simulated system consists of a suspended 30 nm Ag film in air. The Ag dielectric function in the frequency region of interest is quite accurately described by a Drude model. Placing an oscillating dipole source (exciton) near the Ag layer, we observe that plasmons are seen to build up on both Ag-air interfaces. A 90° phase difference develops in the field distribution on front and back surface, suggesting a resonant coupling of surface plasmons on opposite sides of the film. Optimum imaging is observed at when rAg is 1.4, yielding a FWHM of 34 nm, equivalent to X/10. This resolution is a factor two better than obtained without the silver film, showing the beneficial effect of the Ag layer.

Our FDTD simulations suggest that experimental verification of the imaging technique is difficult but is not impossible. Materials systems and experimental configurations that could be used in such experiments are discussed. We discuss our sample fabrication method and initial experimental results will be presented involving 30 nm Ag films deposited on thin dielectrics.

2:45 PM 13.4
SIMULATION AND EXPERIMENTAL CHARACTERIZATION OF ENERGY TRANSPORT IN NANOPARTICLE PLASMON WAVEGUIDES
Stefan A. Maier, Peter G. Kik, and Harry A. Atwater, California Institute of Technology, Thomas J. Watson Laboratory of Applied Physics, Pasadena, CA; Sheffer Meltzer, Ehud Hasel, Bruce E. Koel, and Ari A. G. Requicha, University of Southern California, Laboratory for Molecular Robotics, Los Angeles, CA.

The ultimate miniaturization of optical devices to spatial dimensions approaching the molecular scale will require structures that guide electromagnetic energy with lateral confinement below the diffraction limit of light, which is not possible using conventional photonic or plasmonic or photonic crystal waveguides.

We have theoretically shown that arrays of closely spaced metal nanoparticles can work as plasmon waveguides that guide electromagnetic energy on the nanoscale. Energy transport in these arrays occurs via near-field coupling between metal nanoparticles which sets up plasmon modes. This coupling leads to coherent propagation of energy with group velocities of about 0.1c. We report on FDTD calculations of energy guiding in locally excited plasmon waveguides consisting of spherical noble metal nanoparticles. The simulations allow the determination of the dispersion relation and group velocity for energy transport and quantitatively confirm the results of point-dipole calculations. Using effective medium nanoparticles with a 3.1 aspect ratio, group velocities up to 0.2c are predicted for longitudinal excitations in waveguide geometries that can be fabricated using electron beam lithography. We also present the results of optical characterization of the guiding properties of plasmon waveguides consisting of closely spaced gold and silver nanoparticles fabricated using electron beam lithography. Far-field spectroscopy confirms the existence of longitudinal and transverse collective modes of excitation and allows for the estimation of the dispersion relation and group velocities. Measurements of the polarization-dependent absorption confirm that the collective modes arise from near-field optical interactions. Using the tip of a near-field optical microscope on a local excitation source and fluorescence polystyrene nanobeads as detectors, we present experimental evidence for energy transport over a distance of about 0.5 micron for plasmon waveguides consisting of silver rods with a 3.1 aspect ratio and a center-to-center distance of 80 nm. This is the first direct evidence for localized energy transport in nanoparticle plasmon waveguides.

3:30 PM 13.5

Photonic Crystal Fibers belong to a class of fibers that have either a 1-dimensional or 3-dimensional periodic array of materials with varying refractive indices. One of the most common arrays consists of air holes in glass. Photonic crystal fibers (PCF) can be further classified as solid-core and hollow-core photonic crystal fibers. While light is guided in the solid-core version by total internal reflection, the hollow-core photonic crystal fiber (photonic bandgap fiber, PBF) guides light by band-gap effects. The biggest promise of PBFG has been the potential of guiding light in air and the associated ultra low
HYBRID MICROSTRUCTURED OPTICAL FIBERS ENABLING INTEGRATED TUNABILITY.

Charles Kerbage, Benjamin J. Eggleton, OFS Laboratories, Murray Hill, NJ.

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

REALIZATION OF AIR TREND WAVEGUIDES FOR FUTURE MICROPHOTONICS.

S. Akiyama, K. Washi, J. Michel, I. Kimel, Dept. of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA; M. Popovic and H. A. Haus, Dept. of Electrical engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA.

Silica optical bench (SiOB) technology is mature and widely used in integrated WDM applications, such as arrayed waveguide gratings (AWGs). The low-loss contrast waveguides permit low insertion loss at fiber coupling and low propagation loss. However, the major drawback is the large bending radii to keep radiation losses within acceptable bound, limiting the density of integration. We propose a simple and CMOS compatible technology that allows sharp bends in silica air core waveguides with a density of integration by orders of magnitude[1]. Air trench waveguide realizes compact bending radius by introducing air or low index material at the bends and locally increasing index. This air trench waveguide eliminates optical integration on chip using low index contrast material systems. This means that this waveguide has good characteristics for the future microphotonics such as low transmission loss, low bending loss, low coupling loss between fiber and waveguide in addition to compact bending size. Simulations were done using the Finite Difference Time Domain (FDTD) method, primarily in two dimensions. They show that a waveguide bend designed to have a throughput efficiency of 98% can be reduced in size by a factor of 1600 with the use of air trenches, with the bending radius itself reduced 30-500 times. For actual fabrication, we employed silicon oxynitride (SiON) for core and SiO2 for cladding. The fundamental processes such as the optimization of the trench dimensions, the defect removal process, film stress management, and precise deep oxide etch process are established. The comparison between and the experimental results and the actual results will be shown. [1] M. Popovic, K. Washi, S. Akiyama, J. Michel, Journal of Lightwave Technology in Press.
coupled plasma) with chrome etch masks, which were patterned by RIE (reactive ion etching) using chlorine-based gases. In some cases, the etching process generated a square roughness (greater than 100nm) and we call this phenomenon PSSD (plasma-induced surface damage). Rough surface can’t be used as a platform for hybrid integration because of difficulty in alignment and bonding of active devices. PSSD reduces etch rate of glass and it is very difficult to remove residues on a rough surface. The objective of this study is to elucidate the mechanism of PSSD formation. To achieve this end, PSSD formation during different etching conditions of chrome etching: simultaneously etched inlets were examined in detail. PSSD sources were formed on glass surface after chrome etching, and residual chrome, metal chlorides were identified in these sources. Water rinse after chrome etching reduced the PSSD, due to the water solubility of metal chlorides. PSSD was decreased or even disappeared at high power and/or low pressure in plasma etching, even if PSSD sources were present on glass surface. In conclusion, PSSD sources come from the chrome etching process, and polymer deposition on the glass surface generates these sources in silicon etching causing the PSSD to sources to grow. Each rate on the area immediately of the PSSD source would be increased due to increased ion flux, and this results in the formation of pits.

4.4 Abstract Withdrawn.

4.5 STUDY OF DIELECTRIC CONTRAST IN THE FABRICATION OF SEMICONDUCTOR OF LIGHT AND TUNING OF THE PHOTONIC BAND GAP. G.K. Jotri, Ashikahle Thart, Manoj Jotri, Department of Physics and Electronics, B.A.V. College, Kangra, INDIA.

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

4.6 PHOTONIC CRYSTAL MULTI-CHANNEL ADD/DROP FILTERS. Chul-Sik Kee, Dae-Hee Cho, Jong-Ho Jung, Ilko Park, Sun-Gu Lee", Hae-Won Han", and H. Lim, Division of Electrical and Computer Engineering, Ajou University, Suwon, KOREA. "Dept. of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang, KOREA.

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

4.7 Abstract Withdrawn.

4.8 SOFT CROSSLINKABLE AZOBENZENE POLYMER FOR RAPID SURFACE RELIEF FORMATION AND PERSISTENT FIXATION. Nobuyuki Zettou, Chemical Resources Laboratory, Tokyo Institute of Technology, Yokohama, JAPAN; Takahiro Seki, Department of Applied Chemistry, Graduate School of Engineering, Nagoya University, Nagoya, JAPAN; Ken'ichi Ishimuru, Research Institute for Science and Technology, Science University of Tokyo, Chiba, JAPAN.

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

4.9 STRESS EFFECTS ON MULTILAYER OPTICAL WAVEGUIDES. Rui Huang and Yungao Peng, University of Texas at Austin, Dept. of Aerospace Engineering and Engineering Mechanics, Austin, TX.

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

4.10 PREPARATION AND PHOTONIC BAND GAP PROPERTIES OF (Pb,La) (Zr,Ti)O3 INVERSE OPALS. Bo Li, Zhe Zhou, Lifeng Hao, Hu Wei, Ruiyong Kong, Mumin Cai, Min Fu, Longta Li, Zhihun Gu, State Key Lab of New Ceramics and Fine Processing, Department of Materials Science and Engineering, Tsinghua University, Beijing, P.R. CHINA; Qi Li, Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL.

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

4.11 LASER CHARACTERISTICS OF SINGLE SPHERICAL MICRODROPLETS LIQUIDATED IN AN ION TRAP. Masahiko Tanu and Masayuki Kimura, Kochi Univ. of Technology, Kochi, Japan.

We have investigated lasing characteristics of single dye-doped microdroplets levitated in an ion trap. A single droplet in the ion trap is suspended electrodynamically without any materials and shaped into a nearly perfect sphere due to the surface tension. Such a droplet acts as a microcavity with extremely high quality values at the selected specific size parameters $r = \pi \sqrt{A}$, where $r$ is the radius of the microsphere and $A$ is the light wavelength. If light waves travel
around the circumference of the droplet due to total internal reflection and round in phase, resonant standing waves are produced near the surface. Such resonances are called "molecular vibrational resonances (MVRs)" because the resonance frequencies depend strongly on x and y. The systems of a microsphere with MVRs are often called "photonics dots" by analogy with quantum dots. The photon confined in the microsphere is analogous to the electron bound in the quantum well. In order to obtain fundamental information on optical properties of photonic dots, we have carried out spectroscopic and microscopic observations of microdroplets composed of liquid glycerol doped with rhodamine 6G (R6G). The droplets were observed by a method of electrophoretic injection and injected into the ion trap. A pulsed green laser irradiated a dye-doped droplet. Both emission spectra and microscopic images were obtained from the direction perpendicular to the pump beam. We will present emission properties of photonic dots, including polarization characteristics of spectra and images, temporal properties and the dependence of lasing modes on dye concentration.

J4.12 MODAL ANALYSIS OF LIGHT TRANSMISSION BY SUBWAVELENGTH SQUARE COAXIAL APERTURE ARRAYS IN METALLIC FILMS. Gerardo Grana, Antonio Moreno, Padi Bhada, Daniel Van Lobele.

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

J4.13 Abstract Withdrawn.

J4.14 HIGH INTENSITY PHOTOLUMINESCENCE IN WAVEGUIDES OF SILICON-RICH SILICON DIOXIDE. R.T. Neal, Dept of Electronics & Computer Science, University of Southampton, Southampton, United Kingdom; M.C. Netti, Micropostic Ltd, UK; Dept of Electronics & Computer Science, University of Southampton, Southampton, United Kingdom; M.J. Norley, Dept of Electronics & Computer Science, University of Southampton, Southampton, United Kingdom; M.J. Parker, Micropostics Ltd, Dept of Electronics & Computer Science, University of Southampton, Southampton, United Kingdom.

Following initial work by Iacon et al. [1] on the growth of silicon nanocrystals, and the recent success in fabricating strong, luminescent planar optical waveguides based on nanocrystalline silicon material, waveguides are fabricated from silicon-rich silicon dioxide through a combination of PECVD deposition and amorphization, and display intensity and wavelength range similar to waveguides from other systems. Our process provides a new medium for the fabrication of silicon compatible LEDs and laser devices suitable for optical communications. In this paper luminescence and waveguiding properties of different waveguides are investigated. The waveguides are composed of an active silicon-rich silicon dioxide core layer deposited between silicon dioxide cladding and buffer layers on a standard silicon wafer. The effects of various anneal times upon the refractive index, luminescence spectrum, and transmittance of the waveguide were investigated. The active layer of the waveguide was pumped at normal incidence using an argon ion laser resulting in intense photoluminescence from 650-1200 nm. Measurements were taken of light emitted from a simple facet. Broad band spectrometric measurements were also performed on the waveguide facets. Results show a high temperature activation anneal of the silicon-rich silicon dioxide, while necessary for the formation of photoluminescent centers, is itself detrimental to the transmission properties of the material in the visible range the electron with work done by M.L. Brongersma et al. [2], the intensity of the photoluminescence increases with increased duration of anneal. Spectral measurements show that both annealed and unannealed material have excellent waveguiding properties and low losses in the 1.55um wavelength window.


J4.15 SPECTRAL CHARACTERISTIC OF COLLOIDAL PHOTONIC CRYSTALS. Kai Deng, Tianxiu Xu, and Thomas Collins.

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

J4.16 TRANSMISSION OF ACOUSTIC WAVES THROUGH WAVEGUIDE STRUCTURES IN TWO-DIMENSIONAL PHONONIC CRYSTALS. J.L. Vinther, V. Kheif, J. Rothe, D. Kunkel, Universitdt Hamburg, Vahrenwalder Strasse 7, D-20137 Hamburg, CHNS 8024, Université de Lille I, France; Y. Pennew, LSPES, UMR 8018, Université de Lille I, France; A. Kheif, LPMO, UPR 3203, Université de Franche-Comte, France; P.A. Deymer, DAESE, University of Arizona, Tucson, AZ; J. Zemzoumi, PHLAM, UMR 8523, Université de Lille I, France.

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

J4.17 Abstract Withdrawn.


Nanofabricated structures formed by Cu nanocrystals (NCs) embedded in amorphous Al2O3 have been shown to exhibit a high third order non linear optical response (χ(3)) together with a fast response time of wavelengths in the vicinity of the surface plasmon resonance (SPR) [1,2]. The figure of merit for non linear materials in waveguide devices is defined as χ(3) / a and in the case of metallic NCs principally limited by its linear absorption (a) which at the same time mainly depends on the content of metal in the film. It is desirable to be able to obtain a higher transmission independently of the NCs attributes. This can be possible in terms of optical band gap structures, where by mean of interferential effects an enhancement of the transmission at a certain range of wavelengths is obtained. A nanofabricated thin film has been grown by pulsed laser deposition (PLD) consisting of six
layers of Cu NCs alternating with ~7 nm thick layers of amorphous Al₂O₃. The average diameter of the NCs is ~5 nm. The film absorption spectrum shows the surface plasmon resonance (SPR) at about 600 nm that has been attributed to the presence of Cu nanocrystals. The optical properties of the nanostructured film has been analyzed by spectroscopic ellipsometry, assuming a multilayer structure (Al₂O₃/Cu NCs). The analysis of the results allows to determine the effective refractive index of the nanocomposite formed by the Cu NCs plus the Al₂O₃ that fills the space between them (Al₂O₃/Cu NCs). The optical constants of this complex material have been used to dependent refractive indices that show an enhancement of the transmission up to 310% at the SPR wavelength in respect to the reference sample, while keeping the same Cu to total extinction and the same Cu nanocrystal size. Films with the best configurations have been synthesized by PLD, and the corresponding experimental absorption spectra will be shown. The agreement with the simulated design is excellent. The advantages of the different designs in terms of the optical response will be discussed.

14.10

This paper describes the application of electronic self-assembly (ESA) processing methods to the fabrication of two-dimensional photonic crystals. The synthesis approach is an extension of conventional ESA deposition techniques in that photodegradable chalcogenide (GeTe) and silicon monoxide (SiOₓ) are deposited as the initial layer of the ESA nanoappendage. SAMs are long chain alkyne molecules, which can adsorb spontaneously onto substrates to form a very ordered monomolecular layer. The SAMs functionality here is to act as ultrathin resist, which establishes regions on a substrate that can prevent the adsorption of ions, based on surface hydrophobicity. Upon UV-exposure, the apolaric portions of the SAM molecule photobleach producing hydrophilic regions having charged hydroxyl groups where subsequent ESA layers can selectively grow. We have investigated octadecyltrichlorosilane (OTS) SAMs for the ESA patterning of 2D photonic crystals. Experimental measurements of photonic bandgap wavelength patterns are operating in the near-infrared optical communications wavelength band are shown and discussed.

14.20
COLLOIDAL CRYSTALS WITH WELL-CONTROLLED CRYSTALLOGRAPHIC ORIENTATIONS. Yucong Yin, Yu Lu, Younan Xia.

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

14.21
SYMMETRY REDUCTION AND DEFECT LAYERS IN MACROPOROUS SILICON 3D PHOTONIC CRYSTALS. J. Schilling, C. Janosi, R.B. Wehrspohn and Ulrich Gosele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY.

Macroscopic silicon 2D photonic crystals which consist of straight air pores in silicon can be extended to 3D photonic crystals by a periodic modulation of the pore diameter with pore depth. Assuming a circular pore cross section this 3D crystal has hexagonal symmetry. Due to the modulation a sub-wavelength stop band opens in the direction along the pore axis. Moreover a 2D defect layer can be introduced in this 3D photonic crystal by etching a straight segment of the pores. Defect resonances at λₐ = 0.8 μm were experimentally determined. The Q-value of the defect resonance depends on the number of modulated rods above and below the defect layer and reaches an experimentally observed maximum of Qₐ = 139 for 7 modulation periods. This corresponds to an attenuation of 4.4 dB per period for the modulated pore sections. For the investigation of these resonances an array of continuous circular dielectric rods mounted within the fundamental stop band. However a transmission measurement with polarized radiation shows that 2 defect resonances exist which couple to different polarization states. The reason for this is the actual shape of the pores. Due to the slight quadratic pore cross section the symmetry of the 3D hexagonal crystal in reality. This leads to splitting of photonic bands causing polarization dependent bandedge positions and the appearance of 2 closely spaced defect modes. The splitting of the bands connected with the reduced crystallographic index of refraction of the defect modes shows that the bands correspond to the 2 different slopes of the split photonic bands in the long wavelength limit. As the bandgap of the pore axis is caused by the shape of the scatterers (poles), it represents a case of for sphirefringence. The described effect can be used for polarization dependent interference filter in the mid-infrared.

14.22
SYNTHESIS OF DIELECTRIC AND METAL-O-DIELECTRIC PHOTONIC CRYSTALS BASED ON POROUS ALUMINA WITH ADJUSTABLE RATIOS OF RADIUS TO INTERDISTANCE. Jiezhong Chao, Yixun Liao, Half B. Weigang, Reinold Hibbel, Jörg Schilling and Ulrich Gosele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY.

Perfect 2D photonic crystals were synthesized based on porous alumina template methods. To fabricate monodomain porous alumina template on a large scale, indentation by a master stamp consisting of Si₃N₄ pyramids with hexagonal patterns was carried out by simple cold pressing before electrochemical modification. The fabricated porous alumina photonic crystal has an interplane distance of 500 nm and an initial pore diameter of 180 nm, which can be increased by anatrophic chemical etching to create photonic crystals with different r/a for fabrication of the photonic crystal. The reflectivity of the photonic crystal with different r/a shows bandgap positions, indicating the porous alumina is composed of two layers: an inner layer consisting of high purity alumina having a refractive index of 1.617 and an outer layer of alumina incorporated with silicon, respectively. For a non-uniform refractive index, we will discuss the index of the inner and the outer layer of porous alumina and compare the bandgaps observed by F′T − IR with band structure and reflectivity calculations.

14.23
EXPERIMENTAL DEMONSTRATION OF HIGHLY DIRECTIONAL RADIATION SOURCES USING SYMMETRIC AND ASYMMETRIC PHOTONIC CRYSTALS. Hameya Caglayan, Irfan Bulu and Ekmel Ozbuga, Department of Physics, Bilkent University, Bilkent, Ankara, TURKEY.

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

14.24
OPTICAL SIMULATION AND MICROWAVE FREQUENCY DEMONSTRATION OF A PLASMON SWITCH. Luke Sweneth and Harry Amers, Harvard University, Cambridge, MA; Stefan Monir, California Institute of Technology, Pasadena, CA.

Plasmonic structures confine light to a fraction of its free wavelength and could potentially enable computational devices at scale of a few hundreds of nanometers. We explore the functionality of an all-plasmonic photonic switch through simulation, and through construction of an analogous laboratory scale structure that operates in the microwave regime (λ = 3.7 cm). Photonic switching is supported by propagating electromagnetic modes similar to the dipole modes in plasmonic waveguides. We assemble arrays of copper rods...
that have a diameter of 0.1 cm (0.038 λ) and length 1.4 cm (0.38 λ); and are spaced 0.2 cm (0.038 λ) apart orthogonal to the long axis. Our interferometric switch consists of two such linear arrays that meet at right angles to form a "T" structure. A center-fed dipole antenna drives the source arm from a klystron, while the gate arm is driven from an identical source but with variable attenuation and phase. A probe dipole antenna on an Agilent E4448A meter was used to monitor the power transmitted to the third arm. When the gate is in phase with the source, the signals add constructively and power is observed in transmission. This can be considered the on state of the switch. Conversely, with the gate out of phase, nulling occurs and the transmitted intensity is lowered. On/off ratios of over 25 dB have been observed. These results agree with simulations performed using finite difference time domain (FDTD) simulation of the system. We will also present FDTD simulation of a nanoscale subwavelength "T" switch formed from silver nanoparticles with 3:1 ellipsoidal aspect ratio, which support propagating modes near their optical frequency surface phonon resonance. Pulsed and CW operation of an acoustic switch, and its radio to optical frequency switch, will be discussed.

14.25 TUNABLE COLOR ELECTROLUMINESCENCE FROM ARRAY OF QUANTUM DOT-POLYMER COMPOSITES. Samit Chaudhary and Mihir Ozkan, University of California Riverside, Dept of Electrical Engineering, Riverside, CA; Congig Ozkan, University of California Riverside, Dept of Mechanical Engineering, Riverside, CA.

Arrays of quantum dot/polymer composites which can exhibit full color tunable electroluminescence have been investigated. For this purpose, different CdSe nanocrystals passivated with a wider band gap semiconductor (ZnS) were incorporated into thin films of Polyvinylcarbazole (PVK) and an azo derivative (4-Bu-Ph). The electroluminescence EL behavior of these formulations were compared to each other under the same biasing condition on the ITO substrate. It is shown that EL spectra of the CdSe[ZnS] film are generally identical to the photoluminescence spectra of the corresponding CdSe[ZnS] nanocrystals. As the size of quantum dots become smaller, their energy increases in accordance with uncertainty principle, band gap open up and electron affinity decreases. Thus the threshold voltage increases and differently sized dots start electroluminescent at different threshold voltages. It was found that electroluminescence signal is almost exclusively generated within the nanocrystals, which act as recombination centers. Conducting polymers also showed luminescence at higher threshold voltages than quantum dots. Therefore, by changing the bias voltage to the quantum dot/polymer mixture, emission wavelength was controlled and full visible spectrum electroluminescence was obtained, tunable by virtue of sizes of quantum dots and their different threshold voltages. The performance of these heterostructure devices was influenced by the thickness of the films. This direct correlation between input voltage and output color leaves tunable pixel panel with immense importance for the development of next generation optical switches, biosensors, LEDs and other optoelectronic devices.


14.27 Abstract Withdrawn.


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


To realize ultracompact photon integrated circuits based on photonic crystals (PhCs), it is necessary to precisely control the spatial profile of the propagating light. Propagation through divergent beams is particularly desirable in such systems. After the first experimental demonstration of self-collimating phenomena in a hexagonal planar configuration [1], we have now extended the wavelength collimating range from 28nm to 40nm by changing the lattice from triangular to square. Our material system is a GaAs/AlGaAs heterostructure performed by a square photonic crystal lattice with an air-filling factor of 44%. The lattice constant is 330nm and the measurement is performed in the 1280nm wavelength window. Fig.1 shows SEM (top view) of photonic crystals with input and output waveguides. The input waveguide is tilted 10° from normal to the crystal edge (the incident edge is 15°). Vicino micrographs of the output facets as a function of wavelength are shown in Fig.2. Each spot represents one of the output waveguides that are spaced 10° apart and the micrographs obtained for each wavelength have been mounted together in order to show a complete deviation with angle. The corresponding transmission spectra are shown in Fig.3 with the scattered points representing the raw data and solid lines being given as a visual aid. Fig.2 and Fig.3 clearly indicate that light propagates through the crystal along the Z-axis, when the edge is tilted 10° from normal, which means that light beams with up to 20° divergence can be clearly collimated. The useful wavelength range for 20° divergence is 40nm (1280nm to 1320nm). This range will be enough to control the input and output light spatial profile of photonic lattice based devices. Furthermore, we observe good agreement with FDTD calculations and wavevector diagrams based on plane-wave expansion. In conjunction with suitably designed interfaces and the superprism phenomenon in planar photonic crystals that we have already reported [1], the knowledge obtained here represents a further step towards realizing integrated circuits based on PhCs.

SESSION 5: 2D PHOTONIC DEVICES
Chair: Muyong Notomi and Dwe Solgaard
Thursday, April 21, 2011
Golding A3 (Marriott)

8:30 AM 15.1 DESIGN AND CHARACTERIZATION OF OPTICAL NANOCAVITIES. A. Schoer, T. Yoshie, M. Lonzar, J. Vuckovic, D. Deppe, K. Okamoto, Caltech; Stanford University, U.T. Austin.

(ABSTRACT NOT AVAILABLE)

9:00 AM 15.2 LIGHT PROPAGATION CONTROL IN 2D PHOTONIC CRYSTALS. Muyong Notomi, NTT Basic Research Laboratories, Japan, JAPAN.

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

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

11:00 AM 15.6 SUBWAVELENGTH OPTICAL ELEMENTS (SOEs) AND NANOFABRICATION – A PATH TO INTEGRATE OPTICAL COMMUNICATION COMPONENTS ON A CHIP. Stephen Y. Chou, NanoStructure Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ.

Subwavelength optical elements (SOEs) are a special class of optical elements, where the feature size is less than the wavelength of light, hence having non-zero order diffraction. SOEs behave fundamentally different from bulk [i.e. ray] optics or diffraction optics [1-4]. First, SOEs can create new optical functions that are unachievable in bulk or diffusive optical. Second, SOEs can perform an optical function with a size that is orders of magnitude smaller than that of a bulk optical element. And third, SOEs perform different optical functions by using different geometries (shape and size) of features but the same materials, rather than different materials in bulk optics. The second and the third properties of SOEs make them particularly suited for integrated communication optical elements on a chip and be manufactured at the wafer scale.

Examinations will be given where the size of the features of the sub-wavelength feature, while keeping the materials are the same, a SOE will be changed from a waveguide to an antireflection surface, to a prism, to a beam splitter, to a fiber, and to a lens. It will also be shown that each of the above functions has been achieved with a SOE layer of less than one micron thick. Examples on the integrations of these SOEs are also given.

The SOEs also can be integrated with active elements such as lasers or detectors. We will describe how SOEs can be used to (a) turn a multi-mode laser into a single mode, (b) tune the frequency or polarization of a laser, and (c) create a very high-frequency optical clock.

The promise of SOEs will not be realized, unless we have a low-cost, high-throughput nano-manufacturing technology. This is also the reason that it took so long for us to realize the importance of SOEs. Nanoprint lithography [5,6] is one of the most promising nano-manufacturing technologies that can impact many different industries, including optical communications [5,6]. Fabrication of SOEs on wafer scale by NIL will be presented. Using SOEs as optical elements to enable small winning of malicious technology, the material for optical elements integrated on a chip - a revolution similar to the vacuum-tube-to-transistor revolution in electronics will be greatly accelerated.

References
We present the design, fabrication, and characterization of a 3D slab photonic crystal waveguide with low propagation loss and wide spectral transmission. The waveguide is created by altering one row of holes in a hexagonal photonic crystal lattice. By increasing the diameter of the circle from 0.6a to 0.9a, one can create a waveguide with a spectral width of 10% of the operating wavelength. However, such a photonic crystal waveguide is difficult to fabricate because the critical dimension, or smallest feature size, is only 0.48a. We have found that the elliptical rather than circular holes allow one to create wide spectral width waveguides without substantially reducing the critical dimension between holes. This is an important factor in the fabrication of these devices. We pattern our photonic crystal waveguides using a JEOL6000Fk electron lithography tool. Our waveguide material is 0.29μm thick Si on oxide. The photonic crystal lattice period is typically 400nm, corresponding to a photonic crystal bandgap from 128 nm to 162nm. The dimensions of the elliptical hole are dw=0.58a (220nm) and dy=0.29a (516nm), where x describes the direction of the waveguide. We use a thin SiO2 layer as a hard mask during the RIE etching of the Si layer. We do not etch or remove the underlying 1 μm layer of SiO2. Initial experimental results show propagation loss of 5dB/m from 1545nm-1585nm. Due to suboptimal control of the hole sizes during fabrication, the bandwidth is approximately 80 nm which is less than 5% of the original design wavelength. Using finite difference time domain modeling to simulate transmission through the waveguide, we are able to predict this narrow transmission spectrum and show that by using optimal dimensions (dx=0.57a and dy=0.16a) the transmission spectrum increases to 200nm.

11:45 AM 15.8 TUNING OF GAs BASED 3D PHOTONIC CRYSTALS BY INFILTRATED LIQUID CRYSTALS Ch. Schauer, F. Klopf, J.P. Reithmeier and A. Forchel, Technische Physik, Universitaet Wuerzburg, Am Hubland, Wuerzburg, GERMANY.

In photonic crystals (PC) the propagation of electromagnetic waves is strongly affected by the dielectric contrast. We are able to tune the photonic band gap by infiltrating liquid crystal into the voids of the 2D PC and controlling the refractive index of the liquid crystals. To investigate the tuning of photonic crystals, planar microcavities with two PC mirrors with lattice constants of about 300 nm are used. They are fabricated on AlGaAs/GaAs-wafer with a single InGaAs/GaAs layer lattice. The crystal is excited by a wavelength of 1 μm by high resolution e-beam lithography in PMMA and transferred by RIE into the SiO2-mask. The pattern is etched down into the semiconductor using ECR-RIE. In a final step the liquid crystals are filled into the evanescent field of the photonic crystal. The transmission experiments are done by optical pumping of the embedded dots. The emitted TE polarized light propagates in-plane through the microcavities and is detected by a CCD camera from a cleaved facet. The microcavities are investigated with and without liquid crystal. After filling the voids with liquid crystal of type E7 the resonance shifts about 50 nm to longer wavelength while the linewidth and the transmittance slightly increases. By raising the temperature until the clearing point of the liquid crystal the refractive index slightly increases which can be observed by a continuous resonance shift of about 5 nm. Above 60°C the liquid crystals lose their nematic order which results in a step-like jump of more than 4 nm of the resonance with no further change in the peak position for higher temperatures. Thus the first tunable photonic crystal could be fabricated on InGaAs/InP-semiconductor waveguides. The results are compared with finite difference time domain (FDTD) simulations. The simulated shift of the resonance fits well with the measured ones. Also the raise in transmittance and the symmetric peak shape is reproduced.
ENHANCEMENT OF RADIATION FROM SOURCES EMBEDDED IN PHOTONIC CRYSTALS. Israel Bari, Hameya Caglayan and Ekmel Oztop, Department of Physics, Bilkent University, Bilkent, Ankara, TURKEY.

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

DEVELOPMENT OF A NANOSCALE SILICON LASER. Sugriy Jaiawal, University of Virginia, Charlottesville, VA and Oak Ridge National Laboratory, Oak Ridge, TN; John Simpson, Steve Withrow, C.W. White, C. Roskrets, Oak Ridge National Laboratory, Oak Ridge, TN; Pamela Norris, University of Virginia, Charlottesville, VA.

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

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Chair: Jean-Michel Gerard
Thursday Afternoon, April 30, 2003
Golden Gate A3 (Marriott)

CHIRAL NANOSTRUCTURE AND SQUARE SPIRAL PHOTONIC CRYSTAL FABRICATION. Michael Breit, Dept. Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, CANADA.

The glancing angle deposition (GLAD) process has been demonstrated to be capable of fabricating sub-micron structures of posts, zigzags, helices, and square spirals, utilizing a substrate mask and glancing incidence of evaporative flux. With an appropriately designed periodic array of seeds or dots on the substrate, GLAD nanostructures grow only from the seed locations, enabling simple fabrication of arrays of helices or other structures. This process has recently been harnessed to grow arrays of tetragonal square spirals, which are proposed [J. Tondi and S. John, Science 292, p.1133 (2001)] as a large bandgap three dimensional photonic crystal material. The process is also capable of fabricating chiral or helical nanostructures which have been used in hybrid liquid crystal devices. A wide range of materials can be used for GLAD, manipulation of lattice constant and helix pitch ensures optical tunability, and the GLAD films are robust to micromaching and post-processing. The presentation will review the GLAD process and detail the characteristics of the seed array necessary to provoke fabrication of nanostructures. Examples will be given of a variety of types of chiral and square spiral geometries, and of the effect of inclusion of defects in the arrays. Optimal characterization of these chiral nanostructures and in particular of square spiral arrays of Si will be presented.

4:00 PM 17.5 TEMPERATURE INSENSITIVE PHOTONIC BANDGAP STRUCTURES IN SILICON. Sharon M. Weiss, and Philip M. Fauchet, *b. “The Institute of Optics, University of Rochester, Rochester, NY, Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY.

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

4:15 PM 17.6 SENSING BY PHOTONIC CRYSTAL SUPERPRISMS. Tushar Prasad, Silvia Rubio Monzon, Vicki Colvin, Dept. of Chemistry, Rajesh Renganuj, Daniel Metzlem, Electrical & Computer Engineering Dept., Rice University, Houston, TX.

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

4:30 PM 17.7 NANOPARTICLE-MEDIATED ASSEMBLY OF COLLOIDAL CRYSTALS ON PATTERINED SUBSTRATES. Carlos J. Martinez, Michael Bevan, Woonmok Lee, Paul V. Braun, and Jennifer A. Lewis, University of Illinois, Urbana, IL. *Present address: Texas A&M, College Station, TX.

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

4:45 P.M. 17.5

**Mesoscopically Photo-Patterened Colloidal Photonic Crystals.**
S. GiRa Yi, Sarah Kim, Yong-Hak Park, Seung-Min Yang, Dept of Chemical and Biomolecular Engineering, Diptec, KOREA, David J. Pine, Dept of Chemical Engineering, University of California, Santa Barbara, CA.

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