SYMPOSIUM L

Photonic Crystals—From Materials to Devices

April 1 – 3, 2002

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TUTORIAL

ST L: INTRODUCTION TO PHOTONIC CRYSTALS

Monday, April 1, 2002
1:30 p.m. - 5:00 p.m.
Nob Hill C/D (Marriott)

Photonic crystals have attracted world-wide interest during the last decade. But what, exactly, are the new interesting physical properties of photonic crystals, how can we make them and where is their place in integrated optics? This tutorial tries to give an introduction to the physics of photonic crystals by the use of wavevector diagrams, as well as to provide a current state of the art of silicon-based photonic crystals, followed by an outlook on possible application of photonic crystals in integrated optics.

Instructors:
Reinhard März, Infineon Technologies AG
Philip St. Russell, University of Bath
Ralf Wehrspohn, Max-Planck-Institute of Microstructure Physics

SESSION L1: THEORY

Chair: Costas M. Soukoulis
Tuesday Morning, April 2, 2002
Golden Gate B3 (Marriott)

8:30 AM *L1.1
SOLID STATE THEORETICAL METHODS FOR DEFECT COMPUTATIONS IN PHOTONIC CRYSTALS. A. Garcia-Martin, D. Hermann, K. Busch and P. Wölfle, Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, Karlsruhe, GERMANY.

Defect structures in Photonic Crystals such as waveguides and micro-cavities represent a basis set for novel functional elements that may eventually form the basis for integrated photonics. To date, the theoretical description of such structures is largely limited to general computational methods such as FDTD or FEM simulations that make little or no use of the information available through the fact that these defect structures are embedded in the highly ordered lattice of a Photonic Crystal.
Based on these considerations, we present a solid state theoretical approach to the problem of computing the optical properties of defect structures such as waveguides and micro-cavities in Photonic Crystals. The approach is based on efficient computations of photonic Wannier functions directly from the Bloch functions, thereby transfering recent advances in electronic structure calculations to photonic bandstructure theory. By construction, Wannier functions correctly incorporate the symmetry properties of the underlying Photonic Crystal and, as a consequence, represent a set of localized basis functions that is well-suited to the description of defect structures in them. As an application of this technique, we present computational results for mode structures of waveguides and micro-cavities in two-dimensional Photonic Crystals as well as time-domain calculations for pulse propagation through these structures.

9:00 AM *L1.2
MINIMIZING SCATTERING LOSSES IN PHOTONIC-CRYSTAL SLABS. Steven G. Johnson, J.D. Joannopoulos, Massachusetts Institute of Technology, Dept of Physics and Center for Materials Science and Engineering, Cambridge, MA.

Photonic-crystal slabs are hybrid systems, employing a combination of vertical index guiding and a two-dimensional band gap in the horizontal plane. For high-contrast systems, operating below the light line, the in-plane periodic structure itself does not cause out-of-plane scattering, even for strong periodicity. However, any time the periodicity is broken, e.g. by a resonant cavity or waveguide bend, vertical scattering is possible. In this talk, we discuss mechanisms for minimizing such scattering losses, focusing in particular on the case of high-Q resonant cavities, which are most sensitive to any losses. We show how one can trade off field localization for Q (cavity lifetime), and alternatively demonstrate how one can cancel low-order multipole moments of the radiated field in order to maximize Q for a fixed degree of localization. The resulting high-Q cavities are an important component of many potential devices, such as filters.

9:30 AM L1.3
NEW CLASSES OF THREE-DIMENSIONAL PHOTONIC CRYSTALS. R. Biswas, I. El-Kady, K.-M. Ho, Dept. of Physics, Ames Laboratory, and Microelectronics Research Center, Iowa State University, Ames, IA; S. Lin, Sandia National Laboratories, Albuquerque, NM; M.M. Sigalas, Agilent Technologies, Palo Alto, CA.

Recent research in the field of three-dimensional photonic crystals has largely focused on the inverse-opal and the layer-by-layer families of photonic crystals. We examine alternative photonic crystals that have been designed theoretically and whose fabrication has recently been achieved with state-of-the art advanced silicon processing methods. One class of photonic crystals is based on the simple cubic lattice geometry. Modifications to the basic structure are discussed that can lead to an enlarged 3-d photonic band gap. Another class of structures consist of stacked meshes of hexagonal nets, that include a “planar diamond-like” structure which has a large fundamental full band gap. Photonic band calculations will be presented that optimize the band gaps of these new structures. We will present transfer matrix calculations for the reflection and transmission through these crystals which agree well with experiment. The advantages and disadvantages of these new 3-d structures over existing inverse-opal and layer-by-layer crystals will be discussed. We will survey possible areas where these new photonic crystals may be applied. Supported by Department of Energy, Office of Basic Energy Sciences.

SESSION L2: DEFECT ENGINEERING IN 2D AND 3D

Chair: Reinhard Maerz
Tuesday Morning, April 2, 2002
Golden Gate B3 (Marriott)

10:15 AM *L2.1
SOI PHOTONIC CRYSTAL SLABS AND PHOTONIC BANDGAP WAVEGUIDES. Masaya Notomi, A. Shinya, E. Kuramochi, I. Yokohama, NTT Basic Research Laboratories, Atsugi, JAPAN; K. Yamada, NTT Telecommunication Energy Laboratories, Atsugi, JAPAN.

We fabricate 2D Si photonic crystal slabs having large photonic band gap from SOI (Silicon-On-Insulator) substrate by using e-beam lithography and F-based ECR plasma ion-stream etching. We experimentally demonstrate the structural tuning of the waveguiding modes of line defects in photonic crystal slabs. By modifying the geometrical structure of line defects in various ways (width control, phase shift, and so on), we can tune the waveguiding modes with a large degree of freedom. By utilizing such tunability, we realized efficient single-mode waveguides that operate within photonic band gap frequencies in SOI photonic crystal slabs. The observed waveguiding characteristics agree very well with 3D finite-difference time-domain calculations. We also experimentally investigate group-velocity dispersion of line defects in photonic crystal slabs as a function of defect widths. The defects have waveguiding modes with two types of cutoff within the photonic band gap. Interference measurements show that they exhibit extraordinarily large group dispersion, and we found waveguiding modes whose traveling speed is two orders of magnitude slower than that in air. These characteristics can be tuned by controlling the defect width and the results agree well with theoretical calculations, indicating that we can design light paths with made-to-order dispersion.

10:45 AM *L2.2
APPLICATIONS OF PHOTONIC CRYSTALS IN LASERS AND LIGHT EMITTING DIODES. A. Scherer, J. Vuckovic, M. Loncar, T. Yoshie, O. Painter, Caltech, Pasadena, CA.

Microfabricated two-dimensional photonic crystals provide us with the geometries needed to guide and concentrate light into extremely small volumes and to obtain very high field intensities. Fabrication of such optical structures has now evolved to a precision which allows us to control light within such etched nanostructures. Sub-wavelength nano-optic cavities can be used for efficient and flexible control over both emission wavelength and frequency, and nanofabricated optical waveguides can be used for efficient coupling of light between devices. The reduction of the size of optical components leads to their integration in large numbers and the possibility to combine different functionalities on a single chip, much in the same way as electronic components have been integrated for improved functionality in microchips. The past rapid emergence of optical microcavity devices, such as Vertical Cavity Surface Emitting Lasers (VCSELs) can be largely attributed to the high precision over the layer thickness control available during semiconductor crystal growth. High reflectivity mirrors can thus be grown with sub-nanometer accuracy to define high-Q cavities in the vertical dimension. Recently, it has also become possible to *microfabricate* high reflectivity mirrors by creating two- and three-dimensional periodic structures. These periodic “photonic crystals” can be designed to open up frequency bands within which the propagation of electromagnetic waves is forbidden irrespective of the propagation direction in space and define photonic bandgaps. When combined with high index contrast slabs in which light can be efficiently guided, microfabricated two-dimensional photonic bandgap mirrors provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Here we show how to use photonic crystals in functional nonlinear optical devices, such as lasers, modulators, add/drop filters, polarizers and detectors. These components can now be combined into very compact nanophotonic integrated circuits.

11:15 AM L2.3

CHANNEL-ADD OPERATION OF A DEVICE USING DEFFECTS IN A TWO-DIMENSIONAL PHOTONIC CRYSTAL SLAB. Takashi Asano, Susumu Noda, Kazuaki Kiyota, Yoshinori Tanaka, Yoshikazu Akahane[a], Bong-Shik Song, Masamitu Mochizuki, and Masahiro Imada, Dept. of Electron. Sci. & Eng., Kyoto Univ., CREST, JST, Kyoto, JAPAN; [a]Sumitomo Electric Industries, Itami, JAPAN.

We previously reported a channel-drop-filtering function of a device based on defects in two-dimensional (2D) photonic crystal (PC) slab.1) In this symposium, we will report on a reverse function: a channel-add-filtering operation of the device for the first time. The device basically consists of a slab of InGaAsP (thickness = 0.25μm), which has a triangular lattice structure of air holes (lattice constant a = 0.42μm, radius ~0.3a). A line-defect waveguide is formed by filling air holes along Γ-J direction, and an acceptor-type point defect (an enlarged air hole) is formed nearby. In the case of the channel-drop operation, we introduced photons to the line-defect waveguide from the edge. The photons propagating through the waveguide were trapped by the point defect when the photon frequency is matched to the resonant frequency of the point defect, and the trapped photons were emitted to the free space since the defect cavity is leaky in regard to the direction vertical to the slab. In this work, we have made just reverse experiment and successfully observed that the photons, which were introduced on the surface of the point defect from free space, were trapped by the defect and were transferred to the waveguide and were emitted from the edge. The spectrum of the add-filtering operation had a single peak at 1382 nm (spectral width ~3nm) in this particular device, and the spectrum agreed well with that of the drop-filtering operation. These results indicate that photons can be not only dropped-from but also added-to a line-defect waveguide through the point defects in a 2D-PC slab. We believe that this is a very encouraging result since we can expect to apply the 2D PC to a very compact component for the optical communication systems (for example, WDM). 1) S. Noda, A. Chutinan, M. Imada: Nature 407 (2000) 608.

11:30 AM *L2.4

COUPLED CAVITIES IN PHOTONIC CRYSTALS. Ekmel Ozbay, and Mehmet Bayindir, Bilkent University, Department of Physics, Ankara, TURKEY.

Photonic crystals are three dimensional periodic structures having the property of reflecting the electromagnetic (EM) waves in all dimensions, for a certain range of frequencies. Defects or cavities around the same geometry can also be built by means of adding or removing material. The electrical fields in such cavities are usually enhanced, and by placing active devices in such cavities, one can make the device benefit from the wavelength selectivity and the large enhancement of the resonant EM field within the cavity. We used three-dimensional photonic crystals to demonstrate waveguides and beam splitters. By using coupled periodic defects, we have experimentally observed a new type of waveguiding in a photonic crystal. A complete transmission was achieved throughout the entire waveguiding band. We have also obtained the dispersion relation for the waveguiding band of the coupled periodic defects from the transmission-phase measurements and from the TB calculations. We proposed and demonstrated two different methods to split electromagnetic waves in three-dimensional photonic crystals. By measuring transmission spectra, it was shown that the guided mode in a coupled-cavity waveguide can be split into the coupled-cavity or planar waveguide channels without radiation losses. The flow of electromagnetic waves through output waveguide ports can also be controlled by introducing extra defects into the crystals.

SESSION L3: SWITCHING AND SENSING
Chair: Ralf B. Wehrspohn
Tuesday Afternoon, April 2, 2002
Golden Gate B3 (Marriott)

1:30 PM *L3.1

TUNING 2-D SILICON PHOTONIC CRYSTALS. Henry M. van Driel, S.W. Leonard, University of Toronto, Dept of Physics, Toronto, CANADA; J. Schilling, R.B. Wehrspohn, Max Planck Institute of Microstructure Physics, Halle, GERMANY.

The range of applications for photonic crystals would be significantly enhanced if the bandstructure or photonic band gaps of the crystals could be tuned. This might enable the realization of highly-integrated microchips for optical signal processing or even novel discrete optical components. Here I will review our recent work on linear and nonlinear methods to tune the optical properties of photonic crystals. In particular I will demonstrate how the near-infrared bandgap of a 2-D macroporous silicon photonic crystal can be temperature tuned using liquid crystals infiltrated into the cylindrical pores or through electron-hole plasmas injected into the silicon backbone using femtosecond optical pulses. The possibility of making photonic crystal switches or tuning elements is discussed.

2:00 PM L3.2

MECHANOCHROMIC RESPONSE OF PHOTONIC BANDGAP COMPOSITES. Stephen H. Foulger, Amanda C. Lattam, Clemson University, School of Materials Science and Engineering, Clemson, SC; Ping Jiang, Yurong Ying, Dennis W. Smith, Jr., Clemson University Department of Chemistry, Clemson, SC.

Polymeric composites which exhibited a photonic bandgap were fabricated in a two-step procedure which included: (1) the stabilization of a self-assembled crystalline colloidal array composed of polystyrene spheres, with an average diameter of 109 nm, in a hydrogel through the free radical polymerization of a methacrylate functionalized PEG in the presence of the ordered arrays and (2) the replacement of water in the hydrogel with acrylate monomers and their subsequent free radical polymerization. Various acrylate monomers were polymerized both as homopolymers and copolymers which resulted in composites with glass transition temperatures that ranged from -35°C to 35°C, as confirmed by dynamic mechanical spectroscopy, dielectric spectroscopy, and differential scanning calorimetry. Specifically, the replacement of water with 2-methoxyethyl acrylate (MOEA) and its subsequent free radical polymerization resulted in a composite which exhibited a low temperature shear modulus (G') of ca. 2x10^9 Pa that underwent a significant drop at an onset temperature of -35°C. Optical studies on this MOEA-based composite indicated a stop band at a wavelength of 533 nm and an index of refraction of 1.473 at 633 nm. Assuming that the stop band corresponds to the d_{111} interplanar spacing of a FCC lattice, this periodicity translated into a 222 nm nearest neighbor distance of the particles, twice their diameter. Composite films which were mechanically strained exhibited a mechanochromic response, where a strain of 44% resulted in a 102 nm blue shift in the observed stop band.

2:15 PM L3.3

LOW VOLTAGE WAVELENGTH-TUNABLE SILICON-BASED PHOTONIC BAND GAP STRUCTURES FOR WDM APPLICATIONS. Yasha Yi, Kazumi Wada, Jurgen Michael, Lionel C. Kimerling, M.I.T, Microphotonic Center, Cambridge, MA.

Low voltage wavelength switching is reailzed in the one-dimensional Photonic Band Gap structures. By mechanically changing the defect thickness, 65nm resonance wavelength shift is achieved by up to 10V. The potential application in WDM and the localized state properties within the band gap are also addressed.

2:30 PM L3.4

FREQUENCY SELECTIVE SURFACES ENABLE MEMS GAS SENSOR. Irina Puscasu, Martin U. Pralle, Mark P. McNeal, Nicholas Moelders, Lisa Last, William Ho, Anton C. Greenwald, James T. Daly, Edward A. Johnson, Ion Optics, Inc., Waltham, MA; Ihab El-Kady, Rana Biswas, Iowa State University, Ames Laboratory and Dept. of Physics, Ames, IA.

We have developed a thermally stimulated narrow-band infrared source for sensing, spectroscopy and thermophotovoltaic applications by combining the unique advantages of two different structures: a photonic crystal that consists of an array of holes etched into a dielectric substrate and a periodically perforated metallic thin film. The dielectric photonic crystal structure is passive and exhibits a strong absorption at resonance. This acts as a radiation reservoir for the conductive array, which plays an active role through plasmon interaction and is opaque at all wavelengths except those at which coupling occurs. We have fabricated the arrays on silicon, silicon dioxide and silicon nitride substrates using MEMS-based processing methods. Infrared spectroscopic studies were used to characterize reflection, absorption and emission in the 2 to 14 micron range showing narrow band resonance. Spectral tuning was accomplished by controlling symmetry and lattice spacing of the arrays. The effects of the angle of incidence, etch depth, metal and dielectric properties have been studied experimentally and theoretically. Transfer matrix method calculations accurately predict the position of measured absorption features and give theoretical insight into the physical mechanisms responsible. These structures have been used as an emitter/detector sensor chip to selectively detect industrial pollutants like carbon dioxide.

SESSION L4: PHOTONIC CRYSTAL FIBERS

Chair: Masaya Notomi
Tuesday Afternoon, April 2, 2002
Golden Gate B3 (Marriott)

3:15 PM *L4.1

PHOTONIC CRYSTAL FIBRES. P. St.J. Russell, Department of Physics, University of Bath, UNITED KINGDOM.

Photonic crystal fibre (PCF) consists of a thin thread of silica glass, almost unlimited in length, with a parallel array of microscopic air channels running along it [for a review see: J.C. Knight et al, “Holey silica fibers,” in Optics of Nanostructured Materials (Editors V.A. Markel and T.F. George), pp 39-71, (John Wiley & Sons, New York, 2001)]. Guiding cores are created by filling in or enlarging individual air channels, and several new guidance mechanisms have been demonstrated, including photonic bandgap confinement in a hollow core [R.F. Cregan et al, “Single-mode photonic band gap guidance of light in air,” Science 285 (1537-1539) 1999] and an endlessly single-mode structure that sieves away higher order modes [T.A. Birks et al, “Endlessly single-mode photonic crystal fibre,” Opt. Lett., 22 (961-963) 1997]. Many further optical applications are emerging, including efficient supercontinuum generation [J.K. Ranka et al, “Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm,” Opt. Lett. 25 (25-27) 2000; J.C. Knight et al, “Anomalous dispersion in photonic crystal fibres,” IEEE Photonics Technology Letters, 12 (807-809) 2000] gas-Raman amplifiers and cold atom guides. PCF preforms are typically built up element by element from silica rods and capillaries. These are then fused together and drawn into fibre in a standard drawing tower. This generic procedure is highly versatile, and has led to a wide range of different PCF types. For example, if dopants are required, e.g., rare-earths for lasers and amplifiers, then doped glass rods can be incorporated in place of pure silica [W.J. Wadsworth et al, “Yb^{3+} doped photonic crystal fibre laser,” Electron. Lett. 36 (1452-1454) 2000]. Microstructuring transforms optical fibre from a mundane commodity into an almost magical new material full of new effects and useful in a host of applications from high power lasers to telecommunications.

3:45 PM *L4.2

HOLE-ASSISTED LIGHTGUIDE FIBER - A PRACTICAL DERIVATIVE OF PHOTONIC CRYSTAL FIBER. T. Hasegawa, E. Sasaoka, M. Onishi, M. Nishimura, Sumitomo Electric Industries, Yokohama, JAPAN; Y. Tsuji, and M. Koshiba, Hokkaido University, Sapporo, JAPAN.

Usage of air holes in optical fibers has become a hot subject in fiber optics because of the possibilities for novel transmission properties. Although photonic crystal fibers based on photonic bandgap guidance are the most drastic innovation in this subject, optical fibers containing air holes but not having photonic crystal structures are also being intensively studied. Such air-silica microstructured fibers are more practical than the photonic bandgap fibers because the lack of photonic crystal structure makes the fabrication far easier. Even without the photonic bandgap, the microstructured fibers can exhibit valuable properties in terms of group velocity dispersion and nonlinearity, because the index contrast between air and silica is 10 or more times as large as that of the conventional optical fibers based on doped silica glasses. However, one of the major challenges for practical applications of the air-silica microstructured fibers has been their high transmission losses, which have been several tens to hundreds times higher than those of the conventional fibers. As a solution to this problem, we have proposed a more practical structure called hole-assisted lightguide fiber (HALF). In addition to the air holes for realizing novel optical properties, this structure has a material index profile for waveguiding, and hence is closer to the conventional fibers than the other microstructured fibers are. As a result, novel optical properties can be realized without severe degradation in transmission loss. In experiments, an anomalous group velocity dispersion as large as +35 ps/nm/km at 1550 nm wavelength, which would be unattainable in the conventional fibers, has been realized with a loss of 0.41 dB/km, which is comparable to those of the conventional fibers. Analyses of the losses of the fabricated HALFs suggest that the loss should be lowered by mitigating the effect of the drawing tension and minimizing the power fraction in the holes. It is also shown that the full-vector finite element method realizes accurate modeling of the properties such as dispersion and macrobend loss.

SESSION L5: POSTER SESSION

Tuesday Evening, April 2, 2002
8:00 PM
Salon 1-7 (Marriott)

L5.1

LOCAL DENSITY OF STATES IN SiO_2 COLLOIDAL PARTICLES. M.J.A. de Dood, B. Berkhout, L.H. Slooff and A. Polman, FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS; A. Moroz and A. van Blaaderen, FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS and Soft Condensed Matter Department, Utrecht University, Utrecht, THE NETHERLANDS.

One of the best ways to probe the properties of 3-D photonic structures is by studying luminescence of optically active ions incorporated in the structure. In this paper we present new data on the properties of erbium doped colloidal SiO_2 spheres and compare these to calculations of the local density of states (LDOS) of a microsphere. Photonic crystals can be made of these colloids using self assembly and optical tweezer techniques. SiO_2 microspheres (340 nm diameter) were prepared from tetra-ethoxy-silane (TEOS) by a base catalyzed wet chemical process at a size polydispersity of 3-4%. Erbium ions were incorporated by ion implantation. After annealing clear Er luminescence was observed with a luminescence lifetime as long as 17 ms. Immersion of the spheres in an index matching liquid increases the lifetime by 30%, which is in good agreement with the calculated change in the LDOS of a single sphere. The LDOS is obtained from a calculation involving the Greens function for the microsphere geometry. The LDOS strongly depends on the diameter of the microsphere, showing a number of resonances that can be related to Mie resonances of the sphere. Bringing the microsphere into contact with a liquid of higher refractive index leads to a strong shift in the resonances of the sphere and hence leads to a large effect on the decay rate. An acid catalyzed TEOS reaction was used to form SiO_2 microspheres doped with Er ions directly during synthesis. However, this acid based process usually results in micron-sized polydisperse partilces. We have succesfully applied seeded growth to obtain 190 nm diameter Er doped, monodisperse SiO_2 particles starting from 180 nm diameter seed particles. This opens the possibility to incorporate such spheres in colloidal crystals and study the lifetime of these ions inside a photonic crystal, using confocal microscopy techniques.

L5.2

LARGE-AREA POROUS ALUMINA PHOTONIC CRYSTALS VIA IMPRINT METHOD. J. Choi, J. Schilling, K. Nielsch, R. Hillebrand, M. Reiche, R.B. Wehrspohn, U. Gösele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY.

A perfect 2D porous alumina photonic crystal with a 500 nm interpore distance was fabricated via imprint methods on 4 cm^2. A 4$''$ imprint stamp consisting of a convex pyramid array was obtained by modern VLSI processing using DUV-lithography, anisotropic etching, LPCVD Si_3N_4 deposition and wafer bonding. Due to the pyramidal shape, the pressure required to obtain complete prepatterning of the surface of aluminum was as low as 5 kN/cm^2. The aluminum was then anodized in phosphoric acid under 195 V. 100 μm deep straight pores arranged in a 2D hexagonal lattice were electrochemically grown and chemically widened to an $r/a = 0.42$. An almost perfect plane along the Γ–K direction was obtained by cleaving the sample. The optical properties of the porous alumina photonic crystal were measured with an infrared microscope in Γ–M direction. We observe for both polarizations a bandgap at around 1 μm for $r/a = 0.42$. A reflectivity of almost unity for E-polarization in the region of the bandgap is a sign of the high quality of the structure, indicating almost no scattering losses. This experimental results could be fit very well with reflection calculations assuming a dielectric constant of $\epsilon = 2.0$ for the anodized alumina.

L5.3

ANTI-REFLECTIVE MgF_2 COATING ON POLYCARBONATE. Takanobu Hori, Isao Tokomoto, Kazuo Uetani, ShinMaywa Industries Ltd, R&D Center, Hyogo, JAPAN; Masashi Fukinbara, Ibaraki University, Ibaraki, JAPAN; Akira Kato, Hiroshi Kajiyama, Hitachi Ltd, Hitachi Research Laboratory, Ibaraki, JAPAN.

Anti-reflective coating is indispensable to optical devices for reducing optical losses due to reflection at interfaces. Low and high refractive index (n) thin films are alternately stacked to the desired optical thickness. One example is the SiO_2 (n=1.46) and TiO_2 (n=2.30) combination. If the SiO_2 layers could be replaced by a material with a lower n, it enables one to further reduce reflection. Among the candidates, MgF_2 is the most desirable material because of its low refractive index (1.38) and high abrasion resistance. However, MgF_2 deposition on low refractory substrates such as polycarbonate has been unsuccessful so far. The goal of our research is to explore the synthesis method of MgF_2 thin films at substrate temperatures (Ts) that are as low as possible. In this paper, we focus on the abrasion resistance of MgF_2 film. We deposit the film using the advanced ion-plating (AIP) apparatus we developed. The AIP deposition features the RF and DC bias voltages applied to the substrate holder. The effects of Ts and DC bias voltages on the abrasion resistance of films are investigated. It is found that the abrasion resistance is drastically improved by applying a DC bias voltage in addition to a RF bias voltage. The same abrasion resistance as the film deposited by a conventional heat resistive deposition at 573 K was obtained by applying a DC bias voltage of -500 V at a Ts below 323 K. We consider that such enhanced crystal growth was realized by the acceleration of impinging MgF_2 clusters by a negatively biased voltage.

SESSION L6: METALS AND 1D/2D PHOTONIC CRYSTALS

Chairs: Vahid Sandoghdar and Axel Scherer
Wednesday Morning, April 3, 2002
Golden Gate B3 (Marriott)

8:15 AM *L6.1

NEGATIVE REFRACTIVE MATERIALS.

David R. Smith and Sheldon Schultz, University of California, San Diego, Department of Physics, La Jolla, CA.

Negative refraction, a recently investigated phenomenon, has been shown to exist in certain artificially structured materials. In "left-handed" metamaterials–where the dimensions and spacing of the constituent scatterers is much less than the free-space wavelength–an effective permeability and an effective permittivity can be derived, both of which are negative over a limited frequency band. Where the permittivity and permeability are both less than zero, the index-of-refraction is also rigorously negative, so the term "negative refractive index" can correctly be applied to left-handed materials. Photonic band gap (PBG) materials have also been shown (in numerical simulations) to exhibit frequency regions where negative refraction can occur. However, the spacing and dimensions of the scattering elements in PBG structures is typically on the order of the free-space wavelength, and thus applying effective medium concepts such as permittivity and permeability is not well founded. We will discuss the distinction between negative refraction in left-handed metamaterials, presenting results from simulations and experiments, and negative refraction in PBG materials.

8:45 AM L6.2

OBSERVATION OF COUPLED PLASMON-POLARITON MODES OF PLASMON WAVEGUIDES FOR ELECTROMAGNETIC ENERGY TRANSPORT BELOW THE DIFFRACTION LIMIT.

Stefan A. Maier, Pieter G. Kik, Mark L. Brongersma, Harry A. Atwater, California Institute of Technology, Pasadena, CA; Sheffer Meltzer, Ari A.G. Requicha, Bruce E. Koel, University of Southern California, Los Angeles, CA.

The ultimate miniaturization of optical devices to spatial dimensions akin to their electronic device counterparts will require structures that guide electromagnetic energy below the diffraction limit of light. We showed in previous theoretical work that plasmon waveguides consisting of arrays of closely spaced metal nanoparticles guide electromagnetic energy on the nanoscale. Energy transport in these arrays occurs via resonant near-field coupling between metal nanoparticles that sets up plasmon modes. This coupling leads to coherent propagation of energy along nanoparticle arrays with group velocities of about 0.1c and energy can be guided around 90 degree corners and split via tee structures with high efficiency. We report here on the optical characterization of the guiding properties of plasmon waveguides consisting of closely spaced 50 nm gold particles fabricated using electron beam lithography on ITO coated glass substrates. Far-field spectroscopy near the plasmon resonance confirms the existence of longitudinal and transverse collective modes of excitation and allows for the calculation of the dispersion relation of all possible modes of plasmon waveguides. Measurements of the polarization dependent absorption confirm that the collective mode arises from near-field optical interactions. From these far-field measurements, a maximum group velocity of $4.0x10^{6}$ m/s for energy transport was calculated, in agreement with our theory. It should be possible to excite this mode of maximum group velocity for energy transport using local excitation of single nanoparticles as opposed to broad beam illumination of the waveguides. We report on initial measurements using the tip of an illumination mode near-field optical microscope (NSOM) as a local excitation source at 590 nm. Results from near-field spectroscopy measurements will be presented, and we investigate the possibility of using fluorophores as local probes for the energy transport in plasmon waveguides.

9:00 AM L6.3

SILICA/SILVER CORE-NANOSHELL SPHERES FOR METALLO-DIELECTRIC PHOTONIC CRYSTAL APPLICATIONS.

Jason Bouwman, Daniel Cassell, Craig Gallagher, and Miriam Deutsch, University of Oregon, Dept of Physics, Eugene, OR.

Metallo-dielectric photonic crystals (MDPCs) are predicted to exhibit strong nonlinear optical response, as well as prove useful in a variety of optical applications. We report here on the fabrication of silica-core/silver-shell monodisperse colloidal spheres for use as fundamental building blocks in three-dimensional MDPCs. Using a modified electroless plating technique thin silver nanoshells (100-400 *Å* thick) deposit uniformly at the surface of sub-micron colloidal silica spheres. Subsequently self-assembly of the core-shell colloids may be utilized to achieve structures that are ordered on a crystalline lattice. Spectroscopy and transmission electron microscopy of the silica/silver colloids and of annealed self-assembled structures will be presented.

9:15 AM *L6.4

PORE ETCHING IN COMPOUND SEMICONDUCTORS FOR THE PRODUCTION OF PHOTONIC CRYSTALS.

Helmut Föll[a], Sergiu Langa[a,b], Jürgen Carstensen[a], Marc Christophersen[a], Ion Tiginyanu[b], Karin Dichtel[c]; [a]Faculty of Engineering, University of Kiel, GERMANY; [b]Technical University of Moldova, MOLDOVA; [c]Physics Department, University of Kiel, GERMANY.

Some of the most advanced (two-dimensional) photonic crystals including defined defects have been made with electrochemically etched macropores in Si; typical dimensions were in the 1 μm region. Pores in Si, however, are limited to diameters of about 0,5 mm and larger; moreover, Si is not a good material for wave lengths >1043 nm because of its strong absorption.
Clearly, comparable structures in optically active III-V crystals (ideally with dimensions well below 0,5 μm), would be of considerable interest. The paper explores the potential of pore etching for two- and three-dimensional photonic crystals in GaAs, InP and GaP. A striking feature of pore etching in III-V semiconductors is the strong tendency to self-organization and pattern formation. As an example, self-organized well-defined pore lattices (a = 100 nm - 1 μm) can be made in InP. All materials show self-organized diameter oscillations, often synchronized over large distances between pores. Extremely strong diameter oscillations are observed in GaAs. Pores in all materials tend to grow in <111> directions, but can be induced to grow in the direction of current flow, too.
This features can be used to produce two- and three dimensional photonic crystals. The latter goal might be achieved by exploiting the anisotropy of pore growth, by switching periodically between different pore morphologies with depth, or by modulating the diameter with depth - always helped by the tendency to self organization.
Self organization, however, will not lead to perfect crystal structures; lithographically defined nucleation is needed and has been tried. First results show that there are pronounced differences to what is known from Si.
Porous III-V compounds generally exhibit new optical proper-ties, e.g. a strong increase of the cathodoluminescence in the first and second order harmonics in porous GaP. Results will be reviewed and augmented with new findings.

9:45 AM L6.5

NANOFABRICATION OF A PHOTONIC CRYSTAL MICRO-CAVITY EMBEDDING InGaAs QUANTUM DOTS WITH EMISSION AT 1300NM.

Massimo De Vittorio, Adriana Passaseo, M. Teresa Todaro, Cristian Bisconti, Roberto Cingolani, National Nanotechnology Laboratory of INFM, Dept-Ing.Innovazione, Lecce, ITALY.

In this work we report on the fabrication of a photonic crystals microcavity embedding one layer of InGaAs/InGaAs quantum dots inside a GaAs waveguide layer. The sample was grown by Metal Organic Chemical Vapour Deposition (MOCVD) and consisted of a GaAs buffer layer grown on a GaAs substrate, followed by a distributed Bragg reflector (DBR) and a GaAs waveguide layer. The InGaAs quantum dots layer, grown by the Stranski Krastanov technique, was embedded inside a one wavelength-thick GaAs waveguide layer. The DBR consisted of 25 quarter-wave stacks of GaAs/AlAs and it was designed to have the stop-band centered at 1.3 micron, corresponding to the quantum dot ground state emission. The photonic crystals (PCs) was realised by patterning a triangular lattice of air holes inside the GaAs waveguide layer. The pattern was performed by using a low-energy electron beam lithography process on a 100nm thick PMMA resist layer. Reactive ion etching was used to transfer the pattern down to the bottom DBR. The resulting pattern was morphologically characterized by scanning electron microscopy.The PC microcavity was obtained by inserting a point defect in the photonic crystal lattice, whose geometric parameters (holes radius and filling factor) were designed to have a localized mode at about 1.3 micron. Finally, the microcavity was characterized through micro-photoluminescence (micro-PL), by collecting the signal in back scattering geometry both inside the microcavity and outside the point defect. Sharp peaks, corresponding to the localized modes of the microcavity has been evidenced in the microPL in good agreement with the calculated density of photonic modes.

10:30 AM L6.6
PHOTONIC CHARACTER OF FREE-STANDING TWO-DIMENSIONAL SPHERICAL ARRAYS. Sachiko I. Matsushita, Masatsugu Shimomura, RIKEN Frontier Research System, Dissipative-Hierarchy Structures Laboratory, JAPAN.

Two-dimensional (2D) spherical arrays, in which fine particles are two-dimensionally packed in highly dense, highly oriented manner, have been attracted as quasi-2D photonic-type crystals by theoretical and experimental researchers because of their attractive features such as large domains, controllability of the number of the layers, easy preparation (self-assembled process), short-time preparation (generally less than 30 minutes for one sample), et al. The prefix "quasi-" being used to indicate that the array does not have an infinite number of parallel mirror planes, as an array of cylindrical posts would, and is thus not a true 2D photonic crystal. Even though, this type of photonic crystal seems very important as a basic model of opal type and inversed-opal type photonic crystal, and to link the study of photonic crystal with the study of microspherical laser. Recent 2D spherical array's researches show that one of the reasons of the mismatches between theories and experiments is influences of substrates, on which the arrays are prepared. In this presentation, we would show the preparation of free-standing single layers of 2D spherical array, i.e., the thickness is the particle's diameter, utilized sintering process. The free-standing arrays are stable enough in room temperature to check their photonic character easily. Microscopic photonic character, such as light propagation in free-standing composite arrays, in which mixtures of fluorescent and nonfluorescent polystyrene latex particles (3, 1, 0.5 μm), was observed by use of fluorescence microscopy and optical microscopy without any influence of substrate.

10:45 AM L6.7
NEW PROGRESS ON P-TYPE MACROPOROUS SILICON ELECTRODISSOLUTION. Zeno Gaburro, Paolo Bettotti, Luca Dal Negro, Lorenzo Pavesi INFM - Department of Physics, University of Trento Povo (TN), ITALY.

We will present our latest results on fabrication of macroporous structures on p-type silicon samples by electrochemical etching. We have obtained different lattice structures starting from an unique lithographic mask, by exploiting the dissolution mechanism of p-type silicon. Opposed to n-type silicon, the lateral dissolution is not a self-stopping process in p-type. Therefore, by changing the etching conditions, different structures can be obtained, including lattices of pillars, variously shaped pores or even with more complex bases. We report a square lattice whose base has two pores with different diameter. The effects of different electrolytes, the time of etching, the current and the concentration of HF are reported, together with a quantitative measurement of the lateral growth of the pores in several etching conditions.

11:00 AM L6.8
EXPERIMENTAL INVESTIGATION OF THE DISPERSION RELATION IN A HEXAGONAL 3D PHOTONIC CRYSTAL. J. Schilling, F. Müller, R.B. Wehrspohn, U. Gösele, Max-Planck-Institute of Microstructure Physics, Halle, GERMANY; K. Busch, Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, Karlsruhe, GERMANY.

2D photonic crystals based on macroporous silicon are now well established. However to obtain a 3D photonic crystal a periodical variation of the refractive index along the pore axis is additionally necessary. One way to achieve this is by periodic modulation of the pore diameter. Combined with the 2D triangular pore pattern, the resulting structure represents a simple hexagonal 3D photonic crystal. Although it does not exhibit a complete 3D photonic bandgap it has other interesting properties: The modulation period along the pore axis (z-axis) can be independently controlled from the periodicity in the x-y-plane. Transmission spectra along the pore axis for different modulation periods (2μm and 1.69μm) are shown and compared with 3D plane wave bandstructure calculations based on a 3D SEM analysis of the samples. The shift of the stopband caused by the different pore diameter modulations is observed and in very good agreement with the corresponding band structures. Moreover this structure represents an omnidirectional reflector. For a modulation period of 2μm, a spectral region of omnidirectional total reflection around $\lambda \approx 8\mu$m is theoretically perdicted from the 3D bandstructure. Angle resolved transmission measurements were performed which show zero transmission in this spectral range. This corresponds to total reflection in the whole angular range in line with theory. In addition, the dispersion relation of the lower bands along the pore axis is investigated experimentally. Due to the final depth of the 3D photonic crystal, Fabry-Perot resonances occur between the surface (air/porous region) and the interface (porous region/bulk silicon substrate). They contain information on the dispersion relation in the photonic crystal for light propagation along the pores. By the analysis of these resonances the slope, bending and group velocity of the lowest bands are determined. Comparision with 3D band structure calculations shows excellent agreement.

11:15 AM L6.9
TIME-RESOLVED LIGHT PROPAGATION AT BAND-EDGE STATES OF 1D FIBONACCI QUASICRYSTALS. L. Dal Negro[a], C.J. Oton[a], Z. Gaburro[a], P. Johnson[b], Ad. Lagendijk[b], D. Wiersma[c], L. Pavesi[a]; [a]INFM & Dipartimento di Fisica, Universita' di Trento, Povo, Trento, ITALY; [b]Van der Waals-Zeeman Institute, University of Amsterdam, Amsterdam, THE NETHERLANDS; [c]European Laboratory of Nonlinear Spectroscopy, Florence, ITALY.

Infrared time-resolved interferometric transmission measurements have been performed on one dimensional porous silicon Fibonacci quasicrystals, obtained by electrochemical etching a p^+-type silicon substrate, to address experimentally the problem of light transport and localization in deterministic aperiodic structures. Coherent beatings, pulse stretching and strong pulse delay on a picosecond time scale have been measured when the laser wavelength was tuned at the one-dimensional band-edge of a 233-layers Fibonacci quasicrystal where quasi-localized states exist. The observation of these dramatic pulse distortion effects demonstrates the selective excitation of very-narrow localized optical modes. One dimensional transfer matrix and scattering states simulations yield the electromagnetic field distribution inside the structure and reproduce these experimental data supporting the general conclusion about the observation of quasi-localized photonics states.

11:30 AM L6.10
PHOTONIC CRYSTAL PROPERTIES OF SiON (n=1.56). Igor M.P. Aarts, Rob W.v.d. Heijden, Huub W.M. Salemink, Eindhoven University of Technology, COBRA, Dept of Applied Physics, Eindhoven, THE NETHERLANDS.

We report for the first time the use of the relatively low index material SiON (n=1.56) for photonic crystal applications. With this system it is possible to enlarge the complete TE-band gap of a 2D-photonic crystal by properly designing the unit cell filling. This may be practically realised because of the larger dimensions of photonic crystals in low index materials, which allows less stringent etch conditions. Finding the optimal distribution of the refractive index in the unit cell is done by rigorous calculations in Fourier-space. The structure is defined by two figures of merit, the width of the band gap and the smallest feature size, which is the key factor in etching the structure. In addition, we suggest the use of a graded-index profile to reduce out of plane scattering. This graded index profile can be realised by controlling the nitrogen flow during deposition of the SiON layer.

11:45 AM L6.11
TWO DIMENSIONAL PHOTONIC CRYSTALS UTILIZING ORGANIC SEMICONDUCTORS AS ACTIVE MEDIA. J. Crewett, M. Reufer, S. Riechel, U. Lemmer, J. Feldmann, Lehrstuhl für Photonik und Optoelektronik, Sektion Physik and CeNS, Ludwig-Maximilians-Universität, München, GERMANY; A. Gombert, V. Wittwer, Fraunhofer Institut für Solare Energiesysteme, Freiburg, GERMANY.

Organic semiconductors have recently attracted much interest as active materials in light-emitting diodes and other optoelectronic devices. Due to the ease of deposition of thin organic layers on nanostructured substrates these materials are ideally suited for a combination with two dimensional photonic crystals. We have fabricated mechanically flexible conjugated polymer lasers utilizing distributed feedback due to a two-dimensional photonic band-structure. A UV-embossing process is used for nanopatterning a plastic substrate. On top we either spin-coat a conjugated polymer or evaporate small organic molecules as the active laser medium. Upon optical pumping we observe a low threshold and nearly diffraction limited monomode laser emission perpendicular to the surface. For higher pumping levels much more complicated laser patterns arise. Angle resolved emission spectroscopy allows for a detailed analysis of the laser action in the photonic crystal laser. As further steps towards electrically pumped organic lasers we have prepared structures comprising metallic layers for electrical injection as well as high-index dielectric layers to tailor the properties of the photonic bandstructure. In addition, we have explored low-cost routes for inducing optical defects into the photonic crystals.

SESSION L7: 3D PHOTONIC CRYSTALS AND OPTICAL CHARACTERIZATION

Chairs: Ekmel Ozbay and Henry M. van Driel
Wednesday Afternoon, April 3, 2002
Golden Gate B3 (Marriott)

1:30 PM L7.1
PERIODIC 3D STRUCTURES BY MULTI-BEAM INTERFERENCE. Shu Yang, Mischa Megens, Joanna Aizenberg, Pierre Wiltzius, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; Paul M. Chaikin, Dept of Physics, Princeton University, Princeton, NJ; William B. Russel, Dept of Chemical Engineering, Princeton University, Princeton, NJ.

Photonic materials have attracted great interest in the past because they could reflect light incident from any direction. However, it is technologically challenging to create photonic materials, which have highly ordered three-dimensional structures with periods on the order of the wavelength of light. By interference of three or four beams on photosensitive materials, we have created a series of defect-free 2D and truly 3D porous structures, such as hexagonal and face centered cubic patterns, with periods of ~1 micrometer and diameters larger than 0.1 mm.

1:45 PM L7.2
3D PHOTONIC CRYSTALS FABRICATED BY MICRO-MANIPULATION TECHNIQUE. Kanna Aoki, RIKEN, Saitama, JAPAN; Hideki T. Miyazaki, NIMS, Ibaraki, JAPAN; Hideki Hirayama, RIKEN, Saitama, JAPAN; Kyoji Inoshita, Yokohama National Univ., Kanagawa, JAPAN; Toshihiko Baba, Yokohama National Univ., Kanagawa, JAPAN; Norio Shinya, NIMS, Ibaraki, JAPAN; Yoshinobu Aoyagi, RIKEN, Saitama, JAPAN.

Three-dimensional photonic crystals with one (one fourth period) to four (one period) layers of woodpile structure have been fabricated by stacking semiconductor 2D photonic plates with micromanipulation technique. Exact positioning of lattice was achieved by using microspheres as stoppers. First, indium phosphide (InP) two-dimensional air-bridge photonic plates have been fabricated using metalorganic chemical vapor deposition (MOCVD) method and etching. A 0.5 μm-thick InP layer with woodpile patterns with a lattice constant of 1.4 μm and a pile width of 0.4 μm were suspended in the air by four narrow bridges. For accurate positioning of plates, holes were prepared in the frame of the photonic plates. Air bridge 2D photonic plates were stacked using a micromanipulation system that is installed in the specimen chamber of a SEM with a field emission gun. The bridges of the photonic plates were broken with a probe tip. The separated plates would adhere to the probe or the substrate 50% of the time, because electrostatic and/or van der Waals forces have stronger influence than gravitational force. To obtain lattices with precise periodicity, microspheres were inserted into the round openings that were prepared in the same position of the neighboring layers. Positioning error was within 30 nm. Optical characteristics were evaluated by reflectance and transmittance to the wavelength between 1.4 and 14 μm. The formed photonic crystals were expected to have a photonic band gap at around 3.3 μm. As the number of layer was increased, the reflectance at around 3.3 μm increased up to 50%, and the transmittance at the same wavelength region decreased down to 30%.

2:00 PM L7.3
FABRICATION OF COLLOIDAL CRYSTAL FILM ON MODIFIED SUBSTRATE. Zhong-Ze Gu, Osamu Sato, Kanagawa Academy of Science and Technology, Kanagawa, JAPAN; Akira Fujishima, The Univ of Tokyo, Tokyo, JAPAN.

A new approach is proposed for the patterning of the colloidal crystal film by taking advantage of the photocatalytic and photo-induced super-hydrophilic properties of titanium dioxide. The substrate for the patterning of the colloidal crystal film was a titanium dioxide coated glass substrate. The substrate was treated with fluoro-alkylsiliane to make the surface hydrophobic. A photo-irradiation of an ultra violate light through a photomask turns the irradiated surface of the substrate from hydrophobic to hydrophilic. Following dipping process develops patterns of the colloidal crystal film on the hydrophilic surface of the substrate.

2:15 PM L7.4
ELECTROCHEMICAL DEPOSITIONS OF 3-DIMENSIOANL MICROPOROUS STRUCTURES OF II-VI AND III-V SEMICONDUCTORS. Chia-Chun Chen, Yi-Chen Lee, Chong-Zon Kuo, Chi-Zon Shui, Ya-Wen Sue, Department of Chemistry, National Taiwan Normal University, Taipei, TAIWAN.

We have systematically studied the electrochemical depositions of more than six different II-VI and III-V semiconductors on close packed colloidal arrays of silica spheres. Through careful adjustments on current density, deposition time, electrolytes, solvents and temperatures etc. during the depositions, we have successfully fabricated those semiconductor films onto the silica arrays. Following by the removal of silica, 3-D microporous structures made from those semiconductors are built, and their photonic band gaps are measured. In addition, we have fabricated 2-dimensional arrays of those semiconductors using the combined techniques of e-beam lithography and electrochemical deposition. The desired patterns of 2-D arrays can be easily controlled under different experimental conditions of electrochemical depositions.

2:30 PM L7.5
3D PHOTONIC CRYSTALS FROM MONODISPERSE ZnO COLLOIDAL SPHERES. Eric W. Seelig, Betty Tang, R.P.H. Chang, Northwestern University, Dept of Materials Science and Engineering, Evanston, IL; Alexey Yamilov, Hui Cao, Northwestern University, Dept of Physics and Astronomy, Evanston, IL.

While a great deal of work is being done in the area self-assembled 3D photonic crystals [PC], most of the materials involved are optically passive (non-emissive). These materials include SiO_2 and polymers such as polystyrene and PMMA. 3D PC based on optically active materials could exhibit many interesting properties. In the current work, we report the fabrication of 3D PC from ZnO colloidal spheres. We present a solution chemistry method for the controlled synthesis of monodisperse ZnO colloidal spheres over a broad range of sizes from ~100 to 600 nm, and discuss the fabrication of PC from these materials. The structure of these PC is characterized using scanning electron microscopy. Our optical measurements (transmission and reflection spectroscopy and reflection-mode optical microscopy) indicate that the photonic band gap is tunable across the entire visible part of the spectrum and extends into the IR and UV, and these results have been compared with band structure calculations. We demonstrate that it is possible to design a PC in which the photonic band gap overlaps the ZnO electronic band gap at 385 nm. We will also present lasing results from our 3D PC.

3:15 PM *L7.6
VISUALIZING THE CONFINEMENT AND PROPAGATION OF LIGHT IN PHOTONIC CRYSTALS. Vahid Sandoghdar, Swiss Federal Institute of Technology (ETH), Zurich, SWITZERLAND.

Confinement and propagation of light in photonic crystals is very interesting because this typically involves length scales of the order of or smaller than the wavelength. This very fact also makes the experimental observation of these phenomena difficult. We have applied scanning probe techniques to perform microscopy and spectroscopy on photonic crystals including defects. The combination of these techniques has allowed us to directly observe the confinement of light in a photonic crystal microresonator and its propagation in waveguides.

3:45 PM L7.7
THIN OPALINE FILMS AND OPALINE HETEROSTRUCTURES FOR THE VISIBLE. S.G. Romanov, T. Maka, D.N. Chigrin, C.M. Sotomayor Torres, Inst. of Materials Science & Dept. of Electrical and Information Engineering, University of Wuppertal, Wuppertal, GERMANY; M. Müller, R. Zentel, Inst. for Organic Chemistry, Dept. of Chemistry and Pharmacy, University of Mainz, Mainz, GERMANY; N. Gaponik, A. Rogach, Inst. of Physical Chemistry, University of Hamburg, Hamburg, GERMANY; J. Manzanares-Martinez, M. Kaliteevski, D. Cassagne, Groupe d'Etude des Semiconductors, Université Montpellier II, Montpellier, FRANCE.

Improvements of light sources within 3-dimensional photonic crystals rely on the suppression of the spontaneous emission, the enhancement of the emission into localised modes and the directionality of the emission. Self-assembly of opaline materials has proved to be insufficiently precise and rather inflexible. The method behind our approach is to combine colloidal crystallisation with colloidal epitaxy and nanolithography. Our research is aimed at (i) improving the crystallinity of opaline thin films, (ii) preparing sandwiched structures from opaline films to control the density of states, (iii) patterning of colloidal crystals and (iv) investigating the photonic bandgap effect upon the emission. A natural example of a complex stop band is the band branching, which occurs due to the crossing of (111) and (200) bands. Here two stop bands appear at different frequencies in s- and p-polarisations, moreover, the latter is doubled. The double band gap was mimicked by the formation of heterostructured opal, where two opals of different photonic bandgaps form an interface. A further development towards the 3-layer structure has the intermediate layer thickness comparable to the wavelength thus emulating an opal with an artificial plane defect. We provide examples of reflectance/transmission properties of these heterostructures to demonstrate the feasibility of engineering the photonic bandgap profile. We also show photoluminescence experiments with non-structured opals and demonstrate the correlation between the density of states and the spectrum of the emission rate. The enhancement of the spontaneous emission occurs if the emission is coupled to localised optical modes of intrinsic defects, when these modes are in the stop band range. Opaline heterostructures enhance the quality factor of optical modes of defects, intrinsic or intentional, and open different frequency windows for the emission rate enhancement. We present a proof of principle, obtained by examining the modifications of the emission from light sources in different heterostructures made from direct and inverted opals.

4:00 PM L7.8
MODIFIED SPONTANEOUS EMISSION IN SILICON PHOTONIC WOODPILE STRUCTURES. M.J.A. de Dood, B. Gralak and A. Polman, FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS; J.G. Fleming and S.Y. Lin, Sandia National Laboratories, Albuquerque, NM.

Doping 3-D photonic crystals with optical probes is an excellent way to probe their photonic bandstructure. We have performed a study of the luminescence, at 10 K, from a finite 5-layer silicon photonic woodpile structure doped with erbium ions by MeV ion implantation. The woodpile structure under study was designed for 1.5 μm radiation. Both erbium luminescence and intrinsic luminescence stemming from defects in the polycrystalline material are observed for the woodpile structure as well as for planar reference samples. Our measurements reveal the existence of a photonic bandgap around 1.5 μm, which suppresses the luminescence intensity collected in the bandgap region. The photonic crystal has different effects on the lifetime and intensity of Er and defect luminescence. This difference can be explained by the different spatial distribution of the light sources inside the structure. A simple model including the collection efficiency to the detector and quantum efficiencies of the emitting species allows us to quantify results on the Er luminescence. A typical intensity suppression of 5 dB per unit cell is observed, in perfect agreement with data derived from transmission experiments. Polarization dependent reflection measurements on these large single-domain photonic crystals with finite thickness reveal the importance of surface termination and orientation with respect to the polarization of the light.