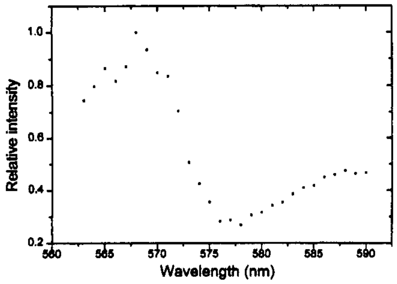

QTuA5 Fig. 1 Absorption spectrum of the dye molecules excited by SPPs. The spectrum has been normalized to the absorption of dye molecules on a grating that does not exhibit a band gap. The dip in the spectrum shows clearly how the absorption of the dye is reduced when the SPP modes—which excite the dye molecules—are inhibited.

sorption spectrum of the system is substantially modified. Incident photons having frequencies within the band gap are unable to generate SPPs. There is, therefore, no field enhancement and the absorption and consequent emission are reduced. Such a gap may be created by addition of an extra modulation to the grating profile,[3] and suitable choice of the profile ensures that the SPP gap lies within the absorption band of the dye.

In our experiment a metallic grating was spin coated with dye molecules (Sulforhodamine 640) and then dye pumped with use of a dye laser that could be tuned through the sulforhodamine absorption band (560–590 nm). This allows us to observe the effect of the band gap on the absorption process by monitoring the dye emission as a function of pump wavelength. Figure 1 shows the normalized absorption spectrum of the dye molecules above a metallic grating with such a band gap. It is evident that the band gap has a strong effect on the absorption of energy by the molecules. The results of numerical modeling will also be presented that demonstrate how the effect of this photonic band gap may be optimized.

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QTuA6 9:30 am

3-D photonic crystals operating at optical wavelengths

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A photonic crystal is a three-dimensional periodic dielectric structure possessing a frequency band or bandgap over which all electromagnetic modes, spontaneous emission, and zero point fluctuations are forbidden irrespective of propagation directions.[1-3] Both theoretical calculations and microwave measurements have shown that the "three hole" face centered cubic (FCC) lattice of cylindrical voids in a dielectric matrix exhibits such a photonic bandgap.[1] Photonic crystals are expected to be useful in making high-Q microcavities for single-mode light-emitting diodes and low threshold lasers.

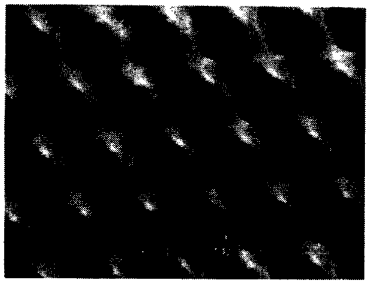
However, use of photonic crystals at optical frequencies requires the modulation of the dielectric constant at a submicron range, which represents a challenging fabrication task. We have reported previously on the technology for nanofabricating photonic crystals by means of high resolution lithography and anisotropic ion etching in compound semiconductors.[4,5] In the present work, we demonstrate the successful fabrication of these 3-D tiny nanostructures with lithographically controlled operating wavelengths.

We have synthesized and characterized photonic crystals, up to four successive vertical layers deep in GaAs, with varying hole diameters and lattice constants. The lattice parameters and structural integrity were confirmed by SEM observations (see Figs. 1 and 2). Their spatial periodicities were chosen from model predictions to yield photonic bandgaps in the near-infrared wavelength range.[6] Indeed, the hole center-to-center spacing is proportional to the lattice constant and defines the midgap frequency of a photonic crystal. Furthermore, the hole diameter changes the porosity of the structure, and thereby alters the average refractive index of the resulting photonic crystal. Thus it is possible to tune the midgap frequency of a photonic crystal during the electron beam mask patterning step.

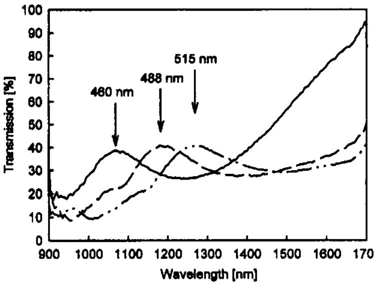
Optical transmission measurements were undertaken on a series of nanofabricated photonic bandgap crystals. Figure 3 shows transmission spectra for three photonic crystals with different lattice spacings but identical hole diameters. As expected, the conduction band edge shifts to higher wavelength as the center-to-center spacing increases. Similarly, we have observed a shift in the spectra when only the diameters of the holes were changed. The shifts are correlated with microwave measurements of a scale model made of Stycast with a dielectric constant equal to 12, thus mimicking GaAs. However, as illustrated in Fig. 3, these tiny mirrors are not as reflective within the forbidden gap as the corresponding microwave scale models. Obviously the precision of the nanofabrication will need to be improved, but it is adequate for now to show the unmistakable evidence of an optical scale photonic bandgap.

We have so far reproduced these measurements on numerous nanofabricated samples and we believe that it is possible to predict the spectral features of photonic crystals by carefully controlling the mask fabrication process. We envision that these novel artificial dielectric structures will lend themselves to applications to optoelectronic technology and will be generically useful in optical science.

QTuA6 Fig. 1 Normal incidence SEM picture of a photonic crystal with cubic lattice spacing $a = 570$ nm.



QTuA6 Fig. 2 Four-vertical-layer-deep photonic crystal with 850 nm cubic lattice spacing. The sample was tilted 25° off the ⟨111⟩ axis.



QTuA6 Fig. 3 Transmission spectra of photonic crystals with varying hole center-to-center spacings.

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QTuA7 9:45 am

Resonant cavity-enhanced detectors embedded in photonic crystals

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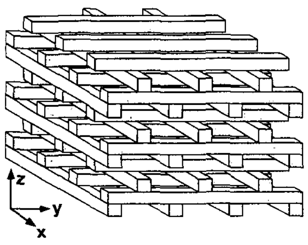
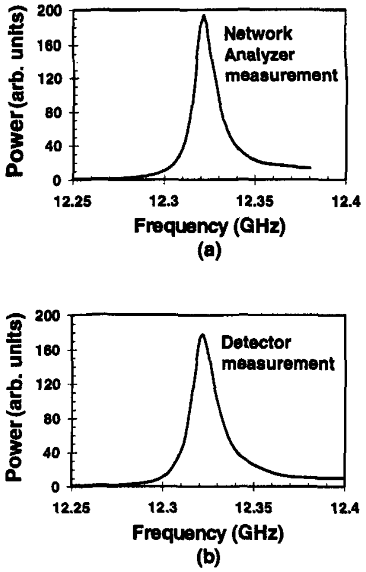
There is a great deal of current interest in the possibility of creating three-dimensional photonic band crystals in which no electromagnetic (EM) propagation is possible for certain frequencies.[1] Recently, Ho *et al.* have proposed a new photonic crystal based on stacked dielectric rods (Fig. 1), which can be fabricated at smaller scales by conventional methods.[2] Defects or cavities around the same geometry can also be built by addition of removal of rods from the crystals.[3] The electrical fields in such cavities are usually enhanced, and by placing active devices in such cavities one can obtain novel properties. This effect has been used already in optoelectronics to achieve novel devices such as resonant-cavity-enhanced (RCE) photodetectors and light-emitting diodes.[4] In this paper, we demonstrate the RCE effect by placing microwave detectors in a layer-by-layer photonic crystal.

We used the output of a network analyzer as the microwave source, and fed the output to a horn antenna to obtain EM waves. The crystal was then replaced in the beam-path of the EM wave, and the electric field inside the cavity was measured by a probe that consisted of a monopole antenna. The output of the antenna was measured by use of two different techniques: network analyzer and microwave detector within the cavity.

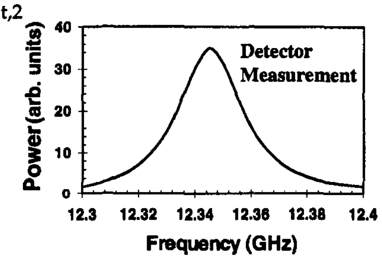
The first cavity structure was similar to a one-dimensional 1d Fabry-Perot resonator made of two mirrors separated by a distance. The front mirror structure was six layers thick, and the back mirror was eight layers thick, with a 7-mm separation between the two mirrors. Both techniques have shown a typical power enhancement factor of 180, with a quality factor of 1200 (Fig. 2). The agreement between two measurements also showed the reliability of the microwave detector.



QTuA7 Fig. 1 Schematic of the layer-by-layer photonic crystal.



QTuA7 Fig. 2 Measured power of the EM field inside a one-dimensional defect structure with use of (a) network analyzer or (b) microwave detector.



QTuA7 Fig. 3 Measured power of the EM field inside a localized defect structure with use of a microwave detector.

To obtain a localized defect, we modified a 16-layer crystal structure in the following manner. Parts of the rods on the 8th and 9th layer were removed such that we obtained a rectangular prism-like cavity. The dimensions of the cavity were $4a \times 4a \times 2d$, where a is the center-to-center distance between parallel rods and d is the thickness of the alumina rods. A microwave detector was placed in the photonic crystal, and a monopole antenna was connected to the input of the detector. The hybrid antenna-detector was then used to probe the EM field inside the localized cavity. Figure 3 shows the measured magnitude of the EM field with the detector. A power enhancement factor of 35 was measured for this cavity, which clearly indicates the resonant cavity enhancement for a localized defect.

Our results suggest the possibility of use of the embedded detector as an RCE detector. By use of a smaller size photonic crystal and a higher-frequency detector, the effect can also be shown at millimeter and far-infrared frequencies. Such RCE detectors will have increased sensitivity and efficiency when compared with conventional detectors and can be used for various applications where sensitivity and efficiency are important parameters.

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JTuB **8:30 am**
Salon F

Joint Symposium on Quasi-Phase Matching

Nasser Peyghambarian, *University of Arizona, Presider*

JTuB1 (Tutorial) 8:30 am

Microstructured media for nonlinear optics: Materials, devices, and applications

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The past decade has seen a renaissance in coherent sources based on nonlinear optical frequency conversion, fueled by improved pump lasers and improvements in available nonlinear materials. Microstructured nonlinear materials, especially those in which the nonlinear susceptibility is periodically reversed to quasi-phasematch (QPM) the nonlinear interaction, are playing an increasingly important part in these developments. Application of periodically poled ferroelectrics, the most important class of QPM materials, has allowed qualitative improvements in coherent sources from the ultraviolet to the mid-infrared. The increase in conversion efficiency available with these materials also enables effective application of quadratic nonlinear optics beyond simple sources of coherent radiation, in fields such as quantum optics, wavelength conversion for WDM systems, and cascade nonlinearities. By shifting the emphasis from materials with appropriate birefringence to those with patternable nonlinear properties, the use of QPM opens opportunities to take advantage of the attractive properties of materials not traditionally used in frequency conversion applications, such as cubic III-V and II-VI semiconductors, polymers, and glasses.

This tutorial will review basic ideas of QPM nonlinear optics, characteristics of available microstructured media, and recent device results in QPM bulk and waveguide SHG, DFG, and OPOs. Opportunities in novel microstructured materials and in applications beyond sources of coherent radiation will also be discussed.