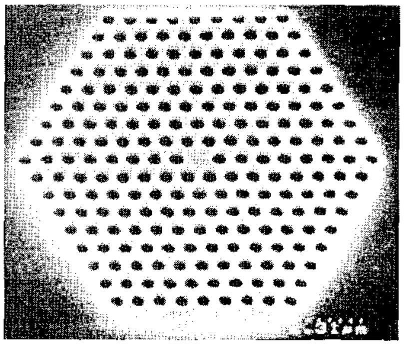
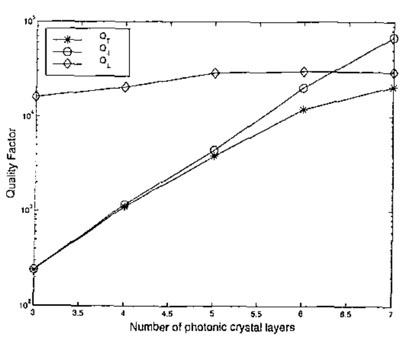


JMB1 **Fig. 1.** Scanning Electron Microscope (SEM) image of a photonic crystal nanocavity laser fabricated in InGaAsP. The lattice spacing is chosen so that the pair of degenerate resonant modes are tuned to match the emission wavelength of the quantum well active region (1.5 microns). The structure consists of a perforated thin membrane, which is roughly 200 nm thick.



JMB1 **Fig. 2.** Plot of the quality factor vs. number of periods of the photonic crystal surrounding the defect region (single removed hole). The total quality factor of the cavity mode is labelled as Q_T, and an effective vertical ($Q_\perp$) and in-plane ($Q_\parallel$) Q have been defined in terms of power radiated in the vertical and in-plane directions, respectively. For only a few periods of photonic crystal the in-plane loss is dominant, but as the number of periods is increased eventually the total Q approaches that of the effective vertical Q and the emission is predominantly in the vertical direction.

these type of photonic crystal based optical cavities may find use in cavity quantum electrodynamic experiments. Apart from the obvious reduction in optical mode volume, the same functionality that makes this technology interesting for lightwave communication may also prove useful for experimental measurements of atom-photon interactions. Through the addition of input and output waveguide channels based on the same planar photonic crystal geometry one may efficiently probe and detect the cavity modes. Also, as shown in Fig. 2, one may adjust the number of periods of photonic crystal in order to obtain vertical or in-plane emission depending on the application. Theoretical calculations of the cavity modes using finite-difference time-domain predict Q factors as high as 20,000 in optimized cavity geometries, limited by vertical leakage of light out of the high index slab.

We will present recent room temperature laser results, as well as tuning of the cavity modes through adjustments in the local defect region, and the splitting of the cavity mode degeneracy into a pair of x and y polarized modes. Progress to date and limitations in terms of obtainable cavity Q and fabrication tolerances will also be addressed.

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JMB2 **4:00 pm**

Surface-emitting laser designs based on one- and two-dimensional photonic crystals

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Surface-emitting lasers have emerged as a useful architecture for numerous applications. Nearly all the current surface emitting lasers are based on planar microcavities, which involve the growth of at least one highly reflecting multilayer mirror, which also has to transport charge to the recombination region. Such mirrors are difficult to fabricate in many material systems such as GaN and semiconductors for 1.3–1.6 μm wavelengths. We propose instead, a class of laser designs based on one- and two-dimensional (1D and 2D) photonic crystals (PCs), which result in surface emitting lasers with a fabrication process similar to that used in edge-emitting distributed feedback lasers. The basic principle employed in our designs is based on our recent discovery that the output coupling characteristics of 2D gratings (or PCs) are significantly different from 1D gratings. In 2D PCs, phase-matching conditions result in the coupling of light to one or a discrete number of directions instead of a cylindrical wave. We have designed numerous combinations of lasers and couplers, which have the potential to couple to a single spot normal to the plane of the waveguide. The lasers are experimentally realized with organic semiconductors and involve photo-excitation of patterned combinations of organic semiconductor and dielectrics (e.g., SiO_2). The patterning is accomplished by advanced optical lithography or electron-beam lithography followed by dry etching and the subsequent deposition of the organic gain medium as a thin coating. One design that has been successfully implemented is a square 2D PC, which functions as a laser and output coupler. We have investigated the physics of 2D photonic crystal lasers and find that they may be useful for high-power lasers. We have experimentally realized such lasers with lattices possessing square, triangular, and honeycomb symmetries. However, for many applications, conventional 1D lasers are quite sufficient. A potentially promising design ensconces a 2D photonic crystal within a set of 1D gratings. For a square PC four 1D gratings are required. The 2D PC can then act as an output coupler/mixer for 1D lasers. In this manner, it is possible to create a compact surface-emitting laser combining the advantages of 1D distributed feedback lasers and 2D photonic crystal couplers.

JMB3 (Invited) **4:15 pm**

Surface plasmon enhanced LED

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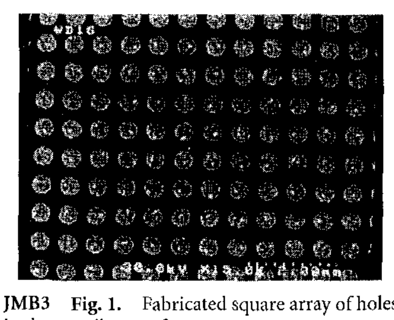
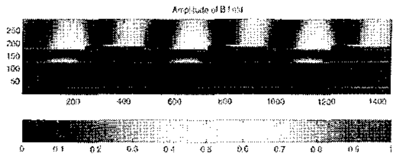
We designed and fabricated an LED based on a thin semiconductor membrane (λ/2) with silver mirrors. A large spontaneous emission enhancement and a high modulation speed are obtainable due to the strong localization of the electromagnetic field in the microcavity. The coupling to surface plasmon modes which are subsequently scattered out by means of a grating is used to improve the extraction efficiency of the LED. The bottom mirror is thick and unpatterned. The top mirror is thin and its top surface is patterned with a two dimensional lattice of subwavelength holes. The membrane consists of an InGaAs quantum well emitting at 980nm with GaAs barriers and p and n type AlGaAs layers positioned next to the silver layers. The silver mirrors may also function as contacts for electrical pumping of the device.

The following sequence of steps is used during the fabrication of the device:

- Deposition of a thick silver mirror (>1μm) on top of the unprocessed wafer;
- Epitaxial liftoff of a membrane by etching a sacrificial AlAs layer underneath;
- Van der Waals bonding of a membrane to a Si substrate. Thick silver mirror is positioned on the bottom;
- Deposition of a thin silver (<30nm) mirror on top of a membrane;



JMB3 **Fig. 1.** Fabricated square array of holes in the top silver surface.



JMB3 **Fig. 2.** The calculated intensity of the magnetic field (vertical slice through the LED).

- Definition of a pattern on a top silver surface using e-beam lithography;
- Transfer of a pattern into the top metal using Ar^+ ion milling (see Fig. 1).

The microcavity mode is coupled to a surface plasmon mode at the top silver surface. The grating at the metal surface scatters the surface plasmon mode out of the cavity. We presently measure 12 times spontaneous emission enhancement with respect to an unprocessed wafer, for an optically pumped structure. Further optimization of the design will lead to larger enhancement values. We are currently working on an electrically pumped device which will help us measure the exact values of the enhancement and the achievable modulation speed of such a device.

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JMB4 **4:45 pm**

Coupling surface plasmon polaritons to radiation

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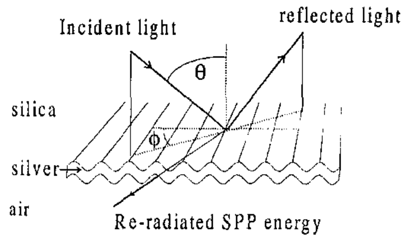
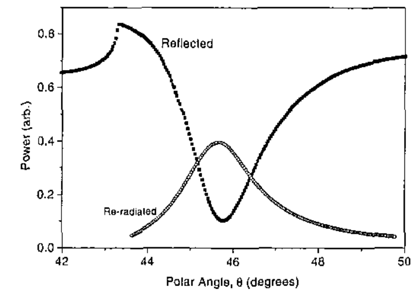
There is a continuing interest in efficiently collecting spontaneous emission, for example in light-emitting diodes and optical sources for quantum communication. Many schemes for improving the efficiency with which spontaneous emission is collected involve the use of a microcavity. Spontaneous emission is typically coupled to the lowest order mode of a microcavity, the microcavity mode in turn being coupled to radiation. Here we investigate an alternative approach,



JMB4 **Fig. 1.** Schematic of arrangement used to generate the SPP mode and recover them via Bragg scattering.



JMB4 **Fig. 2.** Reflected and re-radiated power as a function of the angle of incidence of the SPP generating laser beam.

that of using a surface plasmon polariton (SPP) mode as the intermediate step in generating radiation. In our system the thin emissive layer is placed adjacent to a metal film rather than inside a microcavity.

Coupling between spontaneous emission from, for example, excited states of dye molecules in a thin layer, and the SPP mode of an adjacent metal interface is well known.[1] However, SPPs are usually nonradiative because their wavevector (momentum) is greater than that of a free space photon of the same frequency. This momentum excess can be overcome using a metal surface textured in the form of a diffraction grating,[2] the momentum being modified by Bragg scattering. Spontaneous emission may be efficiently coupled to SPPs[3] so that if these surface modes may in turn be efficiently coupled to radiation it may be possible to develop a new efficient emitter structure.

The issue of how efficiently a SPP mode may be coupled to radiation has only been addressed in a limited way before.[4] The random in-plane (plane of the microcavity) orientation of the dipole moments associated with sources of spontaneous emission, such as excitons and dye molecules, means that SPP modes will be produced propagating in all directions on the metal surface. It is therefore important to know how efficiently SPP modes traveling in different directions may be coupled to radiation. We report results of an investigation into this coupling efficiency as a function of the azimuthal angle between the SPP propagation directions and the Bragg vector of the corrugated metallic surface.

We deposited a thin layer of silver onto a corrugated silica surface. Surface plasmon polaritons propagating in a known direction were generated by a laser beam incident from the reverse side of the metal film, momentum matching to the SPP mode being achieved via prism coupling. By monitoring the drop in reflected power of this laser beam at the SPP matching angle, an upper estimate on the power coupled to the surface mode was obtained. The radiation produced by grating mediated coupling of the SPP mode to radiation was also measured, thus allowing the efficiency of the process to be determined.

For an azimuthal propagation angle of the SPP mode on the surface of 30° (relative to the Bragg vector) we measure a coupling efficiency of > 50%, as shown in Fig. 2. We will report measurements showing how this efficiency changes with propagation angle and discuss the role of the corrugation profile in optimizing that efficiency.

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JMB5 **5:00 pm**

Metallo-dielectric photonic crystals for infrared appliations

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There are a wide range of applications calling for low-loss, broad-band filters in the long-wave infrared, particularly in the atmospheric transmission windows at 3–5 μm and 8–12 μm. McIntosh *et al.*[1] have demonstrated the use of metallo-dielectric photonic crystals (MDPCs) for infrared bandstop filters. Similar characteristics have been obtained at microwave frequencies using flat metal scatterers.[2] In order to obtain a bandpass filter, one might use the Babinet complement of flat metal scatterers—apertures in flat metal sheets (also called inductive mesh). Figure 1 depicts examples of both types of MDPC.

We have fabricated both bandstop and bandpass filters using flat scatterers for infrared wavelengths, and have used a finite-difference time-domain (FDTD) simulation[3,4] to accurately model the filter performance. The bandstop filter consists of three layers of circular Al scatterers (1.9 μm diameter) in triangular planar arrays (3.2 μm nearest neighbor spacing) with 2.6 μm of planarizing polymer dielectrc (n = 1.45) between layers, and 1.3 μm of dielectric on each end. The bandpass filter consists of three square-shaped inductive meshes, of period 4.2 μm with 2.7 μm square apertures, in the same dielectric layers as above. Both