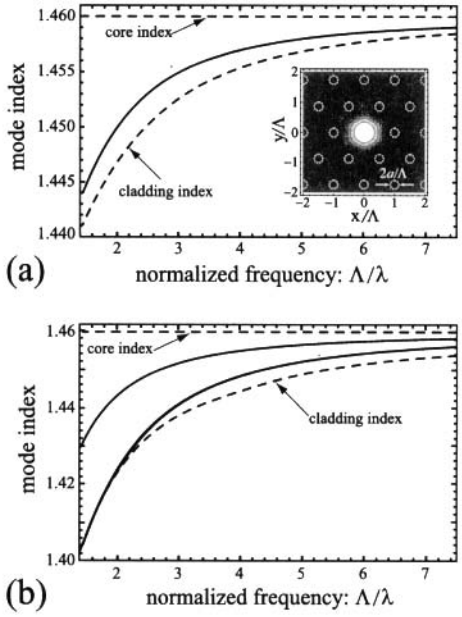
formed by a polarization doublet. The transverse intensity distribution of these guided modes for a wavelength of λ = 632.8 nm was also calculated and the result for one of the polarizations is shown in Figure 1a.

Our work proves that electromagnetic propagation in a realistic PCF can support a robust single-mode structure nearly at all wavelengths for certain fiber parameters. It is notable that this approach is based on a full-vector method, so that polarization effects are incorporated in an exact manner. Our results for both dispersion curves and intensity distributions completely agree with those experimentally measured. This method provides a powerful tool for a better understanding of the PCF's properties because it allows us to fully determine the dispersion curves of their guided modes, as well as their electromagnetic field and intensity distributions.



Ferrando Figure 1. (a) Modal dispersion curves from λ = 300 nm to λ = 1600 nm for a PCF structure with a = 0.3 µm and Λ = 2.3 µm. The variations of the single-mode index for both polarizations coalesce in a single curve. In this figure we also plot the transverse intensity distribution of the x-polarized guided mode for λ = 632.8 nm;
(b) a = 0.6 µm and Λ = 2.3 µm. Here, the two higher-order polarization doublets are slightly shifted.

The flexibility of our approach also permits the simulation of a great variety of fiber designs. By analyzing the dispersion curves of these different fibers, we have already discovered a richer modal structure in some of them. In the example shown in Figure 1b there exists, besides the fundamental doublet, two other polarization doublets. Similarly, we can use this tool to optimize the design of PCFs with unconventional dispersion relations, of potential interest for pulse propagation.

Acknowledgment

This work was financially supported by the Generalitat Valenciana (grant GV96-D-CN-05141), Spain.

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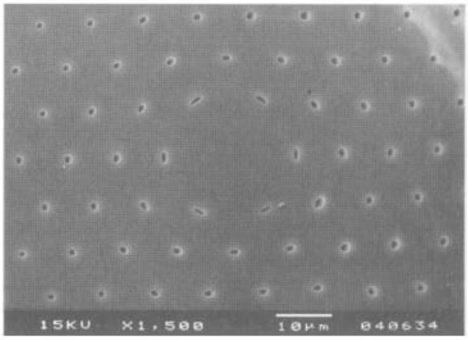
Large Mode Area Photonic Crystal Fiber

J.C. Knight, T.A. Birks, R.F. Cregan, and P.St.J. Russell, Optoelectronics Group, Dept. of Physics, Univ. of Bath, Bath U.K.

Photonic crystal fiber (PCF) is a new type of optical fiber waveguide consisting of a pure silica fiber with a regular array of small holes running through its entire length.[1] A single missing air hole defines a region that effectively has a higher refractive index than the surrounding "holey" material. This region can form the core of a low-loss optical waveguide. Such a structure is readily fabricated by stacking a few hundred silica capillary tubes (of around 40-cm-length and 1-mm-diameter) and then drawing the stack down to a long fine fiber (at an elevated temperature) on an optical fiber drawing tower. A single solid silica rod embedded within the stack forms the fiber core.

By making a fiber with small air holes spaced by about half the core diameter, one can confine the fundamental mode (with one lobe that fills the core) while higher-order modes (which contain much higher spatial frequencies in their mode profiles) can escape between the holes. This fiber will then be "endlessly single-mode," guiding only the fundamental mode independent of the wavelength or scale of the structure. Another way of understanding this result is to assume that the "holey" cladding region behaves as an effective index medium.[2, 3] This effective cladding index, which would be a root-mean-square weighted average of the air and the silica for very long wavelengths and small structures, approaches that of silica as the wavelength gets shorter or the structure larger. This means that the refractive index difference between the pure silica core and the "holey" cladding decreases as the wavelength does—exactly the condition required to maintain monomode waveguiding.

PCF thus offers a new way to fabricate large mode area single-mode fibers.[4] We have demonstrated this with the fiber shown in Figure 1, which guides 458-nm single-mode light, despite having a core diameter of 22 µm. This is equivalent to a fiber with a core diameter of 75 µm guiding 1550-nm monomode light. Large mode area fibers are important because the amount of power that can be transmitted down (or generated in) a single-mode fiber is limited by nonlinear losses, which are a result of the very high-field strengths and power densities occurring in the tiny fiber core. They are difficult to fabricate using conventional means because of the need for a very low, but highly uniform, doping level to define the fiber core. By using the ideas embodied in this



Knight Figure 1. Electron micrograph of a cross-section through a large-mode-area PCF. The core diameter is 22 µm and guides a single-mode at a wavelength of 458 nm.

discovery, it should be possible to guide higher powers in single-mode fiber than previously.

Acknowledgments
This work is supported by the EPSRC and DERA Malvern.

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Creation of a 3-D Silicon Photonic Crystal

Shawn-Yu Lin and J.G. Fleming, Sandia National Laboratories, Albuquerque, NM.

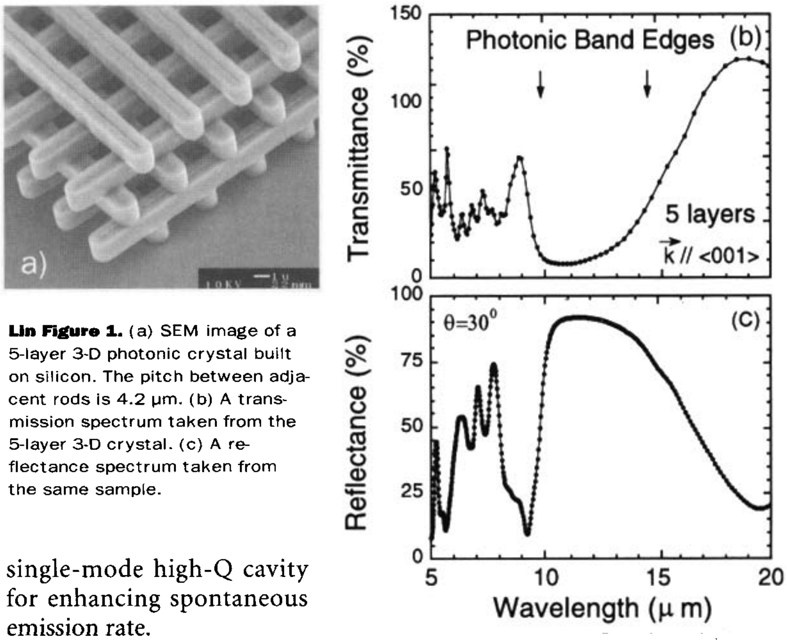
A 3-D photonic crystal is an attractive optical material for controlling and manipulating the flow of light on a semiconductor chip. High-speed tera-hertz optical switches, high efficiency μA edge-emitting-lasers, and the guiding and routing of optical signals in all three dimensions are but a few of the potential benefits of these new engineered "materials."

Although the original concept of 3-D photonic crystals was proposed more than a decade ago,[1] its successful experimental realization in the IR and optical wavelengths has always been thwarted by micro-fabrication complexities.

In this work, we report the creation of the first ever silicon 3-D photonic crystal operating in the IR.[2] Our approach takes advantage of two recent breakthroughs: one in the new design of photonic crystals, the other in the advances in micro-fabrication technology. First, after re-examining the elegant, yet difficult to fabricate, 3-hole pattern photonic crystal structure proposed by Yablonovitch,[1] several groups independently suggested a simpler layer-by-layer design[3–5] that is amenable for fabrication at sub-micrometer scale. Second, advances in silicon processing, especially chemical mechanical polishing, has supplied the tools required for the successful fabrication of devices active in the IR.

Using these new tools, a 5-layer photonic crystal structure was successfully fabricated. An SEM of a layer-by-layer 3-D photonic crystal built on a silicon substrate is shown in Figure 1a. The structure possesses a distorted face-center-cubic crystal symmetry.

The transmission spectrum of light propagating along the <001> direction of the 3-D crystal, *i.e.*, normal to the substrate, is shown in Figure 1b. At λ = 10–14.5 μm, a strong transmission dip was observed, signifying the existence of photonic bandgap in the 3-D structure. A reflectance spectrum taken from the same sample is shown in Figure 1c. As expected, a high reflectivity was observed in the bandgap regime. Indeed, a 3-D photonic crystal may be regarded as a 3-D dielectric high reflector and applied to construct a truly single-mode high-Q cavity for enhancing spontaneous emission rate.



Lin Figure 1. (a) SEM image of a 5-layer 3-D photonic crystal built on silicon. The pitch between adjacent rods is 4.2 μm. (b) A transmission spectrum taken from the 5-layer 3-D crystal. (c) A reflectance spectrum taken from the same sample.

This demonstration will not only lead to high performance optoelectronic devices, such as thresholdless lasers, but also opens the door for Si-based photonic devices that are compatible with the well-developed Si microelectronics processes and are suitable for large scale photonic integration.

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Efficient Polarized Laser Mirror

R. Magnusson, Z.S. Liu, D. Shin, S. Tibuleac, and P.P. Young, Dept. of Electrical Engin., Univ. of Texas at Arlington, Arlington, TX.

Waveguide-mode resonance effects in thin-film layers can be applied to realize an efficient laser mirror. We have demonstrated the application of a high-efficiency guided-mode resonance (GMR) filter as an output-coupling mirror in a dye laser. This simple two-layer device provides polarized output laser light without the use of laser Brewster windows. The experimental value of the mirror reflectance is ~98% at the resonance peak with corresponding laser transmission of ~2%.[1] Similar experiments with an ~50% reflective corrugated-waveguide mirror have been reported in which parasitic lasing via Fresnel bulk reflections occurred simultaneously due to the low value of the mirror reflectance.[2]

Thin-film dielectric multilayers incorporating a periodic element and a waveguide layer exhibit sharp varia-