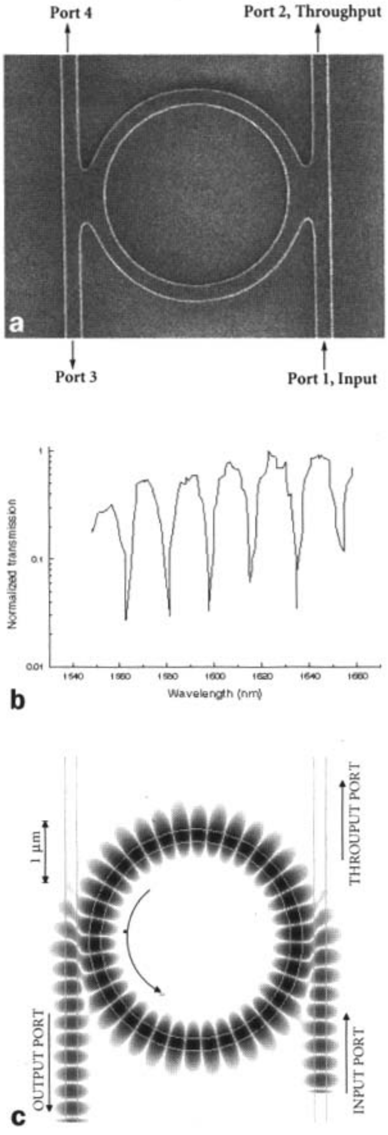
wavelength scale dimensions radiates excessively unless appropriate geometries and material systems are selected. Silicon on oxide, or GaAs surrounded by air, are two feasible material systems choices. Rings or disks, which support low-loss whispering gallery modes, are the geometries of choice for planar technology. Fabrication technologies have advanced to the point where such material combinations and structures can be processed with sufficient quality to yield practical devices.[4]

Figure 1 shows an SEM scan of a channel dropping filter (CDF) incorporating a microring resonator 3 μm in radius.[4] The CDF is comprised of a resonator evanescently side-coupled to a pair of bus waveguides. The resonator extracts a particular wavelength from the input bus and drops it into the output waveguide. The waveguides and ring in Figure 1 are composed of a 0.2-μm-thick layer of polycrystalline silicon (polySi), which rests on a 1-μm-thick layer of insulator (SiO_2). The waveguide widths are 0.5 μm, a dimension that ensures single-mode characteristics. Rings with radii from 3–5 μm were fabricated, with the 5-μm devices of this set exhibiting the lowest losses. The throughput response of a 5-μm ring is also shown in Figure 1b. Note that there are deep nulls at each resonant wavelength, indicating that the resonator is extracting a large portion of the incident signal from the bus waveguide. High extraction is vital in CDF applications, since a new signal may be reinjected at the same wavelength, and crosstalk must be avoided. Figure 1c shows a numerical simulation of the detailed electric field present in the device at resonance.



Little Figure 1. Silicon microring resonator channel dropping filter. (a) SEM of a 3-μm ring device. (b) Throughput response of a lower loss 5-μm device. (c) Numerical simulation of the instantaneous electric field at resonance. (See color image, page 15.)

The resonators now being realized are ideal candidates for very large scale integration. They can perform many of the required optical signal processing operations, while 10,000 well spaced devices of the type depicted in Figure 1 can fit in an area as small as 1 × 1 mm.

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PHOTONIC STRUCTURES

Vector Description of a Realistic Photonic Crystal Fiber

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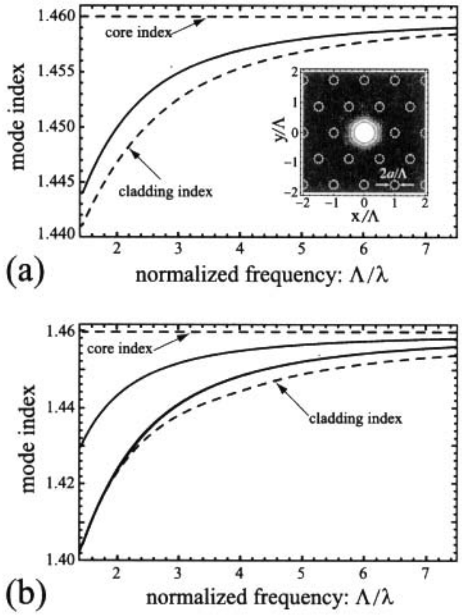
The most relevant property of periodic dielectric structures (*i.e.*, photonic crystals) is the possibility of generating photonic bandgaps.[1] A related phenomenon occurring in photonic crystal structures is light localization at defects. Although the previous phenomenon of light confinement at defects has already been analyzed in 2-D structures,[2] the study of the guiding properties of dielectric crystals that have a 2-D periodicity in the $x - y$ plane broken by the presence of a defect, but are continuous and infinitely long in the z direction—the so-called photonic crystal fibers (PCFs)—has not yet been performed. However, the experimental feasibility of these fibers has been recently proven.[3] A robust single-mode structure was observed for an unusually wide range of wavelengths, a remarkable property not present in ordinary fibers.

Our aim is to analyze the guiding properties of a realistic PCF in an accurate and rigorous way. We used a novel full-vector modal technique, an adapted version of our biorthogonal-basis modal method[4] in which the vector character of electromagnetic propagation is thoroughly taken into account. This method is based on the mathematical properties of the nonself-adjoint operator describing the dynamics of electromagnetic propagation in a fiber. We have simulated a realistic PCF, characterized by a hexagonal distribution of air holes with a central defect, by using periodic boundary conditions for the electromagnetic field.[5] The hole radius, a, the horizontal distance between the center of two consecutive holes, Λ, and the wavelength of light, λ, are free parameters that we change at will. We first simulated a realistic air-filled fiber with parameters a = 0.3 μm and Λ = 2.3 μm. Our simulation allowed us to calculate the modal dispersion curves for the fiber under consideration in a wavelength range extending from 300–1600 nm (see Fig. 1a, page 34). In that remarkably wide wavelength window, it revealed a single-mode structure, 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.

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.



Ferrando Figure 1. (a) Modal dispersion curves from $\lambda = 300$ nm to $\lambda = 1600$ nm for a PCF structure with $a = 0.3$ µm and $\Lambda = 2.3$ 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 $\lambda = 632.8$ nm;
(b) $a = 0.6$ µm and $\Lambda = 2.3$ µm. Here, the two higher-order polarization doublets are slightly shifted.

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Large Mode Area Photonic Crystal Fiber

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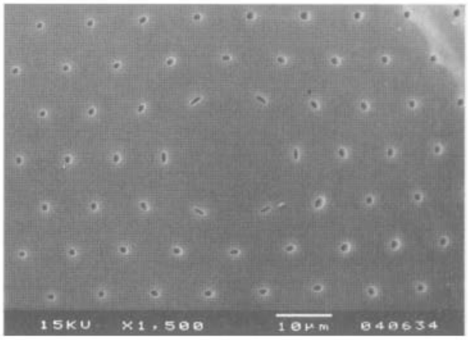
Photonic crystal fiber (PCF) is a new type of optical fiber waveguide consisting of a pure silica fiber with a regular array of small holes running through its entire length.[1] A single missing air hole defines a region that effectively has a higher refractive index than the surrounding "holey" material. 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.