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All-silica single-mode optical fiber with photonic crystal cladding

J. C. Knight,* T. A. Birks,* P. St. J. Russell* and D. M. Atkin

Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK

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We report the fabrication of a new type of optical waveguide: the photonic crystal fiber. It consists of a pure silica core surrounded by a silica–air photonic crystal material with a hexagonal symmetry. The fiber supports a single robust low-loss guided mode over a very broad spectral range of at least 458–1550 nm.

Substantial effort has been invested over the past few years in fabricating photonic crystals—materials that have a periodic modulation of the refractive index on the scale of the optical wavelength. The interest in such materials lies in their ability to interact unusually strongly with light of certain wavelengths: For example, appropriately designed structures can exhibit band gaps at optical frequencies (photonic band gaps).[1] Light that is incident upon a band-gap material from the outside would be totally reflected. Similarly, light that existed at a structural-defect site in such a material would be permanently trapped, being unable to propagate through the lattice. These properties make photonic crystals of both fundamental and technological interest. The observation of these effects requires a large variation in the refractive index, such that the photonic crystal must be formed of at least two bulk materials of different optical properties. Because of the difficulty of fabricating structures on the scale of an optical wavelength that are periodic in three dimensions, much recent experimental research has been aimed at producing materials with a two-dimensional variation by use of etching techniques in semiconductors[2] and glasses[3] to form structures that are periodic in a plane but are of limited extent in the third dimension. However, some of the most interesting effects in two-dimensional photonic crystals occur for waves that have a nonzero wave-vector component β normal to the periodic plane.[4,5] It is difficult if not impossible to study some of these effects by use of the previous structures, which are at most a few millimeters in depth (and usually much less). Here we describe the fabrication of a two-dimensional hexagonal silica–air photonic crystal that is extended into the third dimension. The structure is in the form of a fine silica fiber. Air holes arranged in a regular hexagonal pattern run the entire length of the fiber, which is many meters long. We investigate the properties of guided modes that are predicted to occur at purposely introduced lattice-defect sites (a lattice-defect site is any structural feature that breaks the regularity of the crystal lattice). By introducing a high-index defect site into the middle of the fiber during fabrication we have created a novel monomode optical fiber with a hexagonal symmetry.

We form the hexagonal unit cell on a macroscopic scale by drilling a hole of 16-mm diameter down the length of a 30-mm-diameter silica rod. Six flats are milled on the outside of the rod, forming a regular hexagon. This preform is then drawn on a fiber drawing tower at ~2000 °C to produce hexagonal cane of a diameter of 0.8 mm, which is cut to length and stacked to give the required crystal structure. This stack is again drawn on the tower, fusing the stacked canes together and reducing the pitch (center-to-center spacing) to ~50 μm. Finally, a piece of this fused stack is drawn down again to yield the final fiber. During the three-stage drawing process the size of the unit cell is reduced by a factor of more than 10^4, yielding a final pitch of ~2 μm.

It has been predicted[5] that a hexagonal silica–air photonic crystal with a pitch of ~2 μm will exhibit a band gap at a wavelength of 1.5 μm for certain values of β and for certain values of the air-filling fraction. In this case guidance could be achieved by introduction of any sort of defect into the periodic structure, which would have the effect of pulling a spatially localized mode from the band edge into the band-gap region. The fiber presented here does not rely on the existence of a complete band gap. We have demonstrated low-loss guidance by the photonic crystal in a different regime by purposely introducing a high-index defect into the center of the fiber. We do this at the stacking stage by replacing one of the hollow hexagonal canes with a similar cane that does not have a hole in the middle. In this case we expect any light with β greater than a certain value to be confined to the core, as the surrounding silica–air matrix has a reduced effective refractive index compared with the solid core. The fiber bears some resemblance to previously fabricated single-material fibers[6] but differs from them in having a periodic index modulation in the cladding region and a unique hexagonal symmetry.

A scanning electron micrograph of the fiber is shown in Fig. 1. The structure shown in the figure is virtually invariant over a length of several meters. The flat-to-flat width of the fiber shown is 38 μm, the pitch is 2.3 μm, and the solid core region is nominally 4.6 μm wide. The relative diameter of the air holes shown in the figure is smaller than in the original

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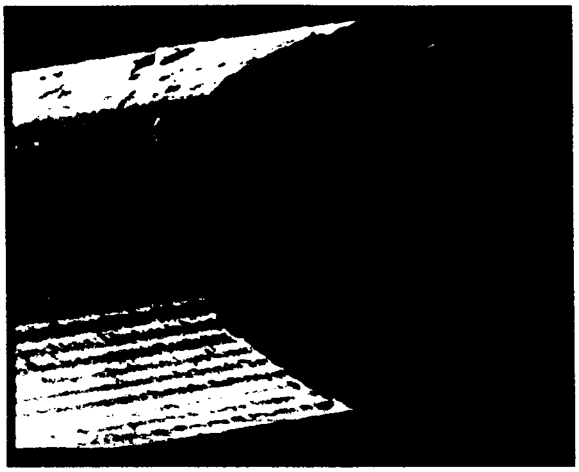


Fig. 1. Scanning electron micrograph of the photonic crystal fiber.

unit cell—this is caused by the effect of surface tension during the final stages of the drawing process. By varying the furnace temperature during the pulling process, we were able to exert some control over the relative size of the air holes in the final fiber and have drawn fiber with a pitch similar to that shown in Fig. 1 and with air holes of 0.2– 1.2 μm diameter. The fiber is quite robust and easy to handle despite its small size.

To investigate the guidance properties of the fiber, we coupled light from argon-ion (wavelength λ = 457.9 nm), He–Ne (632.8 nm), Ti:sapphire (850 nm), and diode (1550 nm) lasers into one end of a 1-m length of fiber with an objective lens, using index-matching fluid to strip off light in cladding modes. It was relatively easy to achieve a coupling of more than 50% into the guided mode, comparable with that for standard monomode optical fiber. We then used a vidicon camera and photographic film to record the near- and far-field patters of the guided mode at the output end of the fiber. Figure 2(a) shows a contour map of the near-field pattern at 632.8 nm that we recorded by imaging the output end of the fiber onto the vidicon camera, using a 60× objective lens. The contour map is shown superimposed upon a portion of an approximately scaled scanning electron microscope picture of the fiber output surface to show the relative orientation of the modal field with respect to the fiber. The light is strongly confined to the core region, and the field pattern is dominated by minima occurring at the six nearest air holes. Figure 2(b) shows the Fourier transform of the recorded near-field pattern, which is strongly peaked in the center. The hexagonal nature of the guided mode is manifest as six symmetrically placed spots occurring around the central peak, with much weaker spots further from the center (not visible in Fig. 2).

Next we photographed the spatial far-field pattern falling upon a sheet of paper several centimeters from the far end of the fiber [Fig. 3(a)]. The observed pattern shows qualitative similarity to the Fourier transform of the observed near-field pattern shown in Fig. 2, as expected. The central part of the pattern has been overexposed in Fig. 3(b) to show the higher-order terms present on the fringes of the pattern, which demonstrate the integrity of the periodic structure. This far-field pattern is independent of the way in which light is launched into the fiber and is unaffected by any bends imposed upon the fiber, implying that there is only a single low-loss guided mode. This is the case from at least 457.9 to beyond 1550 nm—over this whole range the far-field pattern looks remarkably similar to that shown in Fig. 3, although the numerical aperture of the output increases approximately linearly with wavelength (from ~0.13 at 457.9 nm to 0.36 at 1550 nm) and the outer spots become somewhat weaker at longer wavelengths.

In the visible region of the spectrum the modal field pattern in the cladding is redistributed into the higher-index silica regions, decreasing the effective index difference between the core and the cladding. On the other hand, at the longer-wavelength end of the range studied the mode was found to be still tightly confined to the vicinity of the core but unable to accommodate the air holes as directly as in Fig. 2. Instead, the photonic crystal cladding behaves increasingly as a uniform medium with the average refractive index. Consequently, the effective refractive index of

(a)

(b)

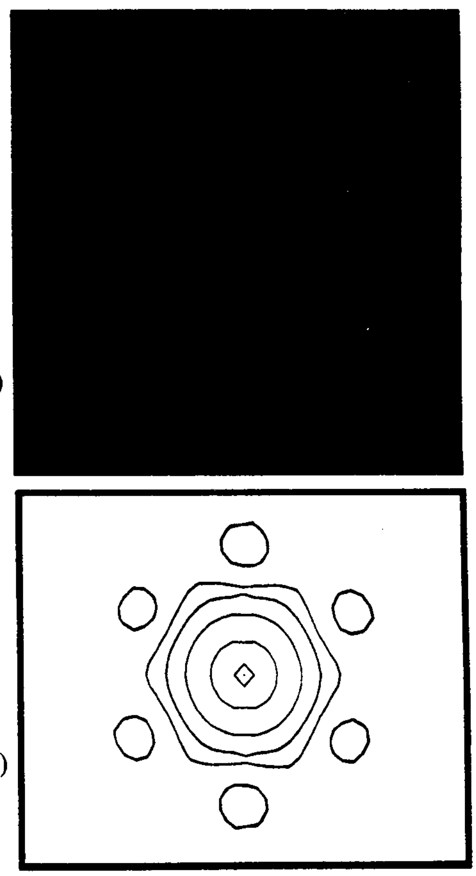
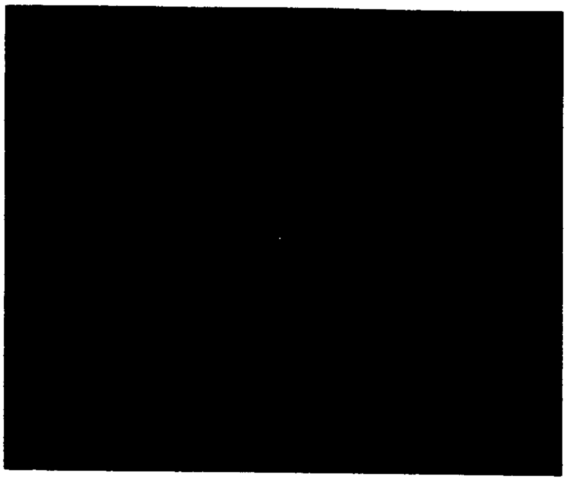
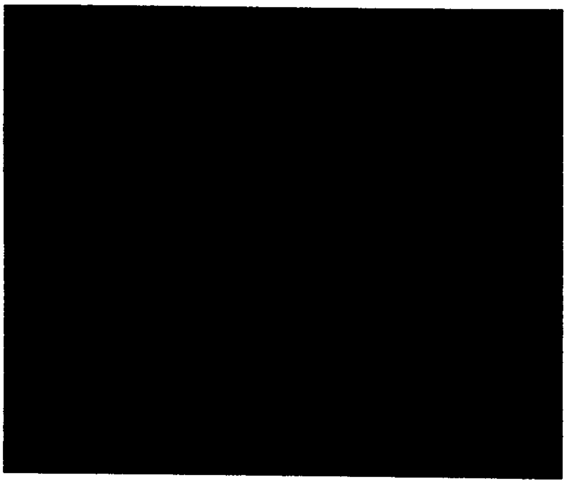


Fig. 2. (a) Contour plot of the recorded near-field pattern of the guided mode (λ = 632.8 nm) superimposed upon an approximately scaled portion of a scanning electron micrograph to show the relative orientation of the modal field pattern and the fiber microstructure. The field is strongly peaked in the center, and there is a factor-of-25 difference between the innermost (strongest) and the outermost intensity contours. (b) Calculated Fourier transform of the pattern, again strongly peaked in the center.



(a)



(b)

Fig. 3. Photographed far-field pattern at 632.8 nm. (b) Same as in (a) but with the central part of the field overexposed to show the higher-order spots on the fringes of the pattern, which demonstrate the integrity of the periodic structure.

the cladding decreases sharply at longer wavelengths. The wide single-mode wavelength range can now be understood qualitatively with reference to the normalized frequency, or V value,[7] $V = (2\pi/\lambda)\rho(n_{co}^2 - n_{cl}^2)^{0.5}$, that characterizes guidance in a step-index fiber of core radius ρ and core and cladding refractive indices n_{co} and n_{cl}, respectively. The effective decrease of the cladding index at longer wavelengths counteracts the increase in wavelength, keeping the V value nearly constant and making possible a single robust guided mode over an extended spectral range.

Despite the hexagonal symmetry of the cladding material, the fiber exhibits two perpendicular preferred polarization axes in its transmission properties. When linearly polarized light is coupled into the fiber with its polarization axis parallel to one of these two axes the output is linearly polarized and parallel to the same fiber axis, even if the fiber is bent or twisted. If the input light is polarized at some other angle the output is in general elliptically polarized. Any coupling owing to defects in the hexagonal structure of the cladding will serve to lift the degeneracy of modes that are rotated apart from each other by 60°. Some evidence of such breaking of hexagonal symmetry is observable in Figs. 1–3.

The fiber presented here could provide a means to enhance the interaction of light with a gas that is in the air holes, for example, for use in a gas sensor or to study nonlinear-optical processes. The support of only a single mode over a broad spectral range is a feature that makes this design of interest in situations in which several different wavelengths are required in the same fiber, such as in frequency-doubling applications. At present we are studying the Bragg scattering from a length of photonic crystal fiber. We intend to fabricate fiber with the correct pitch and air-filling fraction to exhibit a complete band gap for certain values of β and to use this fiber to investigate the possibility of waveguiding by Bragg reflection (the photonic bandgap fiber[5]) at a low-index defect site.

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*Present address, School of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK.

References

1. E. Yablonovitch, J. Opt. Soc. Am. B **10,** 283 (1993); P. St. J. Russell, Phys. World **5**(8), 37 (1992); J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton U. Press, Princeton, N. J., 1995).
2. P. L. Gourley, J. R. Wendt, G. A. Vawter, T. W. Brennan, and B. E. Hammons, Appl. Phys. Lett. **64,** 687 (1994); U. Grüning, V. Lehmann, and S. Ottow, Appl. Phys. Lett. **68,** 747 (1996).
3. K. Inoue, M. Wada, K. Sakoda, A. Yamanaka, M. Hayashi, and J. W. Haus, Jpn J. Appl. Phys. **33,** L1463 (1994); R. Tonucci, B. L. Justus, A. J. Campillo, and C. E. Ford, Science **258,** 783 (1992).
4. P. St. J. Russell, T. A. Birks, and F. D. Lloyd-Lucas, in *Confined Electrons and Photons*, E. Burstein and C. Weisbuch, eds. (Plenum, New York, 1995), pp. 585–633.
5. T. A. Birks, P. J. Roberts, P. St. J. Russell, D. M. Atkin, and T. J. Shepherd, Electron. Lett. **31,** 1941 (1995).
6. P. Kaiser and H. W. Astle, Bell Syst. Tech. J. **53,** 1021 (1974).
7. A. W. Snyder and J. D. Love, *Optical Waveguide Theory* (Chapman & Hall, New York, 1983).