Single-Mode Photonic Band Gap Guidance of Light in Air

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The confinement of light within a hollow core (a large air hole) in a silica-air photonic crystal fiber is demonstrated. Only certain wavelength bands are confined and guided down the fiber, each band corresponding to the presence of a full two-dimensional band gap in the photonic crystal cladding. Single-mode vacuum waveguides have a multitude of potential applications from ultrahigh-power transmission to the guiding of cold atoms.

To be guided along an optical fiber, light must be confined to a central core by reflection from the cladding that surrounds it. All conventional optical fibers guide light by total internal reflection (TIR), which requires that the core have a higher refractive index than the cladding (*1*). TIR is perfect in that it causes no loss other than the intrinsic absorptive and scattering losses of the materials themselves. Even these losses (and other material deficiencies) could be largely avoided if the light filled a hollow core. However, this is not possible with TIR, because no solid cladding material exists with a refractive index lower than that of air. Existing hollow fibers (*2*) use external reflection and are thus inherently leaky; furthermore, they invariably support many different transverse modes; that is, they are highly multimode.

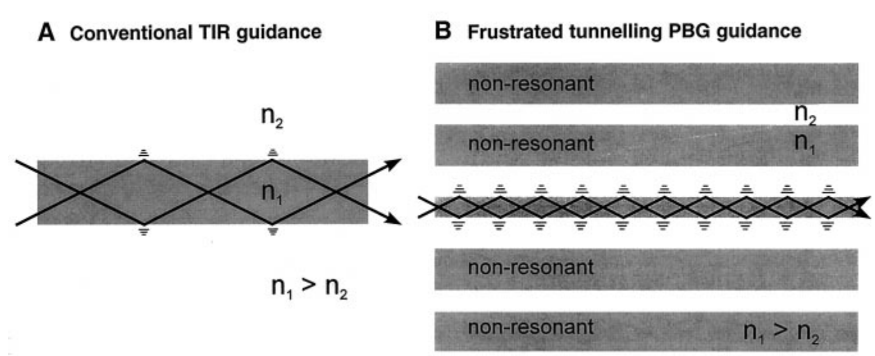
We have developed a fiber in which light can be strictly guided, without leakage, in a hollow core. Light in certain well-defined wavelength bands is trapped in the air by a full two-dimensional photonic band gap (PBG) of the cladding instead of by TIR (*3*, *4*), and it can be guided in a single mode. Here we describe the fabrication and characterization of the fiber and the spatial and spectral properties of the guided modes and compare the results to theoretical models.

The requisite numerical computations for designing a hollow PBG fiber are slow and laborious, and no inverse computational methods exist. The intrinsic need for a two-dimensional (2D) PBG requires that the fiber cladding contain a near-perfect periodic array of air holes (the photonic crystal) with a high air-filling fraction and a small pitch (the distance between adjacent holes in the lattice). Our early photonic crystal fibers (PCFs) had solid cores and guided light by TIR (*5*, *6*). More recently we demonstrated PBG guidance in a silica PCF with a honeycomb array of air holes (*7*); however, the light was evanescent in the air, so the observed guided mode was concentrated in the silica surrounding the extra air hole at the core. This appears to be a fundamental limitation of the honeycomb design.

The wave vector component along the waveguide, known as the propagation constant β, determines whether light propagates or is evanescent in any part of the guide. If $\beta < kn$, the light propagates at an angle θ to the axis in a material of index n, where $\beta = kn \cos \theta$ and k is the vacuum wave constant. If $\beta > kn$, θ is imaginary and the light is evanescent. A 1D planar waveguide geometry (Fig. 1) illustrates the different ways in which light can be strictly confined in dielectric waveguides. Conventional TIR, in which the index n_1 of the core is greater than index n_2 of the cladding, ensures the existence of a range of β where light is propagating in the core while being evanescent in the cladding (Fig. 1A).

In contrast, light can be confined between two multilayer dielectric stacks in a core of arbitrary refractive index (*4*), if the stacks have a PBG for a range of β at a given optical frequency. We identified two regimes of PBG guidance. In the first (Fig. 1B), light propagates ($\beta < kn_1$) in the layers of high index n_1 but is evanescent ($\beta > kn_2$) in the layers of low index n_2. The high-index layers act as individual TIR waveguides, supporting bound modes at specific values of $\beta = \beta_m$. Resonant tunneling between adjacent high-index layers permits the leakage of light through them, provided β lies within the pass bands that open up around each β_m. The widths of the pass bands depend on the strength of coupling between the layers. Between the pass bands lie band gaps; if a high-index core layer with a different (maybe smaller) width supports a mode with β inside a band gap, it is not resonant with the other layers and light leakage by tunneling is frustrated. The mode is thus strictly guided by the frustrated tunneling form of PBG. In the second regime of PBG guidance (Fig. 1C), light can propagate in all layers ($\beta < kn_2$). Band gaps occur at the Bragg condition as a result of multiple scattering and interference, leading to the Bragg form of PBG guidance.

In both forms of PBG guidance the refractive index of the core can be chosen much more



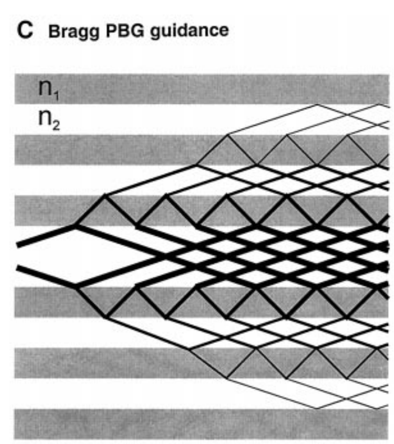


Fig. 1. The different guiding mechanisms. (**A**) Conventional total internal reflection (TIR); this occurs when the wave vector component β in the direction of propagation lies in the range $kn_2 < \beta < kn_1$. (**B**) PBG guidance when the light is evanescent in the air regions; this can only occur when β lies in the same range as in (A); the process is one of frustrated tunneling, that is, the cladding resonators are out of resonance with the core waveguide and hence tunneling is prevented. (**C**) PBG guidance when the light is propagating in all subregions of the fiber; this can only occur when β lies in the range $\beta < k_{n_2}$, the underlying mechanism being a Bragg PBG.

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freely than in TIR guidance, because the PBG conditions depend only on the properties of the cladding stacks. Guided modes can exist with mode indices β/k that are lower than the mean index of the stacks (the frustrated tunneling PBG case) or even lower than the lowest index of the stacks (the Bragg PBG case), conferring extra design freedom on PBG compared with TIR guidance and allowing confinement within a hollow core. To the best of our knowledge, every type of conventional low-loss 2D waveguide so far reported uses TIR as the guidance mechanism [including our own "endlessly single-mode" PCFs (*6*)].

PBG guidance in a fiber requires the existence of a 2D PBG over a range of β values in whichever materials system is used. Although we achieved this with frustrated tunneling PBG guidance in our silica-air honeycomb PCF (*7*), it is clear (*8*) that an even greater breakthrough would be achieved if the fiber guided by means of a Bragg PBG, for this would permit the concentration of optical power in air. Such a "vacuum guide" would have many of the desirable features of an empty metal-clad microwave channel guide, including the ability to support extremely high power densities without breakdown, and it would have the potential to push the threshold intensities for stimulated Raman and Brillouin scattering (among other nonlinear effects) up to extremely high levels.

A

B

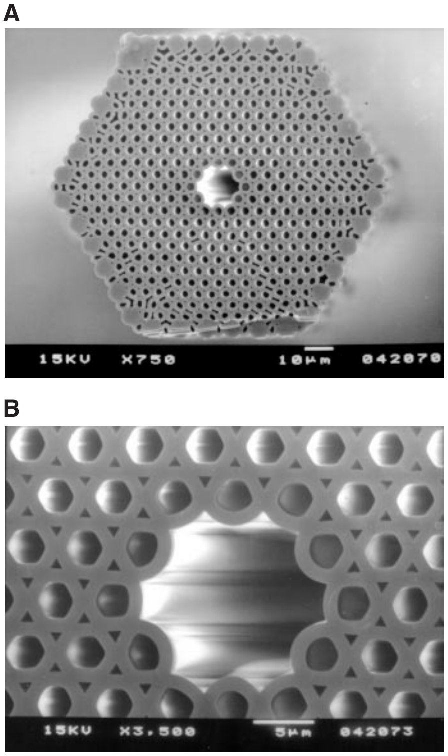

Fig. 2. (**A**) Scanning electron micrograph of the cleaved end-face of a typical vacuum-guiding fiber. The external diameter of the fiber is 105 μm (measured across the flat faces). The solid canes around the outside of the fiber are an aid to the fabrication. This fiber guided light (over lengths of at least several tens of centimeters), as illustrated in Figs. 3 and 4. (**B**) Detail of the fiber illustrated in (A). The air-filling fraction in the cladding (including the interstitial holes) is ~39% and the pitch is 4.9 μm. The core has a diameter of 14.8 μm (measured across the largest dimension).

We have shown that simple triangular lattices of air holes in silica (index contrast 1:1.46) can have full 2D PBGs in the Bragg regime of β values (that is, $\beta < k$) if the air-filling fraction is relatively high (*3*). Theory fails to predict full PBGs in silica-air honeycomb PCFs in the Bragg PBG regime, but this is perhaps not surprising because the honeycomb fiber has a higher proportion of silica and so is less likely to have PBGs at low values of β/k.

The method of fabricating an air-guiding PBG fiber follows our previously reported procedure for PCFs (*5, 9*). Tubes of silica glass are pulled down to capillary canes on a fiber-drawing tower. These canes typically have external diameters of the order of 1 mm. The PCF preform is constructed by stacking together by hand several hundred capillary canes to form the required crystal structure on a macroscopic scale. The entire stack is then held together while being fused and drawn down into fiber by an optical fiber-drawing tower. A typical fiber diameter is 40 to 100 μm, the total collapse ratio being of the order of 10^4. The final fiber cladding consists of a triangular array of air holes in silica, with interstitial holes that result from stacking circular capillaries. The fraction of air in this part of the fiber needs to be relatively large for the fiber to exhibit a sufficiently broad band gap—typically more than about 30% by volume.

The fiber core was formed by including a larger air hole in the center of the preform. We have studied fibers where this larger hole had an area of one or seven unit cells of the cladding material. In each case, the hole was created by leaving out the appropriate number of canes from the center of the preform stack. The whole structure was then fused and pulled into fiber. Of the resulting fibers, those formed by omission of just a single cane did not guide modes in the air (at least not at visible wavelengths). From this point on we restrict our discussion to fibers with a seven-unit-cell air core (Fig. 2).

We carried out initial characterization by holding ~3-cm-long samples vertically, illuminating them from below with white light (using a tungsten halogen lamp), and observing the light transmitted through them in an optical microscope (Fig. 3). The central air core is filled with a single lobe of colored light, its transverse profile being smooth, peaked in the center, and falling off to very low intensities at the glass-air boundary. A significant amount of white light is present in the periodic cladding, and it appears colorless in comparison with the mode trapped in the core. Different colors of the vacuum-guided mode were seen, depending on the overall fiber size and the drawing conditions used. The precise color was sometimes hard to assign by eye, and in some cases appeared to be a mixture of different colors, for example red and blue. For appropriate excitation with the white light source, a few samples supported a similarly colored two-lobed mode, which we attribute to a second guided mode falling in the same band gap as the first.

The transmission spectra through the air core of lengths of fiber were measured by linking the microscope by means of a conventional multimode fiber to an optical spectrum analyzer. The spectral dependence of the waveguiding in the air hole (Fig. 4) demonstrated that several well-defined bands of transmission are present, covering the whole visible spectrum and extending into the infrared. Within each transmission band, the losses are small (over fiber lengths of several centimeters) or zero, whereas between these bands the losses are much larger, as expected in the absence of PBG effects (*10*). We attribute each of these bands to a full 2D PBG. Because the pitch of the crystal is large in

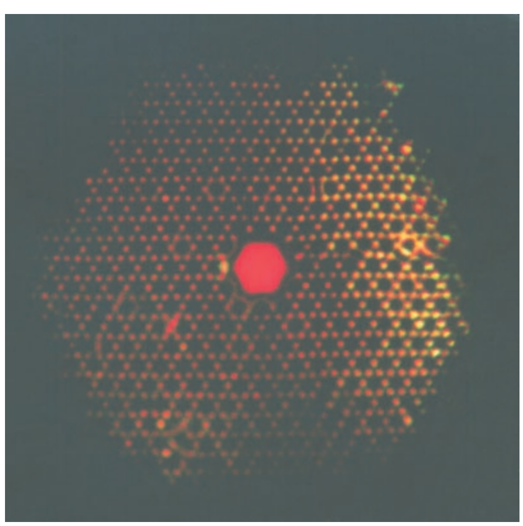

Fig. 3. Optical micrograph of the field intensity pattern at the exit face of a ~3-cm-long piece of fiber for white light excitation at the entrance face. White light is in the cladding regions, and the isolated and brightly colored vacuum-guided mode is in the center. Complete removal of cladding modes is difficult because of the incoherent illumination and the relatively large air holes in the structure, but they have been much reduced in the picture (without affecting the guided mode) by the application of index-matching liquid to the sides of the fiber. The effects of chromatic dispersion of the objective lens, structural features on the flat fiber surface, and the color response of the photographic film account for other minor colored features on the fiber end-face.

comparison with the wavelength, the PBGs responsible for the guidance are of high order. By selecting lengths of fiber that had been found to guide light at appropriate wavelengths, we excited this mode using laser sources. The laser light guided in the air core formed a stable, smoothly varying, single-lobed pattern in the far field. Fibers that have maxima in their transmission spectra at a particular laser wavelength guide such laser light in the core over lengths of several tens of centimeters (corresponding to hundreds of thousands of optical wavelengths). The length is presently limited by fluctuations in the fiber parameters, which cause the wavelengths of the guided modes to vary along the length of fiber. Although the short lengths of fiber that we have available preclude systematic study of losses, we transmitted 35% of a laser beam in the guided mode over a 40-mm length of fiber. The biggest contribution to the overall losses in that experiment was the input coupling efficiency. In other fibers that do not support guided modes at the laser wavelength, laser light coupled into the fiber in exactly the same way leaked entirely into the cladding after propagating only a few millimeters, as expected in the absence of PBG effects (*10*). By incorporating a guiding length of fiber into one arm of a Mach-Zehnder interferometer, we confirmed that the laser light transmitted through the guiding core has a high degree of spatial coherence, giving high-visibility fringes at the interferometer output. This would not be the case if there were many waveguide modes excited in the fiber core.

We observed such confined modes in a variety of samples with similar pitches to those in Figs. 2 and 3 and with air-filling fractions in a range from just more than 30% to almost 50%. Theoretical modeling of these structures is difficult and slow because of the very large values for the normalized frequencies (see Fig. 4). Our initial computations of the band structure revealed the presence of narrow band gaps above the light line in this range of frequencies and for the sample parameters studied. Further comparison with the experimental results will require that the presence of the large air hole be modeled, which will take some time and might require the development of new theoretical tools.

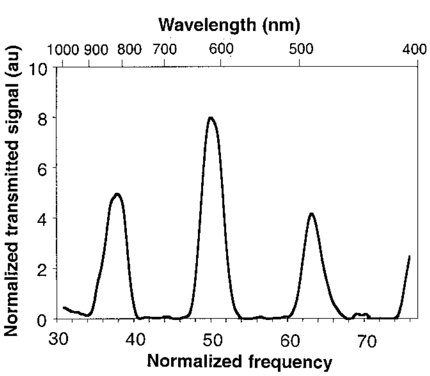

Fig. 4. Intensity spectrum of the light transmitted through the air core, plotted against normalized frequency $k\Lambda$ and wavelength λ, through a fiber excited with white light. Low-loss transmission bands, widths of ~3 frequency units, are separated by regions of much higher loss. The measurement is limited by the low spectral intensity of the white light source in the ultraviolet wavelength region (au, arbitrary units). The spectrum was recorded with a resolution of 10 nm. The relative normalized scales of the different transmission bands reflect the different coupling efficiencies to and from the guided mode at the widely varying wavelengths, and possibly the existence of a second mode in some band gaps.

It is useful to consider why it is that PCFs with similar cladding parameters but with a defect formed by omitting just a single capillary have not been found to support guided modes. The number of guided modes that a conventional fiber can support is determined by the core-cladding refractive index difference and the size of the core. This follows fundamentally from state-space arguments closely analogous to well-known density-of-states calculations in solid state physics and leads to the result that the approximate number of spatial modes in a conventional fiber is as follows (*1*):

$$N_{\mathrm{conv}} = \frac{k^2(n_1^2 - n_2^2)r_{\mathrm{co}}^2}{4} \qquad (1)$$

where r_{co} is the core radius and n_1 and n_2 are the core and cladding indices. (There are of course two polarization states per spatial mode.) In a hollow-core PCF, a similar expression may be derived for the approximate number of spatial modes present in the hollow core:

$$N_{\mathrm{PBG}} = \frac{(\beta_{\mathrm{H}}^2 - \beta_{\mathrm{L}}^2)r_{\mathrm{co}}^2}{4} \quad \text{or}$$
$$= \frac{(k^2n_1^2 - \beta_{\mathrm{L}}^2)r_{\mathrm{co}}^2}{4} \qquad (2)$$

where β_{H} and β_{L} are the upper and lower edges of the PBG at fixed optical wavelength, and the second expression applies if the upper PBG edge extends beyond the maximum core wave vector, that is, if $k^2n_1^2 < \beta_{\mathrm{H}}^2$. Theory shows that, for a typical triangular array of air holes in silica, the photonic band gap width $\Delta\beta = \beta_{\mathrm{H}} - \beta_{\mathrm{L}}$ is a small fraction of its average position $\beta_{\mathrm{av}} = (\beta_{\mathrm{H}} + \beta_{\mathrm{H}})/2$. For example, with the data published in (*3*), at $\beta_{\mathrm{av}}\Lambda = 9$, $\Delta\beta\Lambda = 0.2$, and taking $r_{\mathrm{co}} = \Lambda/2$ for a single missing cane (Λ is the interhole spacing), the expected number of spatial modes is 0.23, making it unlikely that any air-guided mode will be seen. On the other hand, if seven canes are removed, the hollow core area is increased by a factor of 7, the core radius by $\sqrt{7}$, and the expected number of spatial modes becomes 1.61, suggesting that a seven-cane hollow core will support at least a single transverse mode (two polarization states) and perhaps a second transverse mode. These predictions are consistent with our observations that fibers made with a single-cane air hole do not support air-guided modes, whereas those with a seven-cane hole guide light in one or two modes.

The potential practical advantages of a single-mode vacuum guide are myriad. It is easy to couple light into the core, because (unlike the honeycomb PBG fiber, which has a complex six-lobed modal pattern) the phase is constant across the air core (giving a Gaussian-like intensity profile). Fresnel reflections, which are a problem in fiber devices where light is extracted from a fiber and then reinjected after modulation or amplification, will be extremely small in the vacuum-guided fiber, because the refractive index discontinuity between the outside world and the fiber mode can be tiny. Another obvious advantage over other optical fibers is that the performance is much less limited by the interaction (absorptive or nonlinear) between the guided light and the normally solid material forming the fiber core. This will allow transmission of wavelengths and power levels not possible in conventional fibers, and will lead to greatly increased threshold powers for stimulated Raman, Brillouin, and color-center effects. On the other hand, if the hollow core is deliberately filled with a gas, vapor, or low-index liquid, very strong interactions are possible with the light in the guided mode. This may prove useful for gas sensing and monitoring, for the generation of multiple optical wavelengths by nonlinear processes, and more generally in enhanced nonlinear optics. The narrow-band performance of the fiber suggests that it might be useful as a spectral filtering device. The ability to form a single transverse mode in a tube of vacuum offers possibilities in the fields of atom guiding and laser delivery of small particles.

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