Microstructured Silica as an Optical-Fiber Material

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Introduction

Conventional optical fibers are fabricated by creating a preform from two different glasses and drawing the preform down at an elevated temperature to form a fiber. A waveguide core is created in the preform by embedding a glass with a higher refractive index within a lower-index "cladding" material. Over the last few years, researchers at several laboratories have demonstrated very different forms of optical-fiber waveguides by using a drawing process to produce two-dimensionally microstructured materials in the form of fine "photonic-crystal fibers" (PCFs). One such waveguide is represented schematically in Figure 1. It consists of a silica fiber with a regular pattern of tiny airholes that run down the entire length. The optical properties of the microstructured silica cladding material enable the formation of guided waves in the pure silica core.

Fabrication processes to create two-dimensional (2D) microstructures using fiber-drawing were described by Kaiser[1] and later by Tonucci[2] and Inoue and colleagues.[3] We have used a procedure based on stacking and drawing hollow silica tubes to form periodic samples with an index contrast and pitch (periodic spacing) suitable for interesting and useful optical effects. By considering the microstructured material as a single optical medium with its own unique properties (a "photonic crystal"), we have been able to incorporate these materials into our existing understanding of fiber-waveguide performance. This has provided us with greatly improved insight into the performance and limitations of the new structures and is pointing the way to new optical-fiber structures that can outperform conventional fibers in several critical respects.

Redrawn and Microstructured Silica

Silica is an incredibly versatile material and has several properties that make it ideal for drawing optical fibers. One is its very low intrinsic optical loss. Another is the slow change in viscosity with temperature, which makes the fiber-drawing process relatively insensitive to changes in temperature. A third is the very high stability of the glass matrix and its slow devitrification. These same properties make silica the first choice for fabricating PCFs. However, the intrinsic properties of silica also limit the range of microstructure parameters that can be produced; for example, the strength of a strand of silica limits the viscosity at which it can be drawn, while its relatively low refractive index limits the width of bandgaps that can be attained.

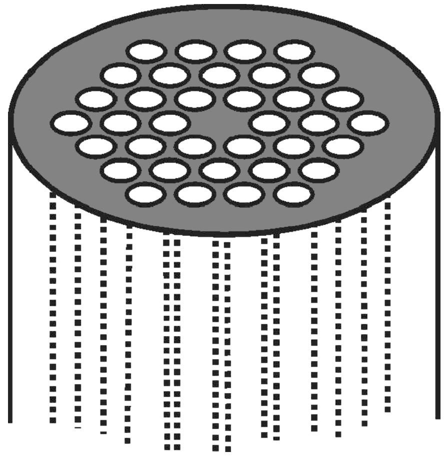

Figure 1. Schematic illustration of a "photonic-crystal fiber" (PCF). A fine silica fiber has a two-dimensional array of airholes running down its length. This photonic-crystal material can then be used to trap light in a core region. In the case shown here, the core is defined by a missing airhole in the center of the array.

Photonic-Crystal Fiber Waveguide Design

Considering regularly microstructured silica as a single photonic-crystal material enables one to attribute to it optical properties of its own. The appropriate optical properties of such a material can be accurately computed numerically, for example, by using an effective-index model[4] or other numerical techniques.

In general, the analysis of the optical properties of a photonic-crystal material in fiber form is best parameterized in terms of β, the component of the wave vector inside the material parallel to the fiber axis. This is convenient because light introduced into the fiber (through an end face) into a mode with a given β remains in that mode of propagation as it travels along the fiber. β can be used to define a modal index by dividing it by the free-space wave vector $\mathbf{k}$. In a material with a refractive index n, the propagating mode with the highest β value (the "fundamental mode") has a value of $\beta_{max} \leq \mathbf{k}n$. Modes having $\beta > \mathbf{k}n$ will be evanescent. In a photonic-crystal material, a simple definition of n is not possible because the material will in general be strongly dispersive, the apparent refractive index depending on the direction of propagation as well as the frequency. However, one can compute the value of β for any given mode of propagation, or for a given β one can compute the frequencies at which propagating modes exist. As might be anticipated, for any fixed value of frequency there is a maximum value of the propagation constant, β_{max}, which can be used to define a refractive index using $n = \beta_{max}/\mathbf{k}$.[4] The refractive index n defined in this way is not general, but is useful in designing waveguides because it describes the value of β at which modes in the material are "cut off" and become evanescent: light incident upon the material with a larger value of β will be totally reflected. This is exactly the condition required to form an optical-fiber waveguide. Surrounding a solid silica core with an array of airholes enables one to excite core modes with $\beta > \beta_{max}$; those modes are then guided in the core by total internal reflection (TIR) from the effective-index material formed by the photonic-crystal cladding. In this article, we shall refer to fibers that guide light by this mechanism as TIR-guiding fibers.

In many ways, core modes with $\beta > \beta_{max}$ are similar to those found in conventional fiber-waveguide theory. In PCFs, however, a second and completely different waveguiding mechanism is possible, which arises directly from the periodic nature of the cladding microstructure. The periodic patterning means that it is possible to find ranges of $\beta < \beta_{max}$ in which there are no propagating modes. Bands of propagating modes are found for both higher and lower values of β, so these regions in which propagation is forbidden are known as bandgaps. The possibility of using photonic bandgaps for creating optical-fiber waveguides was first suggested in 1994,[5] and a fiber in which light is guided with low loss in an air core (the "air-core fiber" reported in 1999[6]) is an especially impressive demonstration of the potential of this waveguiding mechanism.

In conventional fibers, the two most important parameters in determining the fiber characteristics are the refractive-index difference between the core and cladding materials and the core diameter. In a photonic-bandgap fiber, the waveguiding properties are determined by the width of the bandgap (at a fixed frequency) and the core size and material. In order to form an air-core fiber, one also needs to ensure that the bandgap covers the range of β within which one can hope to find modes of the air core, meaning that the bandgap must extend to $\beta < \mathbf{k}$. Computations reported in 1995 predicted[7] that such bandgaps exist in a triangular array of airholes in a silica matrix.

Scale and Regularity in Photonic-Crystal Fibers

In designing a PCF waveguide, it is important to remember that the optical properties of the cladding material *per se* can change quite dramatically as the scale is varied relative to the wavelength. For example, the structure shown in Figure 2 guides light with low losses in a core region of a diameter of 2 μm. However, the cladding material, which consists of a web of fine silica strands, also contains additional "fiber cores" at the intersections between these strands. An optical micrograph of the exit face of such a fiber, when illuminated from below with a white-light source, is shown in Figure 3. These extra cores have diameters of only around 400 nm, and are relatively weak guides that are easily stripped off by bending the fiber. However, if the fiber is scaled up 2.5× so that the main core is 5 μm in diameter, then modes in these cores are sufficiently strong to be difficult or even virtually impossible to strip off as cladding modes. Thus, in designing a waveguiding structure, it is important to consider both the morphology and the scale of the cladding material. One way of thinking about the optical response of a PCF material is to consider it as a 2D array of coupled waveguides. As the coupling between the elements of the array decreases (e.g., because the airholes are large, as in Figure 1), the difficulty of removing modes from the cladding will increase.

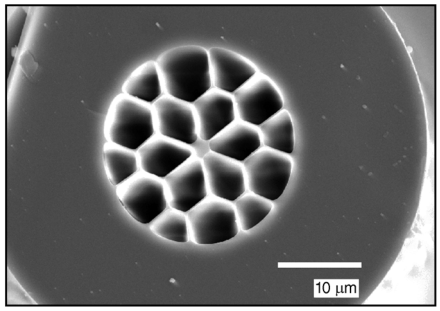

Figure 2. Scanning electron micrograph of a high-index-contrast total-internal-reflection-guiding PCF. The 2-μm-diameter core is suspended in a web of 200-nm-wide silica strands, which are continuous along the fiber length.

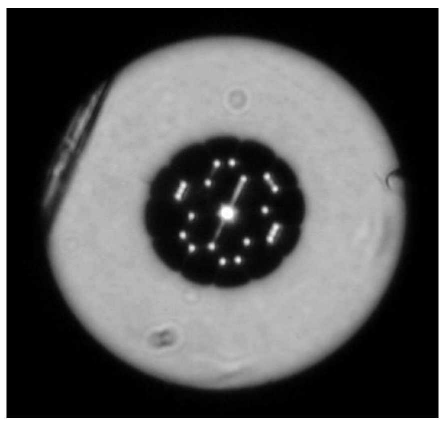

Figure 3. Optical micrograph of the output face of a fiber similar in size to that shown in Figure 2, illuminated with a white-light source at the far end. In addition to the core-guided modes, there are relatively weakly guided modes trapped at specific locations in the cladding, as well as confined modes, which include the core and a part of the cladding. Such modes become more strongly guided as the scale of the fiber is increased.

"Photonic crystals" require a certain degree of regularity to exhibit useful properties. A fiber material consisting of a random array of airholes in a matrix will have unpredictable and purely local optical properties (except in the rather uninteresting long-wavelength regime) and will thus be useless as an optical-fiber material. For example, a region in the fiber cross section that contains one or more airholes that are smaller than those surrounding it will inevitably form a waveguiding core. This core may or may not be coupled to other similar regions that lie close by. Such a core might be a useful waveguide; however, since it (and others like it) will occur at a random position within the fiber, the fiber becomes impractical.

On the other hand, any real structure will exhibit deviations from perfect regularity that do not necessarily have a significant effect on the properties. Clearly, then, a certain degree of randomness is admissible. The degree of regularity and uniformity that is required is quite different for TIR-guiding and bandgap-guiding fibers. For an air-guiding fiber, no true waveguiding is possible without several regular periods surrounding the core; the waveguiding relies directly on such regularity. On the other hand, in a TIR-guiding fiber with very large airholes, the regularity of the airhole array is almost irrelevant as far as the core-guided mode is concerned, and just two or three layers of airholes are sufficient to reduce waveguide leakage to negligible levels. It can nonetheless be useful to model the optical properties of the cladding as a photonic-crystal material, and the degree to which such modeling is valid depends on accounting for any irregularities in the structure.

Optical Properties of Photonic-Crystal Fibers

Number of Guided Modes

In a *TIR-guiding photonic-crystal fiber,* the number of guided modes is a function of (1) the size of the airholes in the crystal cladding relative to their spacing, (2) the lattice type chosen for the cladding, (3) the wavelength, and (4) the size of the solid core relative to the lattice constant. The dependence of the number of modes on the structure can be understood qualitatively by recognizing that light propagating in the cladding region will have to be modulated with the spatial periodicity of the lattice itself, directly imaging the lattice. In passing from the core to the cladding, the β value remains fixed, so that the transverse **k** vector component must decrease by virtue of this being a TIR-guiding fiber. Thus, core modes that have a lower-frequency spatial variation than that of the cladding (i.e., the "lobes" that make up the guided mode pattern are spatially larger than the silica "bridges" between the holes in the cladding; see Figure 1) will be unable to propagate in the cladding and will be trapped within the core region. In contrast, higher-order modes containing higher spatial frequencies will be able to propagate in the cladding and will therefore not be confined to the core—their lobes can fit across the silica bridges of the cladding. This effect has also been described in terms of a frequency-dependent refractive index for the cladding region[8] and as a quantitative effective-index model,[4] and it has been investigated numerically using other methods. These methods reach the same conclusion: that it is possible to form waveguide structures with an extended—and even infinite—range of single-mode operation, even if the core size of the fiber is very large. Such structures have a range of applications, from the generation and delivery of high-power laser light to quantitative fiber spectroscopy using a broadband source.

Air-guiding bandgap fibers can guide one or many modes, just as conventional fibers do. In general, more modes will be guided if the core size is increased while the rest of the structure remains unchanged. More modes are also guided if the width of the bandgap is increased for a fixed core size (which is qualitatively analogous to increasing the refractive-index contrast in a conventional fiber). However, whereas in conventional fibers there is always at least one guided mode (the fundamental), in air-guiding fibers with small core sizes, one is unlikely to find guided modes.[6] The air core is formed by omitting glass from one or more unit cells of the structure. Thus, in order to take best advantage of the broad, lowest-order bandgaps (by using a structure with a small pitch), one needs to form a relatively large core by omitting several canes from the preform to form the fiber core, rather than leaving out just a single cane. Figure 4 shows an optical micrograph of an air-guiding photonic-bandgap fiber illuminated from the far end with a white-light source. The air core has been formed by omitting seven capillaries. The bright light in the core is the guided mode—the strong coloring results from the limited range of wavelengths for which there is a guided mode and is a feature of bandgap waveguiding. Light at other wavelengths is also introduced into the core at the input end, but it quickly leaks out as it propagates down the fiber.

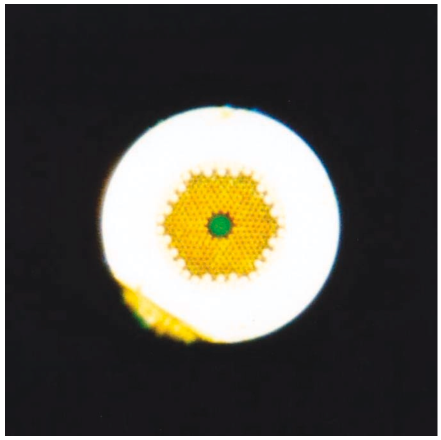

Figure 4. Optical micrograph of the output face of an air-core photonic-bandgap fiber illuminated at the input face using a white-light source. The core is surrounded by the photonic-crystal cladding, which is embedded within a pure silica jacket. The air core has an area of seven unit cells. The strongly colored light in the core is confined by the bandgap of the surrounding photonic crystal. The outer diameter of the fiber is 110 μm.

Birefringence

The triangular lattice most commonly used to form TIR-guiding PCFs is intrinsically non-birefringent. However, these fibers can potentially have a very large-form birefringence because of the large index contrast attainable. We recently reported[9] a single-mode fiber designed with a very high birefringence resulting from our use of different airhole sizes in different positions around the guiding core. The polarization beat length (an indication of the magnitude of the polarization-mode splitting) of less than 0.5 mm at $\lambda = 1550$ nm reflects a significantly higher birefringence than that found in commercially available polarization-maintaining fibers. The group index (indicative of the transfer speed of optically transmitted information) and group-velocity dispersion (the rate of change of the group index with frequency) in such fibers also have strong polarization-dependence.

The unintentional birefringence in TIR-guiding fibers with a small core and a large index contrast is also likely to be high, or even very high, compared with conventional fibers. Quite the converse is true of other fiber structures such as large-mode-area TIR-guiding fibers because of the small transverse **k** vector and the relatively low index contrast in that case. Such fibers will be weakly birefringent and are thus likely to suffer from polarization-mode dispersion (PMD). No measurements of PMD in PCFs have yet been reported.

Nonlinearity

The nonlinear properties of various PCF structures range from being massively enhanced (as in high-index contrast fibers, or in pressurized gas-guiding fibers) to being very low indeed (e.g., large-mode-area TIR-guiding fibers and air guides). These latter arise because of the large core size (resulting in lower intensities for a given transmitted power) or the reduced overlap of the guided mode with silica (the nonlinear response of air is much lower).

Enhanced nonlinear interactions with gases are possible in bandgap fibers because the guided mode is trapped in a gas core over many times—even thousands of times—the Rayleigh length. In comparison with "capillary guiding,"[10] the losses achievable for a given core size have already been hugely decreased. This will lead to exciting developments in Raman gas amplifiers (presently done in bulk cells) and in high harmonic generation using ultrashort pulses (presently done using glass capillaries).

Enhanced nonlinear response from TIR-guiding fibers arises because of the very small core sizes and the unusual dispersion characteristics, giving unusual phase-matching opportunities as well as anomalous group-velocity dispersion in the visible range.[11] The decrease in the core size alone gives a factor of 20× or more in nonlinearity and, when coupled with the unusual dispersion characteristics, has given rise to a range of new and spectacular nonlinear optical effects, including soliton (solitary wave) propagation at short wavelengths,[12] supercontinuum generation,[13] and a substantially increased soliton self-frequency shift.[14]

Dispersion

The high refractive-index contrast that is possible in TIR-guiding fibers with large airholes means that a wide range of dispersion characteristics can be attained in TIR-guiding PCF structures.[11,15] Furthermore, the high degree of control over the fiber cross section—for example, by use of different airhole sizes at different radial distances from the fiber core—means that rather complicated dispersion curves can be readily designed. Just by fixing the airhole size and pitch, it has been shown that a fiber with a low dispersion (<0.5 ps/nm km) over a very wide bandwidth can be designed.[16] Extra degrees of freedom provided by varying the airhole size in a single fiber enable such curves to be designed for a range of different core sizes.

The unusual dispersion curves result directly in the observation of some unusual nonlinear effects: for example, soliton propagation at wavelengths less than 1 μm is possible in PCFs only because the group-velocity dispersion at these wavelengths can be anomalous,[11] instead of normal as in conventional fibers. Likewise, the observation of broadband supercontinua in PCFs is strongly influenced by the shape of the dispersion curves and by the resulting phase-matched nonlinear processes.

Conclusions

The use of microstructured silica as a material for optical-fiber design offers a wealth of new optical-waveguide effects. These manifest in the linear and nonlinear response of photonic-crystal fibers and will enable a range of new applications for optical fibers. Indeed, the possibility of guiding light with low loss in an airhole, or of transmitting solitons at visible wavelengths, suggests a revolution in optical-fiber design. We anticipate that the unusual properties of photonic-crystal fibers will play an important part in future generations of optical systems.

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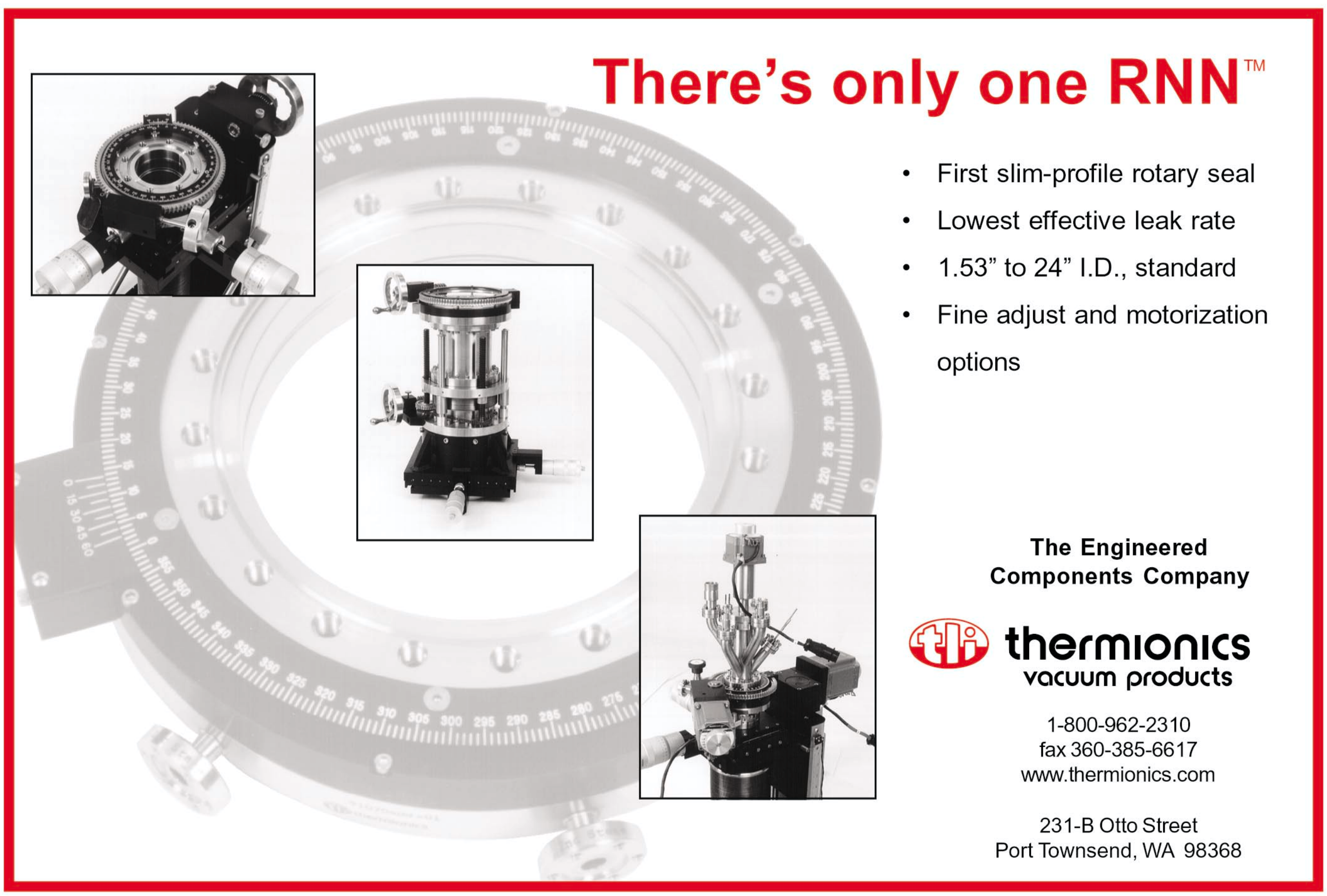

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