Photonic Crystal Fibers

New Solutions in Fiber Optics

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Imagine a world in which optical-fiber performance was not limited by the attenuation of bulk silica; where nonlinearity and dispersion could be reduced by orders of magnitude (or massively enhanced when needed); where fiber properties were unaffected by external factors such as stress or temperature changes. Such musings may sound absurd in the context of today's highly developed optical-fiber designs, in which the performance of single-mode fiber has been pushed towards its ultimate limit. However, the massive opportunities provided by a new optical-fiber technology developed over the past decade make these possibilities decidedly real. The advances made in optical-fiber technology since the 1960s were driven mainly by the telecommunications industry. They have resulted in fiber optics becoming a largely mature technology, in which ever smaller improvements are made to fiber performance. This is not surprising, as there have been relatively few changes to the basic technology over that period, so that it has been developed as highly as possible. With the advent of an alternative fiber technology, we are moving into a new arena, with new physics, new possibilities and new constraints.

Names for the game

The new fibers are based on the use of microscopic holes running parallel to the fiber axis and down the entire length of the fiber. These holes have a strong effect on the optical properties of the composite material, so that the fibers are effectively being made using a new microstructured material that is highly engineerable. Our research group has made a point of calling these fibers photonic crystal fibers because our understanding of their performance hinges on considering the microstructured cladding region as a single material with properties of its own: a photonic crystal. Other researchers making a range of similar fibers, fabricated using the same technology and employing the same physics, are using the terms microstructured, holey, and photonic bandgap fibers. The impact of the new fiber structures on the way we communicate remains to be seen, but they are already revolutionizing the physics of optical-fiber waveguiding. In some respects, the fibers can outperform conventional optical fibers and enable the previously unthinkable. In other ways their potential remains unrealized because of difficulties in modeling and fabricating the unconventional designs. The ultimate performance

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limitations are not yet established, but a concerted effort is underway in laboratories across the world to establish the significance of the new science.

From photonic crystals to optical fibers

During the early 1990s, it was already plain that the intrinsic properties of silica were a fundamental limitation on the performance of single-mode optical fibers. At the same time, the field of photonic crystals and photonic bandgap materials was growing rapidly. This was due in part to work by Eli Yablonovitch, who predicted the existence of complete photonic bandgaps in certain three-dimensionally periodic photonic crystal structures. Such photonic bandgaps correspond to frequency ranges in which there are no propagating modes within the material. This has profound implications for the interaction of light and matter on the quantum level, and promises tremendous control over optical processes. One way of using such materials is to embed within them a "defect"—a spatially localized region in which the electromagnetic mode structure is very different. One can then hope to use the modes of this "defect" as cavity modes of a high-Q cavity.

In practice it turned out to be rather difficult to fabricate three-dimensionally periodic structures with the correct pitch, refractive index contrast, and structural integrity to observe the predicted effects, and interest grew in making two-dimensionally periodic materials. It was in this context that we set out to use the highly developed technology of optical fiber-drawing in a new way: to create fibers with a regular pattern of air holes running down their length. Such a structure is optically an excellent approximation of a two-dimensional (2D) photonic crystal, being periodic in the plane perpendicular to the fiber axis but invariant along the fiber length.

Just as not all properties of electronic crystals rely on their having bandgaps, so not all photonic crystals need have photonic bandgaps. Instead, the photonic crystal formalism becomes a paradigm in which to treat the new structures as conventional fibers that are made of unconventional materials. From the start, we made fibers by stacking rods and tubes made of silica to form the structure of interest on a macroscopic scale. We then

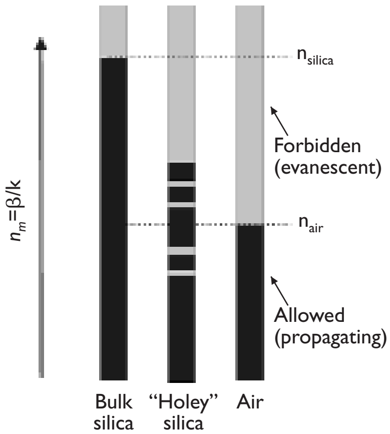

Figure 1. Schematic sketch of allowed (black) and forbidden ranges of modal index $n_m=\beta/k$ in three materials (k is the free-space wave-vector). The work described in the text is based on using "holey" or microstructured material as a fiber cladding, with either a solid silica or an air core.

drew this "preform" down to a fiber using a conventional silica fiber drawing tower.[1] Our early attempts consisted of fibers with an outer diameter of 30 μm or less—necessary to attain the reqired inter-hole spacing of a few micrometers from a stack of reasonable dimensions. These fine strands of glass nonetheless had a periodic array of air holes running down their length. This proved the fabrication technology and opened the lid of a treasure chest of new waveguiding effects that we, and others, have investigated over the past few years. Since then, procedures have been developed to enable the formation of highly complex structures within fibers, with relatively low losses and a standard outer diameter taken for granted.

What can they do?

There are two fundamental properties of photonic crystal fibers (PCFs) that differentiate them from conventional fibers. The first is the 2D nature of the microstructuring. The second is that the refractive index contrast between the two phases—silica and air—is roughly two orders of magnitude higher than that used in conventional fiber technology. Taken together, these two offer greater control over the fiber waveguiding properties, and over a far broader parameter space, than in conventional fibers. The optical properties of a periodic silica-air photonic crystal are compared to those of conventional bulk materials in Fig. 1. This shows the allowed values of the component β parallel to the fiber axis of the total wave-vector in the fiber. β is an important parameter because being parallel to the interfaces, it is preserved in passing from one region to another through the side walls. To form an optical waveguide using any two of the materials represented in Fig. 1, one needs to use a core material that supports modes with β-values that are forbidden in the chosen cladding.

One way in which the microstructured material can be used as an optical-fiber cladding is to embed a region of pure silica within it, by replacing a single capillary in the stack with a solid silica cane. In that case, the resulting structure guides light in the silica core because the silica region can support modes with a propagation constant β higher than the highest β that can occur in the cladding, in a manner analogous to that in conventional fiber waveguiding (see Fig. 1). Where this situation differs markedly from that of a conventional fiber guiding light by total internal reflection is that the optical properties—the effective refractive index and the dispersion—can be readily engineered over a very wide range. A complementary way of thinking about the problem is to note that the very large refractive index contrast between silica and air means that the air holes impose strong conditions on the modal fields within the fiber. We will describe some of these effects by considering two especially interesting classes of structure—those with a small silica core surrounded by relatively large holes [as in Fig. 2(a)], and those with a larger silica core surrounded by smaller holes [Fig. 2(b)].

The fiber in Fig. 2(a) has a high nonlinearity (as a result of the very small core—the nonlinearity is inversely proportional to the effective area of the guided mode) and an unusual group-velocity dispersion characteristic. We have worked with core diameters as small as a single wavelength (for example, a core diameter $d = 0.75$ μm at a wavelength λ of 800 nm), which is difficult using conventional fiber technology because a relatively high refractive index contrast is required to effectively confine the mode to such a small core. Such a high index contrast cannot easily be attained using conventional fiber fabrication processes. In principle, the core size in our fibers could be reduced to significantly less than a wavelength, but the practical difficulties of efficiently and stably coupling light into such a structure make this pointless unless further steps are taken to address the coupling problem.[2]

The group velocity dispersion (GVD) characteristic of the fiber shown in Fig. 2(a) differs markedly from those achievable using conventional fiber technology.[3] GVD tells how the group velocity in a fiber varies with wavelength, and so it is a measure of how fast short pulses will spread out in time as they propagate. In typical single-mode fiber (SMF), the GVD is dominated by the dispersion of bulk silica (see Fig. 3), which is normal—i.e., negative in Fig. 3—for wavelengths shorter than about 1.3 μm, and anomalous at longer wavelengths. Other sorts of conventional fibers, like dispersion-shifted fiber or non-zero dispersion-shifted fiber, have zero dispersion at slightly different wavelengths, typically between 1.3 μm and 1.55 μm. At shorter wavelengths, around 800 nm, for example, these fibers will have a strongly normal dispersion, of the order of -100 ps/nm/km. To a good approximation, the GVD of the fundamental mode of a fiber such as that in Fig. 2(a) can be modeled as that of a fine strand of silica surrounded by air.[4] Several curves are shown in Fig. 3 for different values of the diameter of this strand. The very strong waveguide dispersion of the structure dominates the material dispersion over a wide wavelength range, enabling a variety of unusual and interesting dispersion curves. As shown in Fig. 3, one can readily create structures with anomalous dispersion over virtually the entire visible spectrum. By carefully engineering the air hole size and the inter-hole spacing within the fiber, even more surprising dispersion characteristics have been predicted, such as a fiber with a dispersion $D < 0.5$ ps/nm.km over a wavelength range of several hundred nanometers in the telecommunications band.[5]

Of special interest are fibers that have an anomalous dispersion in the 800-nm band. This characteristic has a substantial impact on the nonlinear optical processes observed when the fibers are excited using ultrashort optical pulses at these wavelengths. One reason for this is that anomalous GVD enables soliton formation, due to the interplay between dispersion and the nonlinear refractive index of silica. Another reason is that a near-zero GVD has the effect of enabling phase-matching for certain nonlinear optical processes, so that these become much more efficient. The combination of high nonlinearity and zero or positive group-velocity dispersion at the pump wavelength gives rise to a range of unusual optical effects, such as the generation of an ultrabroad supercontinuum spanning well over an octave of frequency when the fiber is pumped with a mode-locked laser.[6]

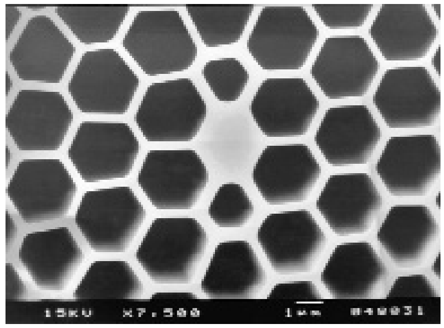

Figure 2 (a). Scanning electron micrograph of a photonic crystal fiber in which light is guided in a pure silica core. In the structure shown, large air holes around the core form a polarization-maintaining fiber with a very high nonlinearity and an unusual group-velocity dispersion characteristic.

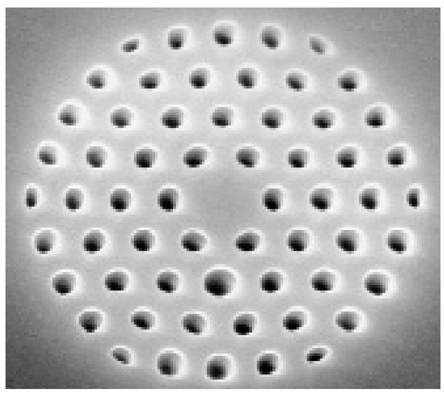

Figure 2 (b). A PCF in which light is guided in a silica core by an array of air holes of intermediate size, causing just a single mode to be guided independent of the wavelength of excitation or the scale of the structure.

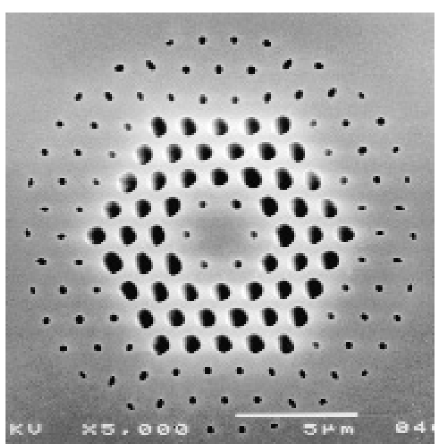

Figure 2 (c). A complex PCF structure in which the existence of small air holes (with diameters of about 350 nm) "within" the core region strongly affects the dispersion of the guided mode.

Research led by Ted Hänsch at the Max-Planck Institute in Garching and by John Hall at JILA has led to a remarkable application of this supercontinuum to the measurement of optical frequencies. The strictly repetitive nature of the supercontinuum implies that the spectrum consists of a large number of distinct modes—the modes of the mode-locked laser cavity—spanning a very wide frequency range. This frequency comb can be calibrated in the time domain (by measuring or controlling the repetition rate of the laser) and then used as a ruler in frequency space, enabling direct and very precise measurement of optical frequencies and frequency intervals.[7]

Fibers such as that shown in Fig. 2(a) do not have to be single mode to be useful. Indeed, the very large index contrast between the pure silica core and the effective refractive index of the cladding means that the fibers might be single mode only for core diameters of the order of the wavelength or less. In practical terms, however, using such fibers in a regime in which they are "overmoded," or in other words in which they support several guided modes, is not very different from the single-mode regime. This is because the core sizes are already small, and it requires a relatively high numerical aperture (NA) to excite the fundamental mode efficiently. Exciting higher-order modes would require more complicated excitation geometries, such as an even higher NA or an angle between the fiber and the incident beam. On the other hand, once light is introduced into the fundamental mode of the fiber, it will not be coupled to other higher-order modes because the propagation constants of those modes are very different from the fundamental, so that impossibly tight bends would be required for coupling from one to the other.

The fiber shown in Fig. 2(a) is also highly birefringent, so that it is a polarization-maintaining fiber.[8] Unlike most conventional polarization-maintaining fibers,

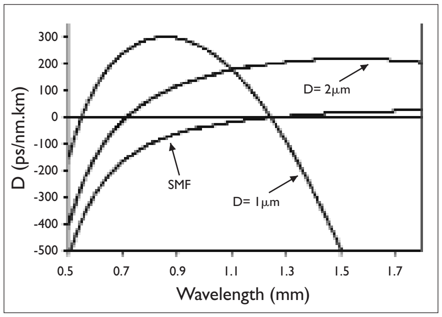

Figure 3. Group-velocity dispersion parameter D for a conventional single-mode fiber (SMF) and for strands of silica with diameters of 1 μm and 2 μm surrounded by air. The air-clad strands are a good approximation to the dispersion of a high-Δ PCF.

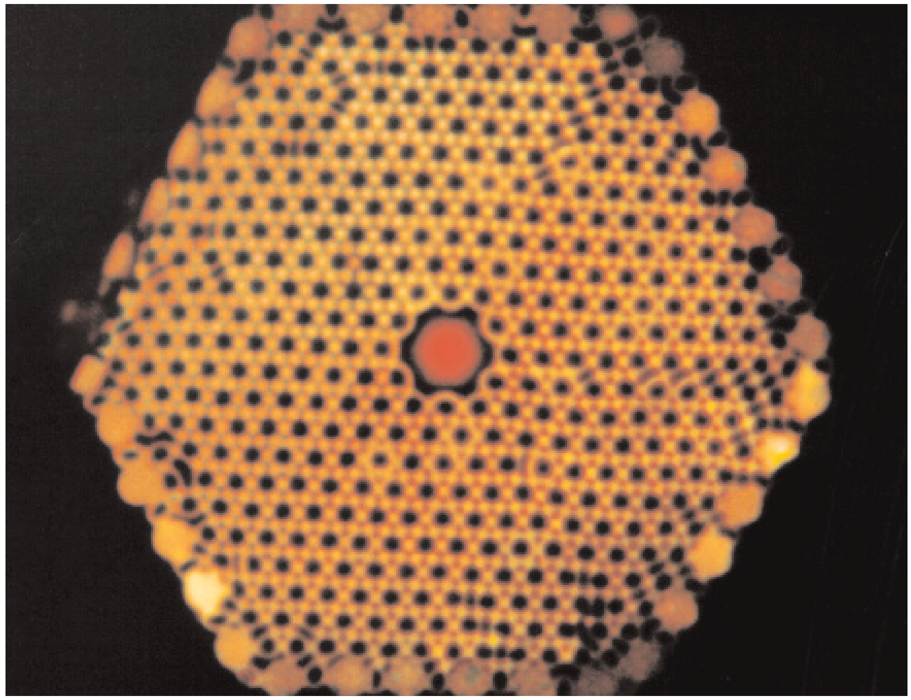

Figure 4. Optical micrograph showing the output face of an air-core fiber when the input is illuminated with a white-light source. Bright red light in the large central hole is trapped by the bandgap of the periodic cladding: other colors have quickly leaked away.

in which the birefringence is created directly in the core material, the birefringence in Fig. 2(a) is due to the ellipticity of the fiber core. Such ellipticity is readily introduced during fabrication by stacking capillaries with different wall thicknesses. The attainable birefringence is extraordinarily high for even relatively modest values of the ellipticity as a result of the large refractive index contrast, so that the values of parameters such as the group-velocity dispersion are markedly different as well.

The fiber in Fig. 2(b) illustrates a different feature of silica-core photonic crystal fibers. Here, the geometrical arrangement of the air holes in the region around the pure silica core defines the number of modes guided in the core region. In the structure shown, only a single mode propagates, independent of the wavelength or physical dimension of the core.[1,9] This is readily explicable if one defines an effective refractive index of the fiber cladding by evaluating the largest propagation constant β_{max} which can be supported by the material, and then evaluating the modal index $n_{eff} = \beta_{max}/k$ of that mode (k is the free-space propagation constant). In this way, we arrive at a value of effective refractive index n_{eff} that is a meaningful measure of when light will be totally reflected from the material "surface" (by a process akin to total internal reflection), and when it will be refracted into the material. On this measure, we would expect that the structure shown in Fig. 2(b) would be a waveguide, as the effective index of the "holey" cladding will be less than the refractive index of silica. On the other hand, what defines the interface between the solid silica core and the surrounding "holey" material, and why does light not escape along the "bridges" between the air holes? These questions cannot be directly answered by conventional fiber optics. The effective index argument can, however, be used to show that the dispersion of the cladding material indeed assures waveguiding in just a single mode, at any optical frequency. This means that one can easily fabricate single-mode fibers with very large mode areas out of plain, undoped silica. Such large mode-area fibers will have lower nonlinearity than normal single-mode fiber, although their performance will ultimately be limited by bend loss.

More sophisticated PCF structures can also be realized. In Fig. 2(c) we show a fiber with a small inner ring of air holes surrounded by several rings of larger holes. The inner holes play only a minor role in confining the light but strongly affect the dispersion of the modes in the core. In the structure shown, the inner holes have diameters of about 350 nm, while the outer hole diameter is closer to 0.8 μm. The small holes towards the outside of the structure play no optical role and are just a result of the fabrication process.

The quest for the "holey" grail

Our interest in photonic crystal fibers started because of the obvious attractions of forming an optical fiber in which the light was guided in an air core by a photonic bandgap mechanism. Such photonic bandgaps cannot occur in a two-dimensionally periodic structure made of silica and air for propagation in the periodic plane. For propagation with an out-of-plane component the requirements are relaxed, giving ranges of β in which there are no modes within the material. As shown in Fig. 1, these bandgaps can occur for $\beta < k$, making it possible to arrange for a truly guided optical mode in an air-core fiber. This concept was described in 1995,[10] and following some years of work we reported the first demonstration of light being guided in an air core confined by a dielectric structure in 1999.[11] Several factors were key to this demonstration at that time: probably the most significant was our development of the fabrication technology to the point where we could draw fibers to the desired parameters. In our original air-guiding fibers we observed optical losses of about 30 dB/m from our 14-μm-diameter air core—high compared to the losses which we expect from optical fibers, but far lower than the roughly 200 dB/m expected from the intrinsically leaky lowest mode of a plain silica capillary of similar bore. What makes the guiding in an air-core fiber especially striking is the strong spectral dependence of the guidance, which at visible frequencies gives rise to brilliant colors when the fiber is illuminated with a white-light source. Figure 4 shows a short length of fiber (of just a few centimeters) illuminated at one end using a tungsten lamp. Brilliantly colored light in the air core results from the strong spectral dependence of the waveguiding mechanism, with only certain frequency bands being confined to the air core. Light at other wavelengths falling outside the bandgap leaks out of the core at a rate determined by the natural attenuation of a leaky mode from a capillary. Further work on these fibers has resulted in optical waveguide losses within the bandgap being reduced to around 1 dB/m so far, with transmission demonstrated over fiber lengths of tens of meters.[12] Further reduction of attenuation will rely on development of fabrication procedures to enable the production of long lengths of fiber with a sufficiently high degree of uniformity both in cross-section and along the fiber length.

The power-handling capability of such fibers will be several orders of magnitude better than in conventional fibers, because the highest intensity in the silica is at least two orders of magnitude down from the peak intensity. This means that nonlinear interactions found in conventional fibers and resulting from the nonlinear response of silica will be correspondingly reduced. For the same reason, the dispersion of the fibers will not be strongly affected by the material dispersion of silica. The fundamental performance limitations of this type of optical fiber—and especially the achievable loss—have yet to be established. Intrinsically, there appears to be no reason why losses cannot be reduced to or below the levels currently obtainable in conventional fibers. Current performance from single-mode optical fibers is the result of over 30 years of intensive research by academic and industrial laboratories. A similar effort into developing photonic crystal fibers could lead to explosive growth of this new technology over the coming years.

Acknowledgments

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