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Photonic Crystal Fibers

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REVIEW

APPLIED PHYSICS

Photonic Crystal Fibers

Philip Russell

Photonic crystal fibers guide light by corralling it within a periodic array of microscopic air holes that run along the entire fiber length. Largely through their ability to overcome the limitations of conventional fiber optics—for example, by permitting low-loss guidance of light in a hollow core—these fibers are proving to have a multitude of important technological and scientific applications spanning many disciplines. The result has been a renaissance of interest in optical fibers and their uses.

Standard "step index" optical fibers guide light by total internal reflection, which operates only if the core has a higher refractive index than the encircling cladding. Rays of light in the core, striking the interface with the cladding, are completely reflected. The wave nature of light dictates that guidance occurs only at certain angles, i.e., that only a small number of discrete "modes" can form. If only one mode exists, the fiber is known as "single mode."

In 1991, the idea emerged that light could be trapped inside a hollow fiber core by creating a periodic wavelength-scale lattice of microscopic holes in the cladding glass—a "photonic crystal" (*1*). To understand how this might work, consider that all wavelength-scale periodic structures exhibit ranges of angle and color ("stop bands") where incident light is strongly reflected. This is the origin of the color in butterfly wings, peacock feathers, and holograms such as those found on credit cards. In photonic band gap (PBG) materials, however, these stop bands broaden to block propagation in every direction, resulting in the suppression of all optical vibrations within the range of wavelengths spanned by the PBG (*2*). Appropriately designed, the holey photonic crystal cladding, running along the entire length of the fiber, can prevent the escape of light from a hollow core. Thus, it becomes possible to escape the straitjacket of total internal reflection and trap light in a hollow fiber core surrounded by glass.

In the early 1970s, there had been the suggestion that a cylindrical Bragg waveguide might be produced in which rings of high- and low-refractive index are arranged around a central core (*3*). Recently, a successful solid-core version of this structure, made using modified chemical vapor deposition (MCVD), was reported (*4*). The effort is now heading toward a hollow-core version, an ambitious goal that requires a materials system with much larger refractive index contrast than the few percent offered by MCVD (*5*).

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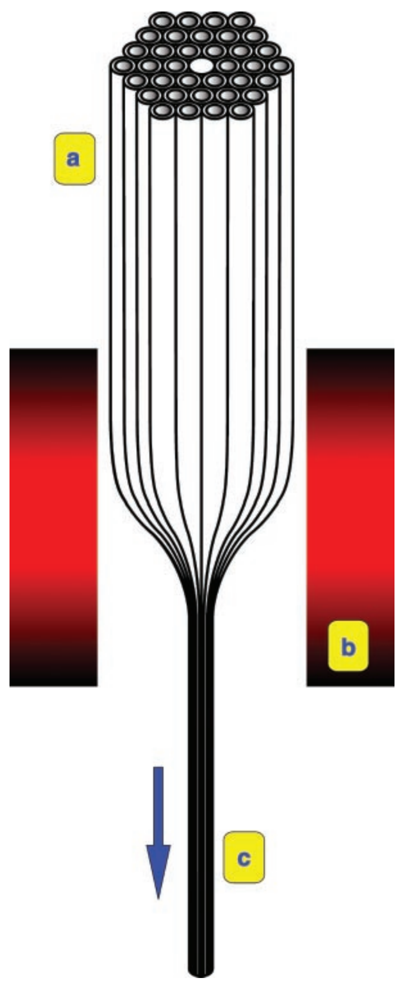

Fig. 1. A stack of glass tubes and rods (a) is constructed as a macroscopic "preform" with the required photonic crystal structure. It is then fused together and drawn down to fiber (c) in two stages using a standard fiber drawing tower. To soften the silica glass, the furnace (b) runs at 1800° to 2000°C.

Was it realistic to imagine making a photonic crystal fiber (PCF)? Fiber fabricators who have long memories will recall how difficult it was to make "single material" fibers. Proposed in the 1970s as low-loss single-mode fibers and made entirely from pure silica, they consisted of a tubular cladding shell connected to a central core by thin webs of glass (*6*). However, such fibers proved very hard to make, and work on them was abandoned with the advent of MCVD (*7*).

So why bother to tackle such a difficult—and apparently impractical—technology? The first reason was simple curiosity: the idea of using a photonic band gap to trap light in a hollow core was intriguing. Second, standard fiber had become a highly respected elder statesman with a wonderful history but nothing new to say. It seemed that, whatever it could do, step-index fiber did it extremely well. The trouble was that it could not do enough. What was needed were fibers that could carry more power, could be used for sensing, could act as better hosts for rare-earth ions, had multiple cores, had higher nonlinearities, or had higher birefringence or widely engineerable dispersion. In fact, conventional fiber was not really good at delivering anything except optical telecommunications. So many new applications and developments have emerged from the PCF concept that there is now a need to rewrite the textbooks on fiber optics (*8*, *9*).

Fabrication Techniques

The first challenge was to devise a fabrication method. There was no particularly helpful precedent; nobody had ever tried to make a fiber like this before. The closest structures were glass nanocrystals (*10*), but these were only a few hundreds of micrometers thick. After several false starts, it was discovered that silica capillaries could be stacked, fused together, and drawn successfully down to PCF (Fig. 1) (*11*). This stack-and-draw procedure proved highly versatile, allowing complex lattices to be assembled from individual stackable units of the correct size and shape. Solid, empty, or doped glass regions could easily be incorporated. My team had chanced upon a technology first used in the third- to first-centuries BC by the Egyptians to make mosaic glass (*12*). The technique's success is largely due to the mechanical stability of the structure—the surface tension forces tend to balance out, allowing formation of highly regular lattices of holes during the drawing process. Overall collapse ratios as large as ~50,000 times have been realized, and continuous holes as small as 25 nm in diameter have been demonstrated, earning an entry in the Guinness Book of Records in 1999 for the World's Longest Holes.

Another promising—though not yet perfected—technique is extrusion (*13*), in which molten glass is forced through a die containing a suitably designed pattern of holes. Extrusion allows fiber to be drawn directly from bulk glass, and almost any structure (crystalline or amorphous) can be produced. It works for many materials, including chalcogenides (*14*), polymers (*15*), and compound glasses. Selective doping of specified regions to introduce rare-earth ions or render the glass photosensitive is much more difficult, however.

The first convincing photonic crystal fiber structure emerged from the fiber drawing tower in November 1995. It had a hexagonal close-packed array of small air channels and was free of any gross imperfections or defects. It was the photonic equivalent of a pure dopant- and defect-free semiconductor crystal, requiring controlled introduction of impurities to be useful. Functional defects could be precisely introduced during the stacking process, allowing fabrication of a wide range of different PCFs.

Light Guidance in PCF

The large index contrast and complex structure in PCF make it difficult to treat mathematically. Standard optical fiber analyses do not help, and so Maxwell's equations must be solved numerically (*16*–*20*). Results are typically presented in the form of a propagation diagram, whose axes are the dimensionless quantities $\beta\Lambda$ and $\omega\Lambda/c$, where Λ is the interhole spacing and c is the speed of light in vacuum. This diagram indicates the ranges of frequency and axial wave vector component β where the light is evanescent (unable to propagate). At fixed optical frequency, the maximum possible value of β is set by $kn = \omega n/c$, where n is the refractive index of the region under consideration. For $\beta < kn$, light is free to propagate; for $\beta > kn$, it is evanescent. For conventional fiber (core and cladding refractive indices n_{co} and n_{cl}, respectively), guided modes appear when light is free to propagate in the doped core but is evanescent in the cladding (Fig. 2A). The same diagram for PCF is sometimes known as a band-edge or "finger" plot (*16*). In a triangular lattice of circular air holes with an air-filling fraction of 45%, light is evanescent in the black regions of Fig. 2B. Full two-dimensional photonic band gaps exist within the black finger-shaped regions, some of which extend into $\beta < k$ where light is free to propagate in vacuum. This result indicates that hollow-core guidance is indeed possible in the silica-air system. It is thought-provoking that the entire optical telecommunications revolution happened within the narrow strip $kn_{cl}\Lambda < \beta\Lambda < kn_{co}\Lambda$ of Fig. 2A. The rich variety of new features on the diagram for PCF explains in part why microstructuring extends the possibilities of fibers so greatly.

Modified total internal reflection. Numerical modeling showed that the holes in the first PCF were too small to expect a photonic band gap, so there was little point in introducing a hollow core in the center. Given that larger air-filling fractions seemed beyond reach in 1995, an obvious thing was to try a solid core. Conceptually, it was difficult to determine whether this structure would be a waveguide or not. From one perspective, it resembled a standard fiber because the average refractive index was lower outside the core. By contrast, between the holes there were clear, barrier-free pathways of glass along which light could escape from the core. The answer was provided by the first working photonic crystal fiber (Fig. 3, A and B), which consisted of an array of ~300-nm air holes, spaced 2.3-μm apart, with a central solid core (*11*). The striking property of this fiber was that the core did not ever seem to become multimode in the experiments, no matter how short the wavelength of the light (*21*); the guided mode always had a single strong central lobe filling the core.

This intriguing "endlessly single-mode" behavior can be understood by viewing the array of holes as a modal filter or "sieve" (Fig. 4). Because light is evanescent in the air, the holes (diameter d, spacing Λ) act as strong barriers; they are the "wire mesh" of the sieve. The field of the fundamental mode fits into the core with a single lobe of diameter (between zeros) roughly equal to 2Λ. It is the "grain of rice" that cannot escape through the wire mesh because the silica gaps (between the air holes encircling the core) are too narrow. For higher order modes, however, the lobe dimensions are smaller so they can slip between the gaps. As the relative hole size d/Λ is made larger, successive higher order modes become trapped. Correct choice of geometry thus guarantees that only the fundamental mode is guided; more detailed studies show that this occurs for $d/\Lambda < 0.4$ (*9*). Very large mode-area fibers become possible, with benefits for high-power delivery, amplifiers, and lasers (*22*). By doping the core to reduce its index slightly, guidance can be turned off completely at wavelengths shorter than a certain threshold value (*23*).

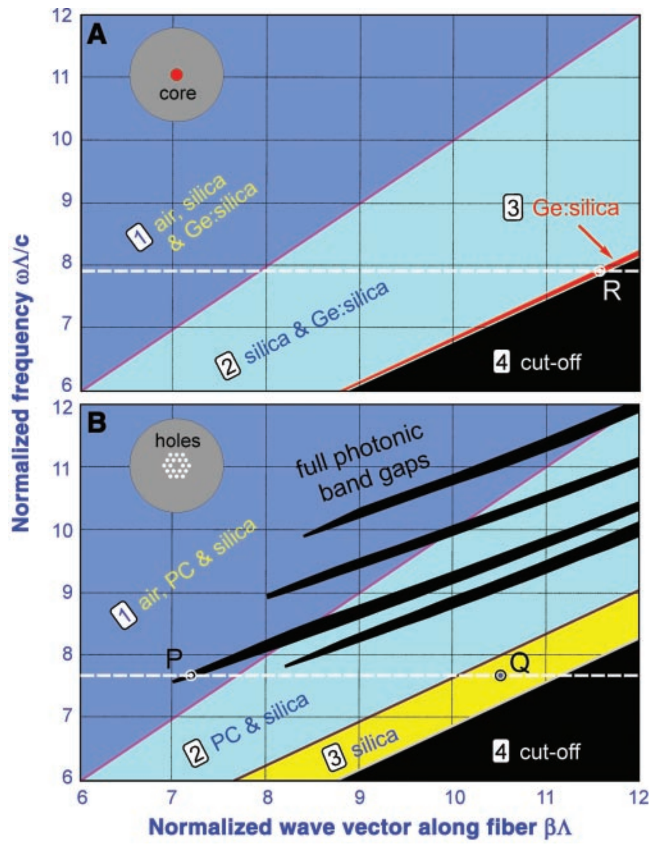

Fig. 2. (**A**) Propagation diagram for a conventional single-mode fiber (see schematic in the top left-hand corner) with a Ge-doped silica core and a pure silica cladding. Guided modes form at points like R, where light is free to travel in the core but unable to penetrate the cladding (because total internal reflection operates there). The narrow red strip is where the whole of optical telecommunications operates. (**B**) Propagation diagram for a triangular lattice of air channels in silica glass with 45% air-filling fraction. In region (1), light is free to propagate in every region of the fiber [air, photonic crystal (PC), and silica]. In region (2), propagation is turned off in the air, and, in (3), it is turned off in the air and the PC. In (4), light is evanescent in every region. The black fingers represent the regions where full two-dimensional photonic band gaps exist. Guided modes of a solid-core PCF (see schematic in the top left-hand corner) form at points such as Q, where light is free to travel in the core but unable to penetrate the PC. At point P, light is free to propagate in air but blocked from penetrating the cladding by the PBG; these are the conditions required for a hollow-core mode.

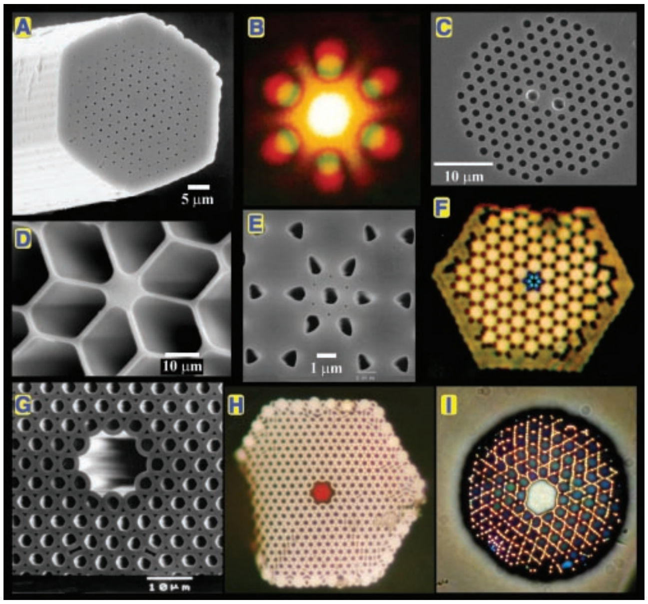

Fig. 3. An assortment of optical (OM) and scanning electron (SEM) micrographs of PCF structures. (**A**) SEM of an endlessly single-mode solid core PCF. (**B**) Far-field optical pattern produced by (A) when excited by red and green laser light. (**C**) SEM of a recent birefringent PCF. (**D**) SEM of a small (800 nm) core PCF with ultrahigh nonlinearity and a zero chromatic dispersion at 560-nm wavelength. (**E**) SEM of the first photonic band gap PCF, its core formed by an additional air hole in a graphite lattice of air holes. (**F**) Near-field OM of the six-leaved blue mode that appears when (E) is excited by white light. (**G**) SEM of a hollow-core photonic band gap fiber. (**H**) Near-field OM of a red mode in hollow-core PCF (white light is launched into the core). (**I**) OM of a hollow-core PCF with a Kagomé cladding lattice, guiding white light.

The guided modes become birefringent if the core microstructure is deliberately made twofold symmetric, for example by introducing capillaries with different wall thicknesses above and below the core (Fig. 3C). Extremely high values of birefringence can be achieved, some 10 times larger than in conventional fibers (*24*). Unlike traditional "polarization maintaining" fibers (bow-tie, elliptical core, or Panda), which contain at least two different glasses each with a different thermal expansion coefficient, the PCF birefringence is highly insensitive to temperature, which is important in many applications.

The tendency for different frequencies of light to travel at different speeds is a crucial factor in the design of telecommunications systems. A sequence of short light pulses carries the digitized information. Each of these is formed from a spread of frequencies and, as a result of chromatic dispersion, it broadens as it travels, ultimately obscuring the signal. The magnitude of the dispersion changes with wavelength, passing through zero at 1.3 μm in conventional fiber. In PCF, the dispersion can be controlled with unprecedented freedom. As the holes get larger, the core becomes more and more isolated, until it resembles an isolated strand of silica glass suspended by six thin webs of glass. If the whole structure is made very small, the zero dispersion point can be shifted to wavelengths in the visible (*25*). The "cobweb" PCF in Fig. 3D has an 800-nm diameter core and a dispersion zero at 560 nm. A PCF was recently reported with close to zero chromatic dispersion over hundreds of nm, making glass almost as free of dispersion as vacuum (*26*).

Hollow-core photonic band gap guidance. Although the first (solid core) photonic band gap fiber was reported in 1998 (*27*) (Fig. 3, E and F), hollow-core guidance had to wait until the technology had advanced to the point where larger air-filling fractions, required to achieve a photonic band gap for incidence from vacuum, became possible. The first such fiber (*28*) had a simple triangular lattice of holes, and the hollow core was formed by removing seven capillaries (producing a relatively large core that improved the chances of finding a guided mode). A vacuum-guided mode must have $\beta/k < 1$, so the relevant operating region in Fig. 2 is to the left of the vacuum line, inside one of the fingers. These conditions ensure that light is free to propagate—and form a mode—within the hollow core while being unable to escape into the cladding.

Optical and electron micrographs of a typical hollow-core PCF are shown in Fig. 3, G and H. Launching white light into the fiber core causes them to transmit colored modes, indicating that guidance existed only in restricted bands of wavelength, coinciding with the photonic band gaps. This feature limits the range of potential applications. More recently it has been possible to greatly widen the transmission bands by fabricating a different structure, a Kagomé lattice (*29*) (Fig. 3I).

Attenuation mechanisms. A key parameter in fiber optics is the attenuation per unit length, for this determines the optimum spacing (~80 km) between repeaters in a telecommunications system. In conventional fibers Rayleigh scattering, unavoidable scattering at nano-scale imperfections in the glass, sets the limit at ~0.2 dB/km at 1550-nm wavelength. Whether PCF can match or improve on this, and perhaps replace conventional fiber in telecommunications, is not yet clear. A number of questions must be asked. Are the glass-air interfaces smooth enough to avoid significant scattering out of the core? Is Rayleigh scattering amplified by the large refractive index step at the interfaces? Will the holes fill with water vapor and thus huge water-related losses develop at 1.39-μm wavelength, where an overtone of the OH bond absorption occurs? The reported losses are steadily dropping, the record presently standing at 0.58 dB/km in a solid-core PCF (*30*).

Hollow-core PCF has the greatest potential for extremely low loss, because the light travels predominantly in the hollow core. Values well below 0.2 dB/km seem at least feasible. The prospect of improving on conventional fiber while greatly reducing the nonlinearities associated with a solid glass core is tantalizing. The best reported attenuation in hollow-core PCF is 13 dB/km (*31*), limited, it is believed, by the high sensitivity of the band gap to structural fluctuations that occur over long fiber lengths; wavelengths that are guided in one section may leak away in another.

Conventional fibers suffer additional loss if bent more tightly than a certain critical radius R_{crit}, which depends on wavelength, core-cladding refractive index step, and most notably, the third power of core radius a^3. For wavelengths longer than a certain value (the "long wavelength bend edge"), all guidance is effectively lost. PCF does not escape this effect, and, in fact, in its endlessly single-mode form PCF exhibits an unexpected short

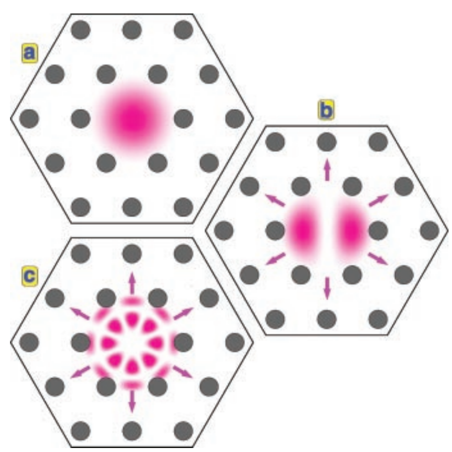

Fig. 4. In a solid-core PCF, the pattern of air holes acts like a modal sieve. In (a), the fundamental mode is unable to escape because it cannot fit in the gaps between the air holes—its effective wavelength in the transverse plane is too large. In (b) and (c), the higher order modes are able to leak away because their transverse effective wavelength is smaller. If the diameter of the air holes is increased, the gaps between them shrink and more and more higher order modes become trapped in the "sieve."

wavelength bend edge caused by bend-induced coupling from fundamental to higher order modes, which of course leak out of the core (*32*, *33*).

Applications

The diversity of new or improved features, beyond what conventional fiber offers, means that PCF is finding an increasing number of applications in ever-widening areas of science and technology. Let us sample a few of the more intriguing and important ones.

Gas-based nonlinear optics. A long-standing challenge in photonics is how to maximize nonlinear interactions between laser light and low-density media such as gases. Efficient nonlinear processes require high intensities at low power, long interaction lengths, and good-quality transverse beam profiles. No existing solution comes close to the performance offered by hollow-core PCF. At a bore diameter of 10 μm, for example, a focused free-space laser beam is marginally preferable to a capillary, whereas a hollow-core PCF with 13 dB/km attenuation is 10^5 times more effective. Such enhancements are rare in physics and point the way to improvements in all sorts of nonlinear laser-gas interactions. Discussed next are just two examples from a rich prospect of enhanced, and more practical, ultralow-threshold gas-based nonlinear optical devices.

An example is ultralow-threshold stimulated Raman scattering in molecular gases. Raman scattering is caused by molecular vibrations, typically in the multi-THz range, that interact spontaneously with the laser light, shifting its frequency both up (anti-Stokes) and down (Stokes) in two separate three-wave parametric interactions. At high intensities, the Stokes wave becomes strong and beats with the pump laser light, driving the molecular oscillations more strongly. This further enhances the Stokes signal, so that ultimately, above a certain threshold power, the major fraction of the pump power is converted to the Stokes frequency. The energy lost to molecular vibrations is dissipated as heat. A stimulated Raman threshold was recently observed in a hydrogen-filled hollow-core PCF at pulse energies ~100 times lower than previously possible (*29*).

Another field where hollow-core fiber is likely to have a major impact is that of high harmonic generation. When gases such as argon are subjected to ultrashort (few fs) high-energy (few mJ) pulses, usually from a Ti-sapphire laser system operating at 800-nm wavelength, the extremely high, short duration electric field momentarily ionizes the atoms, and very high harmonics of the laser frequency are generated during the recombination process (*34*). Ultraviolet and even x-ray radiation can be produced in this way. It is tantalizing to speculate that hollow-core PCF could bring this process within the reach of compact diode-pumped laser systems, potentially leading to table-top x-ray sources for medicine, lithography, and x-ray diagnostics.

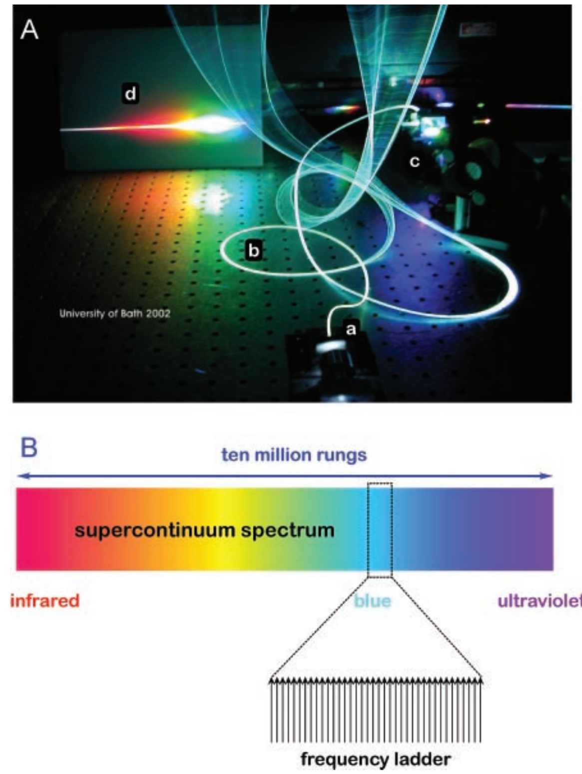

Fig. 6. (**A**) The supercontinuum spectrum produced from an infrared laser operating at 800 nm and producing 200-fs pulses. The infrared light is launched (a) into highly nonlinear PCF (b) and the supercontinuum is dispersed into its constituent colors at a diffraction grating (d). The resulting spectrum is cast on a screen (c). (**B**) The supercontinuum spectrum consists of millions of individual frequencies, spaced by the ~100-MHz repetition rate of the infrared laser. The resulting ladder can be used as a highly accurate "ruler" for measuring frequency (*42*).

Atom and particle guidance. First shown in the 1970s, small dielectric particles can be trapped, levitated, or propelled in a laser beam using the dipole forces exerted by light (*35*). In the now well-developed field of optical tweezers, biological cells, inorganic particles, atoms, and molecules can be manipulated with increasing precision (*36*). A related area is that of atom and particle transport along hollow capillaries, where the optical dipole forces of a co-guided laser beam prevent adhesion to the glass surfaces and provide the acceleration needed to overcome viscosity (*37*). Here, as for gas-laser interactions, the absence of a true guided mode in the capillary severely limits the effectiveness of the technique. Large (~200 μm) bore capillaries must be used to avoid leakage, which means that adequate trapping forces can be obtained only at high laser powers. Hollow-core PCF provides a neat solution to this problem, as shown in recent experiments (Fig. 5) where only 80 mW of 514-nm argon laser light was sufficient to levitate and guide 5-μm polystyrene spheres along a 15-cm length of PCF with a hollow-core diameter of 20 μm (*38*). This technique is being extended to the guidance of atoms and molecules.

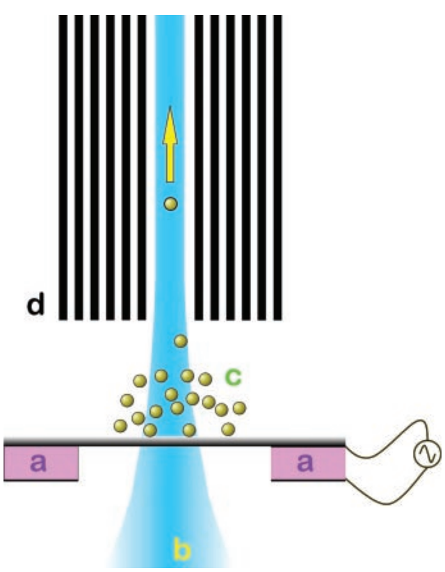

Fig. 5. Particle trapping and guidance in a hollow-core PCF (*38*). The van der Waals forces between the μm-sized polystyrene particles (c) are broken by making them dance on a vibrating plate (a). The laser beam (b) captures them and entrains them into the hollow-core PCF (d).

Ultrahigh nonlinearities. PCFs with extremely small solid glass cores and very high air-filling fractions not only display unusual chromatic dispersion but also yield very high optical intensities per unit power. Thus one of the most successful applications of PCF is to nonlinear optics, where high effective nonlinearities, together with excellent control of chromatic dispersion, are essential for efficient devices.

A dramatic example is supercontinuum generation. When ultrashort, high-energy pulses travel through a material, their frequency spectrum can experience giant broadening due to a range of interconnected nonlinear effects. Until recently this required a regeneratively amplified Ti-sapphire laser operating at 800-nm wavelength. Pulses from the master oscillator (100-MHz repetition rate, 100 fs duration, few nJ energy) are regeneratively amplified up to ~1 mJ. Because the amplifier needs to be recharged between pulses, the repetition rate is only around 1 kHz. Thus, there was great excitement when it was discovered that highly nonlinear PCF, designed with zero chromatic dispersion close to 800 nm, displays giant spectral broadening when the 100 MHz pulse train from the master oscillator is launched into just a few cm of fiber (*39*, *40*) (Fig. 6A) The pulses emerge from a tiny aperture (~0.5 μm^2) and last only a few ps. They have the bandwidth of sunlight but are 10^4 times brighter (>100 GW $m^{-2}sterad^{-1}$). Not surprisingly, this source is finding many uses, e.g., in optical coherence tomography (*41*).

The supercontinuum turns out to consist of millions of individual frequencies, precisely separated by the repetition rate of the pump laser (Fig. 6B). This "frequency comb" can be used to measure optical frequency to an accuracy of one part in 5.1×10^{-16} (*42*). A commercial system is already on the market, based on a compact diode-pumped fs laser source (*43*).

The huge bandwidth and high spectral brightness of the supercontinuum source make it ideal for all sorts of spectroscopy. Measurements that used to take hours and involve counting individual photons can now be made in a fraction of a second. Furthermore, because the light emerges from a microscopic aperture it is uniquely easy to perform spectroscopy with very high spatial resolution.

Concluding Remarks

A full account of the growing number of PCF applications would occupy many pages. Among the more important ones, not discussed here, are rare-earth doped lasers and amplifiers (*44*, *45*) and sensors (*46*, *47*). Also, the possibility of fashioning fibers from traditionally "difficult" materials such as infrared glasses opens up the prospect of a single-mode fiber that could transmit 10.6-μm light with low loss and at high powers; this would revolutionize the field of laser machining.

Photonic crystal fibers represent a next-generation, radically improved version of a well-established and highly successful technology. In escaping from the confines of conventional fiber optics, PCFs have created a renaissance of new possibilities in a large number of diverse areas of research and technology, in the process irrevocably breaking many of the tenets of received wisdom in fiber optics.

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