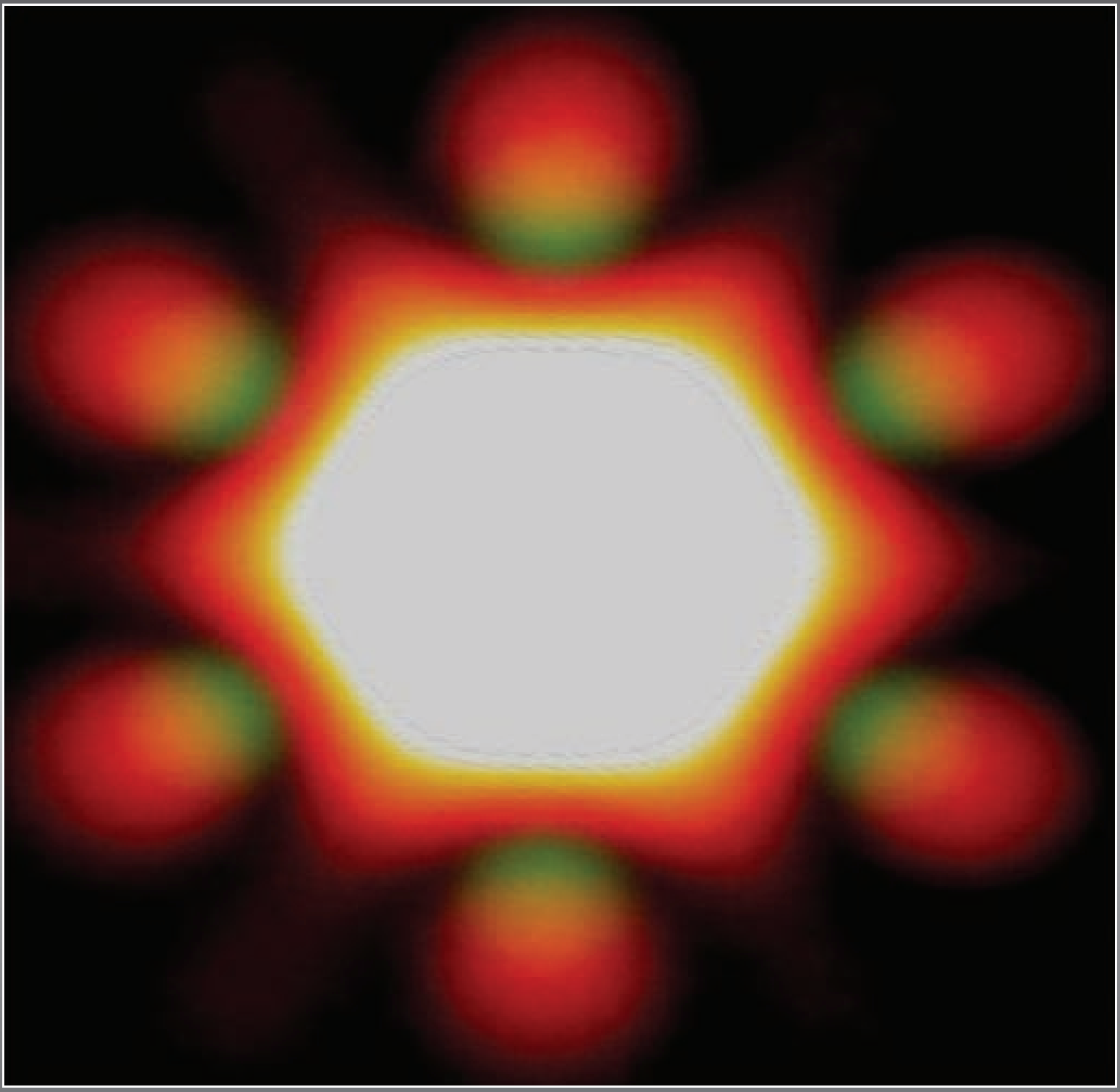
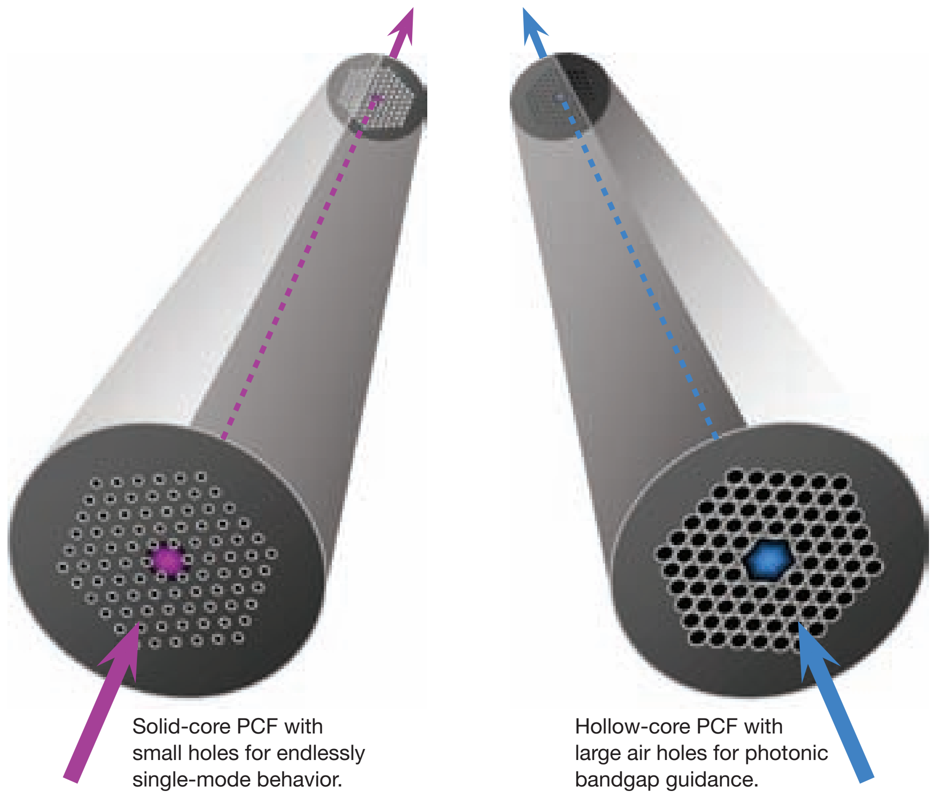
Photonic Crystal Fiber:



Finding the Holey Grail

Philip Russell



Solid-core PCF with small holes for endlessly single-mode behavior.

Hollow-core PCF with large air holes for photonic bandgap guidance.

Photonic crystal fiber (PCF) permits much wider adjustment of key characteristics such as modal phase index, dispersion, nonlinearity and birefringence than is possible in conventional fiber, opening the door to new applications in telecommunications and beyond. PCF can be used to maintain light in a tight focus over kilometer distances inside a hollow core, for example, to laser-guide small particles, molecules or atoms along a curved path, and to fashion a whole range of in-fiber devices and low-loss transitions.

Back in 1991, the idea was simple: to make an optical fiber with a periodic "photonic crystal" lattice of hollow channels in its cladding. Suitably arranged, this lattice might create a two-dimensional photonic bandgap over a range of axial wavevectors $\Delta\beta$ at fixed optical frequency, which would turn the cladding into a "dark space" with no photonic states and allow a guided mode to form inside a central core (a structural inclusion in the lattice).

The skeptics, however, had a lot to say: Why would you want an optical fiber with an array of hollow channels or even a hollow core? Surely, all sorts of difficulties would arise. For example, is it not almost impossible to make such a structure? Worse still, even if you could trap light, wouldn't it leak out if you bent the fiber even by a very small amount? How can you hope to compete with conventional step-index fibers? If an undersea cable made from such fibers was damaged (perhaps chewed by a shark or torn in two by a passing whale), wouldn't water get into the holes, drown out the telecommunications channels and destroy the fiber?

These are examples of the comments and questions I received in the 1990s (the last of which, from a worried journalist, is easily my favorite). In spite of all these drawbacks, real or imagined, working photonic crystal fibers have now been around for more than a decade. Some of them have holes, others are made from two different types of glass, and versions with solid, hollow and multiple cores have been demonstrated.

Of course, it was not easy to work out a way to make such a structure (no really appropriate technology existed), nor was it straightforward to model its waveguiding behavior (though computers were at least available for the job). It took more than four years to come up with—and perfect—the stack-and-draw procedure and to develop efficient numerical algorithms for solving Maxwell's equations in the structures.

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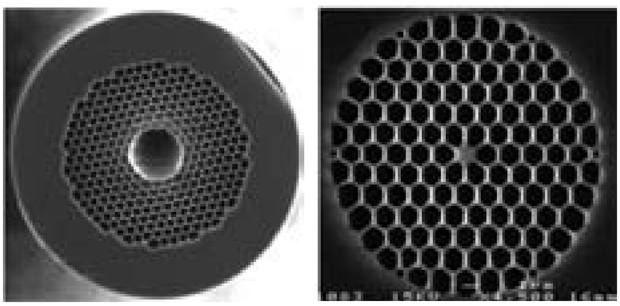
Comparison of guidance mechanisms and properties of solid and hollow-core PCF

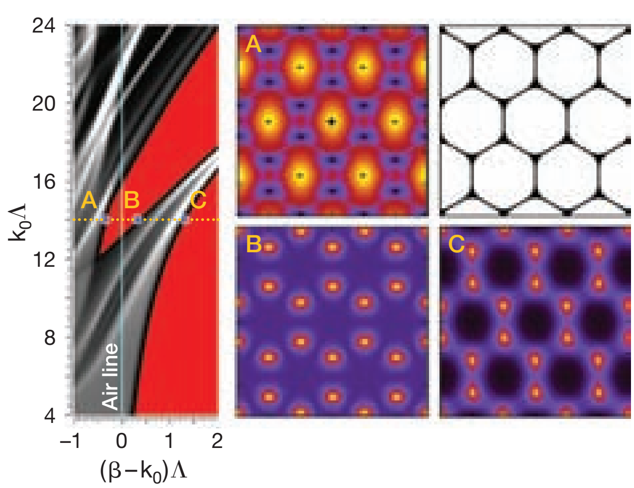
	MTIR Modified total internal reflection	PBG Photonic band-gap	All-solid	Holey	Kagome	ESM Endlessly single-mode	HNL Highly nonlinear	LMA Large mode-area	PM Polarization maintaining
Solid-core	✓	✓	✓	✓	✗	✓	✓	✓	✓
Hollow-core	✗	✓	✗	✓	✓	✗	✗	✓	✓

Hollow-core photonic crystal fiber



(Left) Scanning electron micrograph of an ultra-low-loss hollow-core photonic crystal fiber (PCF) with a core diameter of 20 μm. (Right) highly nonlinear PCF with a solid core, 1.1 μm in diameter.

Density-of-states and field patterns for the photonic crystal cladding



(Left-hand side) Numerically evaluated density-of-states plot for the photonic crystal structure in the top right-hand corner. The red region between edges A and B is a photonic band-gap, and the region to the right of C is beyond the maximum axial refractive index. The pitch of the structure is Λ and k_0 is the vacuum wavevector. The three density plots are the axial Poynting vector distributions at A, B and C. In C, the field amplitudes have the same sign in every antinode; in B, they change sign between adjacent antinodes; and in A, the central lobe has the opposite sign from the six surrounding lobes. A is the “air” edge, B the “dielectric” edge and C the fundamental space-filling mode. Plots courtesy of Greg Pearce (University of Erlangen).

The first fiber that “delivered the goods” was reported in early 1996 in a postdeadline paper at the Optical Fiber Conference in San Jose, Calif. It had a solid glass core surrounded by a triangular array of narrow hollow channels and had the curious property that it guided only the LP_{01} mode at all wavelengths (the holey cladding acts as a sort of modal “sieve,” allowing higher order modes to escape). Interestingly, its six-fold rotational symmetry guarantees zero birefringence, provided the structure is perfectly formed. In 1999, the first hollow-core PCF appeared, and after five more years of development with venture capital investment in the University-of-Bath-based spinoff BlazePhotonics Ltd., the best hollow-core transmission losses stand at 1.1 dB/km at 1,550 nm, only about six times higher than in telecommunications fiber.

The naming of parts

Let’s talk a little about nomenclature. Not taken very seriously in 1991, I made a joke of the situation with a play on words, saying that I wanted to make holey fiber—“spelled with an ‘e’.” Given that a Google search throws up quite a few papers on “holy” fibers, maybe this levity was a mistake. (I am assured by my students, post-docs and colleagues that there is nothing supernatural about PCFs, despite their apparently magical properties.)

There are some who define holey solid-core PCFs as “holey fibers” and holey hollow-core PCFs as “photonic crystal fibers,” despite the obvious fact that both are holey and the best-performing versions of each are periodic in the cladding regions or azimuthally periodic around the core.

Another common misconception is that photonic crystals always have bandgaps, despite the fact that there is nothing in the physics of photonic (or electronic) crystals that states that bandgaps must always be present (metallic crystals do not normally have electronic bandgaps). Yet another faction prefers the term “microstructure fiber,” which seems to me too generic and unexciting, revealing little of the underlying physics. PCFs are, of course, microstructured, but so are all sorts of other man-made entities such as photonic crystals, diffraction gratings, Bragg gratings, single-mode waveguides and just about every type of photonic device. So I prefer to stick to “PCF,” sometimes distinguishing between the different types with suitable qualifiers such as holey PCF, all-solid PCF, solid-core PCF, photonic bandgap PCF and hollow-core PCF.

Bloch waves round the bend

So, what about the skeptic's worry that PCFs would leak light if there are lattice imperfections or the fiber is bent? Many peoples' ideas about periodic structures stem from the Bragg condition, which really only applies to highly perfect structures with very weak unit cell scattering, when the stop-bands are very narrow and the Bragg angle is sharply defined. As the scattering strength is increased, the stop-bands broaden, and the Bragg condition becomes increasingly indeterminate.

In PCF, a full two-dimensional bandgap appears when the stop-bands coalesce to close off propagation for all values of the transverse wavevector. At fixed optical frequency in an appropriately designed PCF cladding, this occurs over a finite range $\Delta\beta$ of axial wavevector β. The larger $\Delta\beta$ is, the more robust the bandgap against structural imperfections in the cladding and fiber bending.

The band-edges coincide with resonances in the unit cells, when the visibility of the field interference pattern is 100 percent and the transverse group velocity is zero. Guidance in hollow-core PCF designed for 1,550 nm transmission is remarkably robust against bends; the bend-radius for noticeable leakage is so small that the fiber usually breaks first!

Holey solid-core PCF is usually viewed as guiding by a modified form of total internal reflection, because the refractive index in the core is higher than the maximum axial index n_{max} supported by the cladding. The cladding may also be viewed as having a one-sided bandgap with a lower band-edge at $\beta = kn_{max}$.

Disorder will not affect the (absent) upper edge, but it will render unpredictable the position of the lower bandgap edge, affecting the dispersion of the guided mode. Clearly, too much uncontrolled disorder would rob solid-core PCF of its valuable designability.

Keeping Lord Rayleigh focused

A (possibly apocryphal) cause of forest fires is the chance focusing of sunlight by a droplet of dew hanging from a leaf. Of course, the "lens" must be placed at precisely the correct distance from the dry undergrowth for the fire to ignite. This is because the depth of focus is proportional to the diameter of the focal spot, as pointed out by Rayleigh at the end of the 19th century and well known to photographers and microscopists.

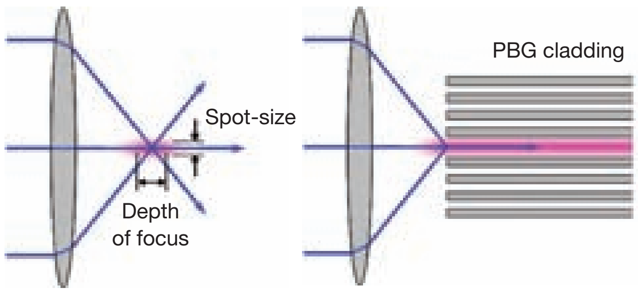
One of the long-standing problems in optical physics—and in many applications of laser light—has been how to increase the depth of focus while maintaining high focal intensity. To achieve this, one must overcome a fundamental property of three-dimensional space: the diffraction (or spreading out) of a beam of light as it travels.

A partial solution emerged with the invention of ultra-low-loss glass fibers, whose microstructure at telecom wavelengths typically consists of a cylindrical core, roughly 9 μm in diameter, surrounded by an annular cladding of pure fused silica glass. The refractive index of the core is less than 1 percent higher than the cladding, creating the conditions for total internal reflection to work. The core glass has astonishing optical clarity—better than 5 km/dB at 1,550 nm. Considering that light can be trapped in a perfect single-mode within this tiny core and guided through oceans and across continents, it would seem that the goal of an infinite depth of focus has already been achieved. Indeed, many fundamental results in nonlinear optics have been demonstrated using telecom fibers, simply because a tight focus can be maintained over huge distances inside a solid material.

But how can we maintain a tight focus on laser light in empty space? There is simply no good way to do this in conventional fiber at visible and near-infrared frequencies, because no cladding material exists that has a refractive index less than unity (one has to move to X-ray frequencies for this to happen). Although metals could perhaps be used to form a mirror around a hollow core, they have extremely high absorption losses, especially in small single-mode cores, when the ratio of circumference-to-area becomes large. Multilayer mirrors might be used to coat the inside surface of a narrow tube, but the ultra-high reflectivity needed for low transmission loss is simply

François Couny, Greg Antonopoulos and Fetah Benabid (University of Bath) delighted over their first observation of low-threshold stimulated Raman scattering in a hermetically sealed, hydrogen-filled, hollow-core PCF.

Light focused by a lens in free space and in a hollow-core PC



(Left) A lens has a depth of focus that is directly proportional to the spot-size. (Right) In contrast, in a lossless hollow-core PCF, the depth of focus can be made infinite (or ~3 km in the best real fibers).

unattainable with current deposition or drawing techniques.

Hollow-core PCF offers for the first time a workable solution to this problem.

The world's best mirrors?

The cladding of a low-loss hollow-core PCF may possibly be the best optical mirror ever made. The number of bounces over length L in a fiber with core diameter d at vacuum wavelength λ is:

$$N_b = \frac{L}{d\sqrt{(\pi d/\lambda z_{01})^2 - 1}}$$

where $z_{01} = 2.405$ is the first zero of a Bessel J_0. This works out at 2.8 million bounces over a fiber 1 km long for core diameter 20 µm and wavelength 1.5 µm. Given that the best loss approaches 1 dB over 1 km, the loss per bounce is 0.35 µdB, corresponding to a mirror reflectivity of 0.99999992 for each bounce.

When we consider that the core-surround has a curved surface and that at each bounce a new mirror is used, it is clear that photonic bandgap mirrors are quite remarkably perfect. The only better reflector is the interface between the Ge-doped core of a telecom fiber and its silica cladding.

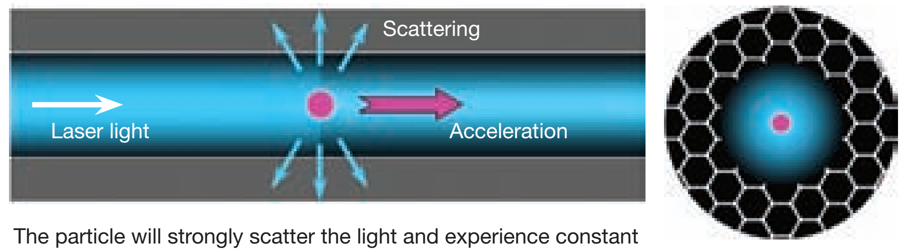
Light and gas in a small space

The availability of hollow-core PCF has started a new chapter in gas-laser physics, the first paragraphs of which are just being written. Being able to keep high-intensity laser light trapped, along with vapors or gases, in a single-mode hollow tube over kilometer-scale distances means that nonlinear interactions can be vastly enhanced—literally by six or seven orders of magnitude. An example is the reduction by more than six orders of magnitude in the threshold energy for stimulated Raman scattering in a single-pass hydrogen cell. For nonlinear optics—a traditionally "difficult" field—such a scale of improvement is simply unprecedented.

For the first time, efficient gas-based laser frequency conversion is feasible at sub-1-W power levels. PCF gas cells can also be hermetically spliced to standard single-mode fiber, allowing easy incorporation of laser-gas devices into telecom systems or even consumer products.

Many other applications are emerging, such as ultra-high sensitivity gas/vapor sensors and acetylene-based optical frequency references in the 1,550 nm band. Work is also underway to explore quantum effects such as electromagnetically induced transparency, as reported by groups in Cornell and Bath, as well as all kinds of nonlinear processes in gases or vapors—for example, high-harmonic generation, saturable absorption and spectral broadening.

[A particle trapped inside hollow-core PCF and propelled by laser light]



The particle will strongly scatter the light and experience constant acceleration (in the absence of fiber loss).

Laser-driven rockets

Laser dipole forces are now commonly used to manipulate micro- and nano-scale objects in many fields. For example, lasers are used as "tweezers" for living cells *in vitro*, and to trap arrays of cold atoms in two-dimensional optical "lattices." Hollow-core PCF offers the unique possibility of guiding small particles, molecules or atoms along a curved path, trapped and propelled by laser dipole forces.

Unlike in normal laser tweezers, where the light is subject to diffractive spreading, hollow-core PCF allows constant acceleration of particles over long distances: It is a kind of laser-driven rocket propulsion system. The velocity that a particle of radius r_p and density ρ_p will reach after accelerating a distance L in a fiber with core radius r_c under laser power P is:

$$V = \sqrt{3LPn/(r_p \rho_p r_c^2 c)}\ ,$$

where n is the modal phase index and c the velocity of light in vacuum. This shows that a particle of diameter 100 nm and density 1,000 kg/m^3 (similar to polystyrene), placed in an evacuated hollow PCF core 10 µm in diameter and subject to a laser power of 1 W, would reach a velocity of 28 km/s after 100 m of propulsion and carry kinetic energy 0.7 pJ.

Brighter than 10,000 suns*

Perhaps the most important attribute of a photonic crystal material is its ability to provide a dispersion that is radically different from that of the constituent materials. This is because the Bloch waves (which enjoy scatter-free propagation) redistribute light between the low- and high-index regions as the frequency of the light is changed. For example, the cladding of a solid-core PCF has a maximum axial refractive index that scales to larger values as the frequency of the light increases.

As a result, it is possible to achieve "endlessly single-mode" behavior because the core-cladding index step falls with decreasing wavelength. In solid-core PCFs with large air-filling fractions and small cores, the waveguide dispersion becomes so strong for the fundamental guided mode that the sign of the

*Of course, the suns would have to be mutually coherent for their brightness to be ten thousand times greater.

natural chromatic dispersion of silica can be reversed, and the dispersion zero (at 1,300 nm in silica) shifted down into the green spectral region for core diameters of less than 1 μm.

The role of dispersion in processes such as soliton formation and four-wave mixing has been well understood for a long time. However, before the appearance of PCF, there was no way to make radical changes in the dispersion landscape in highly nonlinear fibers while maintaining effective lengths of hundreds of meters. The consequences of this new freedom have been wide-ranging, including experiments on four-wave mixing and soliton propagation in new regimes of dispersion.

Perhaps the most dramatic is the appearance of supercontinuum sources pumped by many different lasers, including 120-fs Ti:sapphire, 600-ps Nd:YLF microchip and 5-ps fiber laser systems. The last delivers a remarkable 4.5 mW/nm over the entire range of 450 to 800 nm. The mode-locked Ti:sapphire system produces a comb of frequencies more than an octave wide. It has been used by Theodore Hänsch, winner of the 2005 Nobel Prize for Physics, to measure frequency to better than one part in 10^{15}.

One lesson from this work is that control of the dispersion landscape, as a function of both wavelength and axial position along a fiber, is actually far more important than the level of optical nonlinearity itself.

Microscopic glass-blowing

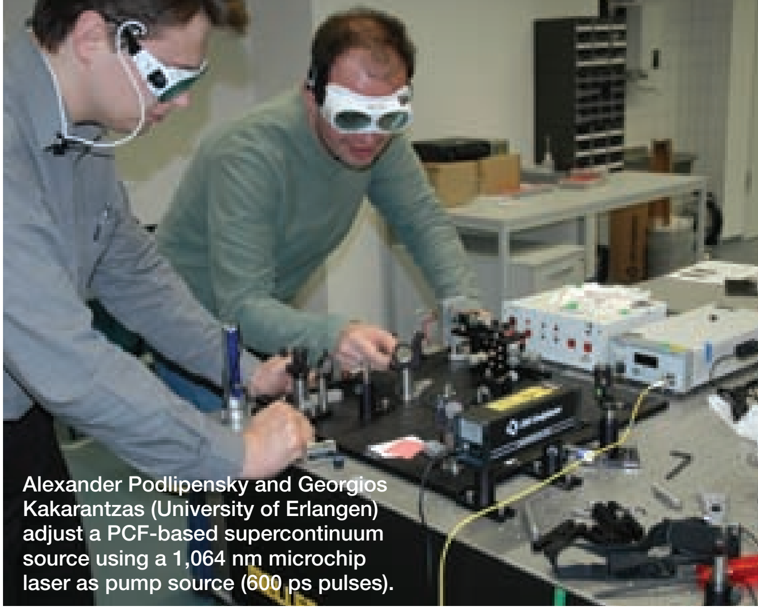
In holey PCF, we are able to apply the ancient craft of glass-blowing to μm-scale structures with nm-scale features. As a result, one can make large morphological changes and fashion a whole range of in-fiber devices and low-loss transitions. By applying pressure and heat, the channels can be inflated, and the degree of inflation can be controlled by the dwell-time at the softening temperature. Channels also collapse slowly under the effects of surface tension when a PCF structure is simply heated to the softening point.

Collapse or inflation of specific channels can be achieved by selective blocking of the holes at the fiber end-face, and tapering allows the overall dimensions of the structure to be reduced. Twisting a polarization-maintaining PCF to and fro while scanning a CO_2 laser beam along the fiber axis results in rocking filters with very high thermal stability.

These are just a few examples from an almost endless list of possibilities.

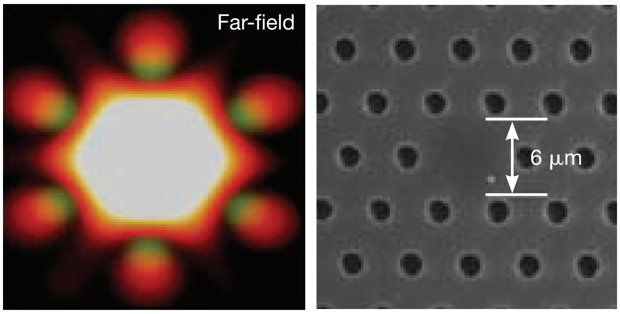
Finally

I do not have enough space in this short article to cover all the exciting developments that are emerging based on PCF in its many forms, including phononic bandgap trapping of GHz acoustic phonons, the combination of micro-fluidics and optical tweezers for control of particles inside hollow-core PCF, all-solid glass PCFs that guide by bandgap effects even when the index contrast is vanishingly small, high-power PCF-based fiber lasers and amplifiers, bright sources of correlated photon pairs, and PCFs for transmission of high laser powers. Clearly, the future is very promising.



Alexander Podlipensky and Georgios Kakarantzas (University of Erlangen) adjust a PCF-based supercontinuum source using a 1,064 nm microchip laser as pump source (600 ps pulses).

[Adjusting a PCF-based supercontinuum source]



(Left) Far-field pattern of the supercontinuum—the shorter wavelengths diffract less as expected. (Right) scanning electron micrograph of the endlessly single-mode PCF used in the experiments.

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