Special 30th Anniversary

Photonic Crystal Fibers: A Historical Account

Philip Russell

Introduction

In 1991, when I first proposed to develop a new kind of fiber – which I initially called "holey fiber," defusing any anxious looks by adding that the word needed an "e" – I was met with a good deal of disbelief. Some friends even questioned my sanity. Who in their right mind could possibly want to make a fiber with an array of microscopic hollow channels ("holes") running along its length, and anyway would this new thing (the "photonic bandgap") really work? Surely, the refractive index of silica glass was too small. Anyone – who knew anything – knew that the literature clearly stated that photonic bandgaps only appear if the refractive index ratio is very large, say 2.2:1 for a two-dimensional dielectric-air structure [1]. And then there were the practicalities of making it. Distressed looks would pass over the faces of those with longer memories, who recalled how difficult it was to make "single material" fibers [2]. Proposed in the early 1970s as low-loss single-mode waveguides for telecommunications, and made entirely from pure silica glass, these structures consisted of a tubular cladding shell connected to a central core by two thin webs of glass. They were very hard to make, and work on them was abandoned when modified chemical vapor deposition (MCVD) came along (quite recently, after almost thirty years of inactivity and prompted it seems by the emergence of PCF, there has been a revival of interest in single-material fibers for nonlinear optics and gas sensing [3, 4]).

So why bother to tackle such a difficult – and apparently impractical – technology? I suppose there were two main reasons. The first was simple curiosity – the idea of using a photonic band gap to trap light in a hollow core was intriguing, even if yet unproven. Secondly, conventional fiber had become a sort of highly respected elder statesman with a wonderful history. One had to concede that, whatever step-index fiber could do, it did it extremely well. The trouble was that it could not do enough. The world was full of scientists and engineers who wanted fibers that could carry more power, fibers that could be used more easily for sensing, fibers that had multiple cores, higher nonlinearities, lower nonlinearities, higher birefringence, more thermal stability and widely engineerable dispersion landscapes … in short, fibers with more versatility.

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Two main factors contribute to this lack of flexibility. The first is the smallness of the core-cladding index difference (Δ is less than 1% in telecommunications fiber), which limits the degree to which group velocity dispersion and birefringence can be manipulated, and produces bend loss (0.5 dB at 1550 nm in Corning SMF-28 for one turn around a mandrel 32 mm in diameter [5]). Although higher values of Δ can be attained (modified chemical vapor deposition yields an index difference of 0.00146 per mol.% GeO_2, up to a maximum $\Delta \sim 10\%$ for 100 mol.% [6]), the core radius for single-mode behavior becomes very small and the attenuation rises through increased absorption and Rayleigh scattering. The second factor is the reliance on total internal reflection (TIR), so that guidance in a hollow core is impossible (at least at UV, visible, and telecommunications wavelengths), however useful it would be in fields requiring elimination of glass-related nonlinearities or enhancement of laser interactions with dilute or gaseous media.

Glass-air PCF seemed to offer for the first time the revolutionary opportunity of escaping the straitjacket of total internal reflection, allowing low-loss guidance of light – in a single-mode – in a hollow fiber core. It also offered a very large index difference (~1.46:1 for silica), setting the scene for solid-core fibers with much smaller mode volumes (and hence higher effective nonlinearities), higher birefringence, and more widely engineerable dispersion. Furthermore, as they were made from only one solid material, the thermal stability of these fibers was likely to be much higher than that of fibers made from two different glasses.

However, I am getting ahead of myself. Before launching into a discussion of the many new aspects of PCF, I would like to make a detour and talk a little about where the idea came from.

Background

It is almost always true that inventions are the result of a multitude of different influences and ideas. In my case, I had been fascinated, since my PhD work, by the behaviour of light in periodically structured media. This started in 1976, when I began work under the supervision of Laszlo Solymar at Oxford, who at that time was developing two and three dimensional coupled mode theories to model the propagation of light in volume holograms. Created by the interference pattern of two or more arbitrary beams, and occupying a volume of space, these holograms bear some resemblance to three-dimensional periodic media, at least locally. Because the behavior of light in these structures was often very complex and therefore hard to understand, I became interested in borrowing concepts and intuitive tools from other fields, especially the dynamical theory of x-ray diffraction [7] and Floquet-Bloch theory for waves in periodic media [8,9]. This naturally led to thinking in terms of electromagnetic band-structure, Bloch waves and the curious effects that appear when group and phase velocity point in different directions, or when the group velocity is independent of the direction of the incident wavevector. This made me very receptive to the suggestion by Eli Yablonovitch and Sajeev John in 1987 that a full electromagnetic band gap might be created by periodically structuring a high refractive index material to produce a "photonic band gap crystal". Their main interest lay in creating an absence of photonic states in three dimensions, something that Yablonovitch went on to demonstrate experimentally at microwave frequencies [10]. I quickly realized that one might be able to achieve low-loss guidance of light in a hollow fiber core. The challenge would be to increase the scattering sufficiently so that, over a range of axial wavevectors, propagation is closed off for all radial and azimuthal directions in the transverse plane – in other words, a two-dimensional photonic band gap (PBG) appears.

Why not annular Bragg fibers?

Another kind of structure that could potentially create this effect had been suggested theoretically in 1968 by Melekin [11] and then studied in more detail by Yariv some ten years later [12]. It consisted of concentric tubular layers of alternating refractive index (Fig. 1(d)). The idea was that rays traveling at an angle to the axis encounter a cylindrical Bragg stack, and are fully reflected back into the core, where they become trapped. The modes that would most naturally guide in such a structure are those where the electric or magnetic fields are parallel to the boundary, i.e., the field polarization turns with azimuthal angle (these are the TE_{01} and TM_{01} modes). In fact, the TE_{01} mode had been used previously at microwave frequencies in hollow metallic waveguides; the field moves away from the waveguide walls as the frequency increases, resulting in very low attenuation, although the guide must be kept very straight to avoid bending-related losses caused by field penetration into the metal.

Although it is straightforward to produce solid-core versions of such Bragg fibers by MCVD [13], for guidance in a *hollow* core one is up against the need for low effective index (the radial stop-band must appear at values of axial refractive index n_{ax} <1) and high index contrast (for strong confinement). As a result, the individual layers must be very thin (thickness ≈ $(1.46^2 – n_{ax})^{-1/2}\ \lambda/4 < 0.69\lambda$, where λ is the vacuum wavelength), which enhances the effects of dopant diffusion during fiber drawing, further reducing the already weak index contrast. Small index contrast has the drawback that, for good confinement, a large number of periods is needed and the structure must be highly perfect to avoid leakage through defect states in the cladding layers.

The ideal structure would be a series of concentric glass layers with air between them; of course, this structure would not hold together mechanically. One could think of increasing the index contrast using two solid materials, but here the problems are extreme for another reason. Pairs of drawable glasses with compatible melting and mechanical properties, a large refractive index difference, and high optical transparency have not yet been found. More exotic combinations of chalcogenide and polymer overcome the mechanical problems, but suffer from extremely high absorption in the polymer layers (nevertheless, 1 dB/m loss at 10 μm wavelength has been reported for the TE_{01} mode [14]).

In the end, it turns out that PCF, with a triangular array of hollow channels, satisfies all of the requirements in one step: high index contrast, mechanical stability, no problems with thermal expansion, and extremely low material absorption.

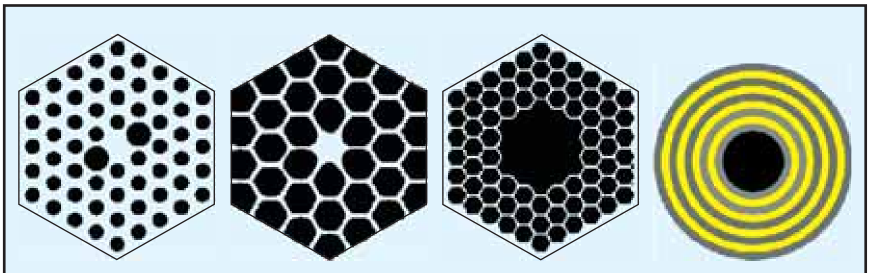

Figure 1: Drawings of various structures: (a) birefringent PCF; (b) ultra-small core PCF; (c) hollow core PCF; (d) hollow core Bragg fiber. The white regions represent silica, the black regions are hollow, and the colored regions are other materials (glasses or polymers).

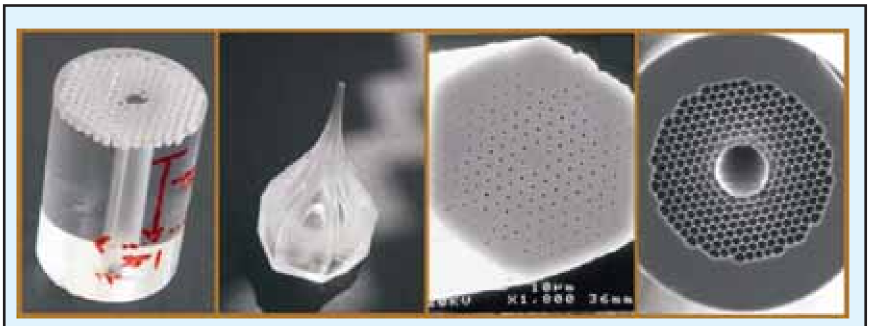

Figure 2: Some PCF structures. (a) the original stub of silica (2.5 cm wide) with holes 1 mm wide partly drilled through it; (b) the hexagonal tube used in the first PCF stack; (c) scanning electron micrograph (SEM) of the first working solid-core PCF; (d) SEM of the latest low-loss hollow core PCF designed for 1550 nm transmission (BlazePhotonics Ltd.)

The undiscovered has no map

Like Thomas Edison in his search to find a suitable material for the element of a light bulb (apparently he tried out 3000 filaments before coming up with one that worked), I had no real idea how to go about producing a fiber with holes that might be as small as half a micron in diameter, spaced a few microns apart in a crystalline lattice. There was no “map”. After all, no one had tried making something quite like this before. Lithography was good for very thin structures, but it was hard to see how it could be adapted to produce even cm lengths of PCF. More promising was work at Naval Research Laboratories in Washington, D.C., where Tonucci had shown that multi-channel glass plates with hole diameters as small as 33 nm, in a tightly packed array, could be produced using draw-down and selective etching techniques [15]. The maximum channel length was limited by the etching chemistry to ~1 mm, and though the structures were impressively perfect, they were clearly not fibers.

My earliest attempt, in 1991, involved drilling a pattern of holes into a stub of silica glass, my hope being that it could be drawn into fiber. Machining an array of 1 mm holes in a stub of silica ~2.5 cm in diameter (the largest the drawing furnace would accommodate) proved beyond the capabilities of the ultrasonic drill that was available, so this approach was abandoned (Fig. 2(a)). I then had the good fortune to raise some funding from DRA Malvern in the UK, and was joined successively by two post-docs: Tim Birks in 1993 and Jonathan Knight in 1995.

After trying various different approaches, we made the first successful silica-air PCF structure in late 1995 by stacking 217 silica capillaries (8 layers outside the central capillary), specially machined with a hexagonal outer and a circular inner cross-section (Fig, 2(b)). The diameter-to-pitch ratio d/λ of the holes in the final stack was ~0.2, which theory showed was too small for PBG guidance in a hollow core, so we decided to make a PCF with a solid central core surrounded by 216 air channels (Fig. 2(c)) [16]. This led to the discovery of endlessly single-mode PCF, which, if it guides at all, only supports the fundamental guided mode [17].

We soon realized that simple circular capillaries were just as good, 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. The stacking technique resembles a technology first used in the 2nd century BC by the Egyptians to make mosaic glass [18] – and by modern-day Italians to fashion millefiori glass jewelry [19]. It has proved remarkably successful, largely because the lattice of holes is mechanically stable – the surface tension forces tend to balance out, allowing formation of highly regular structures during the drawing process. Overall collapse ratios of ~100,000 have been realized, and continuous holes as small as 25 nm in diameter demonstrated. I am told that this earned us a mention in the Guinness Book of Records for the World's Longest Holes, though I have not seen the entry myself (Fig. 3).

Another versatile technique is extrusion, first used by a team of researchers at Corning Incorporated [20]. In this process, molten glass is forced through a die containing a suitably designed pattern of holes. It allows fiber to be drawn directly from bulk material, almost any structure can be produced, and it works for many materials, including polymers [21].

Designing the first hollow core PCF

Back in 1991 I suspected that working out-of-plane ($n_{ax} > 0$) would enhance the chances of finding a full two-dimensional PBG. Transfer matrix calculations for silica/air multilayer stacks confirmed that broad stop-bands could appear in the region $n_{ax} < 1$ – an essential prerequisite for hollow core guidance. Precise numerical solutions of Maxwell's equations, carried out by John Roberts at DRA Malvern, confirmed this in 1995 [22]. His calculations showed that the familiar stop-bands, which exist in all periodic structures, can coalesce to block all radial and azimuthal propagation over a range of axial refractive indices Δn_{ax} in the region $n_{ax} < 1$. Light could then form a guided mode in a hollow core, while its escape is blocked by a PBG in the cladding.

It turns out that the core diameter must be greater than a minimum value if a guided mode is to appear under these conditions. To understand why this is so – and indeed to understand many other features of PCF – we need to introduce the concept of transverse effective wavelength. For the i-th material, with refractive index n_i, this is defined as follows:

$$\lambda_{eff}^{i} = \lambda (n_i^2 - n_{ax}^2)^{-1/2} \qquad (1)$$

where nax is the axial refractive index. This wavelength can be many times the

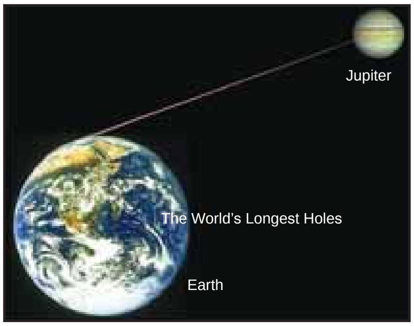

Figure 3: If the Channel Tunnel (connecting England and France) extended all the way to Jupiter, it would have the same length-to-diameter ratio as a hole 25 nm wide and 1 km long.

Year	Milestone	Ref.
1995	2D bandgaps can exist in silica/air PCF for $n_{ax} < 1$	[22]
1996	First solid-core PCF	[16]
1997	Endlessly single mode concept	[17]
1998	Ultra-large mode area	[25]
1999	Dispersion-shifted ultra-small core	[26]
1999	Hollow core photonic band gap PCF	[23]
2000	Multi-core PCF	[27]
2000	Polarisation-maintaining	[28]
2000	Rare-earth doped PCF laser	[29]
2000	Supercontinuum generation	[30]
2001	Carbon-dioxide laser processing of PCF	[31]
2001	Four-wave mixing	[32]
2001	Polymer PCF	[33]
2001	Soliton self-frequency shift	[34]
2002	Laser-tweezer guidance of particles in HC-PCF	[35]
2002	Long-period gratings	[36]
2002	PCF made from Schott SF6 glass for SC generation	[37]
2002	Stimulated Raman scattering in hydrogen	[38]
2003	Phononic bandgaps	[39]
2003	Rocking filters in PM PCF	[40]
2003	Cancellation of the soliton self-frequency shift	[41]
2003	Tellurite glass PCF	[42]
2004	Four-wave mixing	[43]
2004	Twin-photon generation in PCF	[44]
2005	EIT in acetylene	[45, 46]
2005	High energy transmission in HC-PCF	[47]
2005	Low-loss transitions between different PCFs	[48, 49]
2005	Photonic band gaps at 1% index contrast	[50]

Table 1: Key milestones in the development of PCF

vacuum value, tending to infinity at the critical angle ($n_{ax} = n_i$), and being imaginary when $n_{ax} > n_i$ (the fields are then evanescent in the transverse plane). It is a measure of whether or not light is likely to be resonant within a particular feature of the structure, e.g. a hole or a strand of glass, and defines PCF as a wavelength-scale structure. For a strong enough band gap, we can approximately assume that the field reaches zero at the hollow core edge, which for the fundamental mode yields the condition $\rho = z_{01}\lambda^{co}_{eff} / 2\pi; 0.38\lambda^{co}_{eff}$ where z_{01} is the first zero of a Bessel J_0 function. For example, at a vacuum wavelength of 1.55 μm the hollow core diameter would have to be 8.4 mm if the axial refractive index of the guided mode was 0.99.

In 1999, the first hollow-core PCF was reported [23], and the best hollow-core transmission losses now stand at 1.1 dB/km at 1550 nm, only about six times higher than in telecommunications fiber (Fig. 2(d)) [24].

Applications

One particularly attractive feature of PCF structures is that they are highly uniform over very long distances. This means that light launched in at one end has time to sort itself out into a single mode, permitting highly reproducible detection of very small effects. Essentially, unwanted cladding modes are efficiently filtered out before they can interfere with the measurements. This is in sharp contrast to most other kinds of photonic crystals, where taking reliable optical measurements is a challenging and painstaking process. As a result, new PCF structures and PCF-based applications can rapidly be developed (see Table 1 for some key milestones), perhaps the most celebrated being the report in 2000 of supercontinuum generation from un-amplified Ti:sapphire fs laser pulses in a PCF with a core small enough to give zero dispersion at 800 nm wavelength [30].

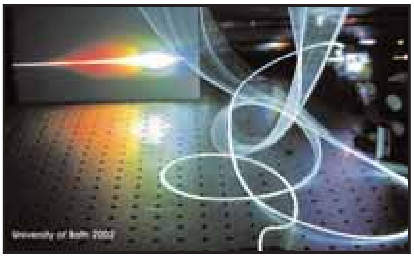

Figure 4: White-light supercontinuum (10,000 times brighter than the sun) generated in PCF with zero dispersion at 800 nm, pumped by 150 fs Ti:sapphire pulses of energy 1~nJ.

Hollow core PCF has many fascinating applications, including gas-Raman cells for high efficiency [38], low threshold color-conversion of laser light. and laser-tweezer propulsion and guidance of small particles along a curved path [35]. Another relatively unexplored area is optical sensing, with myriad opportunities spanning many fields including environmental detection, biomedical sensing, and structural monitoring [51].

As PCF becomes more widely used, there is increasing demand for effective cleaves, low-loss splices, multi-port couplers, intra-fiber devices, and mode-area transformers. The air-holes provide an opportunity not available in standard fibers: the creation of dramatic morphological changes by hole collapse (under surface tension) or inflation (under internal overpressure) when heating to the softening temperature of the glass [52]. Thus, not only can the fiber be stretched locally to reduce its cross-sectional area, but the microstructure can itself be radically altered. Components (couplers, filters, transitions, etc.) made in this way have one great advantage over equivalent devices made in conventional fiber: being formed by permanent changes in structure, they are highly stable with temperature and over time.

Orders of magnitude into the future

At post-deadline sessions in telecommunications conferences, companies often announce incremental improvements in bit-error rates on long-haul fiber systems – the sign of a mature technology. PCF, on the other hand, has often delivered orders of magnitude improvement over the prior art – the sign of a successful disruptive technology. Here is a list of some of the most striking examples:

- Seven orders of magnitude improvement in nonlinear gas-laser devices (e.g. Raman cells), by offering path lengths of order 1 km and single-mode operation
- More than octave-wide supercontinuum sources that are five orders of magnitude brighter than an incandescent lamp (pumped by compact microchip or fiber lasers)
- Pulses of white light ~1 ps long and 10,000 times brighter than the sun
- Frequency measurement to unprecedented accuracy (1 part in 10^{15}) in a compact desktop apparatus using an octave-spanning fs frequency comb (this helped Theodore Hänsch realize a long-standing dream – and win a Nobel Prize in the process)
- Vanishingly small index contrasts can yield photonic band gaps under certain conditions in all-solid PCF [50]
- Low-loss adiabatic tapered transformers allow conversion between the guided modes of radically different PCF structures
- Fiber nonlinearity adjustable over three orders of magnitude (by moving from ultra-small solid core to a hollow core PCF)
- Probably the world's best mirrors in hollow core PCF (1 dB/km, 20 μm core, 1550 nm): 2.8 million bounces per km; 0.35 μdB/bounce (better than 1 part per 10 million loss per bounce); a new mirror at every reflection; and all azimuthal angles & polarisation states are reflected.
- Birefringence that is 10 times higher, and 100 times more stable against temperature fluctuations, than is possible using conventional approaches.

In some of these cases, the penetration is already significant. For example, white-light supercontinuum sources are rapidly becoming an essential tool in laboratories worldwide, even appearing in commercial microscopes.

It is clear that many exciting developments are emerging, and will emerge, based on PCF in its many forms, with applications spanning many disparate fields of science [53].

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