# New Wave Microstructured Optical Fibers

Philip Russell

## Background

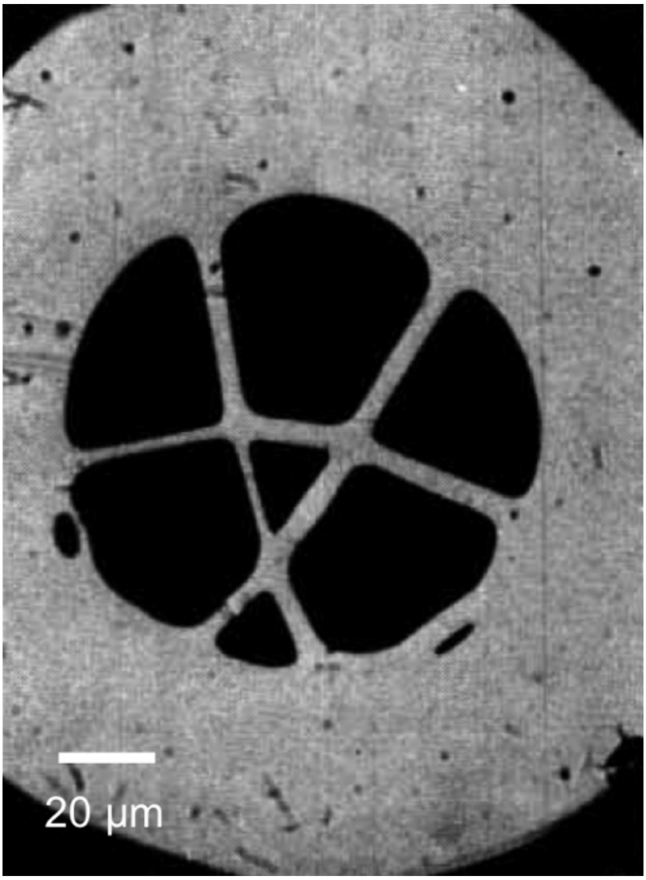
In the early 1990s there was a good deal of excitement about three-dimensional periodic structures in which light cannot exist at frequencies within a photonic bandgap (PBG) [1]. Henry van Driel (Optical Society Fellow, University of Toronto) even compared the atmosphere at a packed-out Quantum Electronics and Laser Science (QELS) session on PBGs (on the afternoon of the last day of the conference) to 1969 Woodstock! At that time it occurred to the author that, if one could create a two-dimensional PBG crystal of microscopic hollow channels in the cladding of an optical fiber, low-loss guidance of light in a hollow core might be possible [2,3]. The challenge would be to design a suitable structure and not least work out a way of making it (in pioneering work at Bell Laboratories in the early 1970s, primitive structures with a small number of large hollow channels had been made, the aim being air-clad glass fiber cores [4]). (See Fig. 1.)

Actually, the first hints that total internal reflection—the workhorse of conventional fiber optics—might not be the only way to guide light had emerged in 1968 with the little known theoretical work of Melekhin and Manenkov in the Soviet Union [5], followed by a more detailed study—again purely theoretical—by Yariv and Yeh at Caltech in 1976 [6]. Their idea was to create a cylindrical Bragg stack from concentric tubular layers of alternating high and low refractive index. Rays of light traveling within a certain range of conical angles would be Bragg reflected back into the core for all azimuthal directions. The trick then was to choose a core diameter that supports a Mie-like resonance at conical angles where the cylindrical Bragg stack has a radial stop-band, resulting in a low-loss guided mode (note that such “Bragg fibers” do not possess a PBG since light is free to propagate azimuthally).

The operating principle of both of these proposals is closely linked to anti-resonant reflecting optical waveguiding (ARROW), in which light is partially confined by a structure of one or more pairs of anti-resonant layers. Originally proposed by Duguay (AT&T Bell Laboratories) in 1986, these are essentially Fabry–Perot cavities operating off resonance so that they reflect light strongly back into the core [7,8]. When the number of such layers becomes large the ARROW structure begins to resemble a Bragg waveguide; i.e., the anti-resonance condition coincides with the presence of a radial stop-band [9].

Although solid-core versions of Bragg fibers have been produced using modified chemical vapor deposition (MCVD) (at IRCOM in Limoges, France) [10], for guidance in a *hollow* core one is up against the need for the radial stop-band to appear at values of axial refractive index less than 1. This means that individual layers must be very thin (~0.69 $\lambda$, where $\lambda$ is the vacuum wavelength), enhancing the effects of dopant diffusion during fiber drawing and further reducing the already weak index contrast. Small index contrast also 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 consist of a series of concentric glass layers with air between them, but of course this would not hold together mechanically. A possible compromise is to fabricate a structure of rings held together with thin glass membranes, but the losses so far reported are quite high [11]. One could think of increasing the index contrast using two solid




▲ **Fig. 1.** Three-core fiber made by Kaiser and colleagues at Bell Labs in the early 1970s. (Reprinted with permission of Alcatel-Lucent USA Inc.)

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 are hard to found. More exotic combinations of chalcogenide and polymer overcome the mechanical problems, offering moderately low losses even though the absorption is extremely high in the polymer layers. Nevertheless, the company Omniguide has achieved 1 dB/m at 10 µm in such Bragg fibers [12], which are now used in laser surgery [13].

## Making the First Photonic Crystal Fiber (PCF)

When the author proposed what he first called "holey fiber," defusing any anxious looks by adding that the word needed an "e," he was met with a good deal of skepticism. Would this new thing, the "photonic bandgap," really work—wasn't the refractive index of silica glass too small? The literature suggested that two-dimensional PBGs appear only if the refractive index ratio is very large, say 2.2:1 for a two-dimensional dielectric–air structure [1] (actually this turns out to be true only for purely in-plane propagation [14]). Even if it did work, would the bend losses not be huge? And then there were the practicalities of making it. The author remembers Clive Day, who had been at the Post Office Research Laboratories in Martlesham (UK) in the 1970s, recalling how difficult the "single-material" fibers had been to make (in 1997 British Telecom donated Day's three-legged drawing tower to the author's then group at the University of Bath, allowing them to make many of the first discoveries about photonic crystal fibers (PCFs)). (See Fig. 2.)

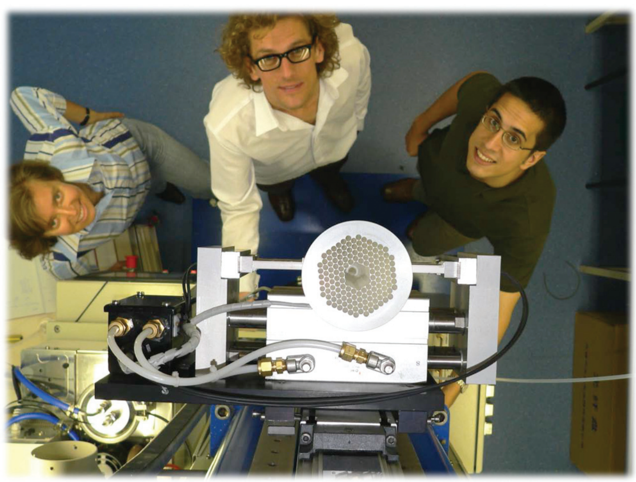
Although conventional lithography worked well for very thin photonic crystal structures, it was hard to see how it could be adapted to produce even millimeter lengths of PCF. More promising was work at Naval Research Laboratories in Washington, where Tonucci had shown that multi-channel glass plates 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 not fibers. The earliest attempt, in 1991, involved drilling a pattern of holes into a stub of silica glass, the 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, so this approach was abandoned. Since then it has been shown that drilling works well for softer materials such as compound glasses or polymers. Another versatile technique is extrusion, in which a molten glassy material is forced through a die containing a suitably designed pattern of holes. Although not yet successfully used for fused silica (existing die materials contaminate the glass at the high temperatures needed [16]), extrusion works well for both polymers [17,18] and soft glasses [19]. (See Fig. 3.)

After various different approaches had been tried, the first successful silica–air PCF structure emerged from the drawing tower in late 1995, the result of the efforts of Tim Birks and Jonathan Knight—postdocs in the author's group at the Optoelectronics Research Center (ORC) in Southampton. The preform was constructed by stacking 217 silica capillaries (eight layers outside the central capillary) into a tight-packed hexagonal array. The diameter-to-pitch ratio of the holes in the final fiber 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 [16]. The result was a working PCF, which guided by a kind of modified total internal reflection. The results were reported in 1996 in a post-deadline paper at OSA's Conference on Optical Fiber Communications and subsequently published in *Optics Letters* [20,21]. (See Fig. 4.)

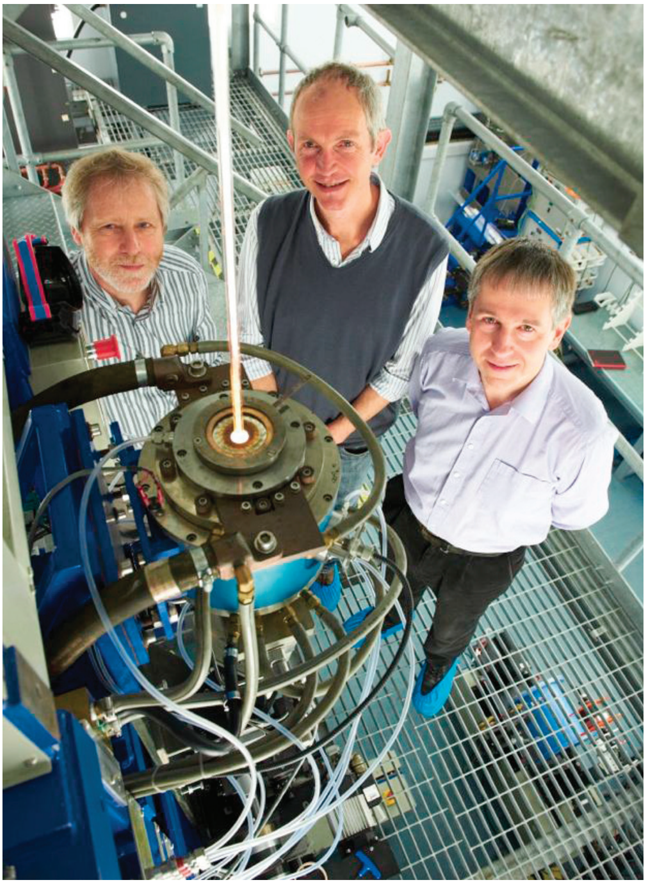
## Breakthroughs and Applications

This work led to the discovery of "endlessly single-mode" (ESM) PCF, which, if it guides at all, supports only the fundamental guided mode [14]. There is a story behind the publication of this result. Submitted to *Optics Letters*, the manuscript received lukewarm or negative reviews and was initially rejected. Feeling that justice was on their side, the group appealed to the editor, Anthony Campillo, who took a look at it and decided to accept it. Currently (October 2015), with more than 1700 citations, it is one of the most frequently cited in the field. ESM behavior is also a feature of ridge waveguides formed by etching a thin film of dielectric material so as to produce a raised strip, and in fact Kaiser points this out in his 1974 paper [4]. The reason is simple: thinner structures support modes with lower refractive indices, which means that the fundamental mode of the thicker ridge will be trapped by the equivalent total internal reflection. Compared to planar ridge waveguides, however, ESM-PCF is

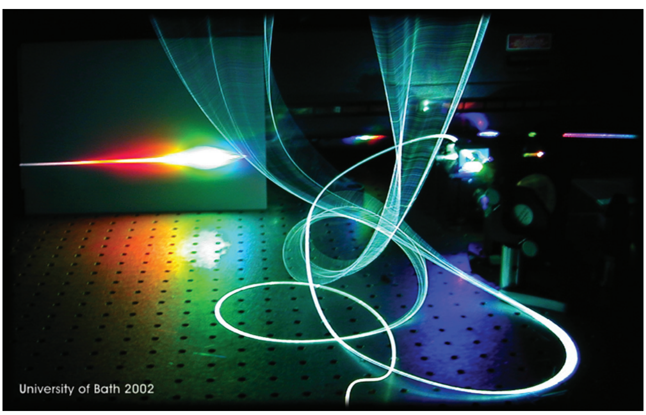
▲ **Fig. 2.** Clive Day working with his three-legged drawing tower at the Post Office Research Laboratories in Martlesham (UK) in the 1970s. (Courtesy Dr. Clive Day and the Post Office Research Centre, Martlesham Health, UK.)



▲ **Fig. 3.** Maryanne Large, Martijn van Eijkelenborg and Alex Argyros drawing polymer PCF at the University of Sydney. (Photograph by Justin Digweed.)



▲ **Fig. 4.** Right to left: Tim Birks, Jonathan Knight, and the author at the University of Bath in 2011. (Courtesy University of Bath.)




▲ **Fig. 5.** Iconic photograph of white-light supercontinuum taken in 2002 by Ph.D. student Will Reeves. (Courtesy University of Bath.)

free of birefringence, provided its structure has perfect sixfold symmetry [22].

Armed with a technique suitable for routine manufacture of microstructured fibers, they set off to explore what could be done—the fun had begun. A string of results followed, the first being an ESM-PCF with an ultra-large mode area [23]. This arose from the realization that ESM behavior allowed one to operate in regimes where a conventional fiber would be multimode. At the other extreme, it was pointed out in 1999 that cores of diameter ~1 μm, surrounded by large hollow channels, would have very high anomalous dispersion at 1550 nm, which it was later realized would push the zero dispersion to wavelengths much shorter than the canonical 1.29 μm associated with conventional silica single-mode fiber [24]. This was to lead to perhaps the biggest breakthrough so far in applications of PCF: the demonstration by a team at Bell Laboratories that an octave-spanning frequency comb could be produced using ~100 fs pulses of few nanoJoule energies from a mode-locked Ti:sapphire oscillator [25,26]. This created huge excitement when it was presented as a post-deadline paper at OSA's Conference on Lasers and Electro-Optics in 1999, and contributed materially to the award of the 2005 Nobel Prize for Physics to Jan Hall of NIST in Boulder, Colorado, and Ted Hänsch of the Max-Planck Institute for Quantum Optics in Munich [27,28]. (See Fig. 5.)

The year 1999 also saw the first report of a hollow-core PCF, indicating that one could indeed guide light using the new physics of PBGs [29]. Fred Leonberger, the program chair of CLEO 2002 in Long Beach, California, was kind enough to invite the author to give one of the plenary talks—a sure sign that PCF had, within only a few years, attracted considerable attention. The next technological steps focused mostly on improving the performance, mainly the loss, of these new fibers. Following intensive development at Corning and BlazePhotonics (a post-deadline paper at OFC in 2004 reported 1.7 dB/km [30]), the lowest published loss of hollow core PCF stands at 1.2 dB/km at 1550 nm [31]. Just before BlazePhotonics closed down, the R&D team actually had reduced the value still further to 0.8 dB/km.

It was rapidly realized that thermal post-processing, together with pressure control, twisting, and stretching, could be used to make radical changes in the local fiber characteristics post-fabrication.

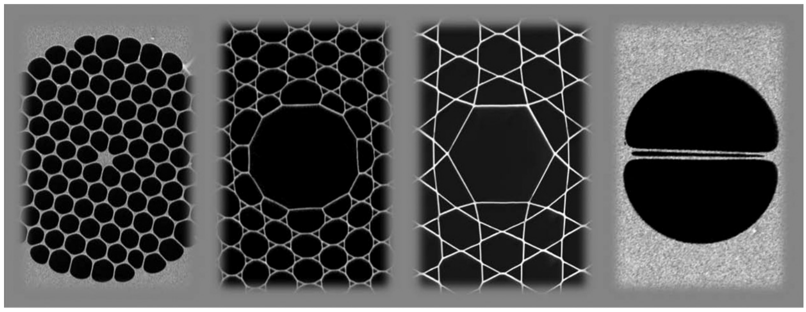


**Fig. 6.** Scanning electron micrographs of a selection of different photonic crystal and microstructured fibers. (Courtesy Max-Planck Institute for the Science of Light.)

These techniques have thrown up a large number of useful devices, including long-period gratings, rocking filters, helical fibers, and the remarkable “photonic lanterns” now used to filter out atmospheric emission lines in fiber-based astronomy [32,33]. Based on all-solid multi-core fibers, these devices perform the astonishing feat of adiabatically channeling each mode of a multi-mode fiber into separate single-mode fibers.

Applications of the new fiber structures continue to emerge, an obvious highlight being broadband light sources millions of time brighter than incandescent lamps and extending into the UV, pumped by Q-switched Nd:YAG microchip lasers or Yb-doped fiber lasers at 1-μm wavelength. These are now to be found in many laboratory instruments, including commercial microscopes. New types of sensing, fiber have emerged, some of them reminiscent of the original single-material fibers of Kaiser (e.g., the so-called “Mercedes” fiber [34]). Hollow core PCF has perhaps opened up the greatest number of new opportunities. For example, it is being employed as a microfluidic system for monitoring chemical reactions, in which guided light is used both to photo-excite and to measure changes in the absorption spectrum [35]. (See Fig. 6.) Compared to conventional microfluidic circuits, the quantity of liquid required is very small, the long path-length means that very small absorption changes can be detected, and the high intensity achievable in the narrow core for moderate optical power means that reactions can be rapidly initiated. PCF is also being used in many other optical sensors, with applications in environmental detection, biomedical sensing, and structural monitoring.

The unique ability of hollow-core PCF to keep light tightly focused in a single mode in a gas is creating a revolution in nonlinear optics. For the first time it is possible to explore ultrafast nonlinear optics in gases in a system where the dispersion can be tuned by changing the gas pressure and composition [36]. Raman frequency combs spanning huge ranges of frequency, from the UV to the mid-IR, can be generated at quite modest power levels [37,38]. Atomic vapors of, e.g., Rb and Cs can be incorporated into the hollow core, permitting experiments on EIT and few-photon switching [39]. Hollow core also adds a new dimension to the important field of optical tweezers: the absence of diffraction means that radiation forces can be employed to transversely trap and continuously propel dielectric particles over curved paths many meters in length [40].

# In Conclusion

The Optical Society, through its conferences and publications (especially *Optics Letters* and *Optics Express*), has played and continues to play a major role in promoting a disruptive technology that, through delivering orders of magnitude improvement over prior art, seems likely over the next decades to have an increasing impact in both commercial and scientific research.

# References


1. E. Yablonovitch, “Photonic band-gap structures,” J. Opt. Soc. Am. B **10**, 283–295 (1993).
2. P. St.J. Russell, “Photonic-crystal fibers,” J. Lightwave Tech. **24**, 4729–4749 (2006).
3. P. St.J. Russell, “New age fiber crystals,” IEEE Lasers Electro-Opt. Soc. Newsletter **21**, 11 (2007). http://2photonicssociety.org/newsletters/oct7/21leos05.pdf.

4. P. V. Kaiser and H. W. Astle, "Low-loss single-material fibers made from pure fused silica," Bell Syst. Tech. J. **53**, 1021–1939 (1974).
5. V. N. Melekhin and A. B. Manenkov, "Dielectric tube as a low-loss waveguide," Sov. Phys. Tech. Phys. USSR **13**, 1698–1699 (1969).
6. P. Yeh and A. Yariv, "Bragg reflection waveguides," Opt. Commun. **19**, 427–430 (1976).
7. M. A. Duguay, Y. Kokubun, T. L. Koch, and L. Pfeiffer, "Antiresonant reflecting optical wave-guides in $SiO_2$-Si multilayer structures," Appl. Phys. Lett. **49**, 13–15 (1986).
8. J. L. Archambault, R. J. Black, S. Lacroix, and J. Bures, "Loss calculations for antiresonant waveguides," J. Lightwave Technol. **11**, 416 (1993).
9. N. M. Litchinitser, S. C. Dunn, B. Usner, B. J. Eggleton, T. P. White, R. C. McPhedran, and C. M. de Sterke, "Resonances in microstructured wavetuides," Opt. Express **11**, 1243–1251 (2003).
10. F. Brechet, P. Roy, J. Marcou, and D. Pagnoux, "Single mode propagation in depressed-core-index photonic-bandgap fiber designed for zero-dispersion propagation at short wavelengths," Electron. Lett. **36**, 514–515 (2000).
11. A. Argyros, M. A. van Eijkelenborg, M. C. J. Large, and I. M. Bassett, "Hollow-core microstructured polymer optical fiber," Opt. Lett. **31**, 172–174 (2006).
12. B. Temelkuran, S. D. Hart, G. Benoit, J. D. Joannopoulos, and Y. Fink, "Wavelength-scalable hollow optical fibres with large photonic bandgaps for $CO_2$ laser transmission," Nature **420**, 650–653 (2002).
13. F. C. Holsinger, C. N. Prichard, G. Shapira, O. Weisberg, D. S. Torres, C. Anastassiou, E. Harel, Y. Fink, and R. S. Weber, " Use of the photonic bandgap fiber assembly $CO_2$ laser system in head and neck surgical oncology," Laryngoscope **116**, 1288–1290 (2006).
14. T. A. Birks, J. C. Knight, and P. St.J. Russell "Endlessly single-mode photonic crystal fiber," Opt. Lett. **22**, 961–963 (1997).
15. R. J. Tonucci, B. L. Justus, A. J. Campillo, and C. E. Ford, "Nanochannel array glass," Science **258**, 783–785 (1992).
16. D. C. Allan, J. A. West, J. C. Fajardo, M. T. Gallagher, K. W. Koch, and N. F. Borrelli, "Photonic crystal fibers: effective index and bandgap guidance," in *Photonic Crystals and Light Localisation in the 21st Century*, C. M. Soukoulis, ed. (Kluwer, 2001), pp. 305–320.
17. H. Ebendorff-Heidepriem, T. M. Monro, M. A. van Eijkelenborg, and M. C. J. Large, "Extruded high-NA microstructured polymer optical fiber," Opt. Commun. **273**, 133–137 (2007).
18. M. A. van Eijkelenborg, M. C. J. Large, A. Argyros, J. Zagari, S. Manos, N. A. Issa, I. M. Bassett, S. Fleming, R. C. McPhedran, C. M. de Sterke, and N. A. P. Nicorovici, "Microstructured polymer optical fibre," Opt. Express **9**, 319–327 (2001).
19. H. Ebendorff-Heidepriem, K. Kuan, M. R. Oermann, K. Knight, and T. M. Monro, "Extruded tellurite glass and fibers with low OH content for mid-infrared applications," Opt. Mater. Express **2**, 432–442 (2012).
20. J. C. Knight, T. A. Birks, P. St.J. Russell, and D. M. Atkin, "Pure silica single-mode fiber with hexagonal photonic crystal cladding," in *Conference on Optical Fiber Communications* (Optical Society of America, 1996).
21. J. C. Knight, T. A. Birks, P. St.J. Russell, and D. M. Atkin, "All-silica single-mode fiber with photonic crystal cladding," Opt. Lett. **21**, 1547–1549 (1996).
22. M. J. Steel, T. P. White, C. M. de Sterke, R. C. McPhedran, and L. C. Botten, "Symmetry and degeneracy in microstructured optical fibers," Opt. Lett. **26**, 488–490 (2001).
23. J. C. Knight, T. A. Birks, R. F. Cregan, P. St.J. Russell, and J. P. De Sandro, "Large mode area photonic crystal fibre," Electron. Lett. **34**, 1347–1348 (1998).
24. T. A. Birks, D. Mogilevtsev, J. C. Knight, and P. St.J. Russell, "Dispersion compensation using single-material fibers," IEEE Photon. Technol. Lett. **11**, 674–676 (1999).
25. J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," Opt. Lett. **25**, 25–27 (2000).
26. J. K. Ranka and R. S. Windeler, "Nonlinear interactions in air-silica microstructure optical fibers," Opt. Photon. News **20**(8), 21–25 (2000).
27. T. W. Hänsch, "Nobel Lecture: Passion for precision," Rev. Mod. Phys. **78**, 1297–1309 (2006).
28. J. L. Hall, "Nobel Lecture: Defining and measuring optical frequencies," Rev. Mod. Phys. **78**, 1279 (2006).
29. R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St.J. Russell, P. J. Roberts, and D. C. Allan, "Single-mode photonic band gap guidance of light in air," Science **285**, 1537–1539 (1999).

30. B. J. Mangan, L. Farr, A. Langford, P. J. Roberts, D. P. Williams, F. Couny, M. Lawman, M. Mason, S. Coupland, R. Flea, H. Sabert, T. A. Birks, J. C. Knight, and P. St.J. Russell, "Low-loss (1 dB/km) hollow core photonic bandgap fiber," in *Optical Fiber Communications Conference* (OSA Technical Digest), post-deadline paper PDP24 (2004).
31. P. J. Roberts, F. Couny, H. Sabert, B. J. Mangan, D. P. Williams, L. Farr, M. W. Mason, A. Tomlinson, T. A. Birks, J. C. Knight, and P. St.J. Russell, "Ultimate low loss of hollow-core photonic crystal fibres," Opt. Express **13**, 236–244 (2005).
32. S. G. Leon-Saval, T. A. Birks, J. Bland-Hawthorn, and M. Englund, "Multimode fiber devices with single-mode performance," Opt. Lett. **30**, 2545–2547 (2005).
33. T. A. Birks, B. J. Mangan, A. Diez, J. L. Cruz, and D. F. Murphy, "'Photonic lantern' spectral filters in mullti-core fiber," Opt. Express **20**, 13996–14008 (2012).
34. C. M. B. Cordeiro, M. A. R. Franco, C. J. S. Matos, F. Sircilli, V. A. Serrao, and C. H. B. Cruz, "Single-design-parameter microstructured optical fiber for chromatic dispersion tailoring and evanescent field enhancement," Opt. Lett. **32**, 3324–3326 (2007).
35. J. S. Y. Chen, T. G. Euser, N. J. Farrer, P. J. Sadler, M. Scharrer, and P. St.J. Russell, "Photochemistry in photonic crystal fiber nanoreactors," Eur. J. **16**, 5607–5612 (2010).
36. J. C. Travers, W. Chang, J. Nold, N. Y. Joly, and P. St.J. Russell, "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers [Invited]," J. Opt. Soc. Am. B **28**, A11–A26 (2011).
37. F. Couny, F. Benabid, P. J. Roberts, P. S. Light, and M. G. Raymer, "Generation and photonic guidance of multi-octave optical-frequency combs," Science **318**, 1118–1121 (2007).
38. A. Abdolvand, A. M. Walser, M. Ziemienczuk, T. Nguyen, and P. St.J. Russell, "Generation of a phase-locked Raman frequency comb in gas-filled hollow-core photonic crystal fiber," Opt. Lett. **37**, 4362–4364 (2012).
39. M. Bajcsy, S. Hofferberth, V. Balic, T. Peyronel, M. Hafezi, A. S. Zibrov, V. Vuletic, and M. D. Lukin, "Efficient all-optical switching using slow light within a hollow fiber," Phys. Rev. Lett. **102**, 203902 (2009).
40. O. A. Schmidt, M. K. Garbos, T. G. Euser, and P. St.J. Russell, "Reconfigurable optothermal microparticle trap in air-filled hollow-core photonic crystal fiber," Phys. Rev. Lett. **109**, 024502 (2012).