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Photonic Crystal Fibers

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Abstract— **Photonic crystal fibers having a complex microstructure in the transverse plane constitute a new and promising class of optical fibers. Such fibers can either guide light through total internal reflection or the photonic bandgap effect. In this paper, we review the different types and applications of photonic crystal fibers with particular emphasis on recent advances in the field.**

I. Introduction

Photonic crystal fibers (PCFs) have in recent years attracted much scientific and technological interest. Broadly speaking, PCFs may be defined as optical fibers in which the core and/or cladding regions consist of microstructured rather than homogeneous materials. The most common type of PCF, which was first fabricated in 1996 [1], consists of a pure silica fiber with an array of airholes running along the longitudinal axis. Later on, PCFs fabricated from other base materials [2] or incorporating sections of doped material [3]–[5] have been demonstrated. Also, a considerable amount of modeling and experimental effort has been put into the design and fabrication of circularly symmetric PCFs with radial layers of alternating index contrasts [6], [7].

In conventional optical fibers, electromagnetic modes are guided by total internal reflection in a core region whose refractive index is raised by doping of the base material. In PCFs, two distinct guiding mechanisms are possible: The guided modes may be trapped in a core with a higher average index than the cladding region by an effect similar to total internal reflection (often termed modified total internal reflection, or just index-guiding), or they can be trapped in a core of *lowered* average index by a photonic bandgap effect. The existence of two different guiding mechanisms is one of the reasons for the versatile nature of PCFs.

PCFs have over the last seven years rapidly evolved from a scientific curiosity to a commercial product manufactured and sold by several companies worldwide. A central issue from the early days to the present has been the reduction of losses, which initially were several hundred dB/km even for the simplest PCF designs. Through increased control over the homogeneity of the fiber structures and the application of highly purified silica as a base material, these losses have been brought down to a level of a few dB/km for the most important types of PCFs, the current world record being 0.37 dB/km [8]. Thus, with respect to losses PCFs have undergone an evolution similar to that of standard fibers in the 1970s and application potentials have opened up accordingly. For some

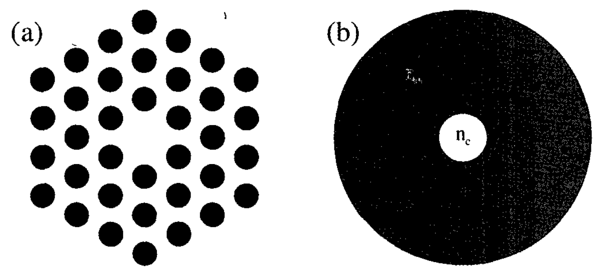

Fig. 1. (a) The most common PCF design at present. Dark areas are airholes while white areas are silica. (b) Effective index model of the design in (a).

types of PCFs, the loss figures are still substantial so more work is definitely required in this area, however for many applications losses have ceased to be a decisive barrier to the application of PCFs.

PCFs are most commonly fabricated by hand-stacking an array of doped or undoped silica capillary tubes or solid rods into the desired pattern, fusing the stack into a preform, and then pulling the preform to a fiber at a temperature sufficiently low (~ 1900°C) to avoid the holes collapsing. The vast improvements of this fabrication process made in recent years have not only served to bring down losses, but have also greatly increased the diversity of structures available to the designer. Consequently, new PCF designs are continuosly appearing, and it will probably be a few years yet before the field can be said to have matured. The present paper intends to provide an overview of the most important types of PCFs fabricated so far, along with a discussion of their potential and possible limitations.

II. Index-guiding PCFs

In the index-guiding PCFs, light is trapped in a high-index core by a mechanism similar to the total internal reflection in standard fibers. A common design, easily fabricated by stacking capillary tubes, is shown in Fig. 1(a): The cladding region consists of a hexagonal array of airholes, with a missing airhole defining the core. Thus, the trapping of modes in the core region can also be regarded as an analogy to the trapping of electrons at defect sites in crystals, which is the origin of the term photonic crystal fibers.

A qualitative understanding of the basic properties of index-guiding PCFs may be obtained by considering the effective index model [9] depicted in Fig. 1(b). Here, the PCF structure is approximated by a step-index fiber with a core index corresponding to the base material (e.g. pure silica), and a cladding index defined as the highest effective index occuring among the space-filling modes of the perfect (defect-free) PCF cladding structure. Crude as this model is, it does reveal a central difference between PCFs and ordinary fibers: Whereas the latter have an index contrast between core and cladding which is almost constant with frequency, this is not the case for the PCFs. This is because light at shorter wavelengths avoids the airholes more efficiently, so the effective cladding index approaches that of the base material in the short-wavelength limit. In silica fibers with the structure depicted in Fig. 1(a), if the ratio between airhole diameter and interhole distance is below ~0.4, this effect makes the fiber single-moded at all wavelengths - a property which is not attainable in standard fibers [9], [10].

A. Dispersion control in PCFs

One of the basic properties of an optical fiber is the dispersion coefficient, D, defined as:

$$D = \frac{\omega^2}{2\pi c v_g^2}\frac{dv_g}{d\omega}, \qquad (1)$$

where ω is the frequency and v_g the group velocity of the guided mode. The broadening of an unchirped pulse propagating in the fiber is proportional to the magnitude of D at the center frequency of the pulse. Therefore, control of the dispersion properties is very important for signal transmission. Also, in many applications of nonlinear effects, the dispersion properties are of crucial importance.

Due to the high index contrast between silica and air, and the flexibility of varying hole sizes and patterns, a much broader range of dispersion behaviours is accessible with PCFs than with standard fibers. For the simple structure in Fig. 1(a), it was early shown that zero-dispersion wavelengths could be varied from the infrared region far down into the visible part of the spectrum [11], [12], simply by varying hole size and spacing. Also, very flat dispersion curves could be obtained in certain wavelength ranges [13], but such fibers turned out to be difficult to fabricate with low losses [14]. A more recent design of a dispersion-flattened fiber is shown in the upper panel of Fig. 2. A central Ge-doped core with raised refractive index is surrounded by three F-doped regions with lowered refractive index, and a triangular array of airholes in the cladding. By varying the many parameters defining this structure, a wide range of dispersion behaviours can be obtained, as evidenced by the calculated dispersion curves in the lower panel of Fig. 2. This structure is a good example of how the design flexibility of PCFs may be used to tailor a specific property.

B. Highly nonlinear PCFs

An attractive property of the silica/air PCFs is that effective index contrasts much higher than in standard fibers may be obtained by making the airholes large, and/or by making the fiber dimensions small so that the light is forced into the airholes. In this way, strong mode confinement can be obtained, which in turn leads to enhanced nonlinear effects due to the high field intensity in the core. In addition, many nonlinear experiments pose specific requirements to the dispersion behaviour of the fibers. Thus, PCFs are particularly well suited for making nonlinear fiber devices, and this is presently one of their most important applications [4], [12], [15], [16].

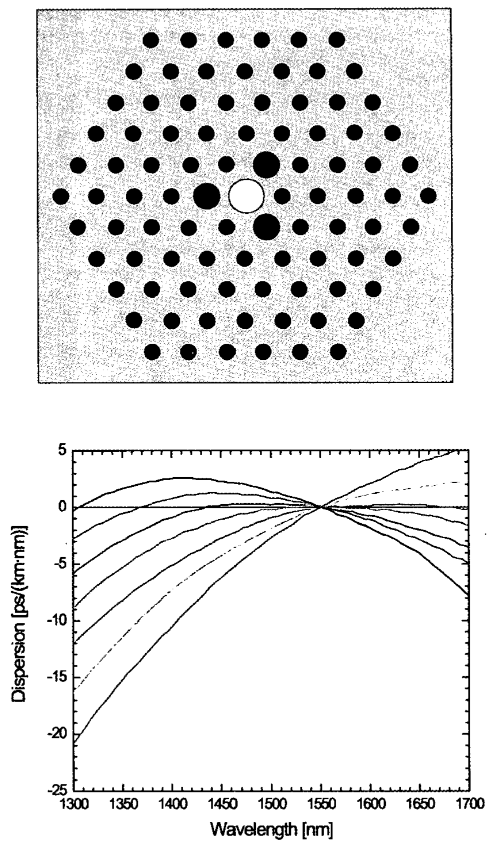

Fig. 2. The generic structure of a Ge/F-doped PCF with flattened dispersion around 1500 nm wavelength (top). Darker regions have lower refractive index. In the bottom panel, some simulated dispersion curves are shown.

An example of a highly nonlinear PCF structure with large airholes is shown in Fig. 3. The fiber has a core diameter of ~1.7 μm, the airhole diameter is ~0.8 μm and the center-to-center distance between the cladding airholes is ~1.2 μm. Due to the small dimensions of the microstructure light at infrared wavelengths has a considerable penetration into the airholes. Since the hole structure is surrounded by a large region of solid silica (the outer fiber diameter has the standard dimension of 125 μm to facilitate splicing to other fibers), the guided mode is of a quasibound, or resonant, nature, and will gradually leak out into the outer silica domain as the light propagates down the length of the fiber [17], [18]. This is a loss mechanism which does not occur in ordinary step-index fibers. Reduction

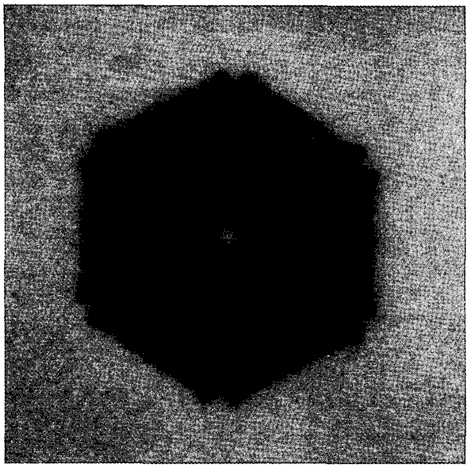

Fig. 3. A nonlinear PCF with large airholes. Note the large number of airhole rings needed to reduce leakage of the guided mode.

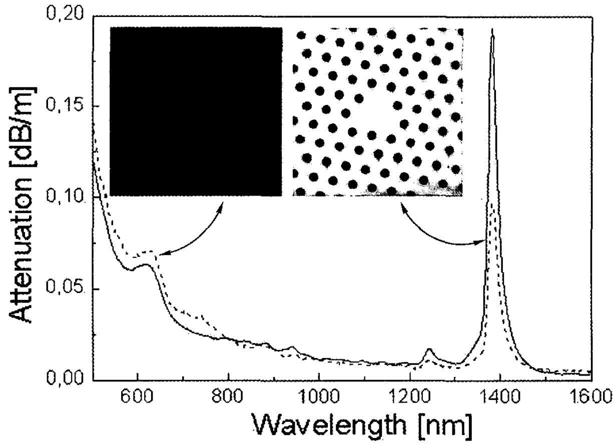

Fig. 4. (a) Loss curves for the two large mode-area fiber designs shown in the insets. The fiber with three holes removed (right) has a mode field diameter of 12 μm, whereas the fiber with one hole removed (left) has a mode field diameter of 10.5 μm.

of this so-called leakage, or confinement, loss requires a structure with many airhole rings in the cladding, thus increasing the complexity of manufacturing the fiber. The design shown in Fig. 3 has a zero-dispersion wavelength of $\sim$0.75 μm. It has been shown by several groups that even short pieces ($\sim$1 m) of such fibers can be used to broaden sub-picosecond pulses into octave-spanning supercontinuum spectra [16], [19]. This effect is useful for creating broadband sources of low coherence for metrology or medical applications.

It is also noteworthy that the dispersion-flattened fiber design in Fig. 2 has a relatively large nonlinearity coefficient of $\sim$11 $(\mathrm{Wkm})^{-1}$ [5]. At the same time, very small and constant dispersion values can be obtained around the important telecommunication wavelength of 1550 nm. Fibers with these properties are of great interest for all-optical signal processing [20].

C. Large mode-area PCFs

The endlessly single-mode property of PCFs with small airholes makes it possible to manufacture single-mode fibers with core diameters, and thereby mode areas, which are very large compared to the wavelength of the light [21]. The advantages of such fibers are very low nonlinearity coefficients, and very high damage tresholds. Such fibers may be useful for high-power transmission and possibly for telecom applications, where high linearity is critical. Using the design depicted in Fig. 1(a), mode field diameters approaching 30 μm have been achieved at a wavelength of 1.55 μm [22].

The limiting factor for the mode area turns out to be bend and propagation losses, because the small effective index contrast between core and cladding means that the light is easily scattered into the cladding modes by bends or inhomogeneities. Enlarging the core defect by removing three airholes instead of one has recently been found to improve the performance [23]. The size of the airholes must in this case be reduced to keep the fiber single-moded, but on the other hand the interhole distance can be reduced for a given value of the mode area. In Fig. 4, the loss curves for the two large mode-area fibers shown in the insets are reported. While the losses of the two designs are similar, the structure with three holes removed has a mode area $\sim$ 30 % larger than the structure with one hole removed. Note the appearance of a short-wavelength loss edge due to the decreasing effective index contrast, another unique feature of the PCFs.

D. Fibers with high numerical aperture

In standard fibers, the light collection efficiency is closely related to the numerical aperture, NA=$\sqrt{n_c^2 - n_{cl}^2}$, where n_c, n_{cl} are the refractive indices of core and cladding, respectively. The large index contrast between silica and air makes it possible to manufacture PCFs with large multimoded cores having very large NA values, > 0.7. Such fibers are useful for collection and transmission of high powers in situations, where signal distortion is not a problem. A more important application is the fabrication of double-clad fiber lasers and amplifiers [3], [24]. An example of such a fiber design is shown in Fig. 5: A large mode-area design similar to the one in the right inset of Fig. 4 has been surrounded by an outer cladding of very large airholes. The triangular core region has been doped with Yb ions to make it an active medium. The airhole diameter is 2 μm, and the center-to-center hole distance is 11.5 μm. The presence of the outer cladding makes it possible to sample pump light efficiently into the inner cladding modes, and propagate it over a long distance without being lost into the fiber jacket. The fiber in Fig. 5 has a relatively large inner cladding, however the large silica/air index contrast allows a reduction of the inner cladding diameter if desired, while still keeping a good collection efficiency. This, in combination with the large area of the core mode, makes for a good overlap between core (signal) and cladding (pump) modes, thereby ensuring higher pump absorption. The large mode-area also serves to limit

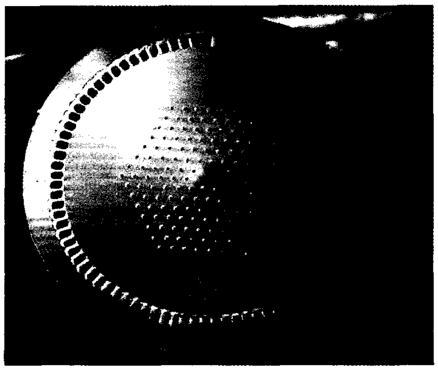

Fig. 5. A double-clad PCF design with a Yb-doped core, and inner cladding radius of 270 μm.

nonlinear effects, which constitute the performance limit of high-power ultrafast fiber lasers and amplifiers. Using a fiber similar to the one shown in Fig. 5 but with the inner cladding radius reduced to 150 μm, a fiber laser with an output power of 80 W and a slope efficiency of 78 % was recently demonstrated [24].

III. PCFs GUIDING BY THE PHOTONIC BANDGAP EFFECT

In a two-dimensional array of scatterers (e.g., airholes), it can be shown that in-plane light propagation in certain frequency windows can be inhibited in all directions by interference effects, provided that the index contrast between scatterers and background material (and thereby the reflection coefficient of the scatterers) is sufficiently large. These freguency windows are commonly termed photonic band gaps (PBGs). In PBG structures, it is possible to trap radiation at point or line defects in the lattice of scattering centers.

The index contrast between silica and air is too small for this effect to occur for in-plane propagation, at least in a periodic structure. However, when out-of-plane propagation in a PCF is considered, the situation is different. As is well known from elementary electromagnetic theory, the reflection from a refractive-index step becomes stronger as the angle of incidence increases. In fact, if light is incident from the high-index side, reflection becomes complete above a critical angle determined only by the index contrast. This means that even small index steps may become efficient scattering centers in the transverse plane provided that the longitudinal wave vector (that is, the propagation constant in a fiber) is large enough. Thus, for a fixed value of the propagation constant, which is sufficiently large, forbidden frequency ranges (PBGs) may be found in a silica/air structure. Conversely one could say that for a given frequency, certain ranges of propagation constants are not allowed. A defect in such a PBG structure may trap localized modes at these forbidden propagation constants.

A crucial difference between index-guiding PCFs and PCFs guiding by the photonic bandgap effect (termed PBG fibers in the following) is, that in a PBG fiber, cladding modes with a higher effective index than the guided mode exists, which is not the case for index-guiding fibers. This means, that the core must be a region of lower average index than the

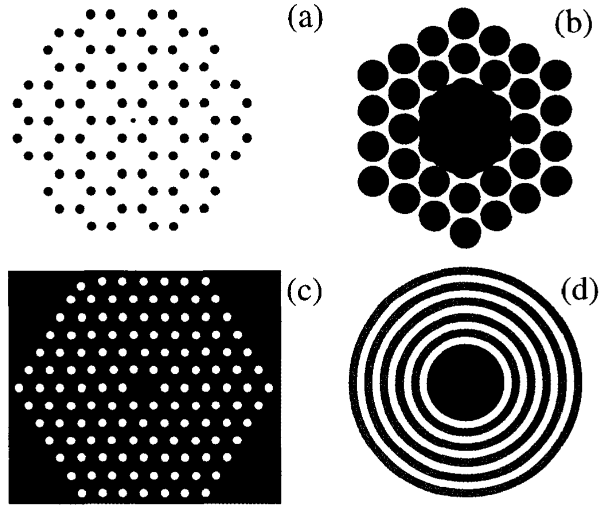

Fig. 6. Schematic pictures of various photonic bandgap (PBG) fiber designs. Lighter color indicates higher refractive index. (a) Honeycomb PBG fiber with central hole defect. (b) Airguiding PBG fiber. (c) PBG fiber with a triangular array of high-index rods, formed e.g. by liquid-filling of the holes in a standard index-guiding PCF. (d) Omniguide PBG fiber.

cladding, so PBG fibers are useful for guiding light in low-index materials. Another distinct feature is, that while index-guiding fibers usually have a guided mode at all frequencies, PBG fibers only guide in certain frequency bands, and it is possible to have frequencies at which higher-order modes are guided, while the fundamental mode is not.

In Fig. 6, four of the most important PBG fiber designs are shown. In the following, we will discuss each of them in turn.

A. *Honeycomb PBG fibers*

Historically, the honeycomb fiber design shown in Fig. 6(a) was the first PBG fiber to be realized experimentally in 1998 [25]. The honeycomb cladding structure makes it possible to obtain photonic bandgaps at smaller hole sizes than in the triangular structure [26], a feature which was important in the early days of PCF manufacturing. However, little experimental activity has subsequently been put into this particular design. Modeling studies have shown, that the majority of the field energy resides in the silica regions, and that substantial nonlinear coefficients may be obtained [27]. At the same time, a relatively large (compared to index-guiding fibers) fraction of the field energy resides in the airholes, which may make this design interesting for sensing applications. Also, the dispersion properties are somewhat different than for index-guiding fibers.

A variation of the design in Fig. 6(a), in which the low-index core is defined by doping rather than by an extra airhole, was recently proposed by several authors [28], [29]. The use of doping alters the transmission windows and dispersion properties somewhat. It has been shown that this design may be useful for making single-mode fibers with short (i.e. visible) zero-dispersion wavelengths, which is difficult to do with index-guiding fibers.

B. Airguiding PBG fibers

In a triangular array of airholes, it is possible to obtain bandgaps at effective indices below the light line, if the airholes are made sufficiently large. This opens up the very interesting possibility, unique to PBG fibers, of guiding electromagnetic modes in air. An example of such a fiber design is shown in Fig. 6(b): A large hollow core has been defined by removing the silica around seven airholes in the perfect cladding structure. In such fibers, which are usually called airguiding, or hollow-core, PBG fibers, it is possible to confine more than 98 % of the guided-mode field energy in the air regions [30].

Airguiding PBG fibers were first fabricated in 1999 [31], and were at an early stage hailed as the future transmission fiber for ultra-broadband telecommunication because the localization of light in the air core lifts the limitations of material absorption losses. However, the fabrication of airguiding fibers with low propagation losses has proven quite difficult, the best results currently obtained being a minimum propagation loss of 13 dB/km [32]. Furthermore, the fibers are highly dispersive [30], transmission windows are narrow, and while single-mode behaviour is possible, it is not as straightforward to obtain as in index-guiding fibers. At the moment, the most obvious applications for these fibers appear to be high-power transmission at wavelengths, where the absorption in silica is high, gas sensing devices and particle transport. The sensitive and dispersive nature of these fibers could also make them interesting for fabrication of tunable components for telecommunications.

In Fig. 7 a single-mode airguiding PBG fiber structure is shown. The center-to-center distance between the cladding airholes is $\sim 3\ \mu$m. Notice that the guided mode has a circular symmetric profile very similar to the mode profiles found in ordinary step-index fibers.

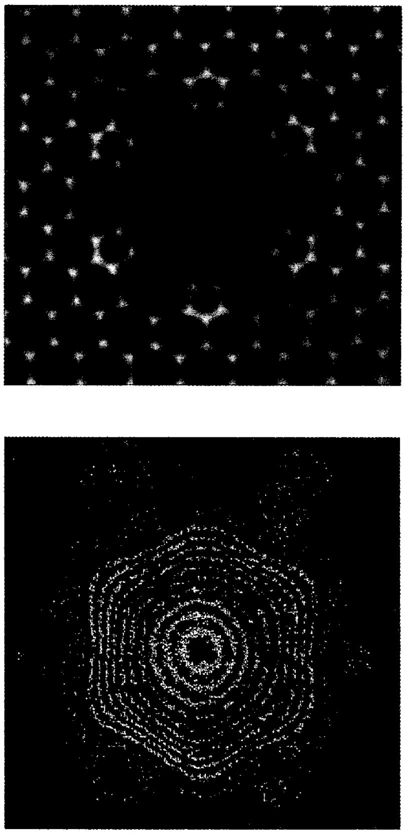

Fig. 7. Microscope picture of a single-mode hollow-core PBG fiber (top), and a near-field image of the guided mode profile (bottom).

C. PBG fibers with high-index rods

A relatively new type of PBG fiber, which has received considerable attention within the last year, is depicted in Fig. 6(c). The cladding structure is similar to the fiber in Fig. 1(a), however, the airholes are now replaced by high-index regions. This can readily be achieved by filling the airholes of an index-guiding PCF with a high-index material, such as a liquid or polymer. The silica defect in the center now forms a low-index core which can trap guided modes by the photonic bandgap effect. These modes can have sizes and effective indices comparable to those of standard fibers, which reduces coupling losses in, e.g., a telecommunication network. However, their properties are strongly influenced by the high-index material, which may be chosen so as to have a high sensitivity to temperature, applied electric fields, or other parameters. In this way, tunable wavelength filters have been demonstrated by several authors, and other tunable components should also be possible. A particularly striking example was demonstrated utilizing the phase transformations of a liquid crystal infiltrated into the holes of a large mode-area PCF: By changing the temperature by 0.4° a 60 dB suppression of the guided mode could be achieved [33]. The insertion loss of the PBG fiber device was as low as 1 dB.

It has recently been shown [34] that the PBG guiding mechanism described above can also be made to work with a small (0.02) index step between the high- and low-index regions. This opens up the possibility of defining the high-index regions by Ge-doping of the silica, and thereby manufacturing solid-silica PBG fibers without introducing holes in the material at all.

D. Omniguide fibers

A PBG fiber design radically different from those discussed so far is shown in Fig. 6(d): Here light is confined in an air core by multiple reflections from circular layers of materials with alternating refractive indices. To get get good confinement in the air region, a large index contrast between the two cladding materials is needed, which makes fabrication difficult, because materials with very different refractive indices, but similar melting temperatures and flow properties, must be found. While some fibers of this type have been fabricated [7], most results presented so far have been of a theoretical nature. It has been found that these fibers (usually denoted OmniGuide fibers) can have very large values of the dispersion coefficient [6], which may make them interesting for dispersion compensation. While absorption losses in the high-index cladding materials is a problem, it has been shown that the overlap of the fundamental mode with the cladding material can be reduced to arbitrarily small values by enlarging the core region [35]. This, however, happens at the expense of making the fiber heavily multimoded.

IV. Conclusion

The many types of photonic crystal fibers available today offer a variety of unique properties, which makes them useful for a diverse range of applications. At present, nonlinear fiber devices, fiber lasers and amplifiers, and fibers for high-power transmission appear to be the most important application areas. Future possibilities include fiber-based signal-processing devices with tunable properties, fibers for dispersion compensation, and new types of fiber-based sensor devices. The most important research challenges right now appear to be the reduction of propagation losses to even lower levels, and further explorations of new fiber designs and applications.

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References

[1] J. C. Knight, T. A. Birks, P. S. J. Russell, and D. M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," *Opt. Lett.*, vol. 21, pp. 1547–1549, 1996.

[2] K. M. Kiang, K. Frampton, T. M. Monro, R. Moore, J. Tucknott, D. W. Hewak, D. J. Richardson, and H. N. Rutt, "Extruded singlemode non-silica glass holey optical fibres," *Electronics Letters*, vol. 12, pp. 546–7, 2002.

[3] K. Furusawa, A. Malinowski, J. H. V. Price, T. M. Monro, J. K. Sahu, J. Nilsson, and D. J. Richardson, "Cladding pumped ytterbium-doped fiber laser with holey inner and outer cladding," *Optics Express*, vol. 9, pp. 714–20, 2001.

[4] K. P. Hansen, J. R. Jensen, C. Jacobsen, H. R. Simonsen, J. Broeng, P. M. W. Skovgaard, and A. Petersson, "Highly nonlinear photonic crystal fiber with zero-dispersion at 1.55 μm, OFC 2002 post deadline paper FA9."

[5] K. P. Hansen, "Dispersion flattened hybrid-core nonlinear photonic crystal fiber," *Optics Express*, vol. 11, pp. 1503–9, 2003.

[6] G. Ouyang, Y. Xu, and A. Yariv, "Theoretical study on dispersion compensation in air-core bragg fibers," *Optics Express*, vol. 10, pp. 899–908, 2002.

[7] S. G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weisberg, T. D. Engeness, M. Soljacic, S. A. Jacobs, J. D. Joannopoulos, and Y. J. Fink, "Breaking the glass ceiling: hollow omniguide fibers," in *Proceedings of 2002 4th International Conference on Transparent Optical Networks*, M. Marciniak, Ed., vol. 2. IEEE, 2002, pp. 5–6.

[8] K. Tajima, J. Zhou, K. Nakajima, and K. Sato, "Ultra low loss and long length photonic crystal fiber," in *Proceedings of OFC 2003, Postdeadline papers*, 2003, pp. PD1–1.

[9] T. A. Birks, J. C. Knight, and P. S. J. Russell, "Endlessly single mode photonic crystal fibre," *Opt. Lett.*, vol. 22, pp. 961–963, 1997.

[10] B. T. Kuhlmey, R. C. McPhedran, and C. M. de Sterke, "Modal cutoff in microstructured optical fibers," *Opt. Lett.*, vol. 27, pp. 1684–6, 2002.

[11] A. Ferrando, E. Silvestre, P. Andrés, J. J. Miret, and M. V. Andrés, "Designing the properties of dispersion-flattened photonic crystal fibers," *Optics Express*, vol. 9, pp. 687–697, 2001.

[12] J. C. Knight, J. Arriaga, T. A. Birks, A. Ortigosa-Blanch, W. J. Wadsworth, and P. S. J. Russell, "Anomalous dispersion in photonic crystal fiber," *IEEE Photonic Tech. L.*, vol. 12, pp. 807–809, 2000.

[13] A. Ferrando, E. Silvestre, J. J. Miret, , J. A. Monsoriu, M. V. Andrés, and P. S. J. Russell, "'designing a photonic crystal fibre with flattened chromatic dispersion'," *Electronics Letters*, vol. 35, pp. 325–327, 1999.

[14] W. H. Reeves, J. C. Knight, P. S. J. Russell, and P. J. Roberts, "Demonstration of ultra-flattened dispersion in photonic crystal fibers," *Optics Express*, vol. 10, pp. 609–13, 2002.

[15] N. G. R. Broderick, T. M. Monro, P. J. Bennett, and D. J. Richardson, "Nonlinearity in holey optical fibers: measurement and future opportunities," *Opt. Lett.*, vol. 24, pp. 1395–97, 1999.

[16] 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.*, vol. 25, pp. 25–27, 2000.

[17] L. Poladian, N. A. Issa, and T. M. Monro, "Fourier decomposition algorithm for leaky modes of fibres with arbitrary geometry," *Optics Express*, vol. 10, pp. 449–54, 2002.

[18] D. Ferrarini, L. Vincetti, M. Zoboli, A. Cucinotta, and S. Selleri, "Leakage properties of photonic crystal fibers," *Optics Express*, vol. 10, pp. 1314–9, 2002.

[19] G. Genty, M. Lehtonen, H. Ludvigsen, J. Broeng, and M. Kaivola, "Spectral broadening of femtosecond pulses into continuum radiation in microstructured fibers," *Optics Express*, vol. 10, pp. 1083–98, 2002.

[20] L. K. Oxenløwe, A. J. Siahlo, K. S. Berg, A. Tersigni, A. T. Clausen, C. Peucheret, P. Jeppesen, K. P. Hansen, and J. R. Jensen, "A photonic crystal fibre used as a 160 to 10 gb/s demultiplexer, OECC 2002 post deadline paper PD-1-4."

[21] J. C. Knight, T. A. Birks, R. F. Cregan, P. S. J. Russell, and J.-P. De Sandro, "Large mode area photonic crystal fibre," *Electron. Lett.*, vol. 34, pp. 1347–1348, 1998.

[22] J. C. Baggett, T. M. Monro, K. Furusawa, and D. J. Richardson, "Comparative study of large-mode holey and conventional fibers," *Opt. Lett.*, vol. 26, pp. 1048–50, 2001.

[23] N. Mortensen, M. Nielsen, J. Folkenberg, A. Petersson, and H. Simonsen, "Improved large-mode area endlessly single-mode photonic crystal fibers," *Opt. Lett.*, vol. 28, pp. 393–5, 2003.

[24] J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, A. Tunnermann, R. Iliew, F. Lederer, J. Broeng, G. Vienne, A. Petersson, and C. Jakobsen, "High-power air-clad large-mode-area photonic crystal fiber laser," *Optics Express*, vol. 11, pp. 818–23, 2003.

[25] J. C. Knight, J. Broeng, T. A. Birks, and P. S. J. Russell, "Photonic band gap guidance in optical fibers," *Science*, vol. 282, pp. 1476–1478, 1998.

[26] J. Broeng, S. E. Barkou, A. Bjarklev, J. C. Knight, T. A. Birks, and P. S. J. Russell, "Highly increased photonic band gaps in silica/air structures," *Opt. Commun.*, vol. 156, pp. 240–244, 1998.

[27] J. Lægsgaard, N. A. Mortensen, and A. Bjarklev, "Mode areas and field energy distribution in honeycomb photonic bandgap fibers, to appear in J. Opt. Soc. Am. B."

[28] T. P. Hansen, J. Broeng, and A. Bjarklev, "Solid-core photonic bandgap fiber with large anomalous dispersion," in *Proceedings of OFC03*, 2003.

[29] J. Lægsgaard and A. Bjarklev, "Doped photonic bandgap fibers for short-wavelength nonlinear devices," *Opt. Lett.*, vol. 28, pp. 783–5, 2003.

[30] J. Lægsgaard, N. A. Mortensen, J. Riishede, and A. Bjarklev, "Material effects in airguiding photonic bandgap fibers, to appear in J. Opt. Soc. Am. B."

[31] R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. J. Russell, P. J. Roberts, and D. C: Allan, "Single-mode photonic band gap guidance of light in air," *Science*, vol. 285, pp. 1537–1539, 1999.

[32] N. Venkataraman, M. T. Gallagher, C. M. Smith, D. Müller, J. A. West, K. W. Koch, and J. C. Fajardo, "Low loss (13 db/km) air core photonic bandgap fiber, 28th European Conference on Optical Communication, ECOC '02, September 2002, Copenhagen, Denmark, post-deadline paper PD1.1."

[33] T. T. Larsen, D. S. Hermann, J. Broeng, and A. Bjarklev, "A novel photonic crystal fibre switch," in *Proceedings of CLEO Europe*, 2003, post-deadline paper CEP1-9-THU.

[34] J. Riishede, J. Broeng, and A. Bjarklev, "All silica photonic bandgap fiber," in *Proceedings of CLEO 2003*, 2003, p. CTuC5.

[35] S. G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weisberg, T. D. Engeness, M. Soljacic, S. A. Jacobs, J. D. Joannopoulos, and Y. J. Fink, "Low-loss asymptotically single-mode propagation in large-core omniguide fibers," *Optics Express*, vol. 9, pp. 748–79, 2001.