INVITED

CPT
Japan
15-17 Jan '02

2328

Holey fibers: fundamentals and applications

D.J. Richardson, W. Belardi, K. Furusawa, and Tanya M. Monro

Optoelectronics Research Centre, Southampton University, SO17 1BJ, UK
Tel: +44 23 8059 4524, Fax: +44 23 8059 3142,
E-mail: djr@orc.soton.ac.uk

Abstract

The wavelength-scale features in holey fibers lead to novel properties including endlessly single-mode guidance and anomalous dispersion below 1.3 μm. Fundamentals and recent progress are reviewed, ranging from fabrication and modelling to devices and applications.

Since the first demonstration of optical guidance within a microstructured fiber in 1996 [1] this field of research has expanded explosively and, for the reasons discussed herein, is proving of intense interest to a wide range of researchers across a broad range of application sectors. Microstructured fibers can in fact be classified into three classes. Holey fibers (HFs), which we focus upon for the purpose of this paper, possess a solid core surrounded by a cladding region that is defined by a fine array of air holes that extend along the fiber length. (Such fibers are also often referred to as Photonic Crystal Fibers). HFs can be made from a single material (typically pure silica), and guide light due to the effective refractive index difference between core and cladding regions. Cross-sectional profiles of two typical silica holey fiber types produced in our laboratories are shown in Fig.1. The combination of wavelength-scale features and design flexibility offered by HFs leads to a significantly broader range of optical properties than are possible in conventional optical fibers [2]. As well as being of fundamental scientific interest, these novel guidance properties can be exploited to develop technologically important devices, and a range of HF-based devices are described herein. The second category relates to photonic band gap (PBG) fibers [3]. In these fibers, the holes that define the cladding region need to be arranged in a periodic fashion so as to lead to the formation of a photonic band gap. Frequencies within this band gap cannot propagate in the cladding, and so can be confined to the core, which acts as a defect in the otherwise 'perfect' periodic structure. The fabrication of this form of fiber is less well developed than for holey fibers although guidance in short lengths of such fiber has now been observed [3]. The third category of microstructured fiber includes fibers that guide light through some more conventional mechanism e.g. a conventional doped core, but take advantage of the transverse microstructuring in some other way, for example by using holes to modify the dispersion [4], or the distribution of cladding modes [5].

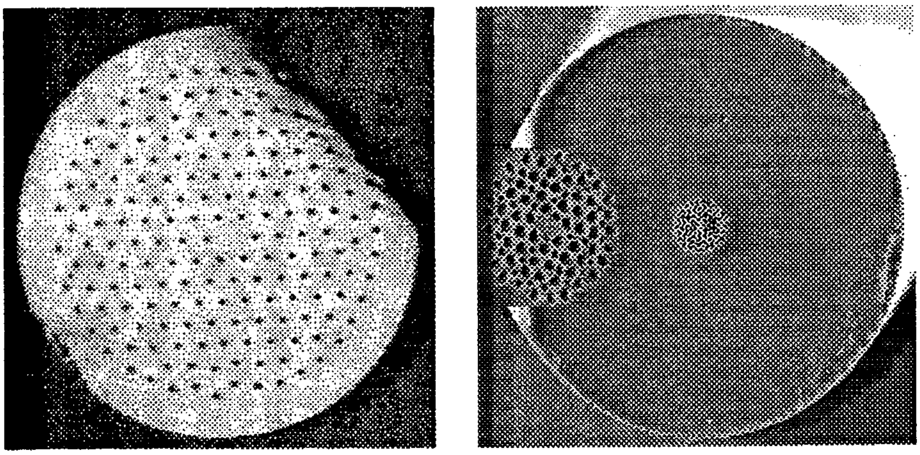

Fig.1. Some typical generic holey fiber types: (a)(-left) A large mode area holey fiber (core diameter ~15μm) for high optical power delivery, (b) (-right) a small core holey fiber (~1.5μm in diameter) which provides tight mode confinement and high optical nonlinearity (inset is a magnified SEM image of the core).

Holey fibers are typically fabricated by stacking an array of capillaries in a hexagonal configuration around a rod, which ultimately forms the core. The resulting preform is then reduced to fiber dimensions using a conventional fiber drawing tower, and if a large scale-reduction factor is required, a two-step drawing procedure is generally used. At the second stage, the microstructured region can be over-clad with a solid jacket, which allows extremely small structural dimensions to be achieved in a robust fashion (see Fig.1b). Even though this stacking procedure produces near-periodic profiles, periodicity is not required for this guidance mechanism [6]. Rare-earth dopants can be incorporated into HF designs to facilitate the development of active devices (see Figs. 2a and b). In addition, these fibers can be made from other glasses [7], and recently polymer HFs have been manufactured [8]. By controlling the conditions under which the fiber is drawn, the geometry of the fiber produced can be modified. For example, at high temperatures, the holes reduce in size because of surface tension effects. In this way a range of fiber profiles can be produced from one preform. As the optical properties of a microstructured fiber depend critically upon the hole arrangement, it is important to understand how the fabrication parameters influence the final cross-section [9]. Holey fiber technology has now reached the point that km-lengths of polymer-coated fiber and losses below a few dB/km at 1.55μm are possible. In addition, HFs can be spliced to conventional fibers, allowing ready integration with existing components and systems.

A modified form of total internal reflection operates in a HF: light is guided if the volume average index in the core region of the fiber is greater than that of the surrounding regions. Note that the hole diameter (d) and pitch (Λ=hole to hole spacing) in a HF are typically on the scale of the wavelength of light λ guided within the fiber. The fundamental physical difference between these fibers and conventional types arises from the way the guided mode 'experiences' the cladding region. In a conventional fiber, this is to first-order largely independent of wavelength. However, in a holey fiber, the large index contrast between glass and air and the small structure dimensions combine to make the effective cladding index a strong function of wavelength. Short wavelengths remain tightly confined to the core, and so the effective cladding index is only slightly lower than the core index. However, at longer wavelengths, the mode samples more of the cladding, and so the effective index contrast is larger. This unusual wavelength dependence leads to a host of highly unusual and tailorable optical properties. One striking property is that fibers with a low air fill fraction ($d/\Lambda < 0.4$) can be single-moded regardless of the wavelength [10]. This property is particularly significant for broadband or short wavelength applications. Tailoring the scale of the cladding features allows the effective fundamental mode area of a holey fiber at 1.55μm to be varied over three orders of magnitude from ~ 1 μm^2 to 1000μm^2 [2].

The simplest method for modelling the optical properties of holey fibers is the effective index model [10], which uses a (scalar) equivalent step-index fiber approximation. Although this model can provide some insight, it cannot accurately predict modal properties such as the dispersion and birefringence, which depend critically on the cladding configuration. Note that when the air fill fraction is large or the structure scale is small, it is necessary to use a full vector method. One general vector approach to describing the complex spatial index distribution in a HF involves decomposing the refractive index profile and modal fields into plane waves [11,12]. This technique is computationally intensive, since it does not take advantage of the localization of the guided modes in the fiber core. A multipole method has recently been developed to study HFs [13], and this method is well suited to evaluating the confinement losses and symmetry properties of single-material HF designs. A hybrid approach, which is efficient, since it uses localized functions to describe the guided modes, and accurate, because it uses plane waves to describe the index profile, is described in Refs.[2,14].

Perhaps the most exciting possibility afforded by holey fiber technology is the possibility to develop fibers with a very high optical nonlinearity per unit length. Holey fibers with small-scale features (small Λ) and a large air-filling fraction (large d/Λ) can confine the guided mode tightly within the core, resulting in extremely small mode areas (see Fig.1(b) and Fig.2(a). In such a fiber, modest light intensities can induce significant nonlinear effects. These fibers offer a new route towards efficient nonlinear devices. For example we recently demonstrated a 2R data regeneration device based on a HF with an effective mode area of just 2.8μm^2 at 1.55μm [15]. The 2R regenerative operation was obtained by combining self-phase modulation and offset spectral filtering. Kilometers of conventional fiber are required for this regeneration process, whereas in our experiments just 3.3m of HF was needed. This switch was then used as an optical thresholding device in an optical code division multiple access system and shown to provide a significant enhancement in system sensibility and reliability [16]. Such fibers also offer reduced length/power requirements for nonlinear devices based on the Raman effect. For example, using a fiber similar to Fig.1b, we also recently demonstrated a ~70m long, fiber laser pumped Raman amplifier providing gains of up to 43dB in the L^+ communications band [17]. Note that these particular demonstrations have used silica based holey fibers but that further significant increases in fiber nonlinearity should be achievable using fibers made of other glasses, such as the Chalcogenides [7], which have around two orders of magnitude higher nonlinear optical coefficient than silica.

At the other extreme holey fibers with small holes and large hole spacings can be produced which offer extremely large mode areas (and correspondingly low optical nonlinearities), such as the fiber shown in Fig.1a. Large mode area fibers have potential applications in high power delivery including laser welding and machining, and high power fiber lasers and amplifiers. Holey fiber technology has now emerged as an alternative to conventional doping techniques for producing fibers with large mode areas [18]. Although holey and conventional fibers can exhibit similar characteristics at any given wavelength, HFs have a distinct advantage for broadband and short wavelength applications due to their ability to be single-moded over a large wavelength range. The largest mode size that can be tolerated in practice is determined by macroscopic bending losses, and recent work [19] demonstrates that HFs can possess comparable bend losses at 1.55μm to similarly sized conventional fibers.

The unusual wavelength dependence in HF also leads to a range of novel dispersion properties and which are relevant for both linear and nonlinear device applications [2,20]. For example, fibers with a small pitch ($\Lambda<2$ μm) and large air holes ($d/\Lambda > 0.5$) can exhibit anomalous dispersion down to as low as 550nm [20]. This has made the generation and propagation of optical solitons in the near-IR and visible regions of the spectrum a reality [21], something not possible in conventional single mode fibers. Moreover, such a shift in zero-dispersion wavelength to regimes in which there are convenient short pulse sources, coupled with the small associated mode area, also allows the development of efficient supercontinuum sources whose spectral content extends from the UV out to beyond 1.8μm [22]. Such sources are attractive for many applications including optical sensor systems, pulse compression and the definition of precise frequency standards. It is also possible to design HFs with extremely high values of dispersion [23], and normal dispersion values as high as -2000 ps/nm/km have been predicted, which suggests that these fibers may find application in dispersion compensation. Other work has shown that broadband dispersion-flattened holey fibers can also be designed [2,24], a property that is likely to be useful for the development of WDM devices.

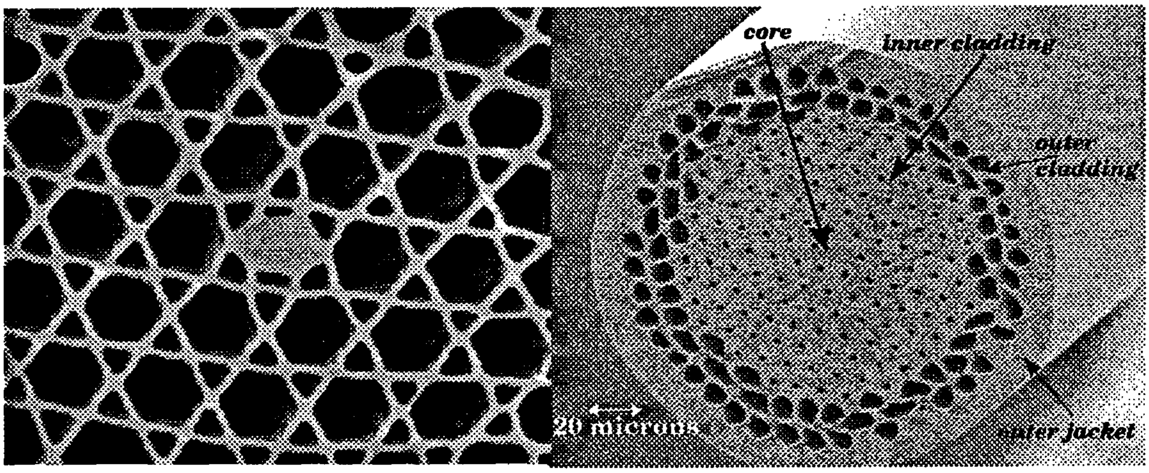

Fig.2 Rare earth doped holey fibers: (a)(-left) a small, (1.5μm by 2.5μm), elliptical core, Yb-doped holey fiber with anomalous dispersion for $\lambda>800$nm and, (b) An air clad, Yb-doped, large mode area holey fiber suitable for cladding pumped fiber laser and amplifier applications.

As previously mentioned holey fiber technology is also of relevance to the production of doped fibers, as required for example in fiber laser and amplifier systems. For example, using the small-scale Ytterbium-doped HF shown in Fig.2a, a low threshold, tunable, mode-locked soliton laser has been demonstrated [25]. With the same fiber, a soliton source continuously tunable over the wavelength range 1.06-1.33μm has also been developed based on the soliton self frequency shift [26]. Whilst soliton concepts might be familiar in the context or erbium doped fibers operating at 1550nm, it is to be appreciated that these systems operate around 1μm and that anomalous dispersion cannot be achieved in single mode fibers in this wavelength range using conventional fiber technology. It is also worth noting that the structural asymmetry evident in this fiber coupled with the large index contrast and small core dimensions result in a high birefringence and polarisation maintaining properties. For example, the measured beat length in this fiber at 1.55 μm was just 0.3 mm. Holey fiber technology also lends itself readily to cladding pumping techniques as shown in Fig.2b. In this fiber the small inner holes about the central Yb doped solid glass region define a large single mode core, and the large air holes that surround the holey inner cladding region define a high NA multimode guide for 980nm pump radiation. Using this all-glass structure we achieved laser action in the range 1030-1100nm on a single transverse mode with a power conversion efficiency of 76% [27].

In conclusion, holey fibers has advanced now to the point that km-lengths of robust coated fiber can be produced with losses as low as a few dB/km and with a wide range of unique and useful optical properties. Such fibers have the potential to enable a host of practical new optical devices for a whole host of applications areas, both within telecommunications and beyond.

References

[1] J. C. Knight, T. A. Birks, P. St. J. Russell and D. M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," Opt. Letts. , **21**, 1547-1549 (1996).

[2] T. M. Monro, D. J. Richardson, N. G. R. Broderick and P. J. Bennett, "Holey optical fibers: an efficient modal model," J. Lightwave Technol., **17**, 1093--1102 (1999).

[3] J. C. Knight, J. Broeng, T. A. Birks, and P. St. J.Russell, "Photonic band gap guidance in optical fibers," Science, **282**, 1476-1478 (1998).

[4] T. Hasegawa, et al. "A novel, hole-assisted, lightguide fiber exhibiting large anomalous dispersion and low loss below 1 dB/km," Postdeadline paper **PD5**, Proc. OFC'2001 (2001).

[5] B. J. Eggleton, P. S. Westbrook, R. S. Windeler,"Grating resonances in air-silica microstructured optical fibers," Opt. Letts., **24**, 1460-1462 (1999).

[6] T. M. Monro, P. J. Bennett, N. G. R. Broderick and D. J.Richardson, "Holey fibers with random cladding distributions," Opt. Letts., **25**, 206-208 (2000).

[7] T. M. Monro, Y. D. West, D. W. Hewak, N. G. R. Broderick and D. J. Richardson, "Chalcogenide holey fibers," Electron. Lett., **36**, 1998-2000 (2000).

[8] M. A. van Eijkelenborg, M. C. J. Large, A. Argyros, J. Zagari, S. Manos, N. A. Issa, I. Bassett, S. Fleming, R. C. McPhedran, C. M. de Sterke and N. A. P. Nicorovici, "Microstructured polymer optical fiber", Opt. Express, **9**, 319-327 (2001).

[9] A. D. Fitt, K. Furusawa, T. M. Monro and C. Please, "Modeling the Fabrication of Hollow Fibers," J. Lightwave Technol. to appear in **19**, (2001).

[10] T. A. Birks, J. C. Knight and P. St. J. Russell, "Endlessly single-mode photonic crystal fiber," Opt. Letts., **22**, 96-963 (1997).

[11] E. Silvestre, M. V. Andres and P. Andres "Biorthonormal-basis method for the vector description of optical-fiber modes," J. Lightwave Technol., **16**, 923--928 (1998).

[12] J. Broeng, S.E. Barkou, T. Sondergaard and A. Bjarklev, "Analysis of air-guiding photonic bandgap fibers," Opt. Letts., **25**, 96-98 (2000).

[13] T. P. White, R. C. McPhedran, C. M. de-Sterke, L. C. Botten and M. J. Steel, "Confinement losses in microstructured optical fibers," Opt. Letts., **26**, 1660-1662 (2001).

[14] T. M. Monro, N. G. R. Broderick and D. J. Richardson, "Exploring the Optical Properties of Holey Fibers," in Nanoscale Linear and Nonlinear Optics, M. Bertolotti, Ed., New York: American Institute of Physics, (2000).

[15] P. Petropoulos, T. M. Monro, W. Belardi, K. Furusawa, J. H. Lee, and D. J. Richardson, "2R-regenerative all-optical switch based on a highly nonlinear holey fiber," Opt. Letts., **26**, 16--18 (2001).

[16] J.H. Lee, P.C. Teh, Z. Yusoff, M. Ibsen, W. Belardi, T.M. Monro and D.J. Richardson, "An OCDMA receiver incorporating a holey fiber nonlinear thresholder," Postdeadline paper **PD.B.1.2**, Proc. ECOC'2001 (2001).

[17] J.H. Lee, Z. Yusoff, W. Belardi, T.M. Monro and D.J. Richardson, "A holey fiber Raman amplifier and all-optical modulator," Postdeadline paper **PD.A.1.1**, Proc. ECOC'2001 (2001).

[18] J. C. Knight, T. A. Birks, R. F. Cregan, P. St. J. Russell and J. P. de Sandro, "Large mode area photonic crystal fiber," Electron. Letts., **34**, 1346-1347 (1998).

[19] J. C. Baggett, T. M. Monro, K. Furusawa and D. J.Richardson, "Comparative study of large mode holey and conventional fibers," Opt. Letts., **26**, 1045-1047 (2001).

[20] J. C. Knight, J. Arriaga, T. A. Birks, A. Ortigosa-Blanch, W. J. Wadsworth and P. St. J. Russell, "Anomalous dispersion in photonic crystal fiber," IEEE Phot. Tech. Lett., **12**, 807-809 (2000).

[21] W. J. Wadsworth, J. C Knight, A. Ortigosa-Blanch, J. Arriaga, E. Silvestre and P. St. J. Russell,"Soliton effects in photonic crystal fibers at 850 nm," Electron. Lett., **36**, 53-55 (2000).

[22] 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. Letts., **25**, 25-27 (2000).

[23] T. A. Birks, D. Mogilevtsev, J. C. Knight and P. St. J. Russell, "Dispersion compensation using single-material fibers," IEEE Photon. Technol. Lett, **11**, 674-677 (1999).

[24] A. Ferrando, E. Silvestre, J. J. Miret, J. A. Monsoriu, M. V. Andres and P. St. J. Russell, "Designing a photonic crystal fiber with flattened chromatic dispersion," Electron. Lett., **35**, 325-327 (1999).

[25] K. Furusawa, T. M. Monro, P. Petropoulos and D. J. Richardson, "Modelocked laser based on ytterbium doped holey fiber," Electron. Lett., **37**, 560-561 (2001).

[26] J. H. V. Price, K. Furasawa, T. M. Monro, L. Lefort and D. J. Richardson, "A tuneable, femtosecond pulse source operating in the range 1.06 - 1.33 microns based on an Yb doped holey fiber amplifier," Postdeadline paper **CPD1**, Proc. CLEO'2001 (2001).

[27] K. Furasawa, 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" to appear Optics Express, Dec. (2001).