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Holey fibers: new possibilities for guiding and manipulating light

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Abstract

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

Holey fibers (HFs) are a class of microstructured fiber which possess a solid core surrounded by a cladding region that is defined by a fine array of air holes that extend along the full fiber length (see Fig.1). HFs are typically made of a single material, usually pure silica, and guide light through a modified form of total internal reflection since the volume average index in the solid core region of the fiber is greater than that of the surrounding microstructured cladding. Note that the hole diameter (d) and pitch (Λ=hole to hole spacing), which are the critical design parameters used to specify the structure of an HF, are typically on the dimension scale of the wavelength of light λ.

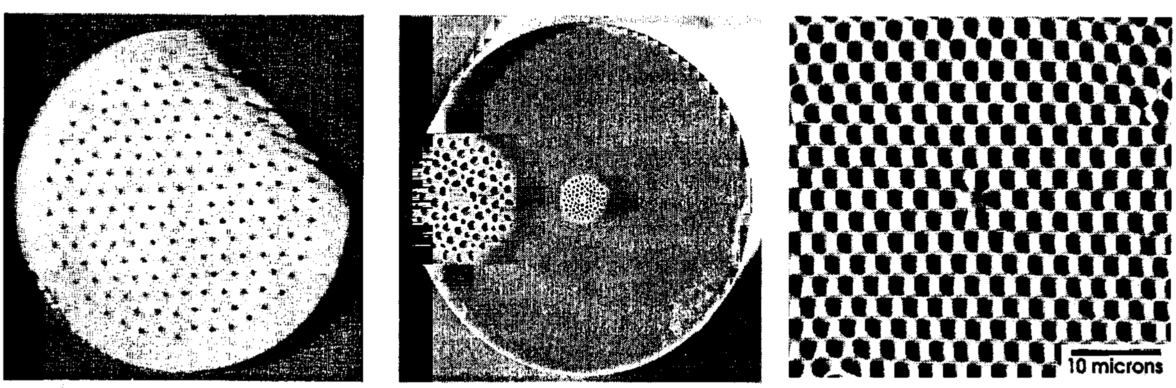

Fig.1. Some typical generic holey fiber types: (a)(-left) A large mode area holey fiber (core diameter ~15μm) for high optical power delivery, (b) (-centre) a small core holey fiber (~1.5μm in diameter) which provides tight mode confinement and high optical nonlinearity (inset is a magnified SEM image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

The first work on guidance in microstructured air:glass fiber actually dates back to the early 1970's when work was performed on fibers containing an effectively air-clad solid core supported on thin structural membranes [1]. This research was directed at the development of low loss fibers for optical transmission and although impressive results were obtained the approach was soon dropped due to the successful development of vapour deposition based techniques for low loss perform fabrication. The field of holey fiber began in earnest in 1996 with the first demonstration of optical guidance within a truly 'holey' rather than air-clad structure [2], and the growth of the field has been explosive ever since. The fundamental physical difference between HF and conventional fiber 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 an HF 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 [3]. 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 [4]. HFs are thus seen to have a significantly broader range of optical properties than conventional optical fibers, which as well as being of fundamental scientific interest, should also open up the possibility for new and technologically important fiber devices. It is to be appreciated that HFs can be spliced to conventional fibers, allowing ready integration of HFs with existing components and systems.

Holey fibers are also often referred to as Photonic Crystal Fibers since the microstructure within the fiber is often highly periodic due to the fabrication processes. It should though be noted that periodic structure is not a required in order to obtain guidance by average index effects. There is another class of microstructured fiber in which a periodic arrangement of air holes is required to ensure guidance. This class of fiber is referred to as photonic band gap (PBG) fiber [5]. In PBG fibers the periodic arrangement of holes in the cladding region of the fiber leads to the formation of a photonic band gap in the transverse plane of the fiber. Frequencies within this band gap cannot propagate in the cladding, and are thus confined to propagate within 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 lengths of PBG fiber has now been observed [5,6]. PBG fibers represent a most fascinating form of optical waveguide and possess truly unique optical properties, arguably the most striking of which is that they can guide light within a low-index, air-filled core. We will not consider FBG fibers any further within this particular paper.

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). Again we reiterate that even though this stacking procedure produces near-periodic profiles, periodicity is not a fundamental requirement for guidance in an HF [7]. Dopants (e.g. germanium, aluminium, erbium, and ytterbium) can also be incorporated into HF designs to facilitate the development of fiber devices (see Figs. 2a and b). In addition, HFs can be made from other glasses [8,9], and recently polymer HFs have been manufactured [10]. It is worth noting that the use of new material with lower melting points facilitates the use of techniques other than capillary stacking for perform production and indeed the first demonstrations of perform fabrication via techniques such as extrusion (SF57 lead glass) [8], and built-in-casting (silica) [11], have recently been reported. By controlling the conditions under which the preform is drawn to fiber, the geometry of the fiber produced can be modified. For example, at high temperatures, the holes reduce in size due to surface tension effects. In this way a range of fiber profiles can be produced from one starting preform. Holey fiber technology has now reached the point that km-lengths of polymer-coated fiber and losses below 1dB/km at 1.55μm are possible [12].

The simplest method for modelling the optical properties of holey fibers is the effective index model [3], 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 [13,14]. 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 [15], 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.[4,16].

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,c) 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 $2.8\mu m^2$ and a nonlinearity per unit length of $\gamma=31\ W^{-1}km$ at $1.55\mu m$ [17]. 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 sensitivity and reliability [17]. 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 [18]. 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 [19], which have approximately two orders of magnitude higher nonlinear optical coefficient than silica. Indeed, we recently produced the first results in this direction and demonstrated an HF in SF57 lead glass with $\gamma=550\ W^{-1}km^{-1}$, which is about 500 times more nonlinear than conventional SMF28 fiber [9].

At the other extreme holey fibers with small holes and large hole spacings can be produced which offer very 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 [20]. 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 [21] demonstrates that HFs can possess at least comparable bend losses at $1.55\mu m$ to similarly sized conventional fibers.

The unusual wavelength dependence in HF also leads to a range of novel dispersion properties which are relevant for both linear and nonlinear device applications [4,22]. For example, fibers with a small pitch (Λ<2 μm) and large air holes ($d/\Lambda > 0.5$) can exhibit anomalous dispersion down to as low as 550nm [22]. This has made the generation and propagation of optical solitons in the near-IR and visible regions of the spectrum a reality [23], 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 [24]. 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 [25], and normal dispersion values as high as -2000 ps/nm/km have been predicted, which suggests that these fibers may find applications in dispersion compensation. Other work has shown that broadband dispersion-flattened holey fibers can also be designed [4,26], a property that is likely to be useful for the development of WDM devices.

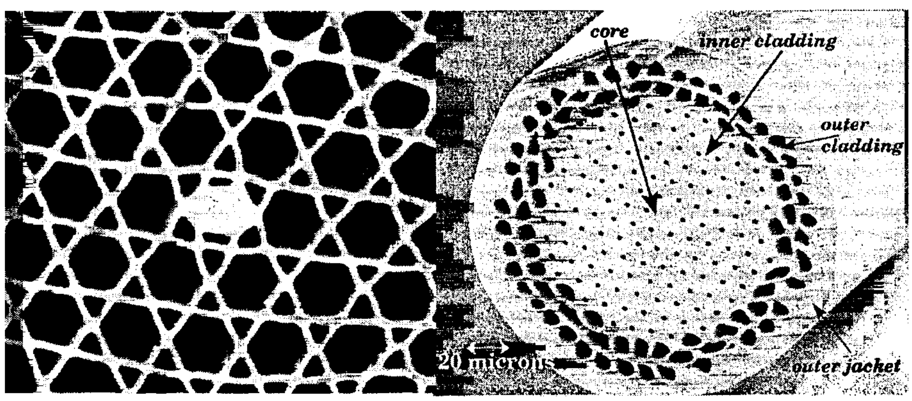

Fig.2 Rare earth doped holey fibers: (a)(-left) a small, (1.5μm by 2.5μm), elliptical core, Yb-doped holey fiber with anomalous dispersion for λ>800nm and, (b) An air-clad, Yb-doped, large mode area holey fiber suitable for cladding-pumped fiber laser and amplifier applications.

As previously mentioned holey fiber technology is also of relevance to the production of rare-earth doped fibers, as required for 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 [27]. 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 [28]. Whilst soliton concepts might be familiar in the context of 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. Note 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% [29].

In conclusion, holey fiber technology has now advanced to the point that km-lengths of robust coated fiber can be produced with losses below 1 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 range of applications areas, both within telecommunications and beyond.

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