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Holey fibers: new opportunities for manipulating light

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Abstract. *The wavelength-scale features in holey fibers lead to novel properties including endlessly single-mode guidance, high optical nonlinearity per unit length, and anomalous dispersion below 1.3 μm.*

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 scale of the wavelength of light.

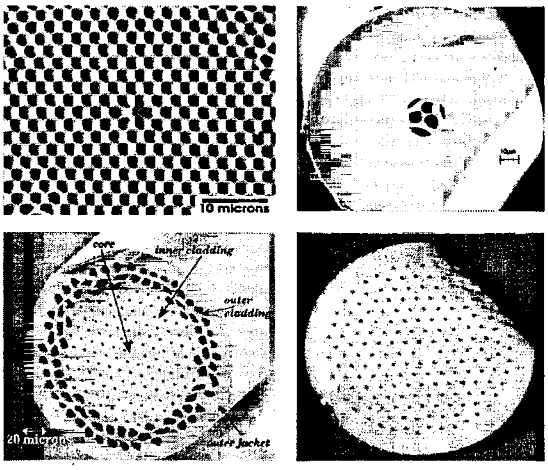

Fig.1 SEMs of various HFs fabricated at ORC: (a) small effective area silica HF, (b) high nonlinearity HF in Schott SF57 glass, (c) Yb doped, air-clad, LMA HF, (d) LMA-HF.

The fundamental physical difference between HF and conventional fiber types arises from the way in which the guided mode 'experiences' the cladding region. In a conventional fiber this is largely independent of wavelength to first-order. 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 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/Λ < 0.4) can be single-moded regardless of the wavelength [1]. 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]. Thus HFs are 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.

Arguably, the most exciting possibility afforded by holey fiber technology is the possibility to develop fibers with a very high optical nonlinearity per unit length [3,4]. 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(a,b)). In such a fiber, modest light intensities can induce significant nonlinear effects. These fibers offer a new route towards efficient, compact fiber based nonlinear devices [5,6]. For example, we recently demonstrated a 2R data regenerator/optical thresholding device based on a HF with an effective mode area of just 2.8μm^2 and a nonlinearity γ=31W^{-1}km^{-1} at 1.55μm [5,7]. The nonlinear switching response was obtained by combining self-phase modulation and offset narrowband spectral filtering. Similar devices based on conventional fibers are typically of order 1 km in length whereas in our experiments just 3.3m of HF was needed. 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 demonstrated a ~70m long, fiber laser pumped Raman amplifier providing gains of up to 43dB in the L$^+$ communications band [8]. Note that these particular demonstrations have used silica based holey fibers but that further significant increases in effective fiber nonlinearity should be achievable using fibers made of inherently more nonlinear material. Recently we fabricated a small core HF from commercial SF57 lead glass (see Fig.1c) which has ~20 times the nonlinearity of silica, and a softening temperature of ~ 600 degC. The measured nonlinearity per unit length γ=550 W^{-1}km^{-1} of this fiber shows that it is about 500 times more nonlinear than conventional SMF28 fiber [9]. Note also that this SF57 fiber was produced from an extruded preform, rather than a preform produced by stacking capillaries. This result highlights the fact that different preform fabrication approaches become more practical when using materials with substantially lower melting points 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 Figs.1c and d. Large mode area HFs [10] 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. 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 unusual wavelength dependence in HF also leads to a range of novel dispersion properties which are relevant for both linear and nonlinear device applications. For example, fibers with a small pitch (Λ<2 μm) and large air holes ($d/\Lambda > 0.5$) can exhibit anomalous dispersion down to wavelengths as low as 550nm [2,11]. This makes the generation and propagation of optical solitons in single-mode fiber in the near-IR and visible regions of the spectrum possible for the first time. 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 can extend from the UV out to beyond 1.8μm [12]. Such sources are attractive for many applications including WDM sources, 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, 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 [13]. Other work has shown that broadband dispersion-flattened holey fibers can also be designed [2], a property that is likely to be useful for the development of broadband WDM devices.

Finally, it is worth noting that although HFs can essentially be single material devices it is possible to incorporate other dopants into HFs for specific device/application requirements. For example, it is possible to add germanium to enable grating writing, or rare earth ions to develop laser/amplifiers. For example, in Fig.1c we show an Yb^{3+} doped, air-clad LMA fiber suitable for cladding pumping. The fine holes in the inner cladding define the guided transverse laser mode, and the larger more-peripheral air holes define a high NA waveguide for 915nm or 980nm pump radiation. Using this fiber we achieved a laser slope efficiency of 76% [14], showing that such fiber can be just as efficient as its conventional counterparts, whilst offering broader bandwidth operation, shorter device lengths and more efficient access to other laser transitions.

In conclusion, holey fiber technology has advanced now to the point that km-lengths of robust coated fiber can be produced with losses below 1 dB/km [15] 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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