Highly nonlinear holey optical fibres: design, manufacture and device applications

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Abstract *Micron-scale features in holey fibres lead to novel properties including endlessly single-mode guidance, high optical nonlinearity, and anomalous dispersion below 1.3 μm. We review progress in developing high nonlinearity holey fibres for device applications.*

Introduction

Holey fibres (HFs) possess a solid core surrounded by micron-scale air holes (see Fig.1). The large index contrast and small structural dimensions in HF can combine to make the effective cladding index strongly wavelength dependent, which leads to unique optical properties. One striking example is that fibres with small air-fill fractions ($d/\Lambda < 0.4$) can be single-mode regardless of operating wavelength [1]. Tailoring the cladding features allows the mode area (A_{eff}) to be varied from 1-1000μm^2 at 1550nm [2]. HFs thus have a significantly broader range of properties than conventional fibres.

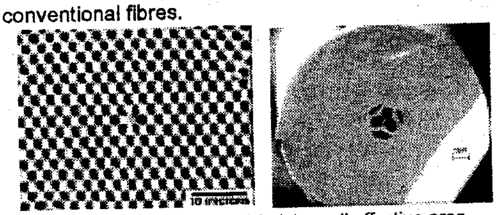

Fig.1 HFs fabricated at ORC: (a) small effective area silica HF, (b) high nonlinearity HF in Schott SF57 glass.

Design of highly nonlinear holey fibres

Arguably, the most exciting possibility afforded by holey fibre technology is the opportunity to develop fibres with high optical nonlinearity per unit length [3]. HFs with small features and a large air-filling fraction (large d/Λ) can confine light tightly within the core, resulting in extremely small mode areas. Modest optical powers can then induce significant nonlinear effects. These fibres offer a new route towards efficient, compact fibre based nonlinear devices [4,5].

Small core HFs also have novel dispersive properties of relevance for nonlinear applications [2]. They can exhibit anomalous dispersion down to 550nm [6], which has made soliton generation in the near-IR and visible spectrum possible. An application of this regime was reported in [7], in which the soliton self frequency shift in an Yb-doped HF amplifier was used as the basis for a fs pulse source tunable from 1.06-1.33μm. Shifting the zero-dispersion wavelength to regimes where there are convenient sources also allows the development of efficient super-continuum sources [8], which are attractive for DWDM transmitters, pulse compression and the definition of frequency standards. It is also possible to design nonlinear HFs with large normal dispersion [9].

We have used the multipole technique [10] to explore the design of small-core HFs [11]. Since HFs are typically made from a single material, usually pure silica, their modes are leaky because the core index is the same as that beyond the cladding region. One current limitation on the practicality of small-core HFs is the fibre loss, which is typically in the range 10-50 dB/km. Although losses as low as 1 dB/km have been achieved in larger-core HFs [12], our recent work shows that when Λ is comparable to the wavelength, confinement loss arising from the leaky nature of the modes can contribute significantly to the overall loss. Unsurprisingly, as Fig.2 shows, tighter mode confinement and lower loss is achieved using a larger air-fill fraction, and A_{eff} is effectively independent of the number of rings of air holes used. In addition, increasing the number of rings also improves the loss. With careful design, it is possible to envisage practical HFs with small core areas ($<2\mu m^2$) and low confinement loss (<loss of conventional fibre).

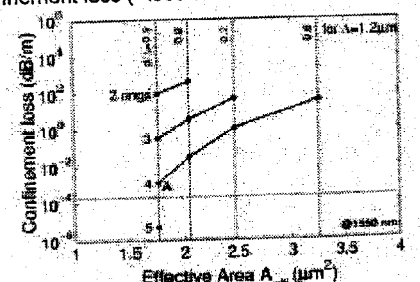

Fig.2 Predicted mode area and confinement loss for a range of small-scale silica HF designs with Λ=1.2μm.

Fabrication approaches

HF preforms are typically made by stacking capillaries (see Fig.~1(a)), and most HFs produced to date have been made from silica. The effective fibre nonlinearity is $\gamma=2\pi n_2/(\lambda A_{eff})$, and as the smallest A_{eff} that can be achieved in a silica/air fibre is ~1.3μm^2, values of γ as large as 60/(W.km) are possible in silica HFs. This could be enhanced using compound glasses. Stacking techniques pose significant challenges for the development of small-core non-silica glass HFs. However, compound glasses have low softening temperatures, which opens up new possibilities for preform fabrication.

Our recent work has shown that extrusion can be used to produce HF preforms. Extrusion allows the definition of cross-sections not possible using stacking. This work used SF57, a Schott glass with $n_2=4\times10^{-19}$ m^2/W [14] and a softening temperature of 520°C. The preform was caned on a drawing tower, inserted within a jacket, and drawn to fibre (Fig.1(b)). The 2µm core is suspended by three 2µm long supports less than 400nm thick. Light is confined tightly to the core because the supports are long and fine enough to isolate the core [13]. This fibre is effectively single-mode over at least 633-1500nm, and we have measured $\gamma\approx550/(W.km)$ [$A_{eff}\approx3\mu m^2$] at 1550nm, more than 500 times larger than standard fibre. Such fibres promise a new generation of compact, efficient, fibre-based nonlinear devices.

Device applications

We recently demonstrated 2R data regeneration based on a silica HF with a mode area of just 2.8µm^2 [γ=31/(W.km)] at 1550nm [4]. Regeneration was obtained by combining self-phase modulation (SPM) with offset narrowband spectral filtering. Typically, devices based on conventional fibers are ~1 km long, whereas in our earliest experiments just 3.3m of HF was needed for an operating power of 15W. We went on to use an 8.7m long variant of this switch to provide a thresholding function within an optical code division multiple access (OCDMA) system [14].

A schematic of the thresholder is shown in Fig.3a. Fig.3b shows the spectrum of 2.5ps soliton pulses prior to and after propagation through the HF. SPM generates new spectral components within the fibre. Fig.3c shows the pulse power transmitted through a 1.0nm narrowband filter (offset by +2.5nm relative to the incident pulses) as a function of incident pulse peak power. The S-shaped characteristic is suitable for thresholding since at low powers transmission is negligible, whereas for higher powers (~2W here), transmission becomes appreciable. We used such a switch prior to our receiver to eliminate low-level pedestal components arising from the matched filtering of a coded bit and obtained a significant improvement in the overall system performance [14].

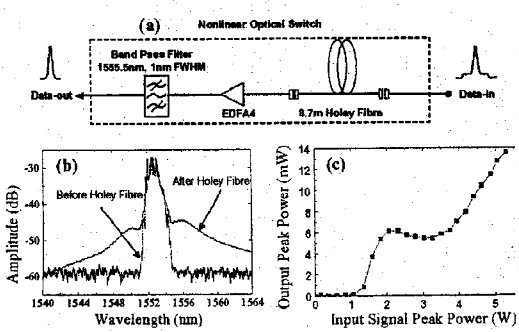

Fig.3.(a) Schematic of thresholder (b) pulse spectra before/after HF (c) power transmitted (including offset narrowband filter).

Such fibers also offer length/power advantages for devices based on other processes such as Brillouin and Raman effects. We recently demonstrated a 70m fiber laser pumped Raman amplifier [15] (Fig.4). The amplifier was pumped using a pulsed fiber laser and provided gains of up to 43dB in the L+ band (Fig.4b) for peak powers of ~7W (Fig.4c). More recently, we constructed a CW Raman laser pumped at 1080nm using a high-power, cladding-pumped Yb-doped fiber laser [16]. The laser had a CW threshold of 5W, and slope efficiency of 70%. Note the CW power density at the facet (0.2 GW/cm^2) demonstrates that HFs can exhibit a good resilience to damage.

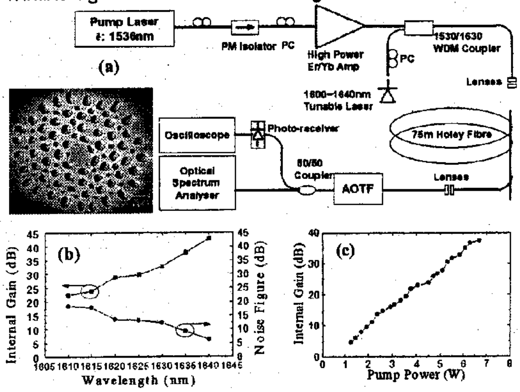

Fig.4.(a) Amplifier schematic (AOTF=acousto-optic tunable filter) (b) Gain (c) gain efficiency curve at 1635nm.

Conclusions

Holey fiber technology has advanced now to the point that km-lengths of robust fiber can be produced with losses below 1dB/km and with a broad range useful optical properties. Such fibers have the potential to enable a wide range of practical nonlinear optical devices for telecommunications and beyond.

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