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# Nonlinearity in Holey Optical Fibres

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**Abstract**: We discuss recent experimental results concerning the use of microstructured optical fibres as novel nonlinear media. Continuum generation, short wavelength soliton propagation and optical frequency comb generation have been obtained thanks to a combination of unusual dispersive properties and the small mode area available in holey fibres.

Holey fibers (HF) provide a new paradigm for the transverse guidance of light. Unlike conventional optical fibers, which use different core and cladding materials, HFs can be made from a single material, and guidance is provided by the difference in *effective* indices of the core and the `holey' cladding [1,2]. This difference arises from the inclusion of a central high index defect, which is surrounded by a number of air holes. A typical holey fiber is shown in Fig.1. When these holes are arranged periodically, such fibres can also possess a complete photonic bandgap [3] depending on the relative size of the air holes of the period of the lattice.

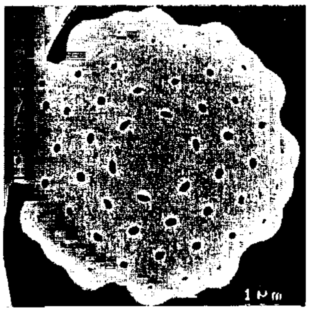
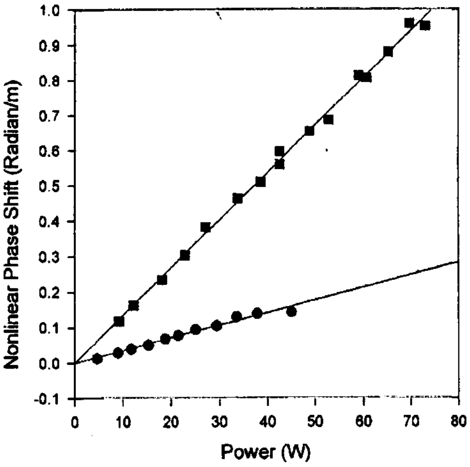


**Figure 1:** A typical holey fibre

Holey fibers are attractive for photonic devices because their optical properties can be engineered over a much broader parameter range during fabrication than conventional fibres [4]. For example, HFs can have anomalous waveguide dispersion at wavelengths less than 1.3 microns and be single-mode, which is impossible in conventional step-index fibers [5]. Such fibers offer the potential for creating soliton fiber lasers at visible wavelengths. Solitons have been generated using 850nm light in a HF [6], and this could be done at even shorter wavelengths. In particular, doping a HF with ytterbium would allow easy fabrication of sub-picosecond high repetition pulse sources at 1μm, which would find use in a variety of areas.

As described above, the unusual optical properties of HFs result from the presence of air holes in the cladding. It is then natural to ask how the holes affect the effective nonlinearity of HF, and whether or not it is possible to significantly alter it via the fiber design. Holey fibers offer two distinct ways to achieve this. Firstly, by appropriate choice of HF geometry, the mode size can be tailored by as much as three orders of magnitude [6], a much larger range than that possible in conventional fiber types. Changing the mode size alters the effective nonlinearity of the fiber by increasing/decreasing the intensity inside the fiber which increases/decreases the nonlinear phase change experienced by light during propagation. A more direct way to affect the nonlinearity would be by using HFs in which the hole spacing is less than the wavelength of the light. In this regime, a large fraction of the mode can propagate in the air [7], and thus by filling the HFs with a suitable nonlinear material the effective nonlinearity could be significantly enhanced.

Holey fibre modes typically have a non-circular shape that reflects the way in which the air holes in the cladding are arranged. This makes the measurement of the mode size in the fibres difficult using conventional approaches, which typically assume a circularly symmetric modal profile. To avoid this problem, we used the method of Boskovic *et al.* [8] to measure the nonlinearity of our fiber. This approach involves the use of high power dual frequency beat signals. The fiber nonlinearity creates spectral sidebands and the intensity ratio between the signal and the first side band gives the nonlinear phase $\phi = 2\,\omega\,\gamma\,L\,P/c$ where L is the effective fiber length and P the signal power. Using this method, the effective nonlinearity $\gamma$ can be calculated for the fiber under test. Note that $\gamma$ is proportional to the material nonlinearity and the effective area of the mode. The HFs considered here are composed solely of silica, and so $n_2$ is known. Hence this method provides a direct way of accurately measuring the effective mode area in HFs. This technique for measuring the effective area is particularly useful for HFs, as it makes no assumptions about the mode shape. The mode of the HF in Fig.1 has 6-fold (hexagonal) symmetry, and so cannot be approximated by a simple circularly-symmetric Gaussian. This is particularly noticeable in the wings or at shorter wavelengths, where the mode becomes more hexagonal. More traditional methods, which rely on Gaussian optics to estimate the area, would fail in these cases.



To perform the nonlinear measurements we used a diode-seeded erbium doped amplifier chain. The input was derived from two tuneable DFB lasers coupled together and the resultant beat signal externally modulated to produce 5ns square pulses at a repetition rate of 200 kHz. After amplification the peak power in the pulses was ~100mW, and we coupled 50% of this power into the HF (length 1.175m). We also tested (1.9 m) of dispersion-shifted fiber (DSF) to test the procedure. We recorded the output spectra at a range of powers and measured the amount of self phase modulation from the degree of spectral enrichment, which gives us the nonlinear phase. The results obtained for both the DSF and HF are shown in Fig. 2 along with the results of least squares linear fits. As expected the nonlinear phase increases linearly with peak power and the slope of the fit gives the nonlinearity. For the holey fiber we obtained $\gamma=1.56\ 10^{-10}\ W^{-1}$. This gives an effective area of $13.9\mu m^2$ as compared to our theoretical estimate of $14\mu m^2$. Hence in this HF, the mode area is approximately four times smaller than in the DSF.

The fibre shown in Fig.1 has a zero-dispersion wavelength at approximately 1.1 microns [9], and as shown above, it also has a small effective core area. In addition, this fibre is single-mode over an extremely broad wavelength range. As first demonstrated in Ref [10], this combination of properties can be used to generate a broadband continuum spectrum. A range of efficient nonlinear processes occur when this fibre is pumped at 1.1 microns, near its zero dispersion wavelength. This produces a broadband continuum spectrum from at least 400 – 1850nm, as shown in Figure 3.

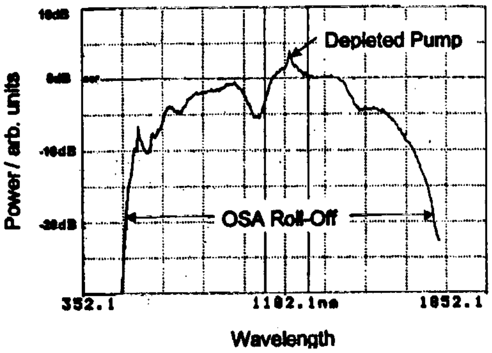


**Figure 3:** Continuum generation using the HF shown in Figure 1.

In conclusion, we have successfully measured the Kerr nonlinearity for a typical holey fiber, and we find that it is considerably enhanced by the small effective area of this HF. Note that mode areas as small as $1\mu m^2$ are possible for different hole arrangements. The technique described here is a fast easy way to measure the effective area of HFs. In the future, we hope to construct holey fibres out of other more highly nonlinear materials as well using these fibres to construct soliton fibre lasers.

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