A HOLEY FIBRE RAMAN AMPLIFIER
AND ALL-OPTICAL MODULATOR

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Abstract: We demonstrate the use of a short length of highly nonlinear holey fibre to obtain strong L-band Raman amplification. Using a 75m long HF fibre with an effective area of 2.85μm² we obtain internal gains of over 42dB and a noise figure of -6dB. In addition, using the same fibre we obtain an 11dB extinction ratio in Raman induced all-optical modulation experiments.

Introduction
The area of Holey Fibre (HF) technology has progressed rapidly in recent years and has resulted in the development of a wide range of optical fibres with unique and highly useful optical properties [1,2]. Arguably, the most exciting prospect offered by this new technology is the development of fibres with a high optical nonlinearity /3/. The large refractive index contrast between silica and air means that it is possible to confine light to transverse modes with a dimension of the order of the wavelength of light, meaning that such fibres have an effective nonlinearity per unit length 10-100 times higher than that of conventional silica fibre. Typical nonlinear fibre devices, such as Kerr gates based on conventional fibre types, need to be several km long for realistic operating powers. This makes them impractical for anything other than laboratory usage. By contrast, HF based equivalents of such devices need to be just several tens of metres or less in length to obtain similar performance levels, making them a far more realistic proposition for real world telecommunications applications. Recently we illustrated this point experimentally by demonstrating a nonlinear optical switch based on Self Phase Modulation (SPM) effects in just 3.3m of HF. This regenerative switch operated at 1.55μm and had a peak pulse switching power of ~10W /4/.

In this paper we show that HF technology can also be used to reduce the length/power levels required for another important class of nonlinear telecommunication devices - namely those based on the Raman effect. More specifically, we provide what we believe to be the first experimental demonstrations of both: (a) a HF Raman amplifier and (b), an all-optical, HF Raman modulator.

Experimental setup and results
Our experimental Raman amplifier setup is shown in Fig. 1. The amplifier was configured for copropagating pump and signal. The pump source, based on a diode seeded, fibre amplifier based MOPA configuration, was operated in a pulsed mode with 20ns square pulse at 500 KHz repetition rate, corresponding to a 100:1 pump duty cycle. The pump wavelength was 1536nm. We combined the pump and the input signal beams together using a 1530/1630nm WDM coupler prior to launching the light into the HF Raman amplifier. The signal light was generated from a continuous wave external cavity laser tunable in the range 1600-1640nm. Polarisation controllers were included on both the pump and signal launching paths into the HF so that both beams could be launched onto a single polarisation axis of the polarisation maintaining HF.

Fig. 1: Experimental setup
Both the pump and signal light were coupled with up to 40% efficiency into the HF Raman amplifier using an appropriately matched lens combination. The maximum peak pump power that we could launch into the HF was ~6.7W, and the maximum launched signal power ~10 dBm. An acousto-optic tunable filter (AOTF) was placed at the output of the fibre to allow us to filter the amplified signal beam from the pump with sufficiently high isolation (>60dB) to permit accurate gain measurements. The Raman gain measurements were made by analysing the temporal response of the signal beam to the pulsed pump beam.

A cross sectional Scanning Electron Micrograph (SEM) image of the HF used in these experiments is shown inset in Fig. 1. The fibre has a core diameter of ~1.6μm and an outer diameter of 100μm. The relatively large hole sizes result in a high optical nonlinearity and their asymmetric arrangement ensures that the fibre is linearly birefringent with a measured birefringence of ~0.4nm at 1.55μm. We used a length of 75m of this fibre in all of the experiments/measurements reported herein. The loss of this fibre was measured using the cut back technique to be 40 dB/km. The 75m of HF thus has an effective nonlinear length L_n of just 54m. The nonlinear coefficient γ of the guided mode in this fibre was measured at 1535nm using a direct CW beat-signal spectral enrichment technique /5/. From a measurement of the SPM induced nonlinear phase shift versus launched optical power we obtained a value of γ=32W⁻¹·km⁻¹. Using the known value of the Kerr nonlinear coefficient of silica of n2=2.16×10⁻²⁰m²/W we obtain an estimate of A_ep=2.85×(γ/0.3)μm² for the effective area of our HF. This value is in very good agreement with
our theoretical prediction of 2.87μm² based on the SEM image shown inset in Fig. 1.

Fig. 2: (a) Internal Raman gain and noise figure for various probe signal wavelengths (signal power -10 dBm, pump peak power: 6.7 W). (b) Typical (high gain) amplifier spectrum showing Raman ASE spectrum. (c) Internal gain vs pump power at 1635nm.

Fig 2a shows internal Raman gain and noise figure for various probe signal wavelengths and fixed pump signal powers. Higher gains and lower noise figures are observed as the probe signal wavelength approaches the peak of the Raman gain curve around 1650nm, corresponding to the peak Raman shift of 13.2 THz (see Fig. 2b). Small signal gains as large as 42.8 dB, and noise figures as low as 6 dB were obtained at 1640 nm (the longest wavelength to which we could tune our signal laser). The observed variation in gain with wavelength was in good agreement with our expectations based on published data on the Raman lineshape of silica /6/. We also measured the internal gain as a function of pump peak power for a signal wavelength of 1635 nm. The input signal power was again fixed at -10 dBm. This plot is shown in Fig. 2c. Using the following equation G(dB) = 10 log( exp(\(\frac{\chi}{\Gamma}A_cA_l\alpha_0\alpha_0^2\Gamma)))$, our measured value of gain efficiency (6 dB/W), and our directly measured value of $\chi$, we estimate the Raman gain coefficient $\chi_0$ at the gain peak to have a value of 7.6 · 10^-17 mW. This value is in good agreement with the number for pure silica reported in Ref /6/.

As well as investigating the performance of the HF as a pure Raman amplifier we also performed a Raman modulation/erase experiment. In this instance a strong pump beam at a long wavelength is used to induce loss for a copropagating beam at shorter wavelengths /7/. We used the same experimental configuration as in our Raman amplification experiment shown in Fig. 1 other than that we exchanged the tunable 1600 nm signal source for a 20 dBm, 1458 nm CW semiconductor diode laser. (The 1530/1630 nm WDM coupler can also be used to combine light at 1536 nm and 1485 nm). In the presence of the pump pulses, the signal beam experiences stimulated Raman scattering (SRS), resulting in an effective nonlinearly induced signal loss. This manifests itself in the time domain through the formation of 'dark' pulses at the signal wavelength, where the signal overlaps the pump pulses. Typical oscilloscope traces are shown in Figs. 3a and b.

Fig. 3: (a) Temporal profile of dark pulses at the SRS modulator output. (b) Close up view of the square-shaped dark pulse (the temporal dip at the falling edge is due to ringing of the photoreceiver). (c) Extinction ratio of SRS based signal modulation vs pump pulse peak power.

To quantify the performance of the SRS signal modulator we measured the modulator extinction ratio (defined as the hole depth relative to the background CW level), as a function of pump pulse peak power. The results are summarised in Fig. 3c, where it is seen that extinction ratios in excess of -11 dB were obtained for pump powers of ~5 W and above. It should be possible to obtain even higher extinction ratios by tuning the frequency separation of the signal and pump (10.5 THz in these experiments) to lay closer to the peak Raman shift value, and by better alignment of the polarisation of the two beams relative to a principal axis of the fibre.

Conclusion

We have experimentally demonstrated two Raman based devices using high nonlinearity HF. Our experiments highlight the improvements that can be obtained in terms of reduced device lengths/power requirements relative to Raman devices based on conventional fibre types. As well as being significant from a packaging/environmental stability perspective, the reduced device lengths could also prove advantageous in terms of reducing the deleterious impact of double Rayleigh scattering on Raman amplifier noise. Ultimately, HF technology should prove to be a powerful technology for the development of a wide range of practical nonlinear optical devices such as Raman amplifiers, optical limiters and wavelength converters.

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References