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Subpicosecond soliton transmission over 22 km of dispersion-shifted fibre with loss compensated by Raman gain

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ABSTRACT

We have experimentaly demonstrated transmission of 800 fs solitons over 150 dispersion lengths of dispersion-shifted fibre. Experimental results clearly indicate that the use of readily available high power fibre lasers operating at 1535 nm makes it possible to utilize Raman gain in a simple, all-fibre configuration and achieve 100 Gb/s bit rate in a soliton transmission system.

Introduction: The Raman amplifier has the attraction that the transmission fibre is its own amplifier [1-3] and the first experiments with soliton transmission had produced encouraging results [4-6], but the lack of inexpensive and reliable pump sources and the appearance of more efficient erbium-doped fibre amplifiers put the Raman amplifier into the shadow. However the development of highly efficient fibre lasers with output power up to 1 W [7] could have a significant impact on the application of the imaginary part of the fibre nonlinearity (Raman gain) when and where the real part (the Kerr effect) is already in use and in this paper we demonstrate that the advances of modern fibre optics and in particular high power fibre lasers might result in a re-examination of the Raman amplifiers role in ultra-high bit rate transmission systems.

Experiment and Discussion: In the experiment a 22 km length of commercially available dispersion shifted fibre (DSF) with zero dispersion wavelength at 1540 nm was pumped by a narrow-band fibre laser based on a co-doped Er/Yb fibre. The laser cavity was formed by fibre gratings with 100% and 40% reflectivity at 1535 nm reflectivity. With 3 W of pump power from a Nd:YLF laser the fibre laser produces 500 mW at 1535 nm. The spectral bandwidth of the radiation (0.15 nm) was broad enough to suppress unwanted stimulated Brillouin scattering but sufficiently narrow to ensure low noise due to gain fluctuations caused by the finite bandwidth of pump source [4]. When the pump power was increased up to 5.5 W the fibre laser output at 1535 nm was as high as 800 mW. Fibre loss of 0.23 dB/km makes the effective length of the Raman fibre amplifier equal to $L_{eff} = (1 - e^{-\alpha z})/\alpha = 13.0$ km, where z is the full length of the fibre.

Fig.1 shows the spectral dependence of the Raman gain in the co-propagation scheme. The experimental results indicate that for 250 mW of pump power the fibre loss is compensated for wavelengths longer than 1575 nm, while with 500 mW of pump the wavelength of zero loss shifts to 1560 nm. From the data of Fig.1 one can calculate the Raman gain constant which for a fibre with a 40 μm^2 is equal to $1.5 \cdot 10^{-12}$ cm/W at a frequency shift of 160 cm^{-1}. This corresponds to peak gain ~ $4.2 \cdot 10^{-12}$ cm/W (at 440 cm^{-1}) which is lower than that reported in [1]. The most likely reason for that is the different state of polarization for the pump and signal waves, that results in a lowering of the Raman gain coefficient [1].

Results presented in Fig.1 actually indicate that one can ensure effectively lossless soliton transmission in a simple, all-fibre configuration with a signal wavelength between 1560 and 1640 nm. Note that it is not necessary to choose the signal wavelength at 1640 nm i.e. at the peak of Raman gain, since for high average signal power pump depletion might result in serious degradation of the Raman gain and in order to diminish this effect one may find a wavelength around 1600 nm more attractive at the expense however of higher pump power.

To demonstrate the advantages of Raman amplifiers over conventional erbium-doped fibre amplifiers we have performed a soliton transmission experiment. A passive harmonically mode-locked laser with hybrid saturable absorber [8] was used as a soliton source. The solitons generated by the laser were nearly transform-limited and had a pulsewidth of 800 fs at 1560 nm. These pulses were launched into 22 km of DSF through a fused coupler. The Raman pump was launched through another port of the coupler. The autocorrelation traces of the pulses are shown in Fig.2. Without Raman gain the fibre loss results in pulse broadening to 2.5 ps, while with 600 mW of pump power we observed almost complete restoration of the initial pulse form.

Input and output spectra of the propagating pulses are shown in Fig.3. A 4 nm spectral shift of the output spectrum due to the effect of soliton self-frequency shift [9] is clearly seen. The spectral shift is bigger than that experienced by the 800 fs pulses after propagation 22 km which in accordance with [9] should be around 1.5 nm. This discrepancy is attributed to pulse compression over the first half of the fibre where the pulses undergo compression to ~ 600 fs.

Conclusion: We have experimentally demonstrated subpicosecond pulse propagation over 22 km of dispersion shifted fibre using Raman gain for fibre loss compensation where the availability of efficient Er/Yb codoped fibres and fibre gratings makes it possible to design a simple and robust pump source operating at 1535 nm. The fibre dispersion of 1.2 ps/nm km at the signal wavelength of 1560 nm made the soliton propagation distance as long as 150 dispersion lengths - the longest distance for single span soliton transmission reported so far. We have observed a noticeble spectral shift of the propagating pulses caused by the effect of self-frequency shift. In the present, unidirectional scheme, this effect was enhanced by the non-uniform pump power distribution along the fibre length that results in pulse compression. A bidirectional scheme would allow us to obtain a more uniform distribution of the pump and reduce the amount of non-soliton component, while shifting the signal wavelength to 1600 nm and the use of slightly longer pulses (~1.5 ps) gives rise to the possibility of transmitting a 100 Gb/s stream of solitons over at least 1000 km, which makes the Raman amplifier a real challenger to the erbium-doped fibre amplifier in soliton transmission systems.

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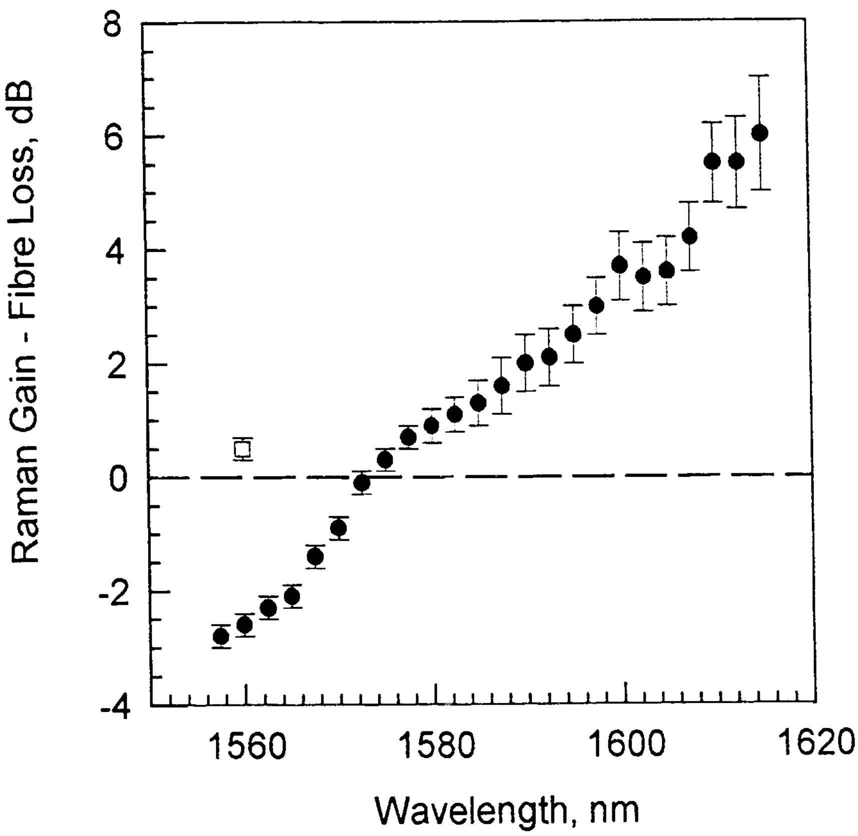
Figure Captions

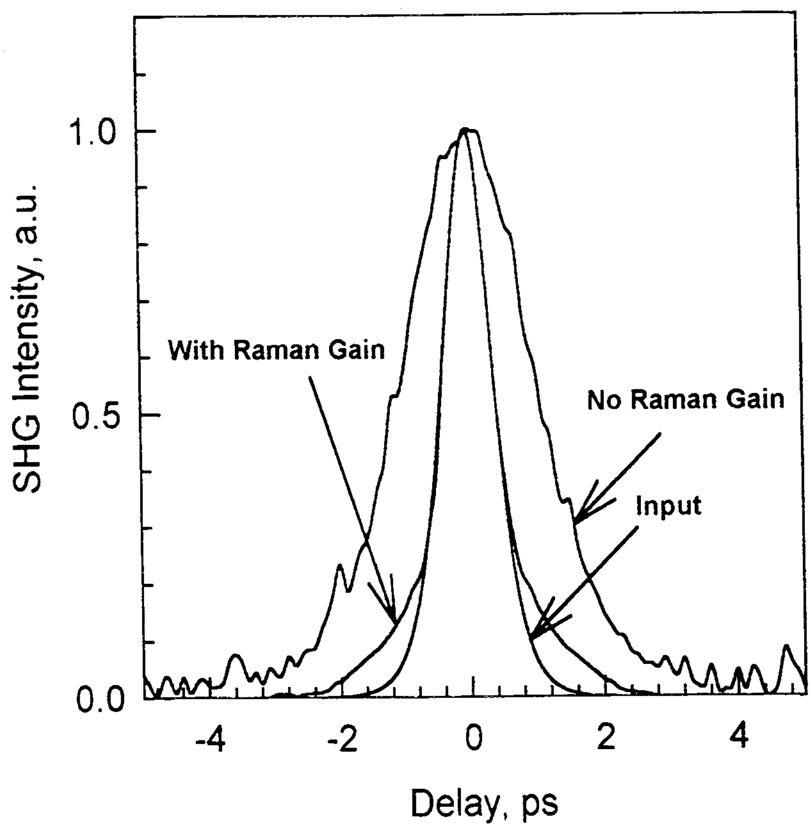
Fig.1 Spectral dependence of the net gain in a 22 km span of fibre pumped by 250 mW at 1535 nm. □ - indicates Raman gain at 1560 nm with 500 mW pump power.

Fig.2 Autocorrelation traces of pulses at the input and output of the 22-km fibre with and without Raman gain.

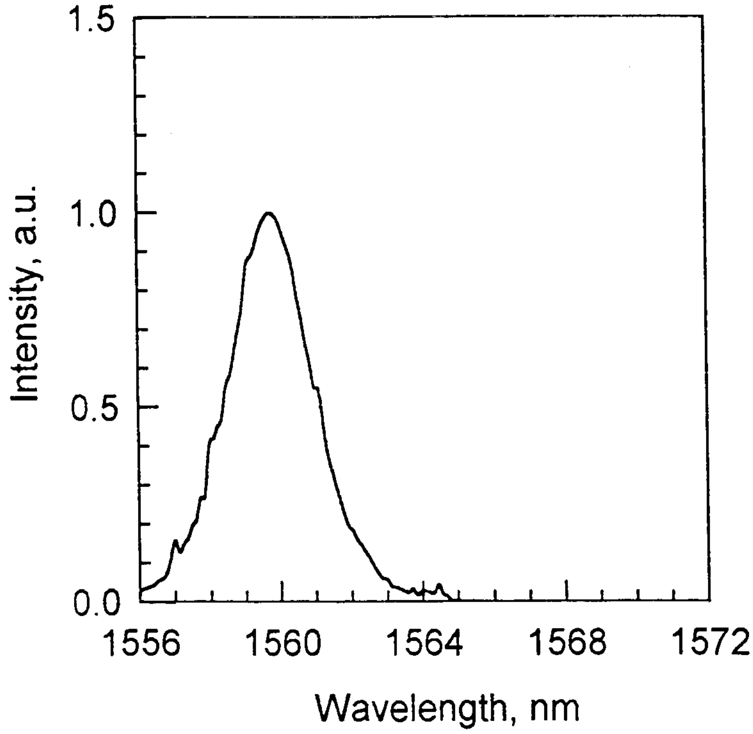
Fig.3 Optical spectra at the input and output of the 22-km fibre with Raman gain

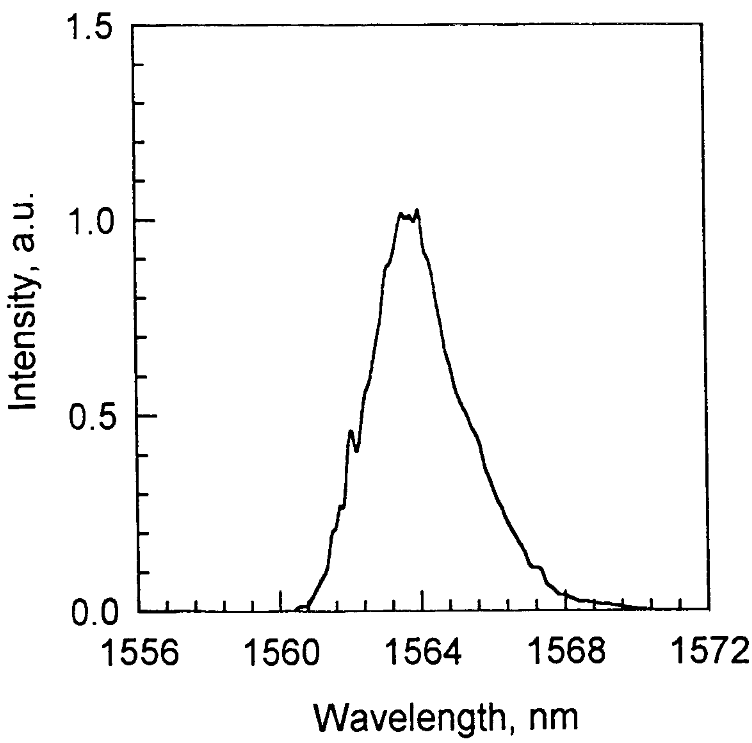


8
6
4
2
0
-2
-4
Raman Gain - Fibre Loss, dB
1560
1580
1600
1620
Wavelength, nm



SHG Intensity, a.u.
1.0
0.5
0.0
With Raman Gain
No Raman Gain
Input
-4
-2
0
2
4
Delay, ps


1.5
1.0
0.5
0.0
Intensity, a.u.
1556
1560
1564
1568
1572
Wavelength, nm


1.5
1.0
0.5
0.0
Intensity, a.u.
1556
1560
1564
1568
1572
Wavelength, nm