The repetition rate of the converted optical pulses is limited by the spectral width $\nu_c$ of the initial optical pulse train. To obtain a higher repetition-rate, we used supercontinuum optical pulses [6] ($\nu_c = 10^{15}$ Hz, $\tau = 0.7$ ps, $\nu_c = 650$ GHz, central wavelength = 1552 nm) as the initial pulses. Fig. 4 shows theoretical and measured pulse waveforms. The chirp velocity is set to be 4 GHz/ps which corresponds to $M = 40$ in eqn. 3. We succeeded in obtaining a 400 GHz optical pulse train and also confirmed that this experimental result agrees well with the calculation. In this experiment, the initial pulse source was synchronised with the external clock. Therefore, the obtained 400 GHz optical pulse train was also synchronised with the external clock (10 GHz). The synchronised high repetition rate optical pulse train may be useful for attractive applications such as ultra-high-speed OTDM systems and ultra-high-speed optical processing.

Conclusion: We have numerically and experimentally examined a high repetition rate optical pulse train generation method that utilises chirped optical pulses. The repetition rate of an initial optical pulse train is multiplied, both by chirping the optical pulses and by a dispersive medium. 50 to 400 GHz optical pulse trains have been successfully generated using a 10 GHz optical pulse train. These high repetition rate optical pulse trains can be synchronised with the external clock by using a low repetition rate optical pulse source. This method is expected to be suitable for operation 100 Gbit/s OTDM.

Acknowledgment: We would like to thank I. Kobayashi, Y. Yumabayashi and S. Nishi for their encouragement, and A. Takada and K. Mori for their fruitful discussions.

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Electronics Letters Online No: 19980558
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References

Lossless transmission of 2 ps pulses over 45km of standard fibre at 1.3 \mu m using distributed Raman amplification

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A 10 GHz, 2 ps pulse stream at 1.3 \mu m is transmitted over a 45 km span of standard telecommunications fibre using distributed Raman amplification pumped with a compact and highly efficient fibre laser. When the pulse source is tuned to the minimum dispersion wavelength of the fibre, lossless, distortionless pulse transmission is demonstrated. By increasing the Raman pump power, a net gain of 8 dB over the span has been achieved, allowing the demonstration of nonlinear pulse compression.

The development of the erbium-doped fibre amplifier has meant that most current telecommunications development work is currently directed towards systems operating around 1.55 \mu m. A large proportion of installed fibre plant worldwide, however, is only suitable for operation in the 1.3 \mu m wavelength region, so it is very important to explore possible ways to upgrade these existing links to higher data rates in order to economically meet the ever-increasing demand for capacity in the short term. Additionally, even the relatively broad bandwidth of erbium-based systems is likely to be filled in the longer term, after which the only way to further increase the information capacity of a fibre will be to extend its operational wavelength range. Thus, the development of practical broadband optical amplifiers operating around the 1.3 \mu m region is vital for future development.

Raman amplification in silica fibres has always been an attractive option for literally the complete transparency bandwidth of single mode silica fibres. It is particularly well suited to short pulse, high bit rate communications because it is essentially instantaneous and has a very broad gain bandwidth, imposing no theoretical limitation on pulse durations or repetition rates. However, real applications rely heavily on the availability of practical high power, fibre-integrable sources for pumping. Raman fibre amplifiers have recently experienced a rejuvenation [1, 2] particularly as a result of developments and rapid progress in efficient, compact and reliable high power ytterbium (Yb)-doped fibre lasers used in conjunction with cascaded Raman lasers for wavelength conversion [3, 4]. In addition, because the gain medium for Raman amplification is simply undoped silica fibre, gain can be achieved in the transmission fibre itself. This means that fibre loss is compensated for by gradual gain distribution along the fibre span rather than by a 'pumped' amplifier at the end of a span, leading to smaller perturbations of the pulses during propagation. This can significantly improve the performance of an optical communications link [5], particularly for the case of soliton systems [6, 7]. Also, because the gain fibre is the transmission fibre, no extra fibre need be added, so span lengths and dispersion remain constant.

In this Letter, we report the distortionless transmission of 2 ps pulses over a 45 km length of standard telecommunications fibre. This is achieved by employing distributed Raman amplification in the transmission fibre pumped by an all-fibre Raman cascade laser operating at 1.54 \mu m and propagating the signal pulses close to the zero group-velocity dispersion (GVD) wavelength. We also describe the effects of varying the Raman pump power and signal wavelength.

The experimental configuration that was used is shown in Fig. 1. The pulse source used was a 10 GHz actively modelocked tunable ring laser, which has been described previously [8]. This laser produced near-transform-limited pulses of ~2 ps duration. A semiconductor optical amplifier (SOA) was placed at the output of the laser to provide gain and provide a convenient way of adjusting the launched pulse power (up to a maximum average value of 1 mW). The pulses were then propagated along the 45 km span of
transmission fibre which had an attenuation of 0.38dB/km at 1300nm and a zero GVD wavelength of ~1306nm. The Raman pump signal at 1.24μm was coupled into the transmission fibre in a counter-propagating geometry to minimise any noise buildup, and excess pump power was coupled out via a 1.06/1.24μm WDM fibre coupler. The output pulses were analysed with a scanning autocorrelator and optical spectrum analyser. The Raman pump laser was a simple all-fibre device based on a Yb-doped fibre amplifier used in conjunction with a cascade-Raman resonator, which has been described in detail elsewhere [2].

The pump laser was capable of delivering up to 1.3W of power in an approximately 20nm wide wavelength band centred at 1.24μm. At this maximum pump level, a total small signal gain of 27dB (pump on/off) was achieved in the 45km fibre span. This was sufficient to compensate for the combined losses of the transmission fibre, input and output isolators and to provide an excess gain of +8dB at the fibre output.

The "fig. 1 Experimental configuration" diagram shows a schematic of the experimental setup. The figure includes labels for 45km transmission fibre, SOA: semiconductor optical amplifier, WDM: wavelength division multiplexing coupler, Fi: Faraday isolator.

"fig. 2 Variation of transmitted pulse duration with launched pulse wavelength for lossless propagation along 45km fibre span" shows a graph with axes labeled as follows: wavelength (nm) on the x-axis and pulse duration (ps) on the y-axis. The graph indicates a decrease in pulse duration as the wavelength shifts towards shorter values, indicating the effect of Raman amplification.

"fig. 3 Variation of transmitted pulse duration with launched Raman pump power for signal pulses at 1307nm (low anomalous dispersion)" displays a graph with axes labeled as follows: launched Raman pump power (W) on the x-axis and pulse duration (ps) on the y-axis. The graph shows how pulse duration changes with varying pump power, indicating soliton propagation.

Initially, the source laser was set to provide an average launched power of ~1mW and the Raman pump power was adjusted such that the propagation down the fibre span was essentially lossless, i.e. the output power was also 1mW. The wavelength of the pulse source was then varied and the output pulses characterised. The results are shown in Fig. 2. It can be seen that the minimum output pulse duration of 2.2ps (essentially identical to the input pulse duration) was achieved at ~1306nm, the nominal zero GVD wavelength of the fibre span. The output pulse duration decreases in both directions away from this wavelength due to the effect of fibre dispersion. In all cases, the measured spectrum of the output pulses was identical to that at the pulse source, indicating that no self-phase modulation occurred and the pulses were propagating in the linear regime. Bit error rate measurements, which will be described in more detail elsewhere, indicated no measurable power penalty for this case when compared with a back-to-back measurement.

The pulse source was then set at 1307nm, in order to ensure a low level of anomalous dispersion in the fibre span, and the Raman pump power was varied. As the pump power increased, the output pulse spectrum was observed to broaden and the pulse duration decreased, as shown in Fig. 3. This presents evidence that nonlinear pulse compression was occurring during propagation, and that soliton propagation has been achieved.

To conclude, we have demonstrated the use of distributed Raman amplification for lossless, distortionless propagation of 2ps pulses at 1.3μm with a 10GHz repetition rate over a 45km span of standard telecommunications fibre. When the signal wavelength was tuned to coincide with the zero GVD wavelength of the fibre, dispersive pulse broadening was eliminated and the output pulses were essentially the same as at the fibre input. With our present pump laser design, an excess gain of 8dB was achieved over this span. Increasing the Raman pump power when the pulses were in the anomalous dispersion regime led to soliton pulse compression, with a minimum pulse duration of 1.7ps. These results show that the characteristics of Raman amplification make it ideally suited to short pulse, high bit rate systems and that recent developments in pump laser technology now make Raman amplification a very attractive tool in the upgrading of communications systems operating around 1.3μm.

Acknowledgments: This work was partly funded by the EPSRC. We would like to thank IRE-POLUS Co. for the loan of the ytterbium fibre laser used in these experiments.

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