RAMAN AMPLIFIER FOR ULTRASHORT SOLITON TRANSMISSION

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Abstract

We consider the choice of pump wavelength for a Raman amplified picosecond soliton transmission system and demonstrate transmission of 800 fs solitons over 22 km using a 1535 nm pump source.

Raman amplifiers are attractive for high bit rate ultrashort soliton because they use the transmission fibre to provide a distributed gain which can overcome the limits imposed on lumped amplifier systems by the average soliton model. But, the lack of inexpensive and reliable pump sources and the development of the EDFA reduced the interest in the development of raman amplifiers. However modern developments in optical fibre technology, such as fibre gratings and high efficiency fibre lasers, calls for a reexamination of the role of raman amplification in transmission systems. In this paper we consider the choice of pump wavelength for a raman amplifier system, examine the gain distribution along a 30 km fibre span and demonstrate subpicosecond soliton transmission.

In silica fibre the peak raman gain occurs for a frequency shift of 440 cm^{-1} which corresponds to a wavelength shift of ~100 nm at 1500 nm. The first choice of pump wavelength is one suitable for amplifying a signal being transmitted close to the zero dispersion wavelength in dispersion shifted fibre with λ_0~1550 nm. This suggests using a pump wavelength of 1460 nm which can be obtained from colour centre lasers, upconversion pumped thulium fibre lasers [1] or by cascaded raman generation from high power solid state lasers operating in the 1 μm region [2]. The second choice of pump wavelength which we consider in this paper is 1535 nm which can be obtained from recently developed high power, high efficiency and reliable erbium lasers [3]. The use of this wavelength suggests transmitting a signal with a wavelength in the region of 1.6μm. The important difference between these two choices of pump wavelength are that the loss at 1460 nm is 0.4 dB/km compared to 0.2 dB/km at 1535 nm. This will obviously affect the required pump power for each wavelength and the distribution of the raman gain along the fibre which may have a significant effect on soliton transmission. Another notable effect is that pump loss due to depletion is proportional to the raman gain and therefore operating away from the raman gain curve, at the expense of higher pump power, results in a more uniform gain distribution.

To investigate the characteristics of soliton propagation using these two pump wavelengths we have carried out a series of numerical simulations. The configuration used in the model was a bidirectionally pumped system with an amplification span of 27 dispersion lengths which corresponds to 40 km for a 2 ps (fwhm) soliton at 1560 nm. The pump powers were chosen such that the soliton intensity and pulse width returned to their original values at the end of the amplification span. Fig. 1a shows the variation in gain along the fibre length.The higher fibre loss of 0.4 dB/km at 1460 nm compared to 0.2 dB/km at 1535 nm means that up to 6 dB more launched power is required for a 1460 nm pump and that the gain variations along the fibre are much larger. Fig. 1b shows the variations in the soliton parameters along the fibre and demonstrates that the perturbations to the intensity and pulse width are smaller for the 1535 nm pump than for the 1460 nm pumping scheme. This is obviously advantageous for a soliton system since strong perturbations will generate dispersive wave radiation which can interfere with the soliton pulses and lead to Gordon-Haus timing jitter at the receiver. We can therefore make a preliminary conclusion that a pump wavelength of 1535 nm is preferable to 1460 nm.

To carry out an experimental study of a raman amplified soliton system pumped at 1535 nm we require a high power laser operating at this wavelength. The source used in our experiments is based on a 5 metre long Er/Yb codoped fibre laser pumped at 1054 nm by a Nd:YAG laser. The doped fibre has an erbium concentration of 600 ppm and a 20:1 ratio of ytterbium to erbium. The laser cavity was formed between two fibre gratings with 100% and 40% reflectivities. The output power as a function of launched pump power is displayed in figure 2 and show a slope efficiency of 23%. Output powers of close to 1W could be obtained from this laser demonstrating that the power required for a raman amplifier is easily achievable at this wavelength and is within the range of a diode pumped unit [4].

The pump was launched into 30 km of dispersion shifted fibre and to determine the distribution of the Raman gain along the fibre we performed a series of optical time domain reflectometry (OTDR) measurements. The pulse source for these measurements was an Er/Yb Q-switched fibre laser operating at 1580 nm pumped by a miniature Nd:YAG. The laser generated pulses of 2 μsec duration, giving a resolution of ~1 km, which were passed through an erbium amplifier to give a launched peak power of ~50 mW.

The results of these measurements are shown in figure 3 for the case no raman pump and with 600 mW of launched pump power. For the case of no Raman pump we saw, as expected, a flat background loss of 0.2 dB/km. With the copropagating Raman pump the measured net gain varied from ~0.1 dB/km at the beginning of the fibre to ~-0.1 dB/km after 30 km. Therefore the gain along the length of the fibre varies by only 0.2 dB/km, compared with an expected variation of over 1 dB/km for an exponentially decaying pump, which represents an extremely flat gain distribution that would be ideal for transmitting soliton pulses. However the initial gain gives a value for the Raman gain coefficient of $g_R=6.1\cdot10^{-15}$ m\W against an expected value of $1.4\cdot10^{-14}$ m\W for a 1580 nm signal pumped at 1535 nm. (Note that this value includes a reduction by a factor of two to account for the random polarizations of the pump and signal beams). Therefore the measured gain is smaller than expected and also the gain distribution along the fibre is much flatter than anticipated for this value of launched pump power.

One possible cause of this gain reduction is stimulated brillouin scattering (SBS) which has previously been shown to saturate raman amplifiers [5,6]. SBS is an interaction between the optical pump beam and acoustic phonons in the fibre which generates a backward propagating stokes beam downshifted in frequency from the pump beam. To model this effect we use the standard coupled equations for SBS [7] and assume a weak input at the end of the optical fibre at the wavelength of the brillouin scattered light. The parameters assumed for this model are a brillouin gain coefficient of $g_B=2.5\cdot10^{-13}$ m/W and an input stokes power of $P_s=100$ nW. The net Raman gain distribution predicted by this model is shown in figure 4 for a launched Raman pump power of 600 mW corresponding to the value in our experiment. Also shown for comparison are the measured value of the gain coefficient from figure 3 and the calculated gain for 150 mW of pump power for the case where no SBS occurs. It can be seen from figure 4 that for 600 mW of pump power SBS rapidly decreases the raman pump within the first 2 km of fibre leading to a much lower gain than if no SBS was present. Beyond 5 km the gain is similar to that shown for 150 mW of pump power with no SBS. Therefore the presence of SBS means that an increase in launched pump power is required to achieve the same gain although the flat gain distribution seen in our experiments may be advantageous for soliton transmission.

Another method to achieve a uniform distribution of raman gain in an optical fibre would be to vary the raman gain coefficient, g_R, along the fibre as the intensity of the pump, I_p, beam decreases. This technique of 'gain management' could be achieved by tailoring the germanium concentration in the fibre to keep the product $g_R I_p$ close to unity. This could be realised using recently developed low loss high germanium doped optical fibres [8] and would act in a similar way to other distributed techniques for soliton transmission such as dispersion decreasing fibre which adjust the fibre parameters to maintain a fundamental soliton throughout the system.

In an experimental demonstration of the feasibility of ultrashort soliton transmission using our 1535 nm pump source we have succeeded in transmitting solitons with a pulsewidth of 800 fs and a wavelength of 1565 nm over a total span of 22 km [9] of dispersion shifted fibre. The input and output optical spectra and autocorrelations are shown in figures 5a and b. With the raman gain there is a spectral shift of 5 nm due to the soliton self frequency shift but there is almost complete restoration of the initial pulse form. The total transmission distance corresponded to 150 dispersion lengths which is the highest number of dispersion lengths in a single span yet reported.

In conclusion, we have shown that for a system using raman amplifiers, because of lower fibre loss and lower pump depletion a pump wavelength of 1535 nm is preferable to 1460 nm and that a very flat gain distribution can be achieved in a 30 km optical fibre span. We have also demonstrated subpicosecond soliton transmission over 22 km with a high power 1535 nm pump source. Experimental results on 100 GHz transmission will be presented at the conference.

1. Y. Miyajima, T. Komukai and T. Sugawa, Electronics Letters, **29**, 660 (1993).

2. S.G. Grubb, T. Strasser, W.Y. Cheung, W.A. Reed, V. Mizrahi, T. Erdogan, P.J. Lemaire, A.M. Vengsarkar, D.J. DiGiovanni, D.W. Peckham and B.H. Rockney, Technical Digest OAA 95, paper SaA4-1, pp 197.

3. S.G. Grubb, OFC 95 Technical Digest, Paper TuJ1, pp 41.

4. W.A. Clarkson, K.I. Martin, D.C. Hanna, CLEO 95 Technical Digest, Paper CMD8, pp19.

5. B. Foley, M.L. Dakss, R.W. Davies and P. Melman, Journal of Lightwave Technology, **7**, 2024 (1989).

6. M.F. Ferreira, J.F. Rocha and J.L. Pinto, Electronics Letters, **27**, 1577 (1991).

7. G.P. Agrawal, Nonlinear Fiber Optics, 2nd Ed. Academic Press 1995.

8. E.M. Dianov, A.A. Abromov, M.M. Bubnov, A.V. Shipulin, S.L. Semjonov, A.G. Schebunjaev, A.N. Guryanov and V.F. Khopin, Tecnical Digest OAA 95, paper SaA2-1, pp 189.

9. A.B Grudinin and S. Gray, Electronics Letters, to be published.