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Gain-flattening of fibre Raman amplifier using non-linear pump spectral broadening and pump power modulation.

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Abstract: We propose a new technique for achieving gain-flattening of fibre Raman amplifiers based on nonlinear pump broadening and rapid pump power modulation. In our experiments, pump broadening of a continuous-wave Raman fibre laser tuned at 1455 nm is achieved by propagation in a non zero dispersion-shifted fibre (NZDSF). The amount of pump broadening is controlled by the pump power delivered into the NZDSF, and the flatness and center wavelength of the gain band is defined by the amount of pump broadening. With a rapid modulation of the pump power, flat gains of 9 dB with 0.2 dB ripples can be obtained in the case of three modulation levels (1.5/1.8/2.1 W) between 1580 and 1630 nm. Gains between 7 and 8.5 dB can be achieved in the spectral region between 1575 and 1640 nm.

1.- Introduction

Raman amplification is now a widely accepted technique for upgrading fiber-optic communication systems. One of the main advantages of Raman amplification in optical fibres is that it might be obtained in any spectral region of the optical fibre, since it depends basically on the frequency separation between pump and signal and not on their absolute frequencies. However, the basic problem of Raman gain is that its spectrum is not flat over a wide range of wavelengths, but rather it has a peak at a certain frequency detuning from the pump spectrum (typically 13-14 THz). Thus, gain-flattening of fibre Raman amplifiers has been widely studied these past few years [1]. Methods to achieve gain-flattening of fibre Raman amplifiers include wavelength-division multiplexed pumping, rapid wavelength-tunable pumping and nonlinear pump spectral broadening [2,3,4,5].

In this work we propose a new technique for achieving gain-flattening of fibre Raman amplifiers based on nonlinear pump broadening and rapid pump power modulation. This scheme is substantially simpler than most of the previous ones while it ensures excellent results. We demonstrate the capabilities of this technique using experimental data. In our experiments, pump broadening of a continuous-wave Raman fibre laser tuned at 1455 nm is achieved by propagation in a non zero dispersion-shifted fibre. The amount of broadening depends on the pump power, and also the gain spectrum of the amplifier [6]. We measure the gain spectrum of the amplifier at different pump power levels. From this data we calculate the effective gain seen by the signal if we apply a rapid modulation of the pump power (pump and signal travel in opposite directions). In this way, we can easily control the effective gain seen by the signal. With 2.1 W of peak pump power, flat gains between 7 and 8.5 dB can be achieved in the spectral region between 1575 and 1640 nm.

2.- Non linear pump broadening.

In previous works we have demonstrated that non-linear broadening of a powerful, continuous-wave pump can be achieved by propagation in the regime of small anomalous dispersion [7,8]. The spontaneous fission of the partially-coherent input cw beam into a sequence of Raman-shifted solitons is the main cause of this extreme spectral broadening. This non-linear broadening provides us with a relatively broadband source with extremely high power spectral density. We propose the use of this source as the pump of a broadband Raman amplifier.

The pump used in our experiment was a continuous-wave Cascaded Raman Fiber Laser (C-RFL) with a single-mode output tuned at 1455.3 nm. The laser output is depolarized and the maximum output power reaches 2.1 W. A feedback control ensures that the output power of the RFL remains constant and controlled with an accuracy of ± 10 mW. The line width of the RFL grows as the power is increased. For a pump power of 2.1 W, the full width at half maximum (FWHM) of the laser output is 1.17 nm, with a RIN < -110 dB/Hz (measured in the range 0-1 GHz). To broaden the pump spectrum we use a 6.8-km-long spool of nonzero dispersion-shifted fiber (NZDSF) with an expected dispersion at the wavelength of the pump of $0.081 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$ ($\lambda_0=1453.5$ nm). The dispersion

slope at this wavelength is $0.045 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$. The dispersion uniformity along the fiber was tested with the method reported in [9], and was found to be better than $\pm 0.1 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$ at the wavelength of 1555 nm (spatial resolution is $\sim 500 \text{ m}$). The fiber loss at the wavelength of 1550 nm is 0.2 dB/km and it remains mostly flat from 1450 to 1620 nm. The pump that we broadened experimentally was a continuous-wave Raman Fibre Laser (RFL) tuned at 1455.3 nm.

Figure 1 shows the spectrum of the RFL alone for different power levels. The line width of the RFL grows as the power is increased. Figure 2 shows the spectrum at the fibre output for the same power levels as in Figure 1. For low pump powers, the signature of modulation instability (MI) is clearly visible as two symmetric gain sidebands at each side of the pump wavelength. As the pump power grows, more power is transferred to the MI sidebands and the initially narrow pump significantly broadens in the fibre. If enough pump power is reached, MI causes the breakup of the partially coherent beam into a sequence of fundamental solitons, which are frequency down-shifted due to the Raman effect. The result of this process is a broadband source as depicted in fig. 2.

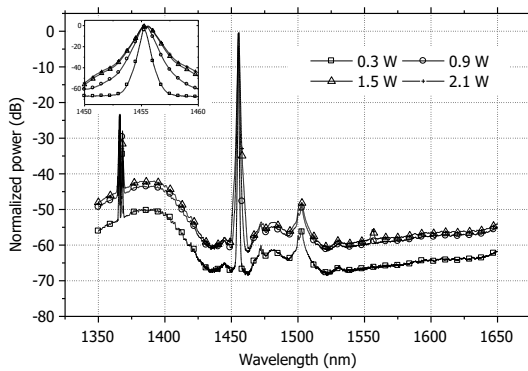


Figure 1: Normalized output spectrum of the RFL. The resolution of the spectrum analyzer used was set to 50 pm, and the sensitivity is better than -70 dBm. The inset shows in detail the spectrum around the pump wavelength. Note that the linewidth of the pump is larger as the power grows.

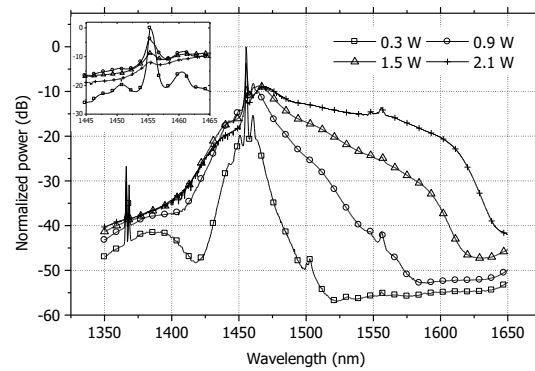


Figure 2: Spectrum of the generated supercontinuum. The settings are the same as in the previous figure. The inset shows how complete pump depletion is achieved for powers higher than 1.5 W. As it can be seen, the amount of pump broadening is controlled by the amount of power delivered in the fiber

3.- Raman gain measurements.

If a Raman amplifier is pumped with a broadband source, the gain spectrum appears significantly smoothed since the final gain spectrum is the convolution of the pump spectrum with the Raman gain spectrum. To demonstrate the concept of gain-flattened Raman amplification using nonlinearity-broadened pumps we developed the experimental scheme depicted in figure 3 [10].

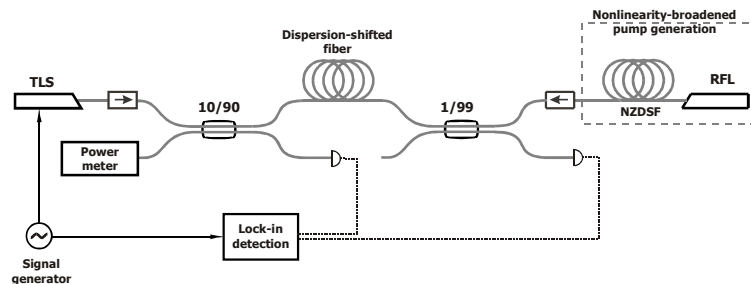


Figure 3: Experimental setup for the characterization of the on-off gain of the Raman amplifier using the nonlinearity-broadened pump. NZDSF: non-zero dispersion-shifted fiber

A modulated tunable laser source (TLS) with a 150 kHz line width acts as the signal source. The modulation frequency is 32 KHz. To minimize the effects of pump depletion and stimulated Brillouin scattering (SBS), the signal is strongly attenuated using a variable optical attenuator (VOA). Additionally, only 10% of the signal power is coupled into the fiber through a calibrated 10/90 coupler. The signal power at the fiber input is monitored constantly by the 90% output of the coupler.

The spare end of the coupler is used to monitor the pump power at the fiber output with a power meter. The amplifying medium is an 11-km-long dispersion-shifted fiber (DSF). The amplifier is configured in counterpropagation, so pump and signal wavelengths are launched from opposite sides of the DSF. Broadband isolators are placed at the pump and signal sides to prevent laser instabilities due to external injection. The pump is coupled into the fiber by the use of the 99% output of a 1/99 coupler. The broadened pump is obtained by propagation of a Raman fiber laser through a fiber with small anomalous dispersion, as detailed in the previous section. The signal power at the fiber output is monitored through the 1% output of the coupler. Measurements were performed at different input pump powers, with and without the NZDSF. Without the NZDSF, we measure the conventional Raman gain spectrum, whose logarithmic gain scales linearly with the power delivered into the fiber. Figure 4 show the on-off gain results of the amplifier with the NZDSF. In this case the pump is broadened, and the peak logarithmic gain does not grow linearly with power, since the amount of pump broadening is strongly power-dependent. For low pump powers (0.1-0.5 W), there is no significant pump broadening and the Raman gain response is basically similar to the one obtained in the case of the non-broadened pump, except for the 40% decrease in the peak gain due to the extra losses caused by the NZDSF. For higher pump powers (0.9-2.1 W), the gain in the amplifier appears smoother, and the characteristic gain ripple of the Raman gain is removed. Simultaneously, the peak gain appears at drastically lower values and shifted towards longer wavelengths.

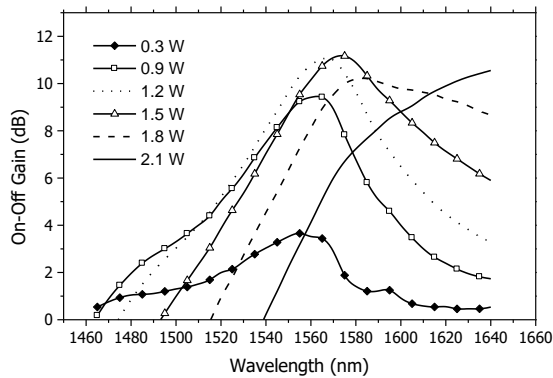


Figure 4: Experimental results when the NZDSF is present in the setup (broadened pump case).

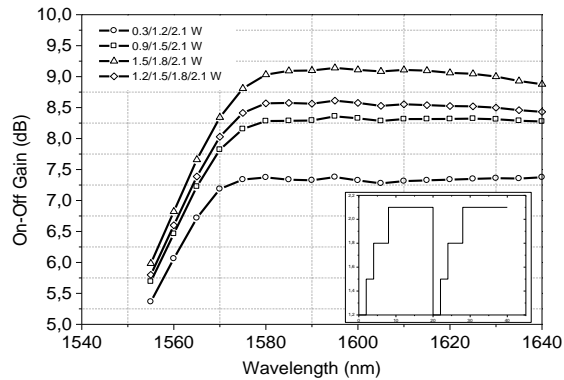


Figure 5: Some calculated effective gain results in the modulated-pump case, using three and four modulation levels. The insert show the modulation profile.

The decrease in the peak gain is caused by the losses introduced by the NZDSF and the redistribution of power from the initial pump spectrum among all the wavelengths forming the broad pump at the NZDSF output. The shift of the gain peak is due to the Raman shift in the centre wavelength of the broadened pump spectrum. The good consequence of the spectral redistribution of the pump power is that the gain spectrum of the amplifier appears drastically flattened. In contrast with the results obtained with the non-broadened pump, in this case the bandwidth of the amplifier grows as the power is increased. If we compare the case of an input pump power of 1.2 W in the broadened and non-broadened pump case we can see that the 1-dB bandwidth of the amplifier in the broadened pump case is 27 nm, while in the non-broadened pump case it is ~9.5 nm. The peak gain in the non-broadened pump case is 14 dB greater than the peak gain in the broadened pump case. We see that a careful setting of the pump power would be necessary depending upon the requirements of gain and flatness. A short look at the spectrum of the broadened pump indicates that a significant amount of pump power falls in the spectral region of the amplified signal. This will surely affect the signal-to-noise ratio (SNR) at the output of the amplifier, since some amount of pump power will be backscattered towards the receptor. The noise figure of the broadened pump case has not reached the low levels obtained in the non-broadened pump case. This is because some residual broadening of the pump occurs in the amplifying fibre. This contribution to the noise figure is, in our view, practically inevitable, and should be considered as a limitation of this technique.

To improve our Raman amplifier we thought on rapid (~MHz) tuning of the pump laser power. In this situation we could 'modulate' rapidly the pump broadening (the nonlinear process occurs on a much shorter time scale). If the pump modulation is rapid enough and/or the amplifying fiber is long enough, the effective gain seen by the signal corresponds to an average of the different gains seen by the signal for each modulation level. By a careful tuning of the pump modulation, this should produce flat Raman gain, since as we can see the gain of the amplifier covers different spectral regions for different power levels present at the NZDSF input. In figure 5 we show the calculated on-off gain for the modulated pump scheme of the inset. Each line represents the Raman gain for different pump levels combination. We can see how if we choose an appropriate modulation scheme, we can obtain a gain of 9 dB with 0.2 dB ripple in the case of three modulation levels (1.5/1.8/2.1 W) between 1580 and 1630 nm. Actually, gains between 7 and 8.5 dB can be achieved in the spectral region between 1575 and 1640 nm by using different modulation profiles. The main issue of this configuration is the difficulty of modulating lasers with 2 W of power.

4.- Conclusions

We have demonstrated that gain flattening of single-pump fibre Raman amplifiers is possible by use of nonlinear spectral broadening of the pump. A balance is found among the peak gain of the amplifier and its bandwidth, both magnitudes being related in different ways to the amount of broadening achieved in the nonlinear medium. The noise figure in this configuration is poor, mainly due to spectral components of the broadened pump that fall into the gain band of the amplifier. A suitable filtering using the appropriate WDMs might partially solve this problem, as we will show in our presentation. If we think on rapid (~MHz) tuning of the pump laser power, we would be able to 'modulate' rapidly the pump broadening (the nonlinear process occurs on a much shorter time scale). In an amplifying fibre of several kilometers, and by a careful tuning of the modulating signal, this could possibly produce flat Raman gain. This scheme offers many advantages in comparison with other existing setups, although the modulation of the pump laser is the main technological challenge.

Acknowledgements

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