Dual-pump Raman amplification with increased flatness using modulation instability

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Abstract: The application of modulation instability-initiated nonlinear broadening of two CW pumps at different wavelengths, in order to achieve superior gain ripple performance in broadband Raman amplifiers, is demonstrated for the first time experimentally. A particular example using Truewave and LEAF fibers is offered, in which the 0.1 dB gain ripple band is extended from 5 nm to 19 nm. Experimental results are in a good agreement with numerical modeling. Guidelines for optimal broadening are discussed.

OCIS codes: (190.5890) Scattering stimulated; (060.2320) Fiber optics amplifiers

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1. Introduction

The application of distributed Raman amplification in long-haul, broadband transmission using wavelength division multiplexing (WDM) relies on the ability of the amplifiers to provide a flat gain profile to enable maximum reach of all signal channels. The gain flatness of the amplifier over its operational bandwidth can be improved by using a large number of pumps [1], but this is not always a practical solution, since it increases both the cost and the complexity of the system while reducing its flexibility. Therefore, alternative approaches to gain ripple suppression are of great practical and fundamental interest. Time-division multiplexing of the pumping waves (smart pumping) capable of producing a very flat gain has been proposed in [2], and another possibility for lowering residual Raman gain fluctuations with a fixed number of pump sources is to apply a nonlinearly-broadened pump [3] as originally demonstrated in [4], and shown later in (for a single pump wavelength) [5,6]. Spectral broadening of the pump in fiber requires some modulation of the coherent optical beam. This can be achieved either by applying external modulators as in [2], or by taking advantage of nonlinear fiber processes. In this work we utilize modulation instability [7, 8] to initially broaden two CW-pumps of a wideband Raman amplifier, and study the improvement achievable on its gain response.

2. System configuration and basic theory

The studied system, depicted on Fig. 1, is a traditional transmission line backward pumped with two conventional Raman laser pumps, centred at 1455 and 1480 nm. Each of the pumps propagates through a different broadening pre-fibre before being combined together by a 3dB coupler and then injected into the transmission/amplification medium, in our case comprised of 25.26km E-LEAF fibre, via a Wavelength Division Multiplexer (WDM). The WDM does not only couple the pump light into the transmission line but also removes any spontaneous component that may otherwise occupy the signal band.

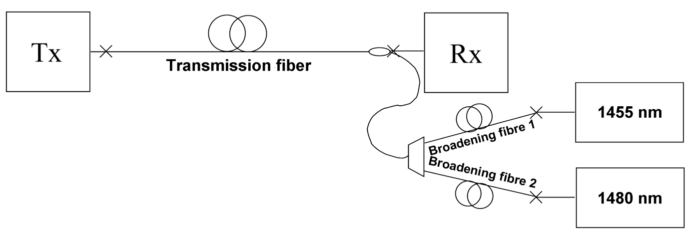

Fig. 1. System schematic

Fibre nonlinearity can be used to broaden the spectrum of a powerful pump wave through the self-phase modulation effect. This, however, requires a temporal variation of the pump waveform. To avoid using more complex schemes based on external modulators, one can utilize an inherently nonlinear fibre phenomenon such as modulation instability. When the signal from a high-power CW source travels through a section of suitable fiber, modulation instability (MI) causes the break-up of the continuous wave into a series of short pulses that then can be broadened due to self-phase modulation (SPM), four-wave mixing (FWM), Raman scattering (RS) and all other nonlinear interactions in the fiber. Eventually, if the input power is high enough and the fiber length allows it, even a supercontinuum can be generated [6,9]. For the application of the effect on Raman amplifiers, such an outcome is not desirable, and we are instead interested in exerting as much control as possible over the bandwidth of the broadened spectrum, in order to optimize the gain performance provided by the pump or pumps. In the first stages of nonlinear broadening, in which MI is the dominating effect, the frequency-dependent gain coefficient, assuming a coherent pump wave, is given by the well-known expression (1).

$$g(\Omega) = |\beta_2 \Omega| [\Omega_c^2 - \Omega^2]^{1/2} \quad (1)$$

Obviously, the gain exists only if (2),

$$\Omega^2 < \Omega_c^2 = (4\gamma P_{in} e^{-\alpha z}) / |\beta_2| \tag{2}$$

Where γ is fibre nonlinear coefficient, β_2 is dispersion, α is the fibre loss, and P_{in} is the pump input power. The modulation instability causes power transfer from the CW pump and generates two bands symmetrically positioned at both sides of the initial pump, with a maximum at (3)

$$\omega_0 \pm \Omega_{MAX}, \ \Omega_{MAX} = [2\gamma P_{in} \exp(-\alpha z) / |\beta_2|]^{1/2}. \tag{3}$$

In the time domain, the CW beam is converted into a periodic pulse train with the period $T = 2\pi / \Omega_{MAX}$. The separation of the side peaks depends on the characteristics of the fibre. A low (but anomalous) dispersion leads to a more substantial broadening. Therefore, a simple design rule is to choose pump/fibre parameters using the expression for Ω_{MAX} in order to shift the side peaks to the required positions in the spectral domain. The dependence of MI characteristics on input power, dispersion and nonlinear coefficient can be used to select the best combination of pump/fibres parameters in order to achieve optimal pump broadening at any given frequency.

Evidently, and since MI is the dominant effect on the initial stages of the pump broadening only, the final spectrum of the broadened pump will be defined by the interplay between the various nonlinear effects on the fiber, so a full numerical simulation is required to properly describe the broadening process at the final stage. Similarly, although the analytical formulae above give a good approximated description of the MI process in the first stages of transmission, which is sufficient for our purposes, a more thorough analysis would require taking into account the field spectrum of the partially coherent pump source, as shown in [10] and [11]. Nevertheless, the necessary conditions for MI initiation set fundamental requirements on pump/fiber parameters, as illustrated by the results of experimental tests presented in Fig. 2. Figure 2 depicts the effect of MI on a CW laser transmitted through a 10.390 km Truewave fiber either side of the zero dispersion wavelength, under slightly normal (grey trace) and under slightly anomalous (black trace) dispersions.

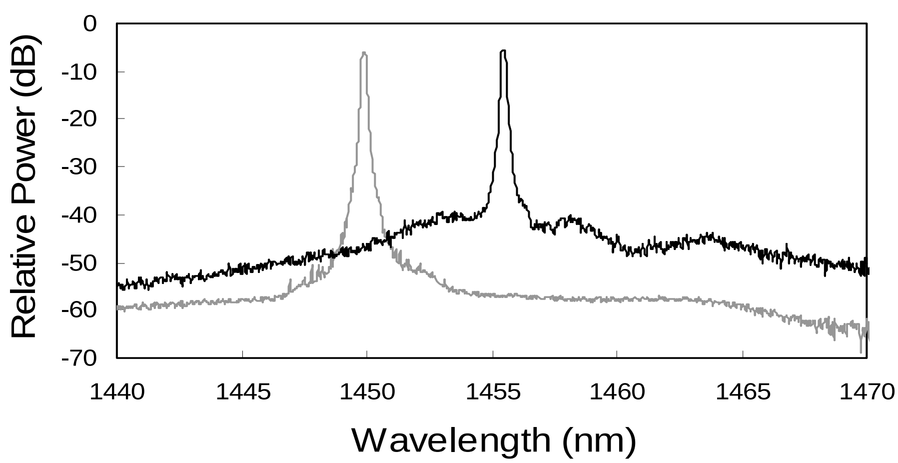

Fig. 2. CW light after propagation through 10.390km length of Truewave, the dispersion zero is approximately at 1454nm. The MI peaks produced at 1455nm can be seen, but are not apparent at 1450nm.

It is interesting to note the asymmetric profile of the broadened pump, with a higher presence of radiation in the blue region of the spectrum for the 1455 nm pump trace on Fig. 2. This asymmetry is, according to our simulations, dependent on the presence of higher-order dispersion terms, and gradually shifts to favour the red region of the spectrum as the pump

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power increases or the pump wavelength is moved further away from the zero-dispersion-wavelength

3. Results

Two Truewave-RS fibers were used for the broadening of the pumping waves. For the 1455 nm pump, a 10.390 km reel with a zero-dispersion wavelength of approximately 1454 nm and a dispersion slope of 0.046 $ps/nm^2/km$ was used. The 1480 nm pump was broadened in a 5.077 km piece of fiber with zero dispersion wavelength at approximately 1475 nm with a dispersion slope of 0.049 $ps/nm^2/km$. The non-linear coefficient of TrueWave (given at 1550 nm) is 1.84 $W^{-1}km^{-1}$. Note that the zero dispersion wavelengths given are an average value and must be considered approximate due their variation along the fiber length. Pump powers at the input and the output of the pre-broadening fibers were monitored using a power meter which integrates over the whole pump bandwidth. Figure 3 shows the pump spectra at the input and output of the broadening fiber, in order to obtain broadened pump powers of 391 mW (1455 nm) and 715 mW (1480 nm), from input powers of 690 mW and 1052 mW respectively. Further losses in the coupler between the broadening fibers and the transmission fiber will bring the pump powers down to 190 mW (1455 nm) and 290 mW (1480 nm).

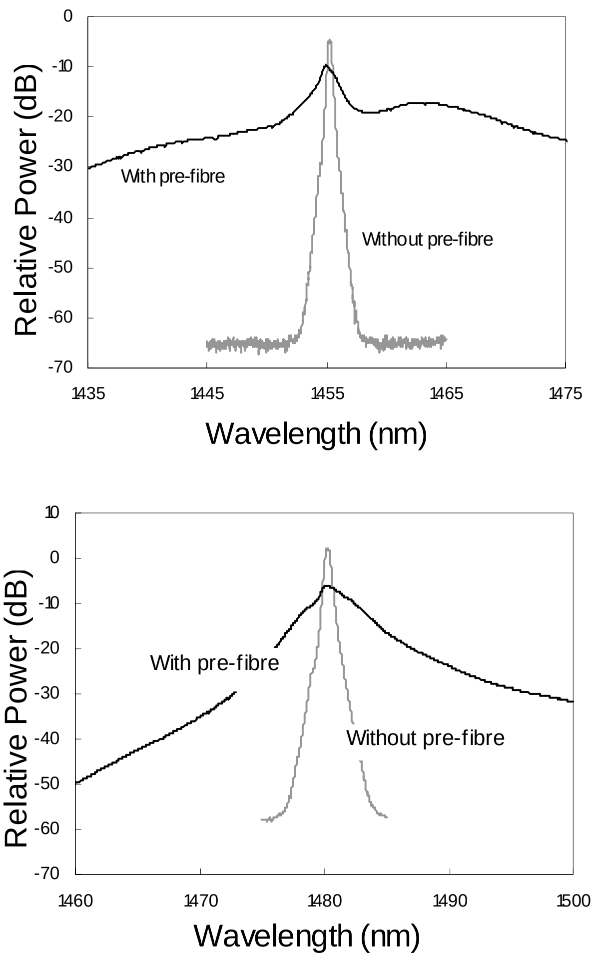

Fig. 3. Pump spectra at the input (grey lines) and output (black lines) of the broadening pre-fibers. Top - 1455 nm. Bottom - 1480 nm.

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Even though the available pre-broadening fibers are not ideal, and Stokes generation at high input powers limit the range of possible outputs, we can see that thanks to the proximity of the zero-dispersion wavelength, the broadening in the 1455 nm pump is excellent, the main limitation to its applicability being the asymmetry of the broadened spectrum that, at high input pump powers, causes a noticeable offset of the effective central wavelength of the pump. Both the broadening and the offset are less evident for the 1480 nm pump, which is more than 5 nm apart from the zero-dispersion wavelength of its broadening fiber and has a shorter length for the MI process to operate over.

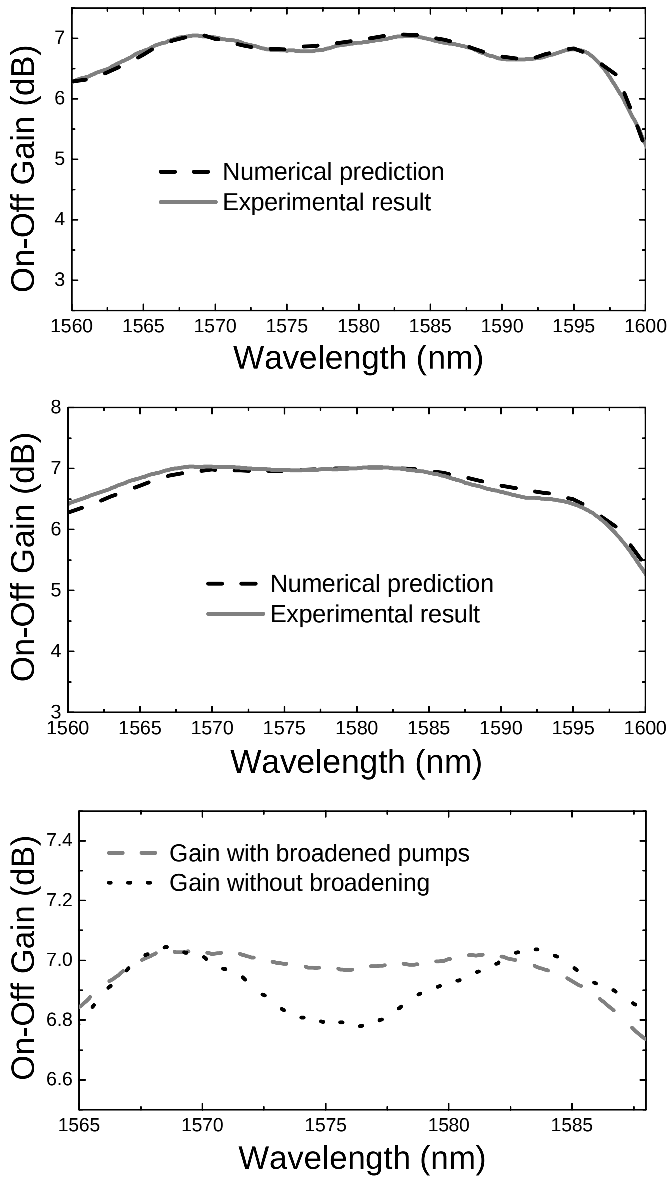

Fig. 4. Gain spectra of the amplifier on its different configurations: Top - With unbroadened pumps. The solid line corresponds to the experimental result, while the dashed line shows the numerical prediction. Center - With nonlinearly-broadened pumps. The solid line corresponds to the experimental result, while the dashed line shows the numerical prediction. Bottom - Comparison between the gain ripples with and without pump broadening.

Figure 4 (top) compares the numerically obtained low-power signal (-10 dBm/channel, 170 GHz channel spacing) on-off amplifier gain for the case of non-broadened pumps (considered monochromatic for the simulation), and the measured experimental gain curve, for pump powers of 118 mW (1455 nm) and 357 mW (1480 nm) after the coupler. The transmission/amplification fiber is composed of 25.26 km of E-LEAF with a Raman gain co-efficient of 0.5 W^{-1} km^{-1}. The numerical model considered, based on the integration of the well-know Raman amplifier average power equations [12], and superior to that used in [4], estimates the gain spectrum for the discretized frequency space, taking into account all important effects, including pump-to-pump interaction, Rayleigh backscattering and pump depletion. The agreement between numerics and experiment is excellent.

The equivalent gain curve obtained with the broadened pumps shown on Fig. 3 is depicted on Fig. 4 (center), which compares again the numerical prediction and experimental result. In this case, a dense series of experimental broadened pump spectra were sampled for their use in the numerical simulations, so that the spectral profile of a broadened pump in our simulations could be approximated by the measured broadened spectra of a pump of similar power. Please note that the optimal pump powers that lead to a flattened gain response of the amplifier differ from the case of monochromatic pumps. The main reason can be found in the wavelength offset of the broadened pumps, which are not centered at 1455 and 1480 nm anymore.

Even though the limitations imposed by the available pre-broadening fibers, especially that of the 1480 pump, led to a drop in the gain at about 1590 nm for the broadened pump amplifier, the improvements in gain ripple performance are evident, as shown in Fig. 4 (bottom). In particular, the continuous bandwidth corresponding to a gain ripple of 0.1 dB is increased from 5 nm to 19 nm, and the total gain variation over a 20 nm window is halved from 0.26 dB to 0.13 dB. From recent work by ourselves, we have seen that a more appropriate ‘pre-fiber’(more effective broadening for less pump attenuation) would allow for encapsulation and extension of the gain bandwidth over that of the case without broadening. One contender for such a fiber is Highly Non-Linear Fiber (HNLF). Future work will involve the implementation of HNLF for a WDM pump scheme along with the removal and replacement of the non-ideal 3 dB coupler which currently combines the two pump wavelengths with a suitable WDM.

4. Conclusions

The effect of modulation instability in transmission fibres has been investigated to generate broadened laser pump spectra for two different pump wavelengths that have been directly applied to the generation of a low-ripple broadband Raman gain. We demonstrate that, by selecting the broadening ‘pre-fibers’ for each pump wavelength in order to boost MI in the first stages of the nonlinear broadening, it is possible to exert some control over the final pump spectra, leading to clear improvements on the flatness of the amplifier gain. In our particular experimental example, we demonstrate an extension of the 0.1 dB continuous gain ripple bandwidth from 5 nm to 19 nm. This work demonstrates the possibility of applying the broadening technique to multi-wavelength Raman amplifier design, although an improvement of the degree of broadening and a reduction of the pump power losses in the ‘pre-fiber’ are required to obtain a more viable solution. It might be possible to achieve this goal by utilizing fibers with more appropriate nonlinear/dispersive characteristics such as HNLF.

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