Record Gain, Low Noise Figure, C+L Band Lumped Raman Amplifier

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Abstract *We demonstrate a compact and high performance dual-stage lumped Raman amplifier using 2x1 km lengths of highly nonlinear fibre. The amplifier provides a record 27-dB gain (2.6-dB flatness) and low 5.8-dB average NF (<1-dB flatness) over a bandwidth of 80 nm.*

Introduction

Raman amplifiers represent an attractive solution to help meet the ever increasing demand for network transmission capacity due to their customisable and broad bandwidth and the fact that they could in principle be readily installed in existing single mode fibre networks to extend the usable spectral bandwidth at wavelengths beyond the C-band, e.g., in the near term to exploit the C+L band. Compared with distributed Raman amplifiers, which are already routinely employed, lumped Raman amplifiers (LRAs) are relatively easy to implement and less of a concern from a laser safety perspective since the high pump power does not need to travel along the transmission fibre itself[1]. Small-core fibres with a large nonlinear coefficient, such as dispersion compensating fibres (DCFs), highly nonlinear fibres (HNLFs) and inverse dispersion fibres (IDFs), have all been used as Raman gain media for LRAs and all can provide good pump conversion efficiency[1-3]. When designing an LRA, careful consideration needs to be paid to the mitigation of a variety of potential issues that can otherwise compromise the performance, in particular multipath interference due to double Rayleigh scattering (DRS) and nonlinear impairments induced by the Kerr effect[1]. DRS can be adequately managed by employing dual-stage amplifier designs incorporating a mid-stage isolator to suppress DRS-induced noise and to increase the usable net gain.

Recently, LRAs have been demonstrated offering ~20-dB gain over a spectral window of >70 nm[3, 4]. However, these LRAs exhibited considerable wavelength dependent noise (i.e., a higher noise figure (NF) at shorter wavelengths) emanating from the thermal distribution of phonons in the fibre[5]. The NF tilt was as large as ~2.5 dB with a maximum NF of >7 dB across the >70-nm-wide bandwidth[3, 4]. This NF issue was addressed in another demonstration by employing an improved pump wavelength distribution scheme across two amplification stages[6]. However, the total net gain was limited in this instance to just 14 dB because the pump wavelengths were grouped to provide C-band-weighted amplification in the first stage and L-band-weighted amplification in the second stage. It should be noted that these demonstrations used >10-km-long fibres for amplification which resulted in a high background loss and relatively large device footprint. As a result of the long device length, each individual amplifier stage has a maximum usable gain limit (usually less than 15 dB) imposed by the onset of DRS-induced system penalties.

In this paper, we report a compact dual-stage LRA providing high performance amplification (27-dB average gain and 5.8-dB average NF) across the wavelength range from 1529 nm to 1609 nm using HNLF. The HNLF has a much higher Raman gain coefficient than other types of fibre, which allowed us to shorten the total device length significantly to just 2 km. The further benefits to employing a short fibre length is that DRS is more manageable at higher power levels. Additionally, we have kept the pump wavelengths the same in both stages, and controlled the gain profile of each amplifier stage by carefully managing the pump powers so as to simultaneously achieve a high overall gain and good noise performance. The spectral flatness of the NF was also improved to only 0.9 dB. A preliminary back-to-back BER measurement was done to validate the performance of our LRA and no fundamental problems in operational input signal power range were found.

Experimental setup

As depicted in Fig. 1, the LRA comprised two

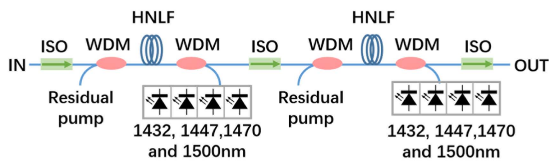

Fig. 1: Structure of the C+L band lumped Raman amplifier

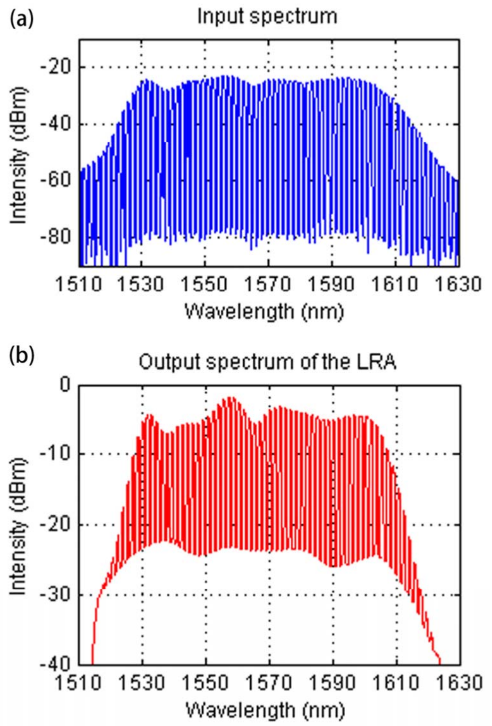

Fig. 2: Spectra recorded at both (a) input and (b) output of the LRA (operated with USGC) (resolution: 0.2 nm)

amplifier stages, each of which consisted of a 1-km-long HNLF and two WDM couplers. The HNLF had a mode field diameter of 3.5 μm and fibre attenuation of 0.6 dB/km at 1550 nm, and a peak Raman gain coefficient of 6.9 $W^{-1}km^{-1}$ (measured with a 1430-nm pump beam). Both amplifier stages were backward pumped by four Raman pump wavelengths (1432, 1447, 1470 and 1500 nm). Two optical isolators were used to prevent feedback from unwanted reflections at the input and output ports of the dual-stage LRA, and a mid-stage isolator was incorporated to reduce the impact of DRS.

To characterise the optical performance of our LRA in a multi-channel signal loaded scenario, a

Tab. 1: Coupled pump powers used in our LRA

Operation schemes	Pump wavelength (nm)	1st stage pump power (mW)	2nd stage pump power (mW)
ESGC	1432	592	550
	1447	307	260
	1470	259	200
	1500	182	186
USGC	1432	592	504
	1447	307	243
	1470	259	229
	1500	66	333

50-WDM channel source with 200-GHz spacing was constructed as an input signal based on a broadband ASE source (1529-1609 nm) and a cascade of 100/200-GHz interleavers. Figure 2(a) shows a typical spectrum of this multi-channel seed. All channels had an optical signal to noise ratio (OSNR) of >45 dB and the intensity flatness was ~8 dB from 1529 nm to 1609 nm. The total input power was set to -7 dBm, corresponding to an average input power per channel of -24 dBm.

Results and discussion

The LRA was tested in two different operating scenarios which are respectively designated as "equalized spectral gain control" (ESGC) and "unequalized spectral gain control" (USGC) for the two amplifier stages in this paper. The experimental coupled pump powers used in these two schemes are summarised in Tab.1. In the ESGC scheme, the first and second stage Raman amplifiers were designed to individually provide flat gain (about 13 to 14 dB net gain per stage), thus achieving a flat overall gain profile (~27 dB) at the output. The pump powers for each amplifier stage were first estimated via numerical simulations, which were then used as initial starting values for further experimental optimisation targeting spectral gain variation of <3 dB. It should be noted that the flatness could be further optimised by more iterations. As

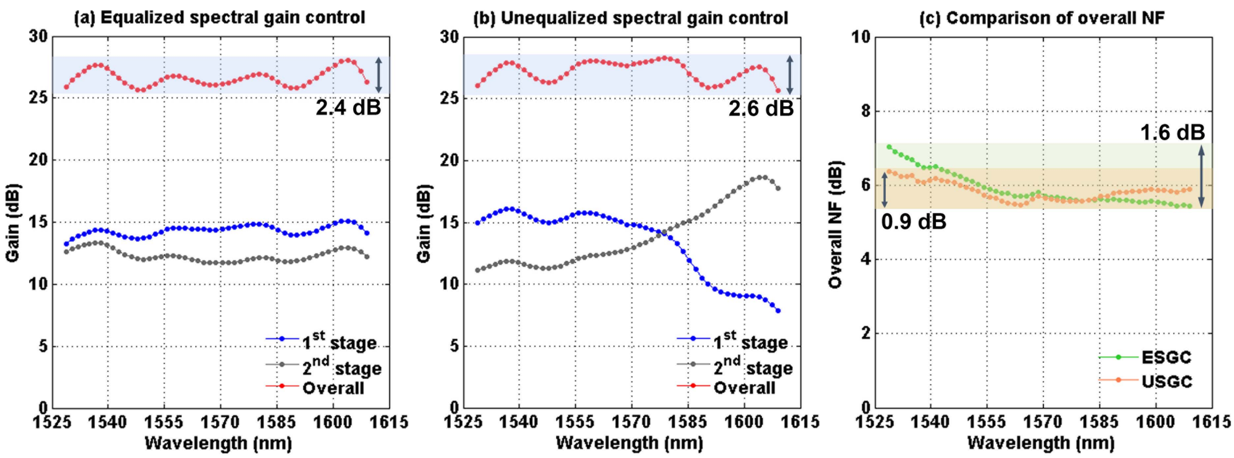

Fig. 3: Gain profiles of the dual-stage LRA under (a) ESGC conditions or (b) USGC conditions; (c) Comparison of the overall NF between the two schemes

illustrated in Fig. 3(a), a relatively flat gain was obtained in both the first and second amplifier stages, and in combination a total average gain of 26.6 dB was achieved with a gain flatness of 2.4 dB over a bandwidth extending from 1529 nm to 1609 nm. In this case, the overall NF was 5.9 dB on average and exhibited a 1.6-dB NF tilt. The maximum NF was 7 dB at 1529 nm and the minimum NF was 5.4 dB at 1609 nm.

This NF tilt was mainly attributed to the thermal noise of the longest pump wavelength (1500 nm) being in close proximity to the shortest signal wavelength (1529 nm). Bidirectional pumping of a Raman fibre amplifier with shorter-wavelength pumps in the forward direction can improve the wavelength dependence of the NF but this requires low-RIN pump laser sources in the forward direction[7]. To improve the NF tilt of the counter-pumped LRA, USGC was introduced into the operation of the dual-stage LRA, where the longer-wavelength pump power in the first stage was deliberately kept low to minimise the thermal noise at shorter signal wavelengths. The reduced longer-wavelength gain was then compensated for in the second stage to obtain a similarly flat overall gain. An example of running the LRA with USGC is plotted in Fig. 3(b). Although the gain in each stage was not flat, a flat overall gain profile was still achievable by carefully managing the pump powers used in both amplifier stages. With the pump power values shown in Tab. 1, the LRA yielded a total average gain of 27.2 dB with 2.6-dB gain flatness for an input signal of -24 dBm/ch. As for noise performance, it can be seen from the orange line in Fig.3 (c) that the overall NF was flattened across the amplifier bandwidth, resulting in an improved noise flatness of 0.9 dB. The average overall NF was measured to be 5.8 dB with the worst channel NF at 6.4 dB. Due to the smaller thermal noise contribution by the 1500-nm pump in conjunction with weaker pump-to-pump energy transfer in the first stage amplifier, the 1432-nm and 1447-nm pump beams were able to propagate further and offered higher gain at shorter signal wavelengths towards the fibre input, thereby improving the NF of the first stage amplifier. In a dual-stage system, the overall NF is primarily determined by the NF of the first stage amplifier. However, the NF at longer signal wavelengths experienced a small degradation because of the lower gain in the first stage and increased ASE in the second stage. Therefore, the overall NF flatness was improved in the USGC scheme. Fig. 2(b) shows the output spectrum of the dual-stage LRA with USGC and an OSNR of ~20 dB was observed for most signal channels at a resolution of 0.2 nm.

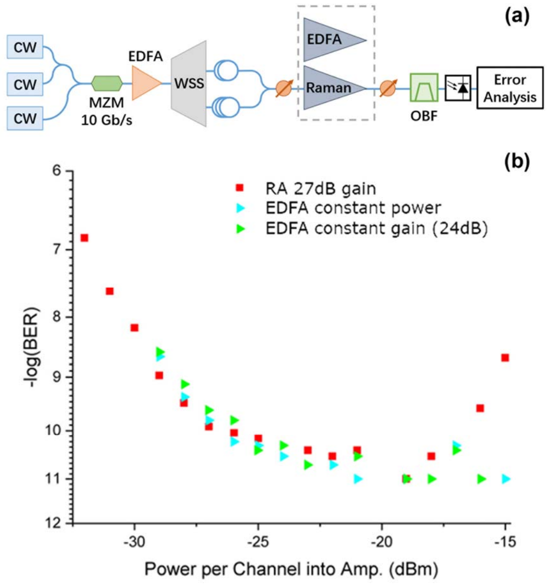

Fig. 4: (a) Schematic of the back-to-back BER test and (b) the performance of the LRA compared with EDFAs

Preliminary transmission test

A back-to-back BER measurement was carried out to compare the dual-stage LRA with EDFAs operating under two different gain control modes (constant gain and constant power). Figure 4 illustrates the schematic and results from this test. Three 10-Gbps-OOK 50-GHz-spaced channels spaced about a centre wavelength of 1550.12 nm were launched into either our LRA or a commercial EDFA. We varied the launch signal power into the amplifier under test, held the power level at the receiver end constant, and recorded the BER of the central channel. As indicated by Fig.4 (b), the LRA and EDFA behaved very similarly at signal input powers of up to -20 dBm/ch, where linear noise dominates. BER degradation mainly due to nonlinear impairments (e.g., FWM and SPM) was only observed in the LRA for an input signal power of >-20 dBm/ch resulting in a >7-dBm/ch output signal power which is beyond conventional operating signal power levels in real-world transmission systems.

Conclusion

We have demonstrated a high gain, low noise, broadband lumped Raman amplifier enabled by tailoring the wavelength dependent gain distributions in the two amplifier stages. Further data transmission tests to check the performance of the amplifier are underway.

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