130 nm SCL-wideband and -7.1 dB effective-noise-figure amplification using third-order distributed Raman amplifier

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***Abstract*—By using multiple and backward pumped third-order Raman, we experimentally demonstrate an ultra-low-noise amplification over 130 nm bandwidth covering SCL band with lowest -7.1 dB effective noise figure and 13.6-dB average gain obtained.**

Keywords—ultra-wideband, ultra-low-noise, third-order distributed Raman amplifier

I. INTRODUCTION

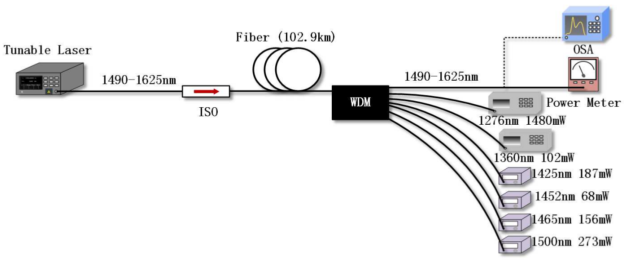
The constantly increasing demand for transmission capacity in communication systems [1] has stimulated research into new optical fiber transmission windows [2, 3]. These new transmission windows can help increase the number of channels in wavelength-division multiplexing (WDM) systems, thereby increasing the upper limit of transmission capacity. However, due to the limitation of devices like optical amplifiers which mostly operates at C band, wideband transmission for large capacity optical communication is still highly limited. As one of the most important devices for optical fiber transmission, erbium-doped fiber amplifiers (EDFAs) can support C+L band amplification by special design.

Raman amplifier, due to its unique Raman scattering mechanism, can theoretically achieve amplification of any wavelength band. Particularly, distributed Raman amplifiers (DRA) have received widespread attention due to their ultra-low-noise characteristics. Some studies have shown that high-order DRA has better noise characteristics and amplification performance compared to standard first-order DRA [4-6]. Several studies have demonstrated the hybrid use of DRA with either semiconductor optical amplifiers or doped fiber amplifiers, wherein Raman amplifiers have exhibited ultra-wideband gain characteristics in these applications [7, 8]. However, research on distributed Raman amplifiers of third-order and above for ultra-wideband amplification is relatively scarce.

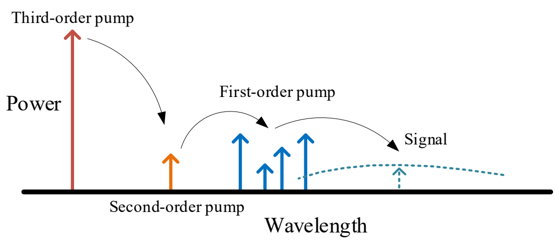
In this work, we experimentally demonstrate and investigate a third-order distributed Raman amplification over standard single mode fiber with multiple and backward pumping configuration. We achieved amplification bandwidth covering the S, C, and L bands, exceeding 130 nm, and the average On-Off gain reaching 13.6 dB with gain fluctuations of less than 2.2 dB. The experimentally measured effective noise figure (NF) is lower than -5.8 dB with a lowest value of -7.1 dB. This demonstration of SCL wideband amplification using purely-backward pumped third-order Raman is of great significance with respect to the advantages of wideband ultra-low-noise guard-band-free operation.

II. EXPERIMENTAL SETUP

The experimental setup and the principle of third-order DRA are shown in Fig. 1, 102.9-km single-mode fiber is used as the transmission and gain medium for the Raman amplification process, and the pump light is coupled into the fiber using a wavelength-division multiplexer. The backward pumping method is adopted to amplify the signal light, with the third-order pump at a wavelength of 1276 nm, the second-order pump at a wavelength of 1360 nm, and the four first-order pumps at wavelengths of 1425 nm, 1452 nm, 1465 nm, and 1500 nm, respectively. A swept-frequency laser is utilized as the signal light source to measure the gain and noise performance of the Raman amplifier. The gain performance is measured using the power meter and the scanning program provided by the swept-frequency laser, and more detailed experimental results are obtained using an optical spectrum analyzer (OSA).



(a)



(b)

Fig. 1. (a) Experimental setup (b) Principle of third-order DRA.

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In this experiment, the powers of the Raman pumps were 187 mW (1425 nm), 68 mW (1452 nm), 156 mW (1465 nm), 273 mW (1500 nm), 102 mW (1360 nm) and 1480 mW (1276 nm), respectively. The power settings of these pumps were obtained through simulation optimization using machine learning based inverse design method.

III. Results and Discussion

We first obtained the On-Off gain spectrum of the third-order DRA using a tunable CW laser (Santec TSL-710) and its built-in power meter through spectral scanning, as shown in Fig. 2. Due to limitations in the wavelength division multiplexing devices, the gain performance over the approximately 4-nm bandwidth at the end of the S band cannot be measured. The highest gain shown in the graph is approximately 14.9 dB, the lowest gain is approximately 12.9 dB, with a fluctuation of 2.0 dB.

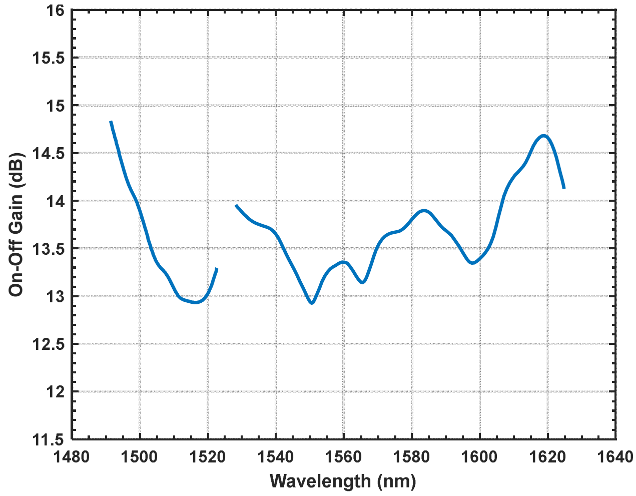

Fig. 2. On-Off gain spectrum measured by power meter.

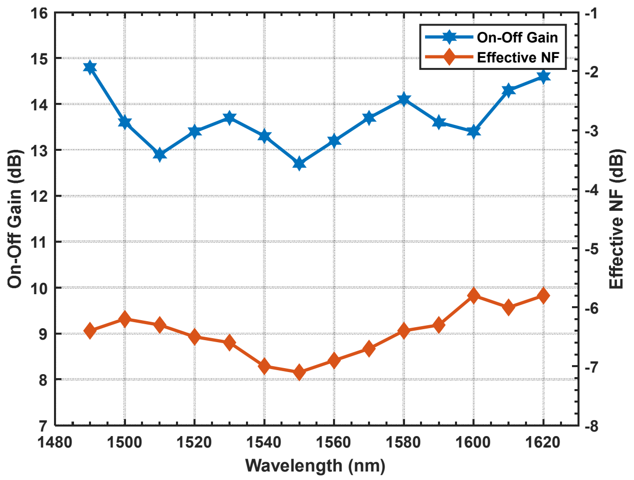

Fig. 3. On-Off gain spectrum and effective NF measured by OSA.

In order to obtain more accurate information on the gain performance and effective NF, a second measurement was conducted using an optical spectrum analyzer (OSA). During the measurement, a tunable laser was used to scan the signal wavelength from 1490 nm to 1620 nm with a step size of 10 nm. The measurement results, shown in Fig. 3, reveal that the gain test results are very similar to those in Fig. 2, but there are still some differences. This is mainly due to the different calculation rules for gain measurement between the OSA and the power meter. In addition, the automatic frequency sweeping of the tunable laser cannot fix the power at a single value, which also leads to different gain measurement results. The maximum gain shown in Fig. 3 is 14.9 dB at 1490 nm, and the minimum gain is 12.7 dB at 1550 nm, resulting in a gain variation of 2.2 dB. The average gain obtained from this measurement is 13.6 dB. The effective NF is minimum at 1550 nm, with a value of -7.1 dB, and maximum at 1600 nm, with a value of -5.8 dB.

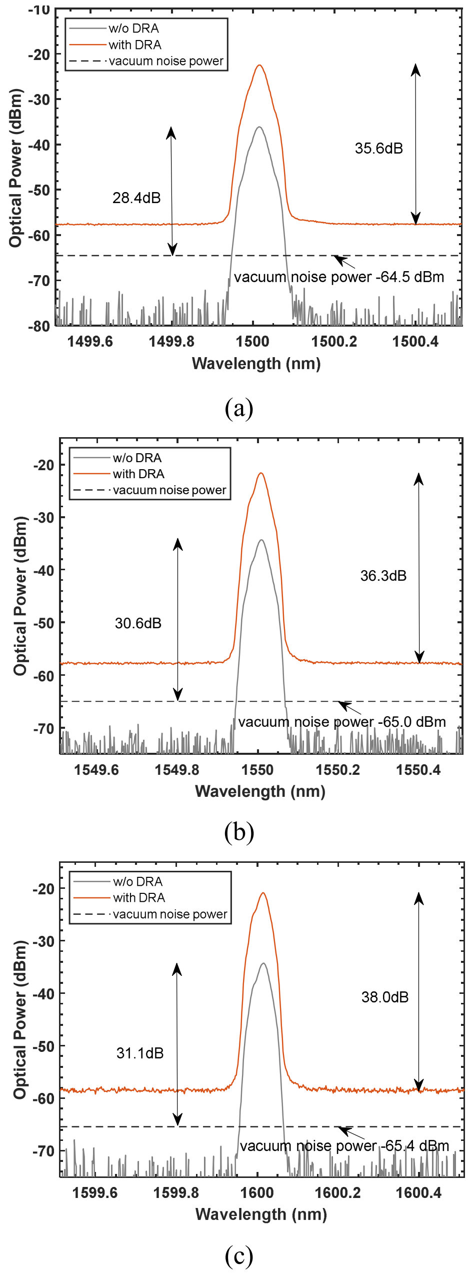

Fig. 4. Optical spectrum without (w/o) amplification (gray curve) and with DRA (red curve) at (a) 1500 nm, (b) 1550 nm and (c) 1600 nm.

Finally, we selected a wavelength in each of the S, C, and L bands, respectively 1500 nm, 1550 nm, and 1600 nm, to investigate the improvement in the optical signal-to-noise ratio (OSNR) by the third-order DRA at these wavelengths, as shown in Fig. 4. Fig. 4(a) shows that without DRA amplification, the OSNR at 1500 nm is 28.4 dB, but with DRA amplification, the OSNR is improved to 35.6 dB. Fig. 4(b) and 4(c) show the results at 1550 nm and 1600 nm, respectively. With DRA amplification, the OSNR is increased by 5.7 dB and 6.9 dB, respectively.

Another advantage of this amplifier is the purely backward pumping configuration which can maximumly utilize the full amplification bandwidth without using guard bands for avoiding pump-signal co-propagation overlapping.

IV. CONCLUSIONS

In this experiment, we achieved ultra-wideband amplification over the S, C, and L bands, exceeding 130 nm, by utilizing purely backward pumped third-order DRA. The average On-Off gain within this range was 13.6 dB, with gain fluctuations less than 2.2 dB, and effective NF lower than -5.8 dB. These results demonstrate the potential of distributed Raman amplification in expanding the communication window for ultra-wideband transmission, as well as effectively mitigating the degradation of OSNR during communication transmission, thereby improving communication quality and reducing system bit error rate (BER). Furthermore, high-order DRA can compensate for the insufficient gain of DRA and further reduce the effective NF.

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