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Gain-enhanced double-pass long-wavelength-band erbium-doped fiber amplifier using backward pumping

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Abstract. We propose and demonstrate a novel high-gain-efficiency long-wavelength band (L-band) erbium-doped fiber amplifier with a double-pass backward-pump configuration, in which the strong backward C-band amplified spontaneous emission is effectively utilized. The L-band gain is greatly enhanced in comparison with the copumped configuration. Without using any excessive components, the new configuration can provide the same gain as the conventional configuration, but only using 40% pump power. Meanwhile, the noise figure is also effectively improved under the low pump power. [DOI: 10.1117/1.2821422]

Subject terms: erbium-doped fiber amplifier; L-band; double-pass configuration; backward pumping.

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1 Introduction

With the rapid growth of the Internet and data traffic, the conventional band (C-band, 1530 to 1560 nm) cannot satisfy the explosive bandwidth demand on optical communications. To improve the channel capacity of wavelength-division-multiplexing (WDM) systems, the short-wavelength band (S-band, 1460 to 1530 nm) and the long-wavelength band (L-band, 1565 to 1610 nm) erbium-doped fiber amplifier (EDFA), even broadband (S+C+L-band) EDFA by utilizing a seed light injection or parallel configuration,[1,2] have been proposed. Among them, L-band erbium-doped fiber amplifiers (EDFAs) perform with relatively low pump efficiency on the gain, as the operation wavelengths are far from the peak emission band of Er^{3+} ions. Generally, to obtain a high L-band gain, a laser diode with a high power pump and a longer EDF length is needed. To improve the pump efficiency of the L-band as much as possible, several methods have been proposed, such as feedbacking unwanted amplified spontaneous emission (ASE) power into EDF to serve as the secondary pump through a circulator,[3,4] or incorporating a fiber Bragg grating,[5,6] C-band light assisted pumping,[7–10] and using a double-pass technique.[5,11–14] Among these methods, the double-pass L-band EDFA is an efficient and cost-effective scheme, which uses a circulator or fiber loop mirror to recycle the L-band ASE into the EDF, again for the enhancement of the L-band gain. However, all the reported double-pass L-band EDFAs use the forward-pumped or dual-pumped[13,14] configuration, so the strong backward ASE power is output together with the amplified signals. This not only leads to the penalty of noise figure (NF), but also degrades the pump efficiency. Incorporating a fiber Bragg grating into a double-pass configuration[6] can reflect a portion of backward ASE power into the EDF for the improvement on the gain and NF, but there is still much ASE power wasted, which can be transferred into the L-band gain.

In this work, we present an L-band EDFA with a backward-pumped double-pass configuration, in which the strong backward C-band ASE power is efficiently recycled into the EDF, and then the C-band ASE power serves as the secondary pump of the L-band signal. In comparison with the copumped configuration, though with slight changes in the design, both the gain and NF are effectively improved. Compared with a dual-pumped double-pass configuration,[14] our scheme is simple, inexpensive, and as efficient as the dual-pumped scheme. For simplicity, this study focuses on the comparison of the proposed and copumped schemes in terms of gain, NF, and pump consumption. Since most of the backward C-band ASE power is converted into an L-band pump, the signal gain is greatly enhanced. Finally, at only 64.8-mW pump power, a gain of more than 27 dB is obtained. Compared with the copumped double-passed L-band EDFA, a gain improvement from 6 to 35 dB under different 980-nm pump powers and signal wavelengths has been demonstrated. Without using any excessive components, the new configuration can present the same gain as the copumped configuration, only using 40% pump power. Meanwhile, the NF is also greatly improved under the low pump power.

2 Experiment

The schematic diagrams of the double-pass L-band EDFAs are shown in Fig. 1, in which Fig. 1(a) represents the conventional double-pass L-band EDFA with a copumped configuration, and Fig. 1(b) is the proposed one with a backward-pumped configuration. In our experiment, a tunable laser source (TLS) is used as the L-band input signal, and both the circulators and the WDM can operate in the C+L band. The first optical circulator (OC1), with insertion loss 0.66 dB from port 1 to port 2 and 0.73 dB from port 2

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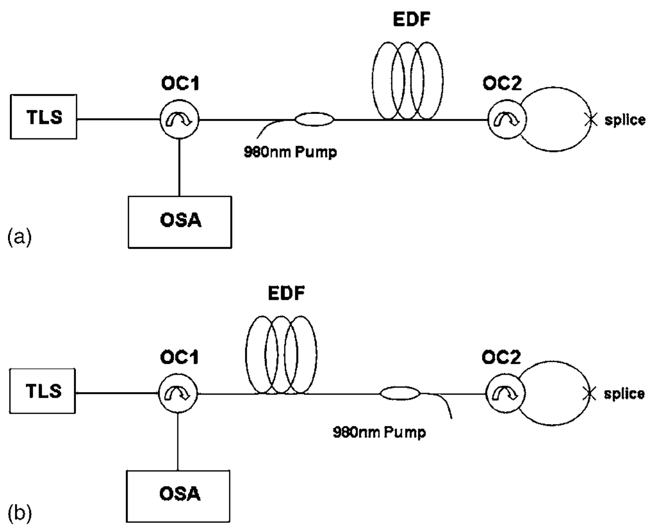

Fig. 1 The experiment setup of the double-pass L-band EDFA. (a) The conventional double-pass L-band EDFA. (b) The new double-pass L-band EDFA.

to port 3, at the input end is used to route the amplified signal into an optical spectrum analyzer (OSA) for measurement. In Figs. 1(a) and 1(b), a 60-m-long EDF of 120-ppm erbium ion concentration is used, and a 980-nm laser diode (LD) provides a maximum power of 150 mW. A 980/1570-nm WDM combines the pump and signal power into the EDF. The second optical circulator (OC2), with insertion loss of 0.65 dB from port 1 to port 2 and 0.71 dB from port 2 to port 3, whose two ports have been connected, is used to feedback the L-band signal with ASE double-passing through the EDF. In Fig. 1(a), the strong backward C-band ASE is output with the signal. In Fig. 1(b), the backward C-band ASE is double-passed to pump the L-band signal. In the proposed configuration, the strong backward ASE power is efficiently utilized.

3 Results and Discussion

Figure 2 shows the output spectra of two types of double-pass L-band EDFAs, in which a 1585-nm signal with −20-dBm power is input for testing, and the 980-nm pump power is set at 85.8 mW. It is evident that the output spectrum of the copumped configuration includes strong unused backward C-band ASE power, but the backward C-band ASE power is effectively utilized in the backward-pumped configuration. In the proposed configuration, the backward C-band ASE power is recycled into the EDF and converted into the L-band gain. Although the L-band ASE level is enhanced, it is more important that this leads to a great improvement on gain. In the figure, the ASE power level and the output signal power at 1585 nm are enhanced by 14 and 21.3 dB, respectively. This obviously shows that the backward-pumped scheme can enhance the gain performance of the double-pass L-band EDFA.

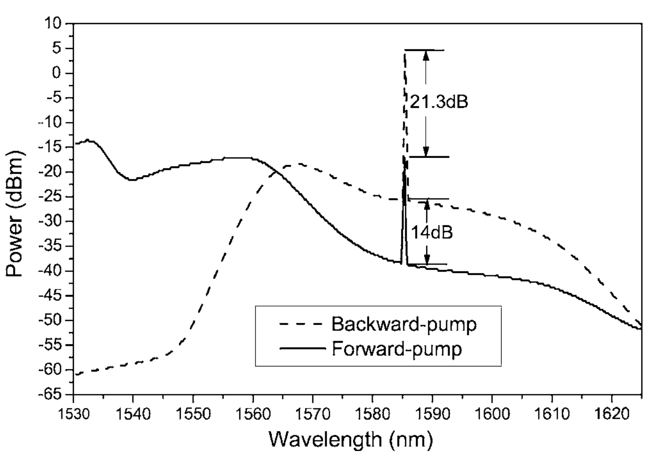

Fig. 2 The output spectra of the two types of double-pass L-band EDFAs.

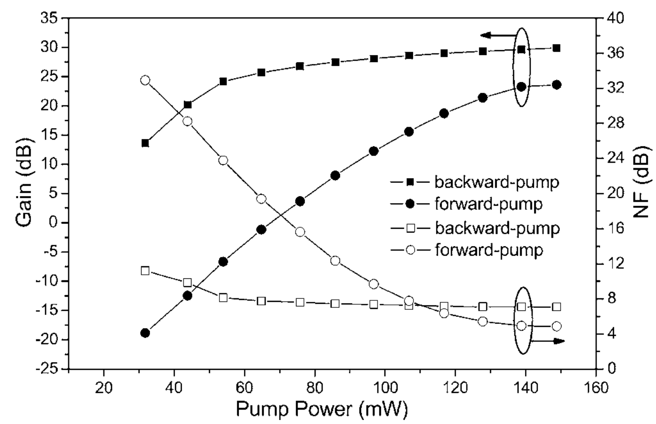

Fig. 3 Gain and noise figure against pump power for the 1585-nm signal with an input power of −20 dBm.

The gain and NF characteristics for the two configurations are shown in Fig. 3, in which the results are measured under the 1585-nm signal with −20-dBm input power. In the backward-pumped case, the gain is measured at 13.6 dB when only 31.8-mW pump power is used. With the increase of pump power, it is rapidly enhanced and then saturated to ~30 dB. However, the gain in the copumped case is negative until 64.8-mW pump power. The low gain is suffered from the waste of the pump power due to the unused strong backward ASE power, so the pump power is not enough to amplify the 1585-nm signal. Compared with the copumped case, the gain is enhanced by 6 to 35 dB, which is dependent on the pump power. In particular, the enhancement is more obvious with low power pumping. The saturation gain is also enhanced by 6.29 dB at 148.8 mW. To obtain the equal gain of 23 dB, the new configuration needs 58.8-mW pump power and the conventional one needs 138.8 mW. In other words, the new configuration can save ~60% pump power.

Also, below a pump power of 106.8 mW, the NF for the copumped case is much bigger than the backward-pumped one because of very low gain. This means that the new configuration also benefits the improvement of NF. In particular, the NF improvement is more obvious with low power pumping. This results from the great gain enhancement. Beyond this pump power, the NF for the backward-pumped case has little penalty due to the relatively high L-band ASE level.

We measured the gain and NF improvement against the

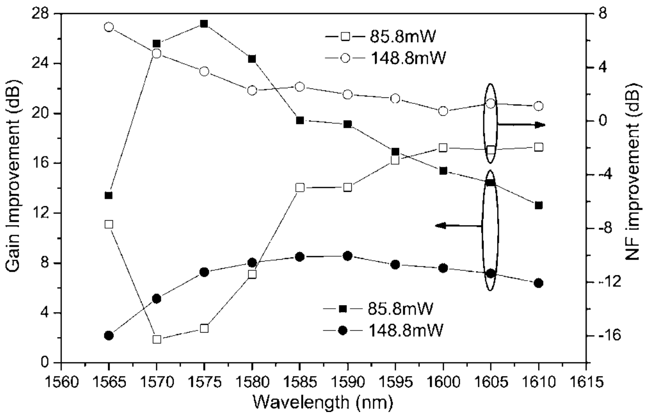

Fig. 4 Gain and NF improvement against the input signal wavelength.

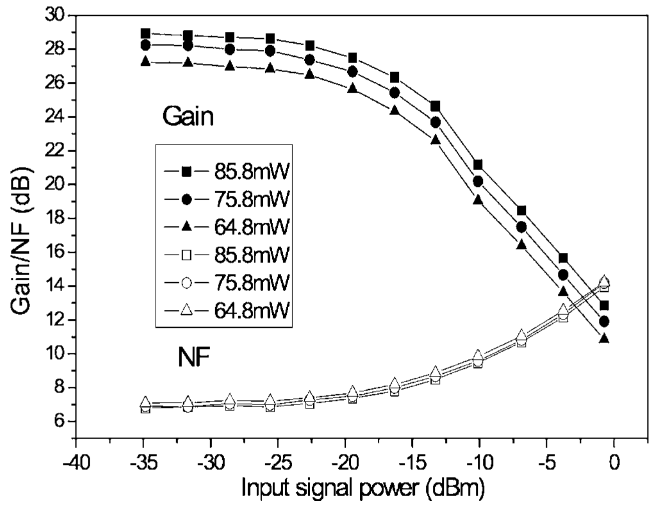

Fig. 5 Gain and NF against the input 1585-nm signal power at different pump powers for the proposed configuration.

input signal wavelength with −20-dBm input signal. As shown in Fig. 4, the pump power is respectively set at 85.8 and 148.8 mW. At the 85.8-mW pump power level, both the gain and NF are greatly improved due to the high gain in the backward-pumped case. The highest gain improvement of 27.21 dB is obtained at a 1575-nm signal with a NF improvement of 15.45 dB. As a whole, the gain enhancement exceeds 20 dB, and the NF improvement is above 10 dB. At 148.8-mW pump power, the gain improvement is degraded due to the pump saturation effect, and the highest gain enhancement of 8.58 dB is achieved at a 1590-nm signal with a NF penalty of 1.97 dB. The reason for the NF penalty can be explained by the recycling of the backward ASE power to enhance the L-band ASE level. NF shows a linear dependency with the ASE level, and performs an inverse nonlinear relationship to the gain. Under strong pumping, the L-band ASE level increases with the pump power, but the gain remains saturated.[7] Thus, the NF in the new configuration performs degraded beyond 106.8-mW pump power.

Finally, we measured the gain and NF of the proposed L-band EDFA against the 1585-nm signal power at 64.8-, 75.8-, and 85.8-mW pump power. The measured results are shown in Fig. 5. At 85.8-mW pump power, the gain and NF for −35-dBm input signal power are respectively 28.93 and 6.73 dB. With the increase of the signal power, the gain is saturated and NF becomes worse. At only 64.8-mW pump power, the gain is as high as 27.23 dB and the NF is at an acceptable level of ~7 dB for the same input signal. When the input signal power exceeds −10 dBm, the NF becomes unacceptable due to the gain saturation and the high L-band ASE level. In further optimizing the length of the EDF, we believe that such a simple, low-cost configuration will be more efficient. Such a configuration is very suitable to be the in-line amplifier, which works on the unsaturated region of the EDFA and requires high gain and appropriate NF.

4 Conclusions

In summary, a double-pass L-band EDFA with a backward-pumped configuration is demonstrated. Compared with the conventional double-pass EDFA with a copumped configuration, both the gain and NF are greatly improved under the low pump power conditions. This is because the unused strong backward C-band ASE power is recycled into the EDF to serve as the secondary pump, and the pump power is efficiently utilized. The new configuration can save ~60% pump power to obtain the same gain as the conventional one. The pump efficiency and NF can be greatly improved without using any excess components, but only changing the location of the 980/1570-nm WDM in the double-pass L-band EDFA. Such a simple, low-cost, and highly efficient configuration would be very suitable in the practical applications of EDFA products.

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