PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 61, No. 1
July 2003
pp. 93–97

# High gain L-band erbium-doped fiber amplifier with two-stage double-pass configuration

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MS received 22 November 2002; revised 13 February 2003; accepted 21 February 2003

**Abstract.** An experiment on gain enhancement in the long wavelength band erbium-doped fiber amplifier (L-band EDFA) is demonstrated using dual forward pumping scheme in double-pass system. Compared to a single-stage single-pass scheme, the small signal gain for 1580 nm signal can be improved by 13.5 dB. However, a noise figure penalty of 2.9 dB was obtained due to the backward C-band ASE from second stage and the already amplified signal from the first pass that extracting energy from the forward C-band ASE. The maximum gain improvement of 13.7 dB was obtained at a signal wavelength of 1588 nm while signal and total pump powers were fixed at −30 dBm and 92 mW, respectively.

**Keywords.** Erbium-doped fibre; optical amplifier; L-band erbium-doped fiber amplifier; two-stage erbium-doped fiber amplifier; amplified spontaneous emission.

**PACS No. 42.60.Da**

## 1. Introduction

The explosive growth of Internet traffic has placed huge demands on our communication networks. One of the key technologies to increase the bandwidth of optical communication systems is to expand the bandwidth of optical amplifiers. Several technologies have been proposed and/or implemented such as application of new host material such as tellurite-based erbium-doped fiber amplifier (EDFA) [1], hybrid erbium-doped and Raman fiber amplifiers [2] and parallel configuration of conventional and long wavelength band (C- and L-band) EDFAs [3]. Application of the L-band EDFA to wavelength division multiplexing (WDM) transmission system is very attractive because the system capacity can be doubled by placing the L-band EDFA in parallel with the C-band amplifier as in-line system repeaters. Since the erbium emission cross-section in the L-band is far from its peak value at 1531 nm, its gain coefficient and quantum conversion efficiency (QCE) are much reduced from that of the C-band amplifiers.

In order for L-band EDFAs to be implemented in the existing communication systems, gain and noise figure performance as well as costs equivalent to those of a C-band EDFA have to be achieved. To date, several techniques have been suggested and experimentally verified to improve gain in this band. One technique uses a detrimental C-band backward amplified spontaneous emission (ASE) as the secondary pump source for the un-pumped erbium-doped fiber (EDF) section of the amplifier [4]. Another technique uses an end-reflector to feedback a fraction of the backward C-band ASE into the EDF as an ASE seed to suppress the backward C-band ASE [5].

In our earlier work, the double-pass technique was introduced to enhance the gain in the L-band EDFA [6]. Here, we demonstrated a highly efficient EDFA structure for L-band signal amplification utilizing a two-stage amplifier with dual forward pumping scheme. The two-stage amplifier performances for both single-pass and double-pass configurations are compared with the conventional single-stage configuration.

## 2. Configuration

Three L-band EDFA schemes are depicted in figure 1. Figure 1c shows a configuration of the proposed two-stage L-band with dual forward pumping scheme in the double-pass system. Two pieces of EDF (EDF 1 and EDF 2) with $Er^{3+}$ concentration of 400 ppm and two 980/1550 nm wavelength selective couplers (WSCs) are employed to act as the gain media and the pump/signal optical combiner, respectively. EDF 1 and EDF 2 are fixed at 20 m and 30 m, respectively. The dual forward pumping scheme is named due to two 980 nm pump semiconductor laser diodes used and the propagation direction of the pump lights is the same as the signal light in the forward direction. The powers of pump 1 and pump 2 are fixed at 35 mW and 57 mW, respectively. Optical circulator C2 is placed at the output end of the EDF (EDF 2) to allow signals to undergo double propagation through the EDFs. The doubly-amplified signal is routed to an optical spectrum analyzer (OSA) by optical circulator C1. The circulator utilizes the well-known magneto-optic rotation in crystals in conjunction with polarizing beam splitting/combining prisms. This allows a signal incident on port 1 to go to port 2 but any signal incident on port 2 is routed to port 3, thereby achieving circulation. The amplifier performances are compared to the conventional single-stage single-pass amplifier and two-stage single-pass amplifier as shown in figure 1a and 1b, respectively.

## 3. Result and discussion

Figure 2 depicts ASE spectra of the three L-band EDFA configurations with a total fiber length and pump power of 50 m and 92 mW, respectively, where the thick line represents the ASE spectra of the proposed two-stage double-pass amplifier. As seen, the spectrum of both two-stage amplifiers are much higher than the single-stage amplifier due to large forward ASE from stage 1 that has been amplified at stage 2. The highest ASE level is shown in the proposed two-stage double-pass amplifier. This is attributed to the double-pass scheme that extracts the very high backward C-band ASE by intra-stark-multiplet phonon energy transfers. The first few meters of the EDF channels a very high pump power, with correspondingly high population inversion rates, in the C-band. This results in a very high backward ASE, which goes out of the system at the point where the L-band signal is input to the amplifier. Reflecting the L-band signal from the single-pass output

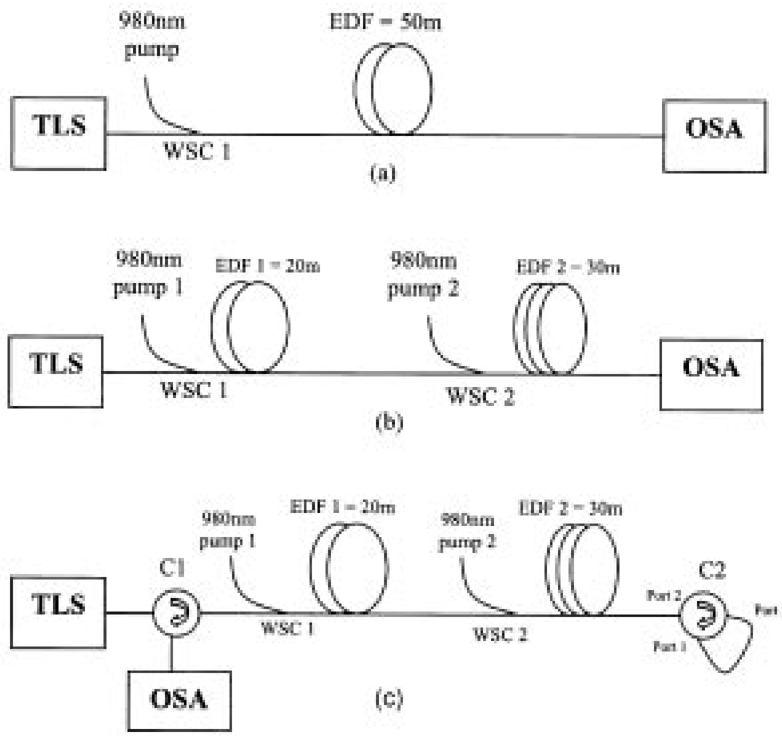


**Figure 1.** Configuration of the L-band EDFAs in (**a**) single-stage single-pass, (**b**) two-stage single-pass and (**c**) two-stage double-pass.

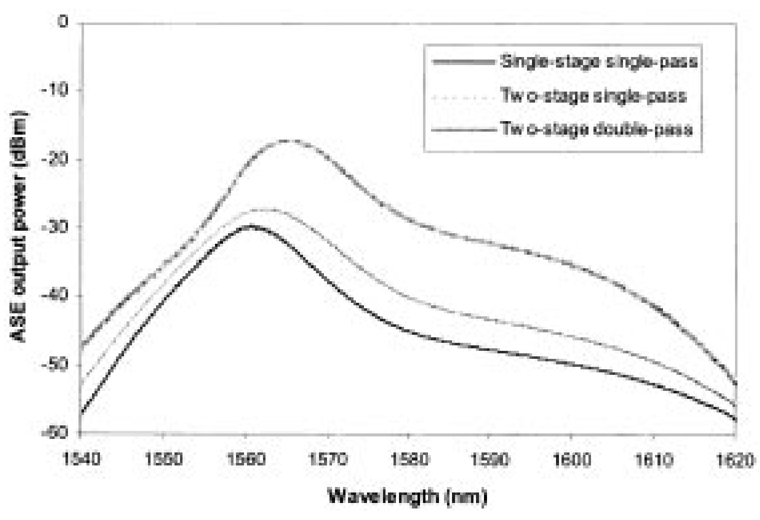


**Figure 2.** ASE spectra of the L-band EDFA while the total pump power is fixed at 92 mW. For the dual-stage amplifiers, pump 1 and pump 2 are fixed at 35 mW and 57 mW, respectively.

back into EDF enables energy transfer from the higher energy C-bands, especially from the backward ASE, to a lower energy L-bands.

The gain and noise figure characteristics of the 1580 nm signal against input signal power were measured for the L-band EDFAs by varying the input signal power from −40 to 0 dBm as shown in figure 3. The gain enhancement of 11 dB and 13.5 dB are obtained at a small signal gain for two-stage double-pass amplifier compared to the two-stage and single-stage single-pass amplifiers, respectively. This is attributed to the dual forward pumping scheme and double propagation of signal through the EDFs. They increased the ASE level and thus the efficiency of the energy transfer from short- to long-wavelength also increases. The saturation power of the two-stage double-pass, two-stage single-pass and single-stage single-pass amplifiers are obtained at −18 dBm, −12 dBm and −12 dBm, respectively. On the other hand, the noise figure of the proposed two-stage double-pass amplifier is increased by 0.7 dB and 2.9 dB compared to the two-stage single-pass and single-stage single-pass amplifiers, respectively, for small input signal powers. Because the noise figure of any amplifier is given by the population inversion distributions along the EDF, the two-stage double-pass amplifier is excited by the forward C-band ASE. On two-stage double-pass amplifier, however, the backward C-band ASE from the stage 2 and the already amplified signal from the first-pass extract further energy from this forward C-band ASE. Therefore, the back-end of the amplifier does not get sufficient excitation. This implies that the overall or average inversion level has dropped, giving rise to a higher noise figure.

Figure 4 shows the gain and noise figure spectra for an input signal power of −30 dBm and total pump power of 92 mW. As is seen, the gain of the double-pass amplifier is higher compared to both single-pass amplifiers. This improvement in gain is obtained because the signal is amplified twice in different directions. Therefore, the effective EDF length is increased due to the reuse of backward ASE facilitated by the feedback loop. It can also be seen in figure 4 that the maximum gain enhancement value of 13.7 dB was obtained in two-stage double-pass amplifier compared with the conventional single-stage single-pass

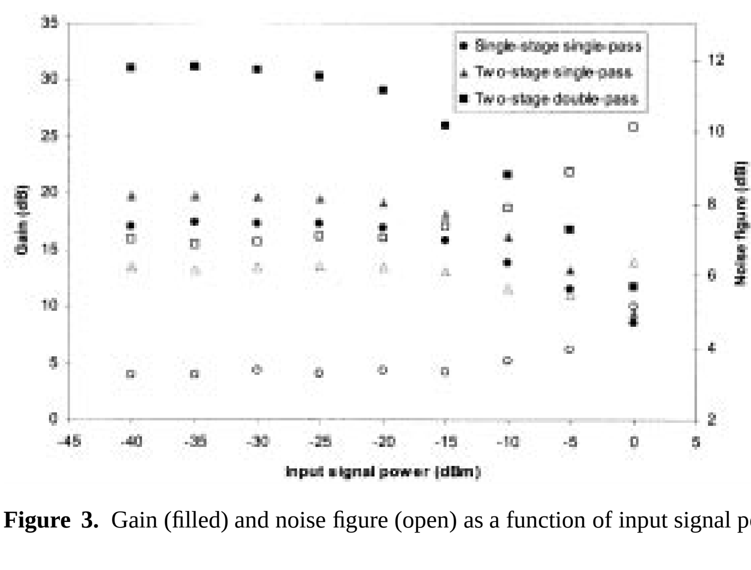


**Figure 3.** Gain (filled) and noise figure (open) as a function of input signal power.

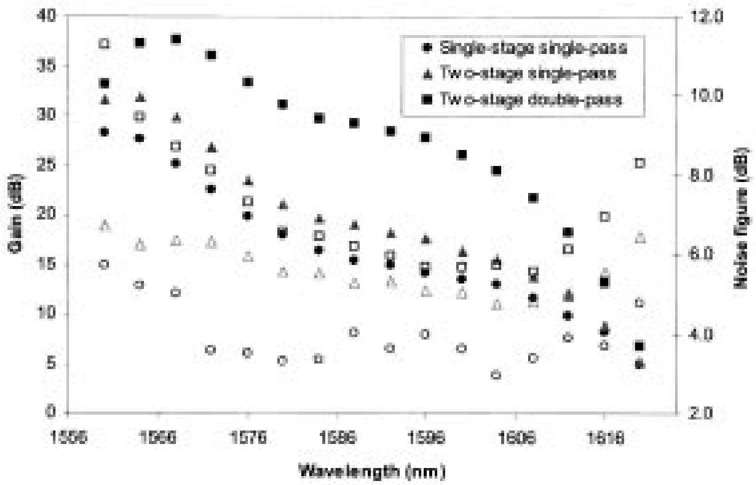


**Figure 4.** Gain (filled) and noise figure (open) as a function of input signal wavelength.

amplifier at signal wavelength of 1588 nm. The corresponding noise figure penalty was 2.2 dB, and it was obtained due to the same reason as explained above.

## 4. Conclusion

The L-band EDFA with improved gain characteristic, which uses dual forward pumping scheme in double-pass system, has been proposed. The proposed amplifier has improved the small signal gain for 1580 nm signal by 13.5 dB at the expense of 2.9 dB noise figure penalty compared to the conventional single-stage single-pass amplifier. The noise figure penalty is due to the backward C-band ASE from stage 2 and the already amplified signal from the first-pass extracting energy from the forward C-band ASE. The maximum gain improvement of 13.7 dB was obtained at a signal wavelength of 1588 nm while signal and total pump powers were fixed at −30 dBm and 92 mW, respectively. These results show that the employment of two-stage amplifier in double-pass configuration will play an important role in the development of practical L-band EDFA from the perspective of economical usage of pump power.

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