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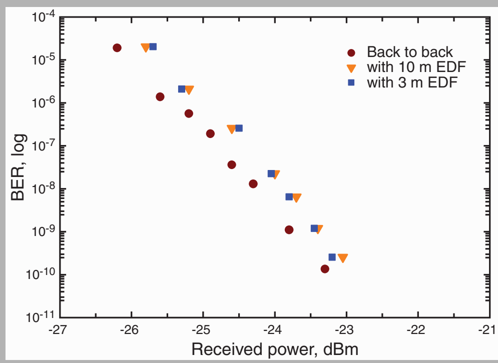
Abstract: A broadband hybrid two-stage fiber amplifier module, constructed of an erbium-doped fiber amplifier (EDFA) and a semiconductor optical amplifier (SOA) in series, is proposed and investigated experimentally. In the proposed amplifier, a short length erbium-doped fiber (EDF) was used in first stage for the pre-amplifier to increase the gain and reduce the noise figure. Therefore, the proposed hybrid amplifier not only enhances gain value, but decreases the noise figure. Moreover, the proposed amplifier can achieve 110 nm amplification bandwidth between 1500 and 1610 nm, when the entire gain are large than 11 dB and noise figure are less than 8 dB for −25 dBm input saturation power. Moreover, the performance of gain and noise figure in the proposed fiber amplifier has also been discussed.



System performance of BER at a test signal of 1552 nm in a 2.5 Gbit/s modulation system

Utilizations of EDFA and SOA in series for broadband gain amplification

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1. Introduction

To satisfy the requirement of the communications capacity, the broadband erbium-doped fiber amplifiers (EDFAs) have been becoming the key techniques in the dense wavelength-division-multiplexed (DWDM) systems. Conventionally, the amplification bandwidths of S-, C-, and L-bands individually for WDM communications were also reported [1–9]. In addition, linking the C- and L-band gain of EDFA can get up to above 80 nm amplification bandwidth [10], which greatly raises the ability of the transmission of WDM system. Though there are many optimized configuration on C- plus L-band EDFA [10–16], the broadband EDFA has only two kinds of basic configurations, i.e. the serial and parallel configurations. In L-band EDFA, the power conversion efficiency (PCE) is too low to get a high gain, because it is far from the erbium ion absorption band. Therefore, several methods to improve the L-band gain had been proposed, such as applying unwanted C-band amplified spontaneous emission (ASE) [12], using the double-pass configuration [17,18] and reflection-type EDFA with fiber grating [19].

In this paper, we propose and experimentally investigate a broadband hybrid two-stage fiber amplifier using an EDFA and a cascaded C-band SOA in series for 110 nm gain bandwidth. Thus, the proposed amplifier not only enhances the gain value, but retrieves a broadband gain bandwidth from 1500 to 1610 nm. Moreover, the performances of the proposed amplifier have also been discussed.

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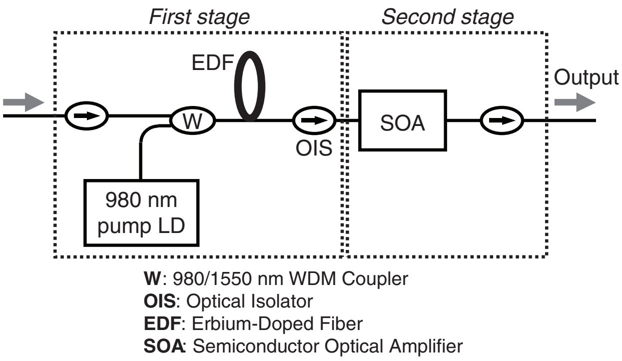

Figure 1 Proposed broadband hybrid two-stage fiber amplifier, structured by an EDFA and an SOA in series

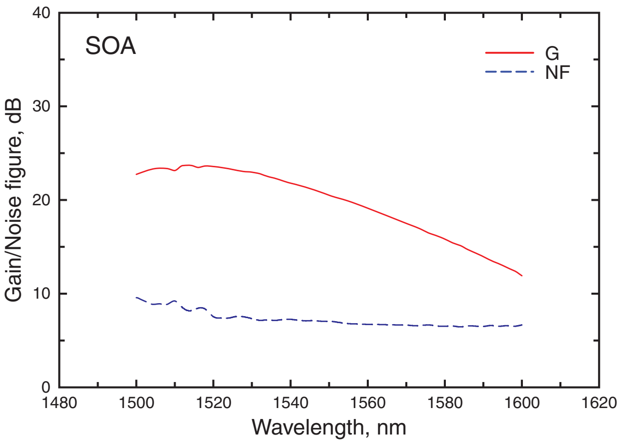

Figure 2 (online color at www.lphys.org) Gain and noise figure spectra of an SOA, when the pumping current operates at 150 mA and the input saturation tone is −25 dBm, in the operating range of 1520 to 1600 nm

2. Experiment setup

The proposed hybrid broadband two-stage fiber amplifier in series is illustrated in Fig. 1. The amplifier consists of an EDFA and a SOA in serial configuration. The first EDFA stage with pre-amplification function is used to reduce the noise figure [10,13] and enhance the operating gain range for the proposed amplifier. The second SOA stage operates at 150 mA pumping current. A threshold and maximum operating currents of the SOA were 50 mA and 250 mA. The SOA also has bi-direction operating function. In Fig. 1, the optical isolator (OIS) was used to avoid the backward ASE of SOA injected into the first EDFA stage. Due to the homogeneously broadened gain characteristics, the multi-wavelength input signal in a WDM system can be simulated using a saturation tone with a power equal to the aggregated power of multi-wavelength input signal [20]. Therefore, a 1550 nm DFB laser was used to serve as a saturation tone to simulate the aggregated power

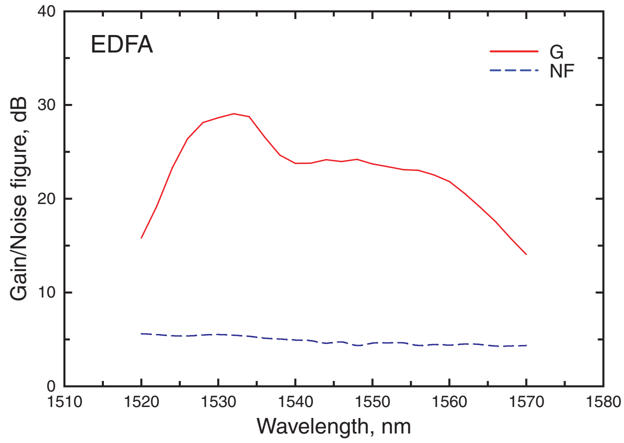

Figure 3 (online color at www.lphys.org) Gain and noise figure spectra of an EDFA when the input satoration power $P_{sat} = -25$ dBm in the wavelength of 1520 to 1570 nm. The length of EDF is 10 m long and the pumping power of 980 nm laser is 60 mW

of input WDM signals in the proposed amplifier. To ensure the performance of the proposed hybrid amplifier, a tunable laser source (TLS) and an optical spectrum analyzer (OSA) with a 0.05 nm resolution are used to probe and measure the gain and noise figure spectra.

Fig. 2 shows the gain and noise figure spectra of an SOA, when the pumping current is 150 mA and an input saturation power is −25 dBm in an operating range of 1520 to 1600 nm. The gain and noise figure spectra of the SOA are distributed at 11 to 23.4 dB and 6.7 to 8 dB, respectively, in the wavelength range of 1520 to 1600 nm when the input saturation power is −25 dBm. From the results, the SOA presents the lower gain and worse noise figure in C- plus L-band, compared with the conventional EDFAs [8–10]. Due to these defects of SOA, thereby it can't be used in optical communication system for amplification. To overcome these drawbacks, an EDFA with pre-amplification function is used. Moreover, to investigate the influence of EDF length of the first stage for the proposed hybrid amplifier, we will use two different EDF lengths in this experiment to realize the amplifier's performance and behavior. Generally, ideal fiber amplifiers need to have the function of wide-band amplification bandwidth, higher gain and lower noise figure for WDM transmission system.

First, a 10 m long EDF (*DF-1500F of Fibercore Ltd.*) length is used in the first EDFA stage with a 60 mW pumping power in the proposed hybrid amplifier. Fig. 3 presents the gain and noise figure spectra of the original EDFA for the input saturation power $P_{sat} = -25$ dBm in an operating range of 1520 to 1570 nm. Fig. 3 shows the gain and noise figure are distributed at 14 to 29.1 dB and 5.9 to 4.3 dB in an operating range 1520 to 1570 nm, respectively. When the EDFA is used to cascade an SOA with 150 mA pumping current, the gain and noise figure profiles of the hybrid amplifier for the input saturation power

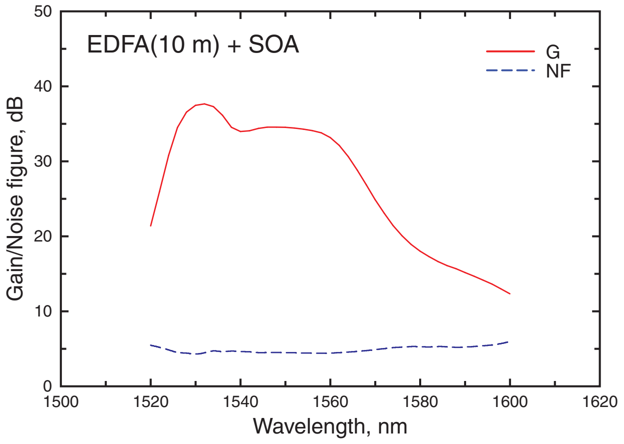

Figure 4 (online color at www.lphys.org) Gain and noise figure profiles of the hybrid two-stage fiber amplifier module (with 10 m long EDF length) for the input saturation power $P_{sat} = -25$ dBm in the operating region of 1520 to 1600 nm. Pumping power of 980 nm laser and pumping current of an SOA are 60 mW and 150 mA

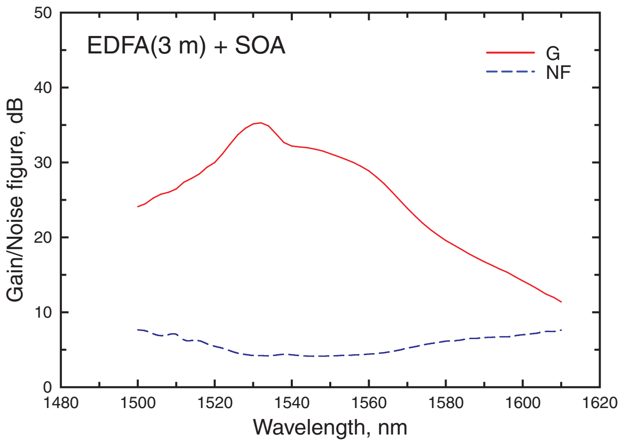

Figure 5 (online color at www.lphys.org) Gain and noise figure profiles of the hybrid two-stage fiber amplifier module (with 3 m long EDF length) with the input saturation power $P_{sat} = -25$ dBm in the operation region of 1500 to 1610 nm. Pumping power of 980 nm laser and a pumping current of an SOA are 40 mW and 150 mA, respectively

$P_{sat} = -25$ dBm in the wavelengths of 1520 to 1600 nm is illustrated in Fig. 4. The effective gain bandwidth of the amplifier is improved between 1520 to 1600 nm. In Fig. 4, the gain and noise figure spectra are distributed at 12.3 to 37.7 dB and 4.4 to 5.9 dB, respectively, for the input saturation power of -25 dBm in the same wavelength range. Compared with Fig. 2, the observed entire results are better than that of an original SOA. That is to say, the proposed amplifier not only enhances the gain value, but reduces the noise figure in the wavelengths of 1520 to 1600 nm.

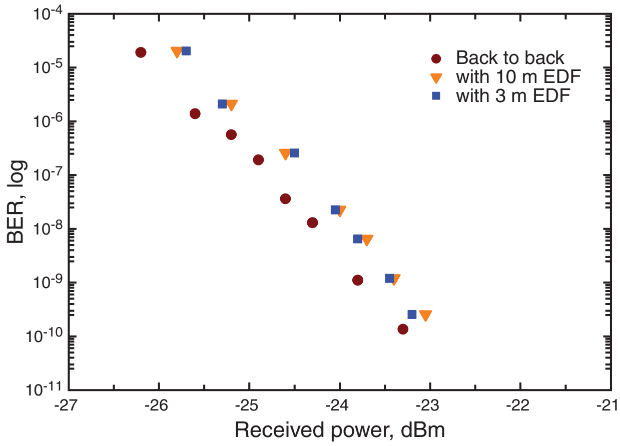

Figure 6 (online color at www.lphys.org) System performance of BER at a test signal of 1552 nm in a 2.5 Gbit/s modulation system

To realize the effect in the proposed amplifier under different EDF length used, then we reduce the EDF length to 3 m long in the first EDFA stage with a 40 mW pumping power to cascade the second SOA stage with 150 mA pumping current. Therefore, Fig. 5 presents the gain and noise figure spectra of the hybrid amplifier in the effective amplification bandwidth of 1500 to 1610 nm for the input saturation power of -25 dBm. Fig. 5 shows that the entire gain and noise figure are distributed at 11.5 to 35.3 dB and 4.2 to 7.6 dB, respectively, for -25 dBm input saturation power in the same operating range. Based on the proposed architecture, the effective operating range of the amplifier will achieve a 110 nm amplification bandwidth of 1500 to 1610 nm when the gain is large 11.5 dB and noise figure is less than 7.6 dB. Besides the first EDFA stage can enhance the gain value, the 980 nm wavelength is also used to serve as an assist beam to improve conversion efficiency for SOA. Compared with the results of Fig. 2, the results of Fig. 5 not only enhance and extend the gain and effective operating bandwidth, but also decrease the noise figure. That is to say, the EDF length of first EDFA stage in the proposed scheme will determine the gain value and gain bandwidth. In accordance with experimental results, the EDF length in the amplifier can be adjusted with suitable function for the optical communication applications.

The two post reports [10,15] showed a C- plus L-bands amplification by two-stage EDFA with ring schemes in parallel and series structure, to achieve the gain bands of 80 and 50 nm, respectively. However, [10] has nearly 15 nm band gap which leads to loss and [15] only presented 50 nm gain amplification. Compared with the two post studies, our proposed two-stage amplifier in series can easily approach 110 nm gain bandwidth without any gap band and enhance the gain value simultaneously, when the proper EDF length is used in the proposed amplifier. In addition, the proposed amplifier can combine the Raman amplifier (RA) or EDFA with broadband amplification function for the future.

To demonstrate the performance of the proposed broadband fiber amplifier module, a bit error rate (BER) is measured in this system. A test input signal at 1552 nm is modulated by a 2.5 Gbit/s non-return-to-zero (NRZ) pseudo random binary sequence (PRBS) with a pattern length of $2^{31} - 1$ on a $LiNbO_3$ electrooptical (EO) modulator. However, the BER performance should be back-to-back without the proposed fiber amplifier module, characterizing the transmitter and receiver. A 2.5 Gbit/s optical receiver is used to measure the proposed amplifier performance. Therefore, Fig. 6 shows the measured BERs of the proposed optical amplifier against the received power for the back-to-back-type and the test signal through the proposed amplifier with 10 m and 3 m long EDF, respectively, in Fig. 1. While a test input signal passes through the two proposed amplifier structures, the observed two optical power penalties are nearly < 0.5 dB at the BER of 10^{-9}.

3. Conclusion

In summary, a wideband hybrid two-stage amplifier in series, constructed by an EDFA and SOA, has been proposed and experimentally investigated. When the first EDFA stage with 10 m long EDF, the observed results not only can enhance gain value but also decrease the noise figure. Then, when the EDF-based pre-amplifier with 3 m long EDF used in the hybrid amplifier, it can extends the effective amplification bandwidth from 1500 to 1610 nm. Moreover, the performances of the proposed amplifiers have also been discussed. As a result, the proposed two amplifiers are very useful to the applications in DWDM networks.

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