Hybrid S- to L-band fiber amplifier module with coupled structure

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1 Introduction

Erbium-doped fiber amplifiers (EDFAs) with wide bandwidth are considerably interesting for high-capacity transmission in dense wavelength division multiplexing (DWDM) systems. However, the transmission capacities in DWDM systems are limited by the gain bandwidth of C-band EDFAs (1530 to 1560 nm). Furthermore, L-band (1560 to 1610 nm) fiber amplifier techniques have been achieved, such as EDFAs using a longer erbium-doped fiber (EDF) than that of C-band EDFAs,[1] fiber Raman amplifiers,[2] or hybrid amplifiers.[3] In addition, a wide-band EDFA from C- to L-band using a coupled structure has also been studied.[4] In other words, two types of wide-band amplifiers with gain bandwidths of around 100 nm have been reported. The first is a coupled-structure amplifier multiplexing the gain bands, namely, the S-band thulium-doped fluoride fiber amplifier (TDFA) or fiber Raman amplifier and the C-band and L-band erbium-doped fiber amplifiers.[5–8] The other is a silica-based fiber Raman amplifier (S-FRA) featuring a multiwavelength pump technique.[9,10] Recently, a new S-band (1450 to 1530 nm) amplification technique, which utilizes erbium-doped silica fiber with a depressed cladding design and a 980-nm pump laser to generate EDF gain extension effects, has been reported.[11] In this letter, we propose and experimentally demonstrate a hybrid S- to L-band optical fiber amplifier in parallel configuration with 120-nm bandwidth (1480 to 1600 nm) employing EDFAs and a semiconductor optical amplifier (SOA). In addition, it also provides a 126-nm (1480 to 1606 nm) amplified spontaneous emission (ASE) light source.

2 Experiments and Disscussions

Figure 1 shows the experimental setup of the proposed hybrid amplifier in parallel structure. This proposed configuration is constructed by two 1480/1550 nm WDM couplers (W_2), an S-band EDFA module composed of two EDFA stages and a power-sharing 980-nm pump laser, and a C-plus L-band amplifier module with three amplifier stages. In Fig. 1, two WDM couples were used to connect two individual amplifier modules in parallel, and the output wavelength ranges of ports 1, 2, and 3 were 1480 to 1600 nm, 1480 to 1520 nm, and 1520 to 1600 nm, respectively.

The S-band erbium-doped fiber inside the EDFA module has a depressed cladding design in order to provide a sharp, high-attenuation, long-wavelength cutoff filter in the erbium-doped fiber. The cutoff wavelength is near 1530 nm. However, the composition of the core is approximately 2.5% GeO_2, 5.5% Al_2O_3, and 92% SiO_2, with 0.15 wt% erbium. The depressed cladding is approximately 3% fluorine, 0.5% P_2O_5, and 96.5% SiO_2. The fiber in the first stage has a fiber length of 20 m, and can provide a low noise figure and medium gain by forward pumping. The fiber in the second stage has a fiber length of 30 m, and can produce large output power by backward pumping. In addition, the optical isolator between these two stages can reduce backward ASE and improve noise figure performance. The total pump power of this amplifier module can be up to 280 mW while the bias current is operated at 356 mA. Furthermore, the evolution from a standard EDFA to this S-band design can be achieved by the introduction of a continuous long-wavelength cutoff filter in the erbium-doped fiber. Although the spectrum indicates strong gain at S-band wavelengths, the gain cannot be realized because of strong ASE at the 1530-nm peak. The introduction of a progressively sharper long-wavelength cutoff filter suppresses the gain in the C- and L-bands, so that the S-band region can exhibit increasing gain, as ASE from the 1530-nm peak does not grow and limit the population inversion. The final result is a complete suppression of the longer wavelength gain, resulting in a usable high net gain in the S-band. To investigate the performances of the proposed amplifier, the input signal powers $P_{in}=0$, -15, and -30 dBm are used to probe the amplifier gain and noise figure spectra, respectively. Figure 2 shows the gain and noise figure spectra of the S-band EDFA over the bandwidth of 1480 to 1520 nm when the input signal powers are 0, -15, and -30 dBm, respectively. Therefore, the gain and noise figure of the S-band amplifier can achieve 34.1

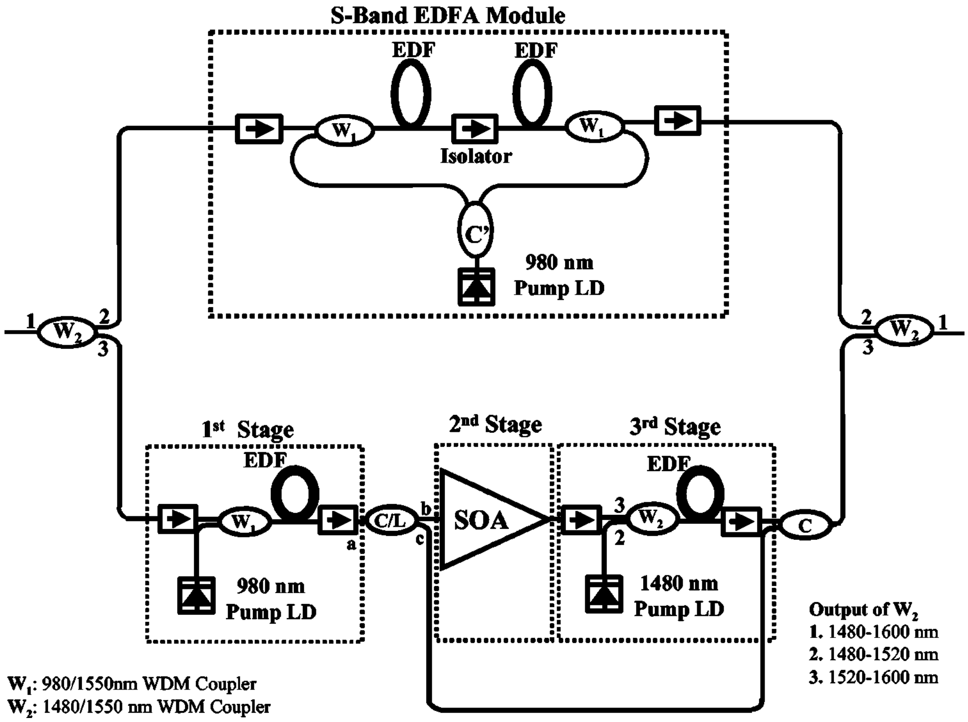

Fig. 1 Experimental setup of the broadband amplifier.

and 5.0 dB at 1506 nm when the input power is −30 dBm, and the saturated output power at 1498 nm can be up to 16.3 dBm for an input power of 0 dBm with a 7.1-dB noise figure.

The hybrid C- plus L-band amplifier module is constructed by three amplifier stages (two EDFAs and an SOA), a 1×2 and 50:50 optical coupler (C), and a C/L (1564/1570 nm) band splitter (BS) with an insertion loss of <0.43 dB as shown in Fig. 1. The output wavelength ranges of the BS for ports a, b, and c were 1500 to 1610 nm, 1570 to 1610 nm, and 1500 to 1564 nm, respectively. The first EDFA stage has a 10-m-long EDF and a 980-nm pump laser of 60 mW. The second SOA stage has an operating current of 250 mA. The third EDFA stage has a 34-m-long EDF and a 1480-nm pump laser of 100 mW. Besides, the first stage EDFA with forward pumping can provide a low noise figure and medium gain. However, the SOA can be used to pump the third EDFA stage for extending the gain bandwidth to the L-band. Figure 3(a) shows the gain and noise figure spectra of the SOA over a bandwidth of 1530 to 1610 nm when $P_{in}=0$, −15, and −30 dBm, respectively. The SOA with worst noise figure will degrade the noise figure spectra of the hybrid structure. To improve the drawback, the first EDFA stage is used to provide the gain medium of the low noise figure. Therefore, the total length of EDF used for the proposed C- plus L-band amplifier is shorter than that of conventional L-band EDFA.[1] Figure 3(b) presents the gain and noise figure spectra over the bandwidth of 1520 to 1600 nm. Peak gains of 35.4 and 38.1 dB can be obtained at 1532 and 1568 nm while the input signal power is −30 dBm, respectively.

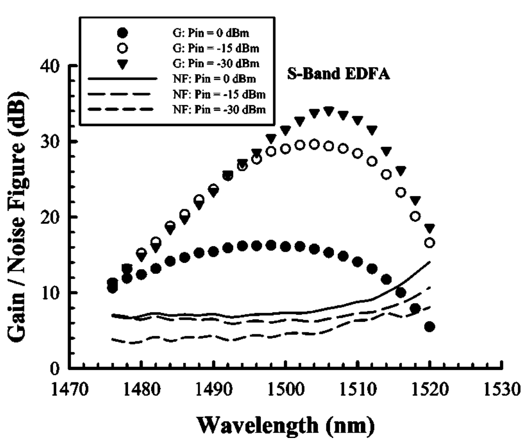

Fig. 2 Gain and noise figure spectra of the S-band EDFA while the input power $P_{in}=0$, −15, and −30 dBm, respectively.

Table 1 Gain and noise figure values of individual amplifiers used in the proposed amplifier.

	Peak Gain (dB)	NF (dB)	Wavelength (nm)
S-Band EDFA	34.1	5.0	1506
SOA	12.7	6.7	1576
C-Plus L-Band Amplifier	35.4	3.6	1532
	38.1	3.4	1568
Proposed Broadband Amplifier	32.7	7.1	1504
	34.5	4.2	1534
	32.9	4.0	1570

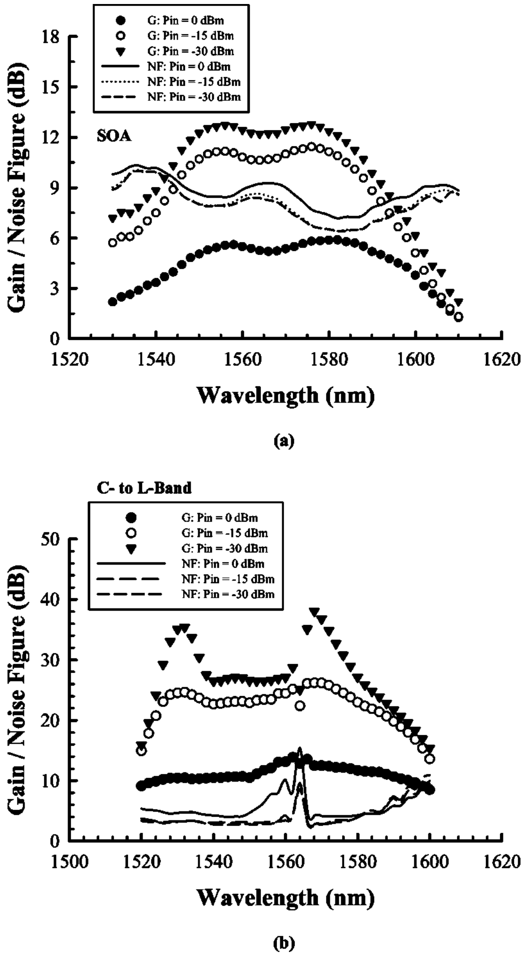

Fig. 3 Gain and noise figure spectra of the C- plus L-band amplifier module in Fig. 1 when the input power $P_{in}=0$, -15, and -30 dBm, respectively.

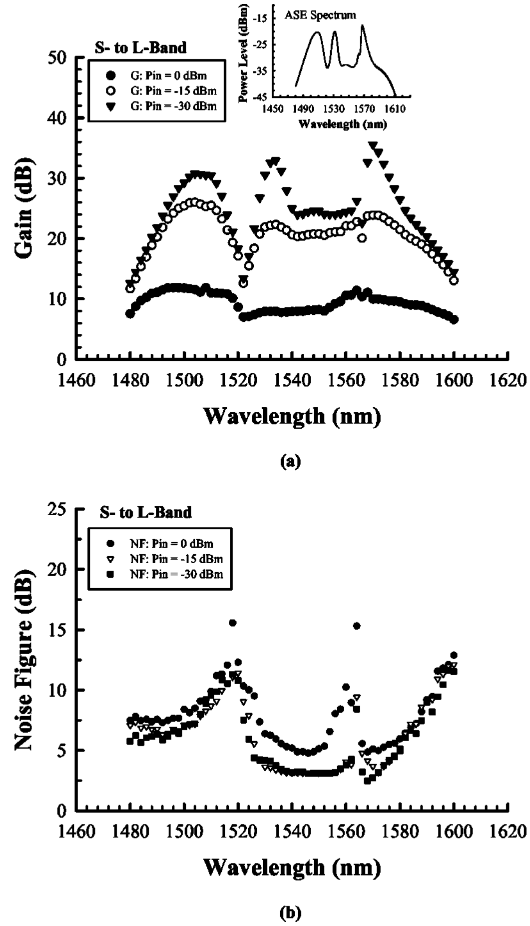

Fig. 5 (a) Gain and (b) noise figure spectra of the proposed configuration in Fig. 1 while the input power $P_{in}=0$, -15, and -30 dBm, respectively. The insert of Fig. 5(a) is the ASE spectrum of the proposed EDFA.

Because of the band gap (1564 to 1570 nm) loss of the C/L BS, the gain and noise figure spectra will drop and degrade at near 1564 nm as shown in Fig. 3(b). Because of the influence of insertion loss (~3 dB) of a 1×2 and 50:50 coupler of coupler, it would lose some gain in this proposed amplifier. However, the C- to L-band gain can be increased about 2.5 dB easily if a C/L coupler is used instead of the optical coupler. Figure 4 presents that the insertion loss spectra of ports 2 and 3 for two 1480/1550-nm WDM couplers, and two loss curves cross around 1522 nm. As a result, SOAs are attractive in WDM networks since they feature extremely high on-off ratios of 40 to 50 dB, which are needed to overcome the severe penalty induced by crosstalk.[12,13] Compared with past-related L-band EDFA,[1,4] the proposed hybrid amplifier can reduce the total used EDF length to 44 m long by a second SOA stage to pump the third EDFA stage for extending the wavelength range from C-band to L-band.

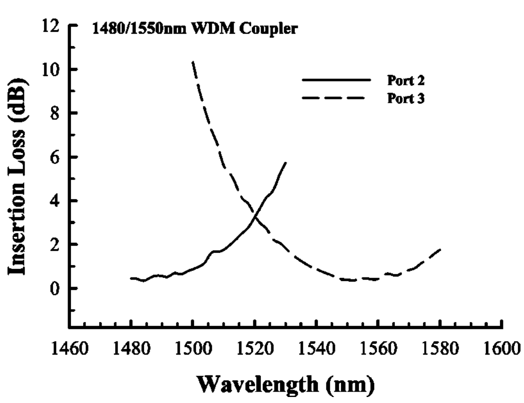

Fig. 4 The insertion loss of two 1480/1550-nm WDM couplers versus the wavelengths.

Figures 5(a) and 5(b) indicate the gain and noise figure spectra for the proposed configuration in Fig. 1 while the input signal power $P_{in}=0$, -15, and -30 dBm, respectively. The insert of Fig. 5(a) shows the ASE spectrum with a 120-nm bandwidth of 1480 to 1600 nm for this proposed wideband structure. Figure 5(a) represents the gain spectra over a 120-nm bandwidth of 1480 to 1600 nm. It also shows the peak gain of 32.7, 34.5, and 32.9 dB at 1504, 1534, and 1570 nm, respectively, when the input signal power is -30 dBm. Due to the insertion losses of two WDM couplers (as seen in Fig. 4), the different gain spectra of this proposed amplifier are smaller than that of the S- and C- plus L-band amplifier individually. The gain spectra could drop at near 1522 and 1564 nm because of the band gap loss of two 1480/1550-nm WDM couplers and the C/L BS. The noise figure also degraded over the bandwidth from 1480 to 1600 nm in this proposed configuration. Furthermore, this proposed amplifier module based on two new EDFA modules and a coupled structure could achieve a 120-nm gain bandwidth of 1480 to 1600 nm. The proposed amplifier can be used as an inline, pre- or postamplifier in a real transmission system. According to Fig. 5, the gain and noise figure spectra also show the behavior and performance of that when the different input signal power levels are applied. This amplifier also provides a broadband ASE light source of 1480 to 1606 nm when the output levels are above −40 dBm. Compared with the past broadband amplifier techniques,[3–10] the proposed amplifier has the advantage of wide bandwidth, potentially lower cost, and simple architecture. We conclude with the gain and noise figure values of the individual amplifiers used, as shown in Table 1. As a result, this proposed broadband amplifier is useful for future applications in DWDM networks.

3 Conclusions

In summary, we have experimentally investigated and demonstrated a new S- to L-band EDFA module with coupled structure, which reaches a 120-nm gain bandwidth of 1480 to 1600 nm. Peak gains of 32.7, 34.5, and 32.9 dB (7.1, 4.2, and 4 dB noise figure) is obtained at 1504, 1534, and 1570 nm with −30 dBm input signal power, respectively. In addition, this proposed amplifier also provides a broadband ASE light source of 1480 to 1606 nm as the output levels are above −40 dBm.

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