

# Hybrid three-stage C- plus L-band optical fiber amplifier in cascade configuration

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## 1 Introduction

Erbium-doped fiber amplifiers (EDFAs) have strongly contributed to recent advances in dense-wavelength-division-multiplexing (DWDM) networks due to their high transmission capacities and optical gain. Usually, EDFAs (C-band) are used in the C-band (1530 to 1560 nm). Recently, L-band (1560 to 1610-nm) fiber amplifier techniques have been achieved using a longer EDF than those of C-band EDFAs (Ref. 1), fiber Raman amplifiers,<sup>2</sup> and different hybrid amplifiers.<sup>3</sup> In addition, a wideband EDFA from the C- to the L-band in parallel structure was also studied.<sup>4</sup> Because the gain profile of EDFA exhibits nonflat and input-dependent behaviors, the stabilized gain versus the variation of input signal power is one of the key issues for DWDM systems. Several gain-clamping techniques have been studied, such as the all-optical gain-clamped method<sup>5</sup> or various optical filters.<sup>6-9</sup> In addition, the gain-stabilizing methods that employ optical feedback were also reported.<sup>5,10</sup> In this paper, we propose and experimentally investigate a hybrid three-stage C- plus L-band fiber amplifier module that is composed of two EDFAs and a semiconductor optical amplifier (SOA), over the operation range from 1540 to 1600 nm. Moreover, we propose a gain-clamping technique in the configuration. Therefore, the be-

**Abstract.** A hybrid C- plus L-band fiber amplifier module with three amplifier stages, which provides an operation range of 1540 to 1600 nm, is proposed and experimentally demonstrated. The proposed amplifier consists of two erbium-doped fiber amplifier (EDFAs) and a semiconductor optical amplifier (SOA) in cascade. Compared with a traditional L-band EDFA having longer EDF length, this amplifier can reduce the total EDF length to 44 m. As a result, 41.5 dB gain and a 3.7-dB noise figure are achieved at 1562 nm over the bandwidth of 1540 to 1600 nm, while the input signal power is  $-30$  dBm. In addition, the behavior and performance of the proposed gain-clamping amplifier module over the C- plus L-band is investigated experimentally under different operation conditions. © 2005 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1905628]

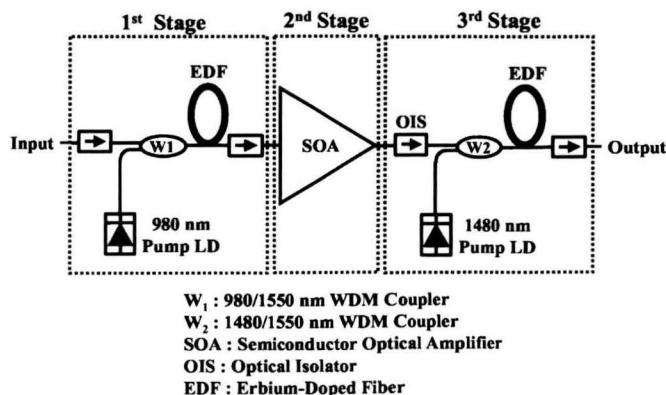
Subject terms: gain clamping; hybrid amplifier; L-band; erbium-doped fiber amplifier; semiconductor optical amplifier.

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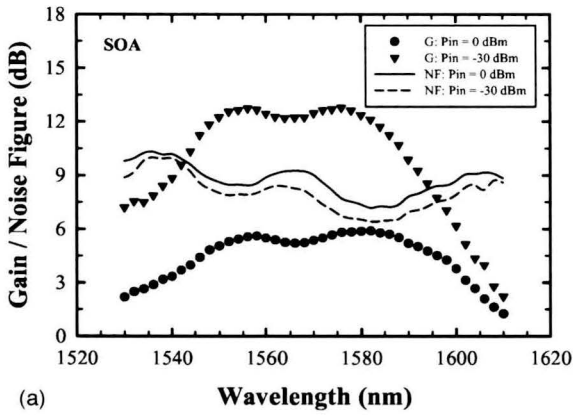
havior and performance of gain clamping for this proposed amplifier are also studied under different operation conditions.

## 2 Experiments and Discussion

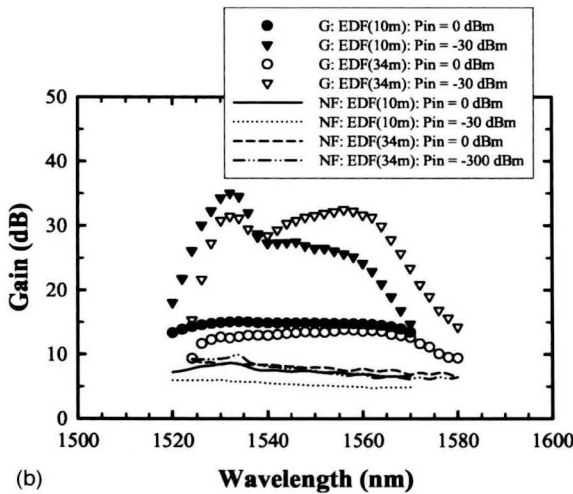
Figure 1 shows the proposed hybrid C- plus L-band fiber amplifier module. The configuration is constructed of three amplifier stages. The first stage is an EDFA module with a 10-m-long EDF and a 980-nm pump laser of 60 mW, the



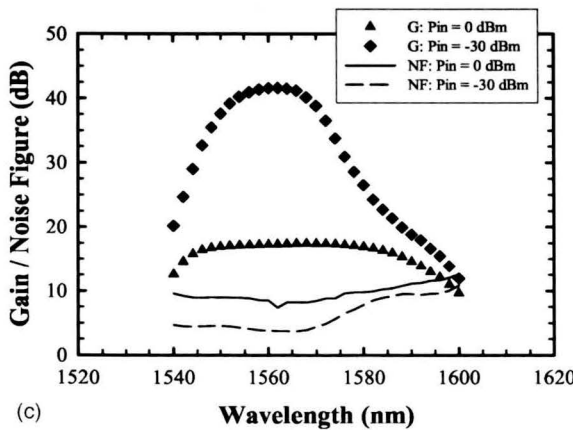
**Fig. 1** Experimental setup of the proposed hybrid amplifier module.



(a)



(b)

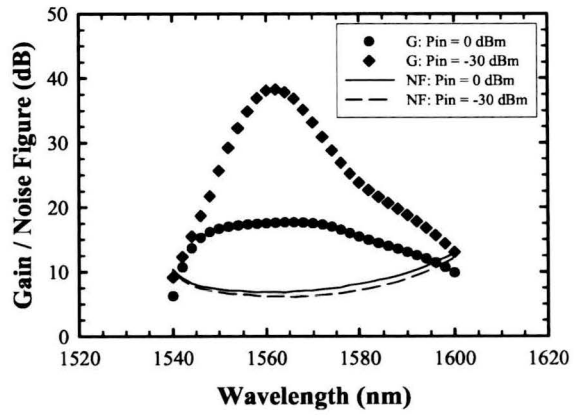


(c)

**Fig. 2** (a) Gain and noise figure spectra of an SOA in the operating range from 1530 to 1630 nm, (b) the gain spectra of the two EDFAs, and (c) the gain and noise figure spectra of the proposed hybrid amplifier. The probe input signal powers are  $P_{in}=0$  and  $-30$  dBm, respectively.

second stage is an SOA with 250 mA of bias current, and third stage is an EDFA module with a 34-m-long EDF and a 1480-nm pump laser of 100 mW, as shown in Fig. 1. To realize the performance of this proposed amplifier module, a tunable laser source (TLS) and an optical spectrum analyzer (OSA) are used to measure the gain and noise figure spectra.

Figure 2(a) shows the gain (G) and noise figure (NF)



**Fig. 3** Gain and noise figure spectra of conventional L-band EDFA with a 92-m-long EDF and a 1480-nm pump laser of 140 mW.

spectra of the SOA over the operation range from 1530 to 1610 nm, when the input signal powers are 0 and  $-30$  dBm, respectively. From Fig. 2(a), the maximum gain of 13.2 dB appears near 1578 nm as the input power is  $-30$  dBm. In this proposed three-stage amplifier, the second SOA stage can be used to pump the third EDFA stage to extend the gain bandwidth to the L-band. However, the bias current of SOA is operated at maximum value (250 mA). Using the smaller operating current affects the extending of the gain bandwidth. The SOA has a worse noise figure spectra in Fig. 2(a). Therefore, the SOA will influence and degrade the noise figure spectra module when the first stage is neglected in this proposed hybrid amplifier. To improve this drawback, we usually can employ a shorter length of EDF in front of the multistage amplifier. Thus, the first EDFA stage is used to provide the gain medium with a low noise figure in the proposed amplifier. Figure 2(b) shows the gain and noise figure spectra of first and third amplifier stages when the input signal powers are  $P_{in}=0$  and  $-30$  dBm, respectively. From Fig. 2(b), the gain spectra of first EDFA stage are distributed in the C-band (1520 to 1570 nm). The third stage presents the gain spectrum slightly shifted to the longer wavelength, and the maximum peak gain of 32.5 dB (a 6.4-dB noise figure) at 1556 nm. Figure 2(c) describes the gain and noise figure spectra of the proposed hybrid amplifier module when the input powers are  $P_{in}=0$  and  $-30$  dBm, respectively. Furthermore, the 41.5-dB gain and 3.7-dB noise figure are achieved at 1562 nm in the bandwidth range of 1540 to 1600 nm, while the input signal power is  $-30$  dBm, as shown in Fig. 2(c).

Conventionally, C- plus L-band EDFA with a longer EDF than that of the C-band EDFA can be easily achieved.<sup>1</sup> Therefore, we reconstruct a L-band EDFA having 92-m-long EDF and a 1480-nm pump laser of 160 mW to compare with the proposed amplifier. Figure 3 shows the gain and noise figure spectra of the L-band EDFA from 1540 to 1600 nm when the  $P_{in}=0$  and  $-30$  dBm, respectively. From Figs. 2(b) and 3, we can see that the two amplifiers have similar gain spectra. Therefore, the proposed hybrid amplifier can reduce the total length of the EDF to 44 m.

In a homogeneously broadened medium, lasing action at a particular wavelength fixes the total population inversion, therefore, the gain for all wavelengths are dependent only on their absorption and emission cross sections and the

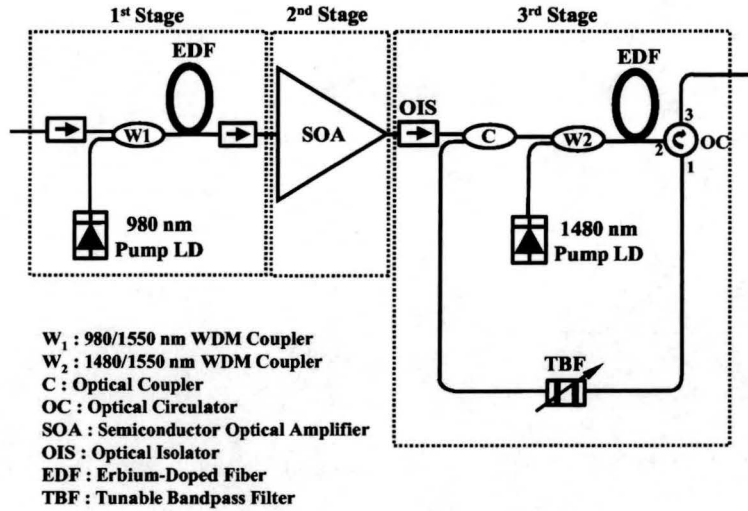


Fig. 4 Experimental setup of the gain-clamped hybrid amplifier module.

overlapping factor. Any variation in input signal powers will be compensated by an adjustment of the lasing signal power. In other words, the lasing wavelength (or saturated tone) will cause the gain saturation due to the population inversion to be maintained. It is important to realize that even in a simple 1-D model of the fiber amplifier, the transverse shape of the optical mode and its overlap with the transverse erbium ion distribution profile are important.<sup>11</sup> As a result, each signal wavelength experiences a constant gain through this amplified system, independent of signal power variation caused by operation such as channel adding or dropping. Based on this principle, Fig. 4 shows the experimental setup for the C- plus L-band amplifier module with backward optical feedback method for clamping gain while a 1×2 coupler, a tunable bandpass filter (TBF), and an optical circulator (OC) are used in this structure. As seen in Fig. 4, the TBF is inside the ring cavity in the third EDFA stage and can be adjusted at 1559 and 1570 nm to act as the saturated tone for clamping gain.

Figure 5(a) shows the measured gain and noise figure characteristics versus the different power levels of the input signal at 1566 nm while the lasing wavelength is at 1559 nm and the input ratios of 1×2 coupler (C) are 95, 90, 70, and 50%, respectively. The gain-clamping effect is observed when the input ratio of C is not larger than 95% for a lasing wavelength of 1559 nm. The traditional loop feedback method would degrade the noise figuration when the lasing is injected.<sup>5</sup> However, the proposed gain-clamped amplifier has very little degradation due to the low noise figure of the first EDFA stage. Figure 5(b) shows the measured gain and noise figure characteristics versus the different input signal power levels at 1550 nm with the operation conditions the same as in the preceding. By using the C of the 90% input ratio, the gain can be kept constant up to the input power of -25 dBm. Therefore, a dynamic range of input signal from -45 to -25 dBm and the gain of >39.5 and 30 dB is retrieved for the optical feedback scheme as the input signal wavelength is 1566 and 1550 nm, respectively. When we exchange the lasing wavelength at 1570 nm, Figs. 6(a) and 6(b) presents the measured gain and noise figure characteristics versus the different power levels

of an input signal at 1566 and 1550 nm, respectively. The gain also will be clamped up to the input power of -25 dBm while the C of 90% input ratio used for Figs. 6(a) and 6(b). A dynamic range of input signal from -45 to -25

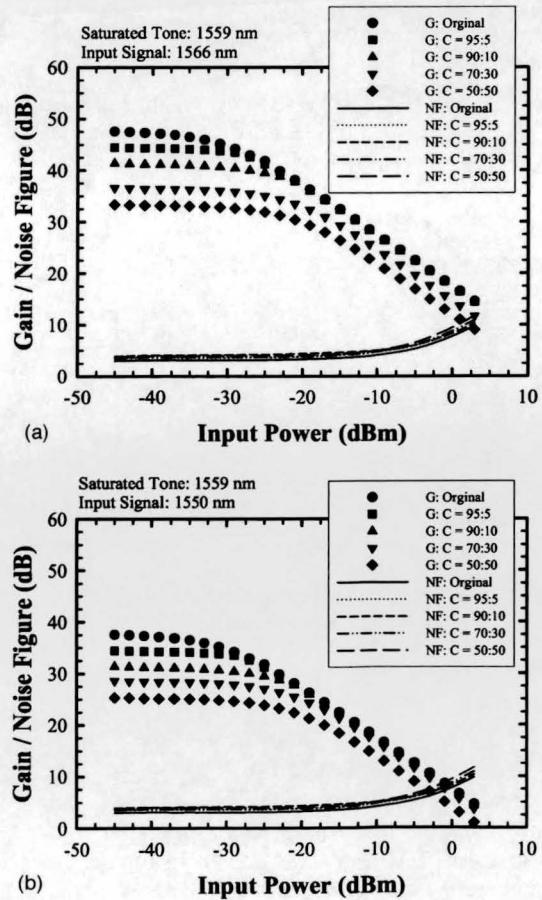
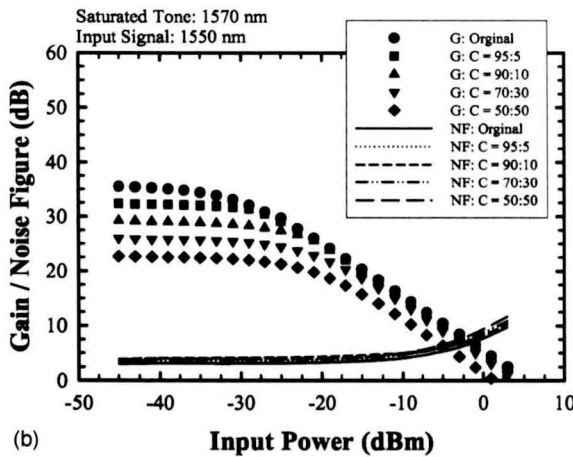
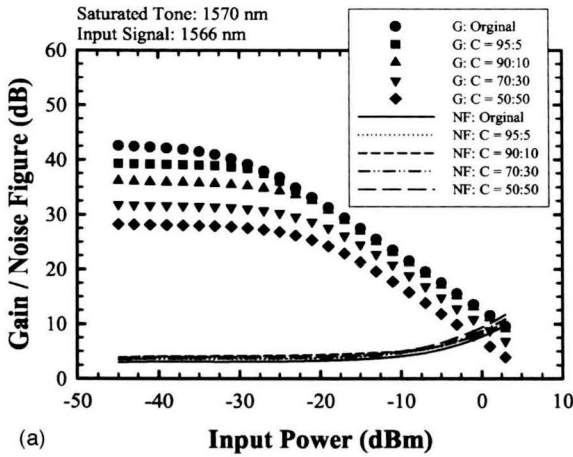


Fig. 5 Gain and noise figure versus the different power level of input signal at (a) 1566 and (b) 1550 nm while the lasing wavelength is 1559 nm and the input ratios of C are 95, 90, 70, and 50%, respectively.



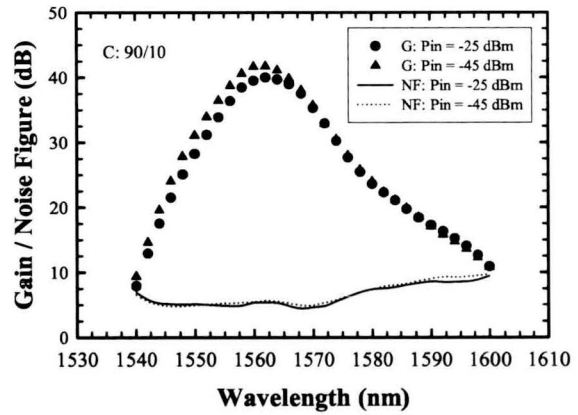
**Fig. 6** Gain and noise figure versus the different power level of input signal at (a) 1566 and (b) 1550 nm while the lasing wavelength is at 1570 nm, and the input ratios of C are 95, 90, 70, and 50%, respectively.

dBm and the gain of >34.3 and 27.4 dB is retrieved for the optical feedback scheme when the input signal wavelengths are 1566 and 1550 nm, respectively. As a result, Figs. 5 and 6 show the gain and noise figure variation of the proposed amplifier module with different input signal powers applied when the testing signal (1550 and 1566 nm) and saturated tone (1559 and 1570 nm) are placed at the C- and L-band, respectively.

Figure 7 indicates the gain and noise figure spectra of the gain-clamped amplifier module with a C of 90% input ratio, when the saturated tone is 1559 nm, at the input signal powers of  $P_{in} = -25$  and  $-45$  dBm, respectively, over the operation range from 1540 to 1600 nm. The maximum gain at 1562 nm is 41.7 dB (5.6 dB noise figure) with the input power of  $-45$  dBm, and the maximum gain variations are less than 2.4 dB over the operating wavelength range and 20-dB ( $-45$  to  $-25$  dBm) input dynamic range.

### 3 Conclusions

We proposed and experimentally demonstrated a hybrid three-stage C- plus L-band fiber amplifier module over the operation range from 1540 to 1600 nm. The proposed amplifier consists of two EDFA and one SOA in cascade configuration. Compared with a traditional L-band EDFA hav-



**Fig. 7** Gain spectra of the gain-clamped amplifier module with C of 90% input ratio at the input signal powers  $P_{in} = -25$  and  $-45$  dBm, when the saturated tone is at 1559 nm.

ing a longer EDF length, this amplifier can reduce the total EDF length to 44 m. Therefore, a 41.5-dB gain and a 3.7-dB noise figure are achieved at 1562 nm over the bandwidth of 1540 to 1600 nm, while the input signal power is  $-30$  dBm. Moreover, the behavior and performance of the proposed gain-clamping amplifier module over the C- plus L-band were investigated experimentally under different operation conditions. This proposed amplifier module is useful for applications of DWDM networks.

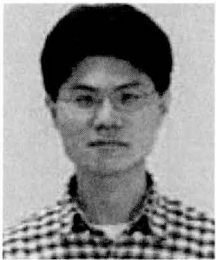
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