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# Investigation of Broadband S-Band to L-Band Erbium-Doped Fiber Amplifier (EDFA) Module

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## Abstract

This chapter presents three sections that describe the broadband S-band to L-band erbium-doped fiber amplifier modules. In the first section, an S-band gain-clamped erbium-doped fiber amplifier (EDFA) module, employing a fiber Bragg grating (FBG) to act as a reflected element for generating a saturated tone injected into the EDFA module by using forward optical feedback method, is proposed. Moreover, the output performance of the gain and noise figure (NF) in the proposed gain-clamped S-band EDFA has been discussed in the wavelength range of 1478–1520 nm. In the second section, we demonstrate experimentally a gain-flattened two-stage erbium-based fiber amplifier (EBFA) module, which is composed of by an erbium-doped waveguide amplifier (EDWA) and a C-band EDFA in serial structure. In an operation range of 1528–1562 nm, the entire gain is larger than 35 dB and the observed NF is between 5.5 and 6.7 dB. Moreover,  $\pm 1.1$  dB maximum gain variation is also obtained for the input signal power of -25 dBm. Hence, the proposed fiber amplifier not only enhances the gain but also achieves the flatness in the wavelength region. In the final section, a broadband hybrid two-stage fiber amplifier, which is composed by a C-band EDFA and a C-band semiconductor optical amplifier (SOA) in serial scheme, is investigated experimentally. Here, we only use a 3 m long erbium-doped fiber (EDF) serving as a preamplifier to increase the gain and reduce the noise figure. Therefore, the proposed hybrid amplifier achieves a 110 nm effectively amplification of 1500–1610 nm (from S- to L-band). In addition, the output performance of gain and NF in the proposed fiber amplifier has also been discussed.

**Keywords:** Erbium-Doped Fiber Amplifier (EDFA), Semiconductor Optical Amplifier (SOA), Erbium-Doped Waveguide, Amplifier (EDWA)

## 1. Introduction

Broadband erbium-doped fiber amplifier (EDFA) was useful to increase the number of wavelength-division-multiplexing (WDM) signals in 1.5- $\mu$ m fiber transmission, routing

network, and optical access network [1]. These days, the EDFA module with 120 nm wavelength bandwidth can be accomplished theoretically and experimentally [2, 3]. However, using the reconfigurable optical add-drop multiplexers (OADM) or carrying burst traffic in optical domain in the dynamic WDM systems, the power transient would be induced by the slow response of EDFA. This is a challenging issue to resolve. The transient effects could be reduced by utilizing either electric or optical control, or the combination of both techniques. In these schemes, the optical gain clamping was a commonly used technique. In the related researches, there have been some studies executed in the C- to L-band fiber amplifiers with gain-clamped effect [4–8]. In previous studies, serial architectures were employed [4, 5], predictably introducing cross talk among the C- to L-band ranges. Using parallel architecture could improve the cross talk [8], but the counter-propagating of transmitted signal and laser lightwave would produce the higher noise figure (NF) [9, 10]. Here, an S-band (1460–1520 nm) EDFA, which utilizes depressed cladding design and 980 nm pump laser to cause EDF gain extension effect, has been proposed [11]. Hence, the gain clamping technique is expected to extend to S-band by the proposed S-band EDFA.

In addition, a gain-flattened was also important key for EDFA dynamically working on WDM communication systems. Mostly, the gain spectra of EDFAs could be flattened by utilizing several methods, such as doping the different material compositions in the erbium-doped fiber (EDF) [12], or using optical filters to compensate for the variations in the gain spectra [13–19]. Moreover, different types of optical filters have been demonstrated for this issue, such as Mach-Zehnder (M-Z) filters [18], fiber Bragg gratings (FBGs) [15], long-period fiber gratings [13, 14], fiber acousto-optic tunable filters [16, 17], a split-beam Fourier filter [19], and hybrid amplifier design [20].

Recently, to satisfy the requirement of communications capacity, the broadband EDFAs have been suiting the major techniques in the dense wavelength-division-multiplexed (DWDM) transmissions. Applying the C- to L-bands' gain of EDFA could be above 80 nm amplification bandwidth. And it would also enhance the ability of the transmission of DWDM systems [21]. Thus, there were many optimized architectures on C- plus L-band EDFAs [21–27]. And the broadband EDFA module design has the serial or parallel configuration individually [28, 29]. In L-band EDFA, the power conversion efficiency (PCE) was too low for obtaining the higher gain, because it was far from the erbium ion absorption band. In addition, several techniques to expand the L-band gain were demonstrated, such as utilizing unwanted C-band amplified spontaneous emission (ASE) [23], employing the double-pass configuration [30], [31], and applying reflection-type EDFA with grating [32].

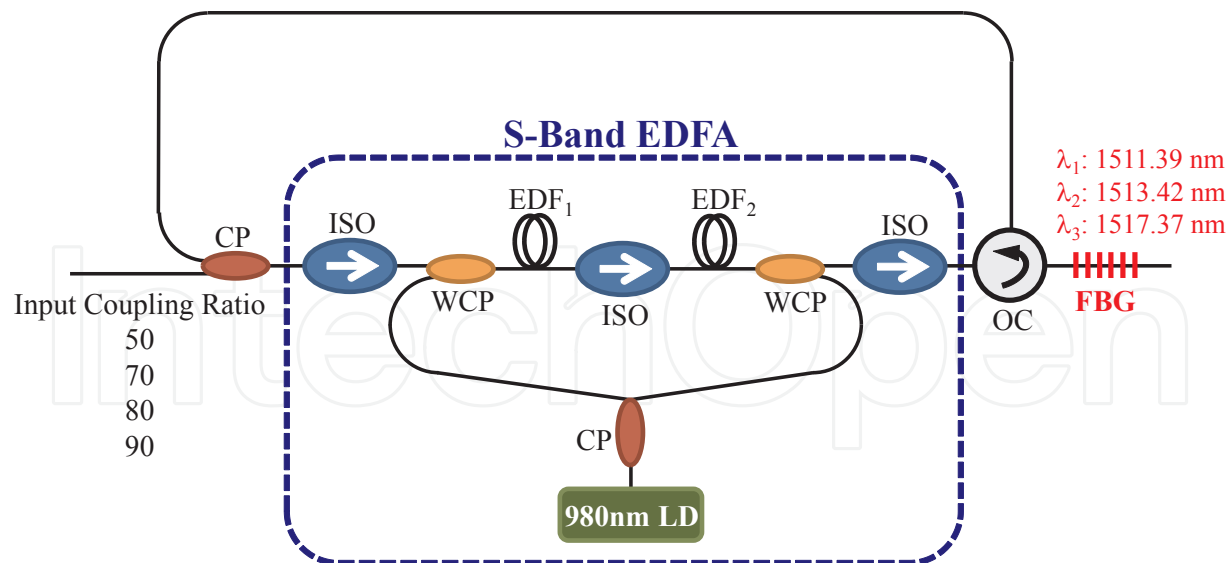
In this chapter, there are three sections that describe the broadband S-band to L-band erbium-doped fiber amplifier modules. In the first section, an S-band gain-clamped erbium-doped fiber amplifier (EDFA) module, employing a fiber Bragg grating (FBG) to act as a reflected element for generating a saturated tone injected into the EDFA module by using forward optical feedback method, is proposed. Moreover, the output performance of the gain and noise figure (NF) in the proposed gain-clamped S-band EDFA has been discussed in the wavelength range of 1478–1520 nm. In the second section, we demonstrate experimentally a gain-flattened two-stage erbium-based fiber amplifier (EBFA) module, which is structured by an erbium-

doped waveguide amplifier (EDWA) and a C-band EDFA in serial structure. In an operation range of 1528–1562 nm, the entire gain is larger than 35 dB and the observed NF is between 5.5 and 6.7 dB. Moreover,  $\pm 1.1$  dB maximum gain variation is also obtained for the input signal power of -25 dBm. Hence, the proposed fiber amplifier not only enhances the gain but also achieves the flatness in the wavelength region. In the final section, a broadband hybrid two-stage fiber amplifier, which is constructed by a C-band EDFA and a C-band semiconductor optical amplifier (SOA) in serial scheme, is investigated experimentally. Here, we only use a 3 m long erbium-doped fiber (EDF) serving as a preamplifier to increase the gain and reduce the noise figure. Therefore, the proposed hybrid amplifier achieves a 110 nm effectively amplification of 1500–1610 nm (from S- to L-band). In addition, the output performance of gain and NF in the proposed fiber amplifier has also been discussed.

## 2. S-Band gain-clamped EDFA module

In this section, an S-band gain-clamped EDFA module, employing a fiber Bragg grating (FBG) to act as a reflected element for generating a saturated tone injected into the EDFA module by applying forward optical feedback method, is proposed experimentally. In the measurement, using a lasing wavelength could regularize the total population inversion under a homogeneously broadened effect for gain-clamped. Thus, the obtained gain of EDFA depends on its absorption, emission cross sections, and the overlapping factor. Any variation of input signal power could be compensated by adjusting the power of lasing wavelength. As a result, each signal would experience a fixed gain through the EDFA module, with the variation of input signals power, which was caused by operation, such as signal adding or dropping. Figure 1 presents the proposed gain-clamped S-band EDFA module with forward optical feedback structure. The proposed fiber amplifier is constructed by an S-band EDFA, an optical circulator (OC), a 1×2 optical coupler (CP), and three FBGs with different Bragg wavelengths. The optical CP has the input coupling ratios of 90, 80, 70, and 50 % for the input signal in Fig. 1, respectively. The optical CP with different input coupling ratio governs the forward injected power level of each saturated tone individually. The FBG is used to serve as a reflected element to generate a lasing wavelength in the S-band wavelength range. The lasing wavelength could be injected in forward direction for clamping the gain spectrum of proposed amplifier. Here, we utilize three different FBGs with various Bragg wavelengths and reflectivities and four optical CPs having different coupling ratios to produce the various injected wavelengths and powers for measuring the gain performance of proposed gain-clamped S-band EDFA module.

To support the sharp, high-attenuation, long-wavelength cutoff filter in active fiber, the S-band EDF with depressed-cladding design is proposed and used inside EDFA module [33]. The used EDF of first and second stages have various physical characteristics. In the first EDF stage, a 20 m long EDF is employed to provide low NF and medium gain by forward pumping. In second fiber stage, a 30 m long EDF is utilized to generate a large output power by backward pumping. Furthermore, the optical ISO between the two EDF stages is used to decrease the backward amplified spontaneous emission (ASE) noise and improve noise figure (NF). Besides, the total pumping power of 980 nm Laser Diode (LD) in the S-band EDFA module

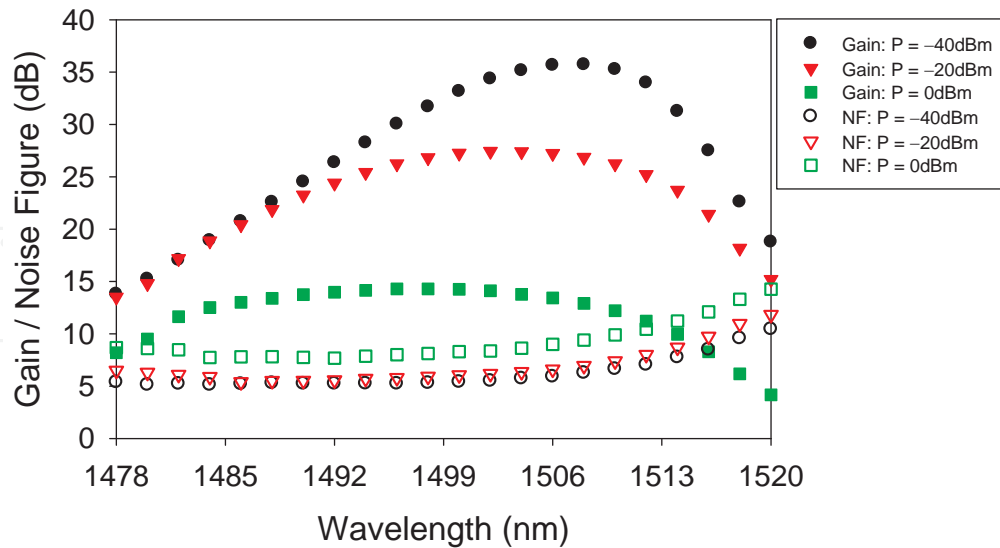


**Figure 1.** Experimental setup of gain-clamped S-band EDFA module by using forward optical feedback method.

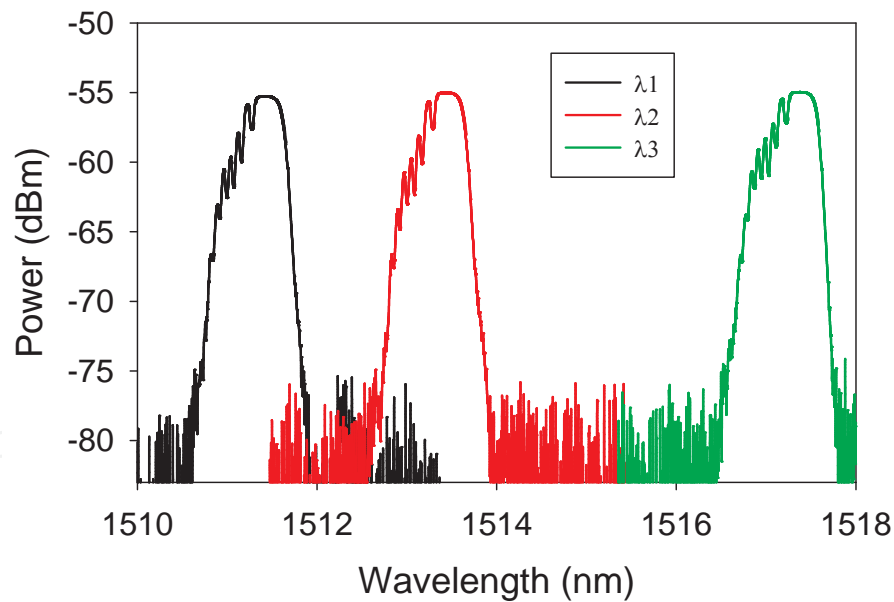
can be set at 280 mW, when the corresponding bias current is 356 mA. To measure the performance of proposed gain-clamping EDFA, a tunable laser source (TLS) is employed to measure the gain and NF profiles. Moreover, the optical signal is observed by an optical spectrum analyzer (OSA) with a 0.05 nm resolution.

Figure 2 presents the gain and NF spectra of an S-band EDFA without gain-clamping over the operation region of 1478–1520 nm, when the input signal power ( $P$ ) is 0, –20, and –40 dBm, respectively. As seen in Fig. 2, the gain and NF of 27.6 and 5.9 dB can be obtained at the wavelength of 1504 nm with the input power of –20 dBm. And the saturated output power of 14.5 dBm is also completed at 1498 nm under a 0 dBm input power. The NFs are measured between 5.3 and 7.5 dB as the input signal power is –20 dBm in the wavelengths of 1478–1512 nm. Besides, the observed gain and NF are 12.4 and 9.6 dB, 26.4 and 6.8 dB, and 35.3 and 6.5 dB, respectively, as seen in Fig 2, when the input signal powers are 0, –20, and –40 dBm at the wavelength of 1510 nm. Here, because some optical passive devices are placed at the input and output ends. Thus, the higher losses in C-band and the splice point of EDF and WDM coupler would produce the higher loss. So, the NF of this S-band EDFA module would be also degraded slightly.

To obtain the gain-clamped operation in S-band EDFA, the FBG is utilized in the proposed amplifier module for producing a saturated tone to fix the total population inversion, as shown in Fig 1. In this experiment, we employ three FBGs with different Bragg wavelengths and reflectivities successively for gain-clamping. Figure 3 shows the reflective spectrum of FBG<sub>1</sub> ( $\lambda_1$ ) to FBG<sub>3</sub> ( $\lambda_3$ ) individually with the reflected Bragg wavelength of 1511.39 nm, 1513.42 nm, and 1517.37 nm, respectively. Here, the reflectivities of FBG<sub>1</sub>, FBG<sub>2</sub>, and FBG<sub>3</sub> are measured at 91.83%, 93.11%, and 82.98%, respectively. Besides, the maximum wavelength shifts of three utilized S-band FBGs are around 2.0–2.3 nm while the strain is applied on the FBGs. Moreover,



**Figure 2.** Measured gain and NF spectra of the original S-band EDFA over the wavelength region of 1478–1520 nm, while the input signal power  $P$  is equal to 0, -20, and -40 dBm, respectively.



**Figure 3.** Measured reflective spectrum of FBG1–FBG3 with the central wavelength of 1511.39 nm ( $\lambda_1$ ), 1513.42 nm ( $\lambda_2$ ), and 1517.37 nm ( $\lambda_3$ ), respectively.

when the temperature is up to  $\sim 90^\circ\text{C}$ , the reflected Bragg wavelength of FBG would drift nearly 1.2 nm.

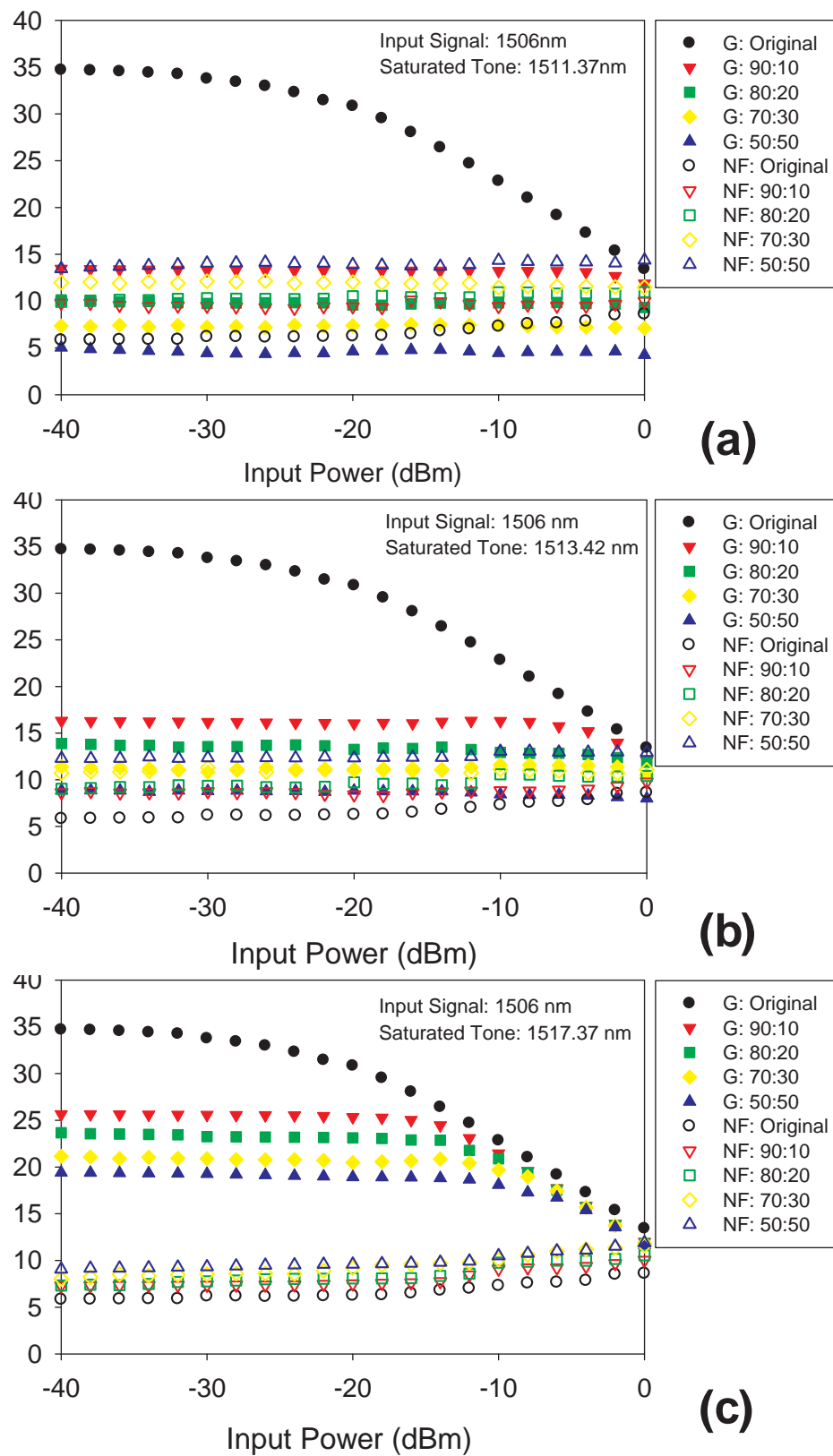
Figure 4 shows the gain and NF spectra under different powers in the input signal of 1506 nm without gain-clamping and with the various input coupling ratios of 90%, 80%, 70%, 50% for



the input signal, when the saturated tones are set at (a) 1511.39 nm, (b) 1513.42 nm, and (c) 1517.37 nm, respectively. Figure 4(a) presents the gain and NF spectra under the different input signal powers. Here, Fig. 4(a) also displays the poorer gain and NF profiles at various coupling ratios of CP. Because of the higher gain region at 1508–1512 nm (as seen in Fig. 2), the saturated signal would obtain a largest gain for clamping and fixing the gain spectrum in the region and lead to the decrease of NF simultaneously. That is to say, while a saturated signal of 1511.39 nm backward injects into the EDFA module, it could get a most  $\text{Er}^{3+}$  ion population inversion to clamp the gain profile. It also would introduce the lower gain and poorer NF spectra in other input signals. Figure 4(b) presents that the gain could be maintained constant in the  $-10$  dBm input signal power at an input coupling ratio of 90%. Moreover, the constant gains are fixed at around 16.1 dB and the NF would be at 8.3–8.8 dB, as the input signal power is less than  $-10$  dBm. Figure 4(b) shows the noise figure of  $> 10$  dB in the input coupling ratio of  $> 80\%$ . At other operating conductions, the gain and NF profiles of Fig. 4(b) also are worse. However, these results are better than that of Fig. 4(a).

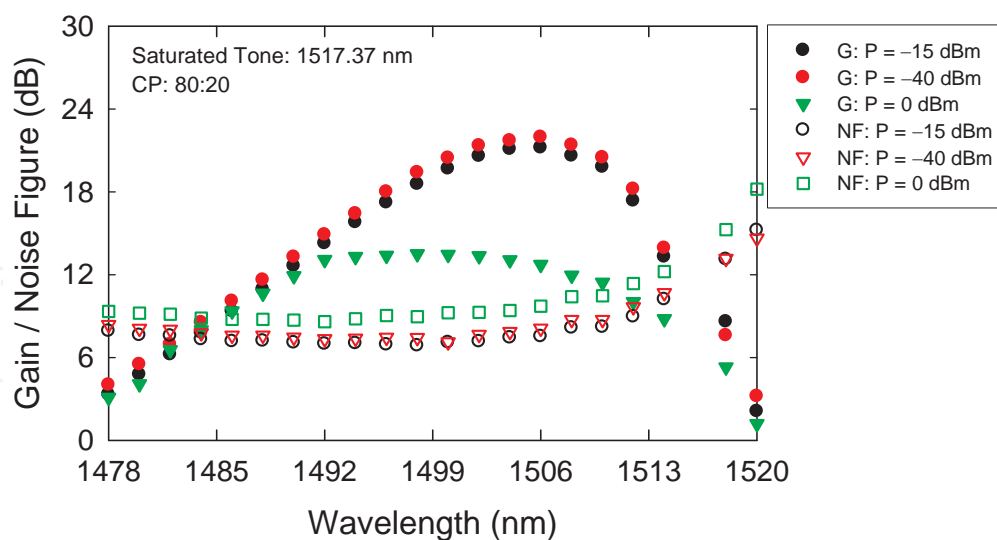
When a saturated tone is set at 1517.37 nm and an input coupling ratio is 50%, the gain could be fixed constant in the input power of  $< -12$  dBm under expense of around 6 dB gain. Then, the gain will be kept at around 19 dB and the NF could be measured between 8.2 and 9.6 dB, as illustrated in Fig. 4(c). Here, the NF degradation is measured in  $\sim 4.1$  dB. While the input coupling ratio is selected from 50 to 80%, the gain is maintained at the input signal power of  $< -12$  dBm, as illustrated in Fig. 4(c). Besides, Fig. 4(c) also presents the gain dynamic range of 28 dB from  $-12$  to  $-40$  dBm when the input coupling ratio is 80%. According to the results, if another channel is added or dropped into the proposed S-band EDFA, it does not influence the gain profile in the channel power of  $< -12$  dBm. In addition, as the gain-clamping is maintained, the input signal power should be putted in the input dynamic range, while the other input signal is added or dropped simultaneously. If not, the proposed EDFA does not bring the gain-clamping action. Figure 4(c) also shows that the gain is fixed at 25.3 dB in the input power of  $< -15$  dBm while an input coupling ratio is set at 90%. Therefore, the minimum NFs of 1 dB damage are measured, as seen in Fig. 4(c). Comparing Figs. 4(a) through 4(c), Fig. 4(c) has a better gain clamping result than that of Fig. 4(a) and Fig. 4(b). Thus, when the saturated wavelength is  $> 1515.69$  nm, it will obtain the larger clamped gain value and better NF value. If a saturated signal is disconnected from the larger gain range, it also will obtain a better gain and NF profiles, as seen in Fig. 4 (c). Therefore, the saturated tone at 1517.37 nm is a better choice for the proposed S-band gain clamped EDFA.

To investigate the gain-clamping performance, the gain and NF spectra are measured in the wavelength range of 1478–1520 nm at the effective input dynamic range according to the result of Fig. 4 (c). Thus, Fig. 5 presents the gain and NF spectra for the S band gain-clamped EDFA in the wavelength range of 1478–1520 nm under the input ratio of 80% when the input signal power is 0,  $-15$ , and  $-40$  dBm, respectively, and the saturated tone is selected at 1517.37 nm.



**Figure 4.** Measured gain and NF spectra without and with the input coupling ratio of 90, 80, 70, 50% for the proposed gain-clamped EDFA under the saturated signals of (a) 1511.37 nm, (b) 1513.42 nm, and (c) 1517.37 nm, respectively.

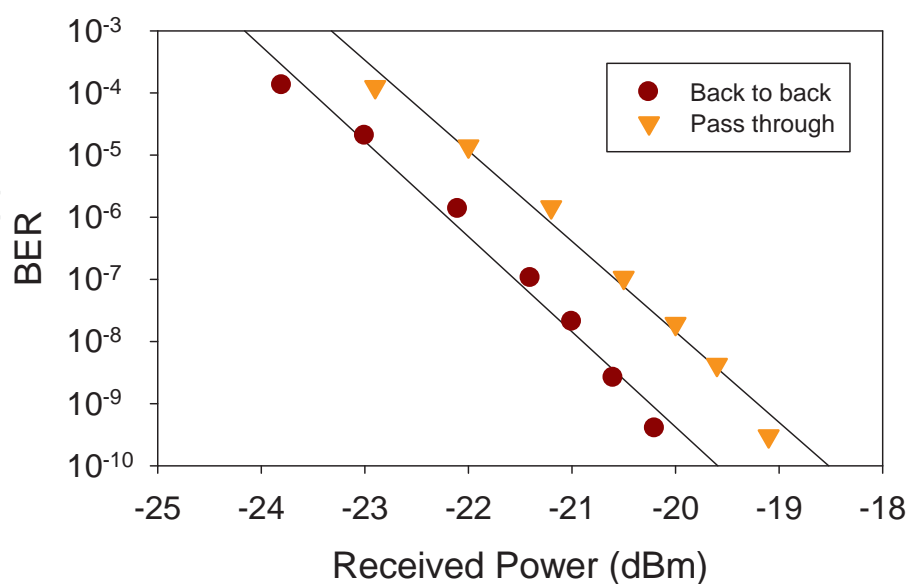




**Figure 5.** Measured gain and NF spectra of the S band gain-clamped EDFA in the wavelength of 1478–1520 nm with 80% input ratio at the input signal power  $P = 0$ ,  $-15$ , and  $-40$  dBm at the lasing wavelength of 1517.37 nm, respectively.

In the measurement, the maximum gain of 24.7 dB is measured at the wavelength of 1502 nm for the input power of  $-40$  dBm. And the maximum gain variations are smaller than 0.6 dB in the operation range. As a result, the input gain dynamic range of 25 dB from  $-40$  to  $-15$  dBm could be detected and obtained, as shown in Fig. 5.

2D Graph 1



**Figure 6.** Performance of BER at a test signal of 1506 nm in a 2.5 Gbit/s modulation system, when a 980 nm pump power is set at 280 mW.

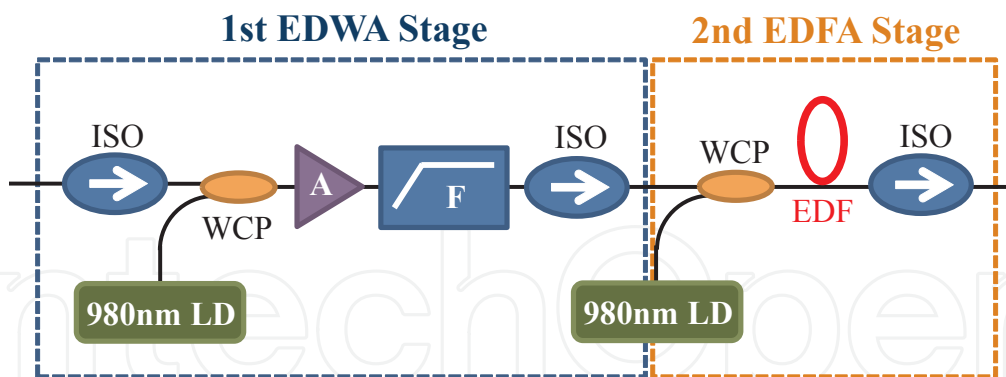
To investigate the output performance of proposed S-band gain-clamped EDFA module, a bit error rate (BER) measurement is performed. In the measurement, we utilize the optical CP of 80% input coupling ratio and FBG of 1517.37 nm wavelength for the proposed gain-clamped EDFA module. We use a test input signal of 1506 nm and modulate externally by using an LiNbO<sub>3</sub> electro-optical (EO) modulator with 2.5 Gbit/s nonreturn-to-zero pseudorandom binary sequence (NRZ-PRBS) under a pattern length of  $2^{31}-1$ . However, the BER of back-to-back (B2B) status is without utilizing proposed EDFA. The 2.5 GHz PIN-based receiver (Rx) is used to detect the testing signal. Figure 6 presents the BER performance of proposed S-band EDFA under different received powers at the B2B status and the testing signal through the gain-clamped EDFA. Here, other input channels are also added or dropped into the gain-clamping EDFA. When a testing input signal transmits through the proposed EDFA, the power penalty of ~1 dB can be retrieved at the BER of  $10^{-9}$ .

### 3. C-band gain-flattened EDFA module

In this section, we will introduce a gain-flattened two-stage erbium-based fiber amplifier (EBFA) module, constructed by an erbium-doped waveguide amplifier (EDWA) and an EDFA in serial structure. Hence, the obtained gain profile of proposed amplifier not only enhances its value, but also possesses flatness performance. In addition, the output performance of the gain and NF in the EBFA has also been discussed.

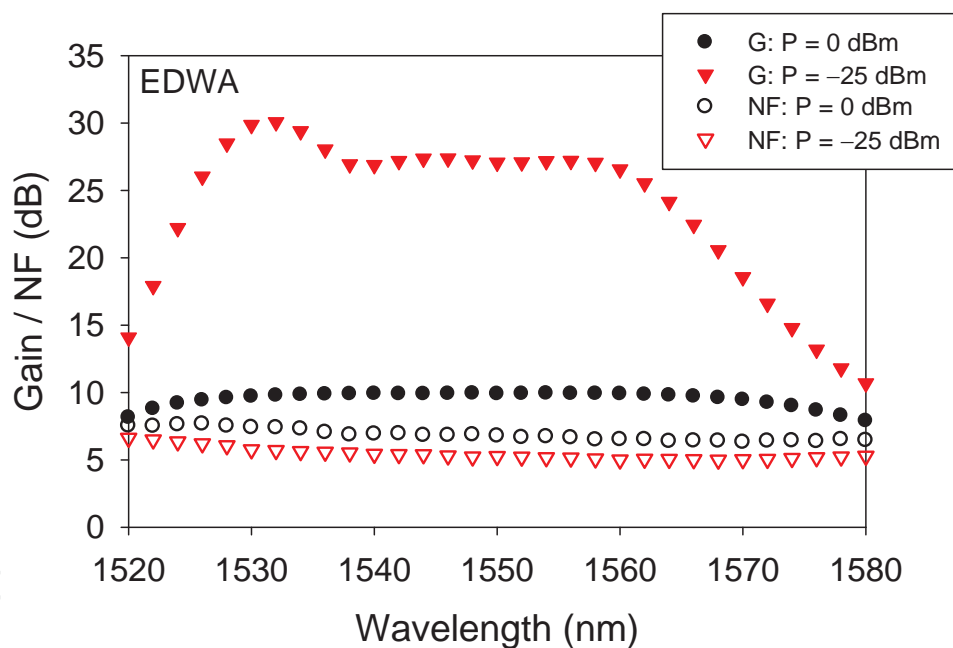
Here, the proposed gain-flattened two-stage erbium-based fiber amplifier (EBFA) in serial configuration is illustrated in Fig. 7. The first and second stages are EDWA and EDFA. Besides, two tunable laser sources are employed to serve as a saturation tone and a probe tone, respectively, for gain and NF measurements. An optical spectrum analyzer (OSA) with a 0.05 nm resolution is utilized to measure the gain and NF. On account of the homogeneously broadened gain distribution, the multi-wavelength input signal would be simulated by applying a saturation signal with a saturated power equals to the collected power of multi-wavelength input signal. Besides, the substantial spectral-hole burning is obtained around the wavelength of 1550 nm; we can set a saturation signal at 1535 nm with -25 dBm in the measurement for simulating the multi-wavelength signals. The probe light should be smaller than 20 dB compared to the saturating signal.

In the measurement, the EDWA, which is produced via a two-step ion-exchange process, has the benefit of inheriting the known characteristics of EDFA such as, low NF, low polarization dependence, and without cross talk between the WDM wavelengths. All of the optical implementations are measured when a bias current of 980 nm pumping laser diode (LD) is 440 mA at ambient temperature. Besides, optical ISOs can reduce backward amplified spontaneous emission (ASE) and improve NF performance, and the pump kill filter is utilized to eliminate 980 nm pump power and keep 1550 nm signal pass. Figure 8 shows the gain and noise figure spectra of EDWA for -25 dBm input saturation power in an operating range of 1528–1562 nm. However, the measured gain and NF of 30.1 and 5.7 dB also are observed at 1532 nm, and the NFs are between 5 and 6.3 dB in the wavelengths of 1524–1572 nm, when the input saturation



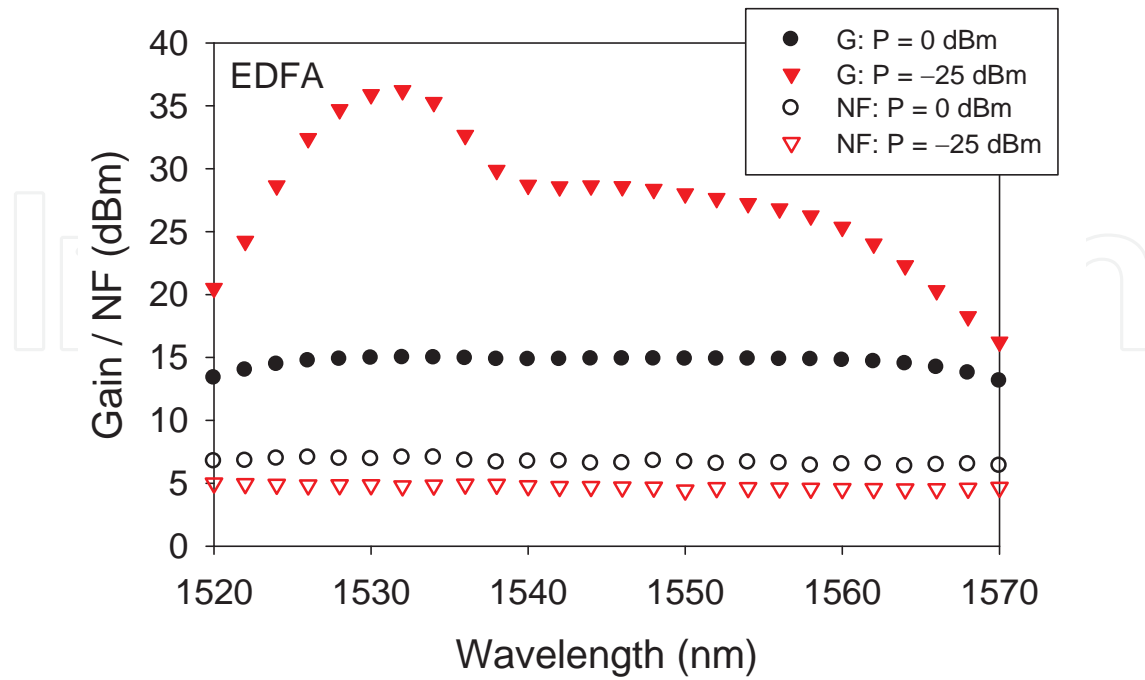
**Figure 7.** Proposed two-stage gain-flattened EBFA module, which is structured by an EDWA and an EDFA in serial.

power is -25 dBm. The maximum gain variation of 4.8 dB is also retrieved in Fig. 8 in the wavelength range of 1524–1562 nm.

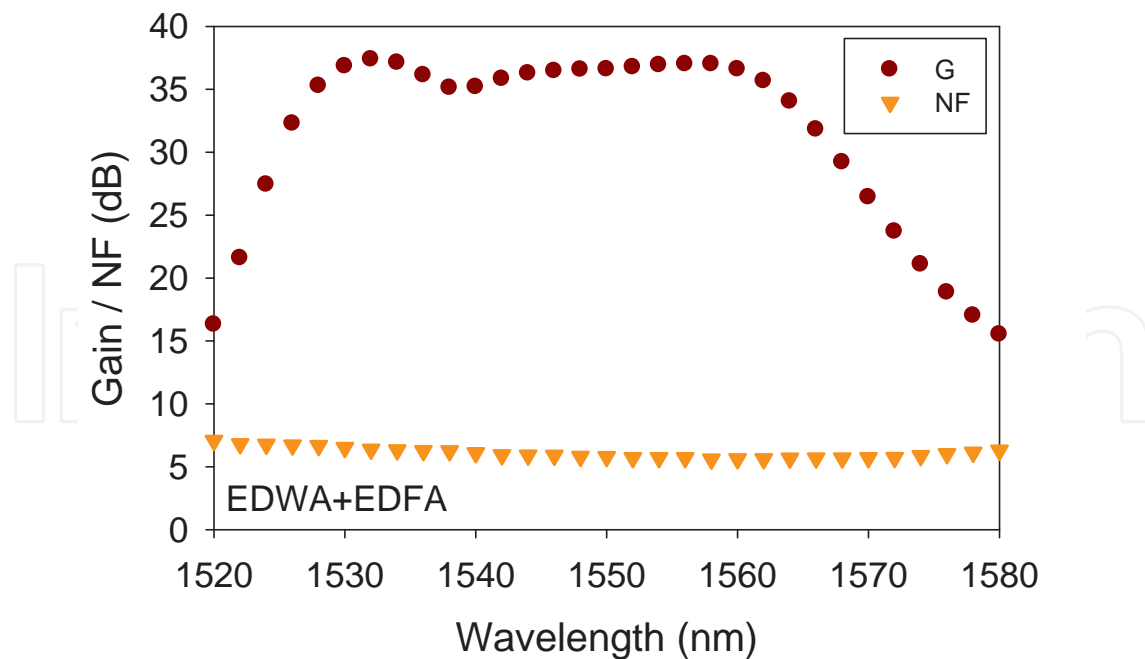


**Figure 8.** Gain and noise figure spectra of the EDWA in a bandwidth of 1520–1580 nm for -25 dBm input saturation power.

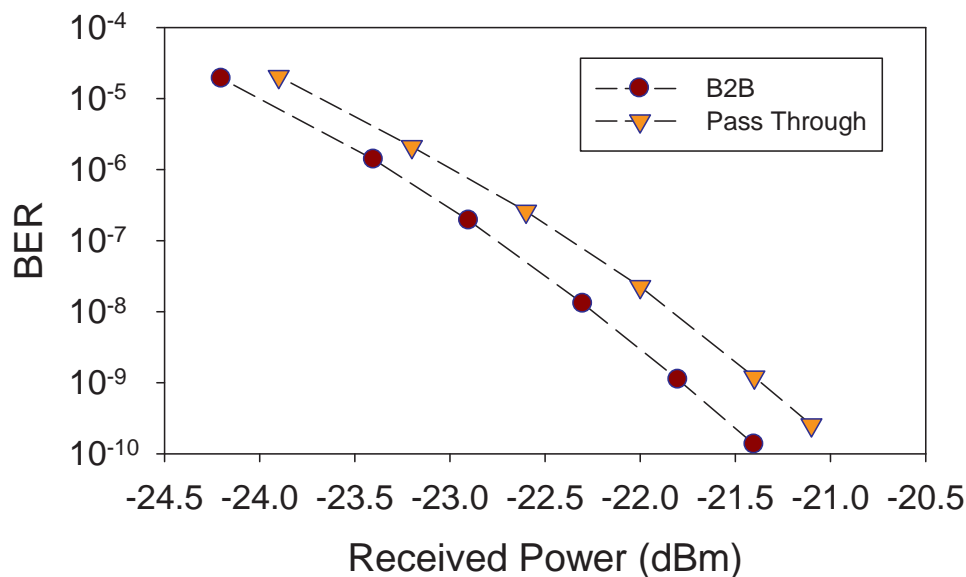
The second EDFA stage is constructed by an EDF of 10 m, a 980 nm pumping LD, a 980/1550 nm WDM coupler (WCP), and an OIS. The pumping power of 980 nm LD is set at 72 mW. Figure 9 displays the measured gain and NF spectra of EDFA when the -25 dBm input saturation power is used in the wavelengths of 1528–1562 nm. Furthermore, the peak gain and NF of 36.2 dB and 4.8 dB are observed at the wavelength of 1532 nm for the input saturation power of -25 dBm. Here, the maximum gain difference of 12.2 dB is also observed in a wavelength region of 1524–1562 nm, as seen in Fig. 9.



**Figure 9.** Gain and NF spectra of the EDFA with 10 m long EDF length in a bandwidth of 1520–1580 nm for -25 dBm input saturation power with the pump power of 72 mW.



**Figure 10.** Gain and NF spectra of the proposed gain-flattened two-stage EBFA in a bandwidth of 1520–1580 nm for -25 dBm input saturation power.



**Figure 11.** Performance of BER at a test signal of 1550 nm in 2.5 Gbit/s modulated system for the back-to-back type and proposed gain-flattened EBFA module.

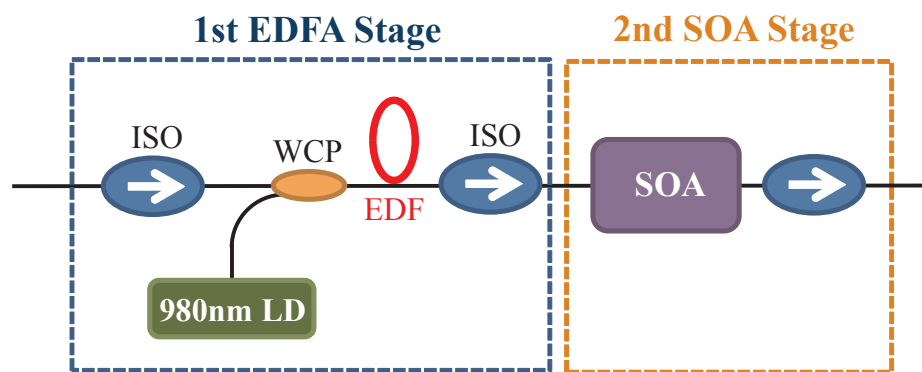
To realize the gain-flattened amplifier, a two-stage EBFA module is illustrated in Fig. 7 for this experiment. The workable mechanism is possibly the gain saturation effect of EDWA and EDFA to accomplish the gain-flattening output. Thus, Fig. 10 displays the measured gain and NF profiles of the proposed gain-flattened EBFA, when -25 dBm input saturation power is utilized in the wavelength range of 1528–1562 nm. Figure 10 shows two maximum gains of 37.4 and 37.0 dB, observed at the wavelengths of 1532 and 1556 nm, respectively. The maximal gain difference of  $\pm 1.1$  dB could be also measured. According to the above results, this gain-flattened EBFA. The proposed EBFA can approach the gain-flattening and also enhance the gain value due to the gain saturation effect and two-stage amplifier. Thus, the EBFA module increases the entire gain (all  $>35$  dB) in the wavelength range of 1528–1562 nm, and the gain spectrum can fix the flatness with the maximum variation of  $\pm 1.1$  dB for the input saturation power of -25 dBm. Generally, the gain-flattened EDFAs could employ the various optical filters for filtering the redundant ASE to maintain the flattening output. However, the previous related technologies could bring the loss and the gain degradation. Therefore, the proposed EBFA not only can flatten the output gain spectrum, but can also increase the gain performance.

Here, a BER measurement is also performed in this experiment. The testing input signal at 1550 nm is modulated by using an EO modulator with 2.5 Gbit/s NRZ-PRBS with a pattern word of  $2^{31}-1$ . Here, we use a 2.5 GHz PIN-based receiver to detect the testing signal. Figure 11 presents the measured BER of the proposed optical amplifier against the received power in the B2B status and passing through the gain-flattened EBFA module. In the measurement, when a testing input signal passes through the amplifier module, the observed optical power penalty is  $\sim 0.4$  dB, while the BER is  $10^{-9}$ .

#### 4. C- to L-bands optical fiber amplifier module

In this section, we experimentally investigate a broadband hybrid two-stage S- to L-band fiber amplifier in serial configuration employing a C-band EDFA to cascade a C-band semiconductor optical amplifier (SOA). Hence, the proposed amplifier could achieve a 110 nm amplification bandwidth from 1500 to 1610 nm, when the preamplifier only has a 3 m long EDF length. In addition, the output performance of the gain and NF for the proposed wideband amplifier has also been analyzed and discussed.

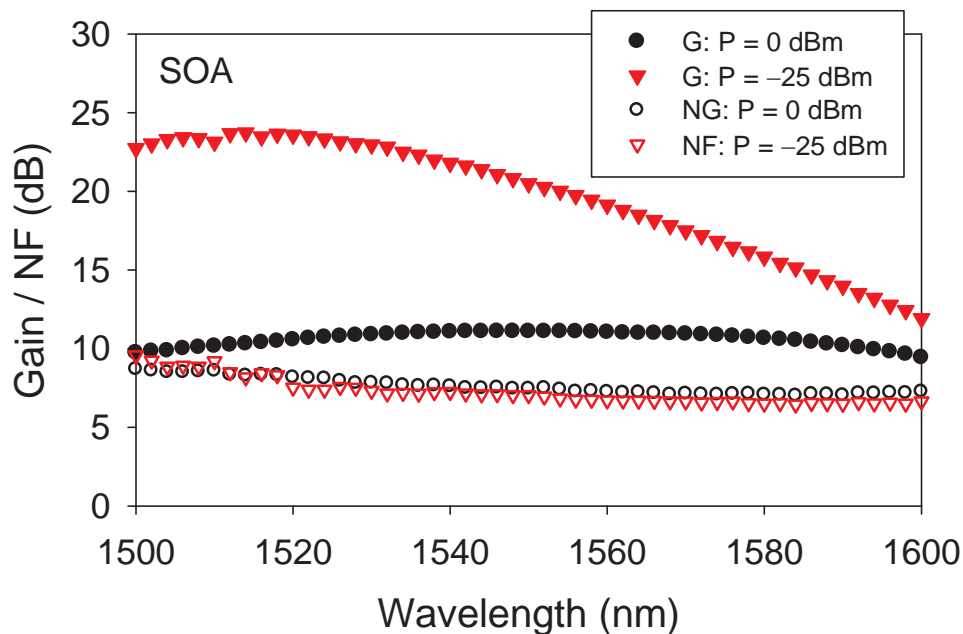
Here, the proposed hybrid two-stage S- to L-band fiber amplifier in serial is illustrated in Fig. 12. The proposed amplifier consists of an EDFA and a SOA in serial configuration. The first EDFA stage with preamplification function is used to reduce the NF value and improve the operated range of gain. Besides, the pumping current of second SOA stage is operated at 150 mA. The threshold and maximum currents of the SOA used are 50 mA and 250 mA, respectively. The SOA can be used in bidirection transmission. In Fig. 12, the ISO is employed to prevent the backward ASE power of SOA launched into the first amplifier stage.



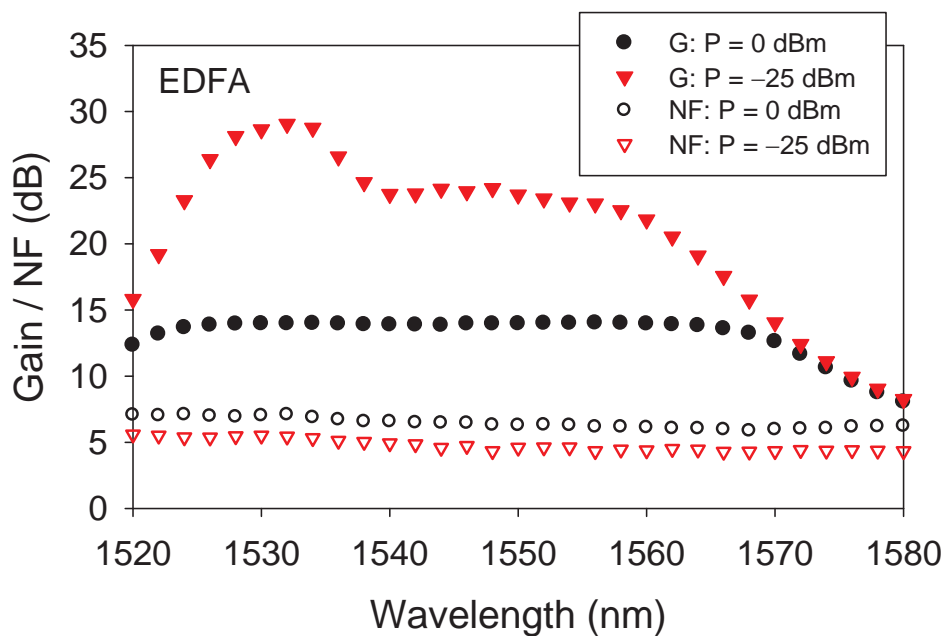
**Figure 12.** Proposed hybrid two-stage S- to L-band fiber amplifier, structured by an EDFA and an SOA in serial.

Fig. 13 shows the gain and NF spectra of an SOA, when the pumping current is 150 mA and the input saturation powers are 0 and -25 dBm, respectively, in a wavelength range of 1520–1600 nm. Besides, a saturated power of the SOA could be up to 11.1 dBm for 0 dBm input saturation power at 1548 nm. And 23.6 dB maximum gain and 7.5 dB NF is observed at 1520 nm when the input saturation power is -25 dBm, as seen in Fig. 13. As illustrated in Fig. 13, the NF spectra of the SOA are between 8.2 and 7.2 dB, and 7.5 and 6.6 dB when the input saturation power is 0 and -25 dBm, respectively, in the bandwidth of 1520–1600 nm. According to experimental results, the SOA presents the lower gain and worse noise figure in C-band. Owing to these defects of the SOA, it cannot be employed in optical communication system for amplification. To solve these drawbacks, an EDFA with preamplification function is applied in the proposed broadband fiber amplifier. However, to realize the impact of EDF length for the first stage, we would utilize various EDF lengths in the experiment. In general, an ideal optical amplifier needs to have the advantages of broadband amplification range, higher gain, lower NF, etc.



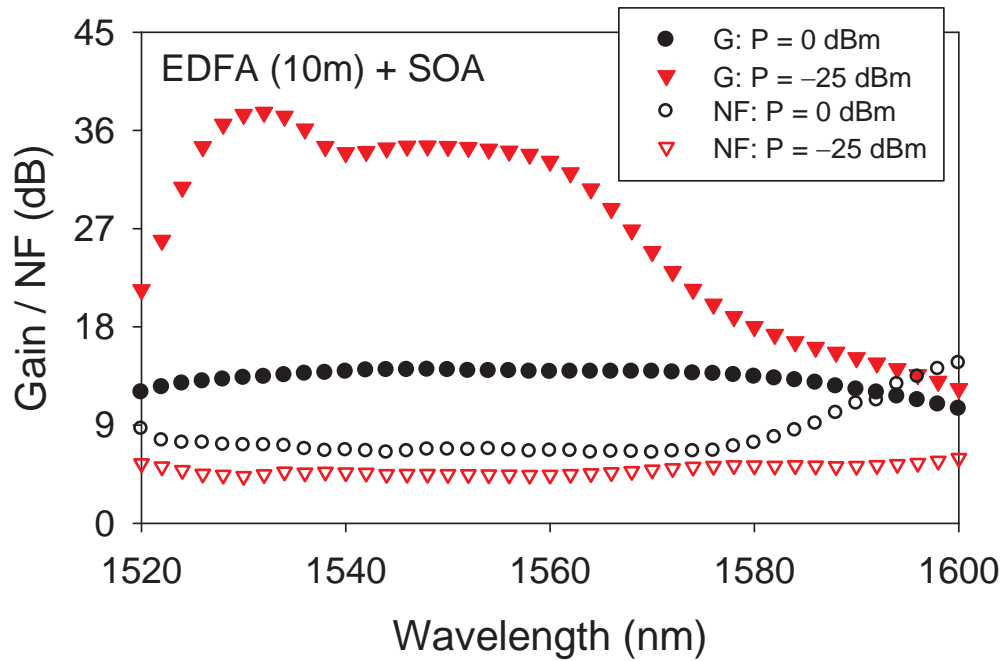


**Figure 13.** Gain and NF spectra of an SOA, when the pumping current operates at 150 mA and the input saturation power is 0 and -25 dBm, respectively, in the operating range of 1520–1600 nm.



**Figure 14.** Gain and NF spectra of an EDFA when the input saturation power  $P_{\text{sat}} = 0$  and -25 dBm in the wavelength of 1520–1570 nm. The length of EDF is 10 m long and the pumping power of 980 nm laser is 60 mW.

First, a 10 m long EDF (DF-1500F of Fibercore Ltd.) length is utilized in the first EDFA stage with a 60 mW pump power. Figure 14 shows the gain and NF spectra of the original EDFA for



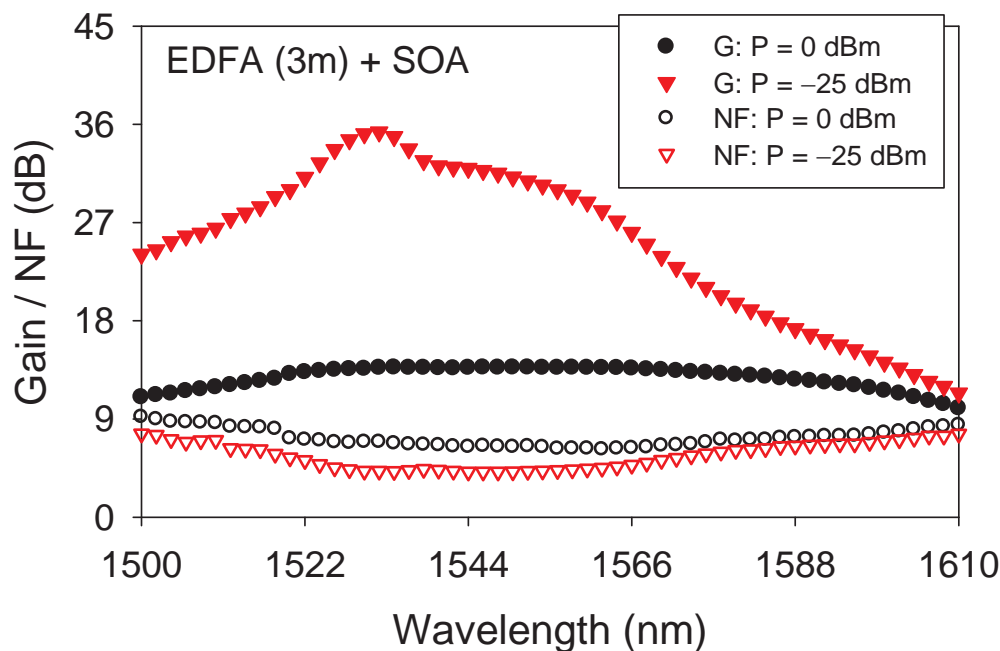
**Figure 15.** Measured gain and NF profiles of the hybrid two-stage fiber amplifier module (with 10 m long EDF length).

the input saturation power  $P_{\text{sat}} = 0$  and  $-25$  dBm in an operating range of 1520–1570 nm. Also shown are the peak gain and NF of 29.1 and 5.4 dB at 1532 nm, when the input saturation power is  $-25$  dBm. Figure 14 also illustrates that all the gain is higher than 12 dB and the NF is less than 7.2 dB at the above-mentioned operating conditions from 1520 to 1570 nm.

When an EDFA with a 10 m EDF and 60 mW pumping power is used to cascade an SOA with 150 mA pumping current, the gain and NF profiles of the hybrid amplifier for the input saturation power  $P_{\text{sat}} = 0$  and  $-25$  dBm in the wavelengths of 1520–1600 nm is illustrated in Fig. 15. The entire gain and noise figure of the hybrid amplifier are improved between around C-band, but the effectively operating range becomes narrower compared with the original C-band SOA. The saturated power could achieve 14.1 dBm for the input saturation power of 0 dBm at 1548 nm. In Fig. 15, the 37.7 dB peak gain and 4.6 dB NF are retrieved at 1532 nm when the input saturation power is  $-25$  dBm. Figure 15 also shows that the noise figure is distributed between 6.3 and 14.8 dB and 4.4 and 5.9 dB in the operating range of 1520–1600 nm for the input power  $P_{\text{sat}} = 0$  and  $-25$  dBm, respectively. From the observed results, those are not enough good in our expectancy.

Then, we decrease the EDF length to 3 m in the first EDFA stage (with a 40 mW pumping power) to connect with the second SOA stage (with 150 mA pumping current) in series. Figure 16 shows the gain and NF profiles of the proposed two-stage amplifier in the operation bandwidth from 1500 to 1610 nm, when the input saturation power ( $P_{\text{sat}}$ ) is 0 and  $-25$  dBm, respectively. Figure 16 also shows that the 13.7 dBm saturated power at 1558 nm is obtained for 0 dBm input saturation power, and a maximum gain of 35.3 dB (4.3 dB NF) at 1532 nm is retrieved for  $-25$  dBm input saturation power. Based on the proposed architecture, the effectively operating range of the amplifier will achieve a 110 nm amplification bandwidth

from 1500 to 1610 nm. The new proposed structure not only enhances the gain value, but also extends the operating bandwidth from 1500 to 1610 nm (S- to L-bands). As a result, the proposed two-stage amplifier has the advantage of simple architecture design, 110 nm broadband amplification region, higher gain, and lower NF.



**Figure 16.** Measured gain and noise figure spectra of the hybrid two-stage fiber amplifier module (with 3 m long EDF length).

## 5. Conclusion

In summary, there are three sections that describe the broadband S-band to L-band erbium-doped fiber amplifier modules. In the first part, an S-band gain-clamped erbium-doped fiber EDFA module, employing an FBG to act as a reflected element for generating a saturated tone injected into the EDFA module by using forward optical feedback method, is proposed. Moreover, the output performance of the gain and noise figure (NF) in the proposed gain-clamped S-band EDFA has been discussed in the wavelength range of 1478–1520 nm.

In the second part, we propose and investigate a gain-flattened two-stage EBFA module, which is structured by an EDWA and a C-band EDFA in serial structure. In an operation range of 1528–1562 nm, the entire gain is larger than 35 dB and the observed NF is between 5.5 and 6.7 dB. Moreover,  $\pm 1.1$  dB maximum gain variation is also obtained for the input signal power of -25 dBm. Hence, the proposed fiber amplifier not only enhances the gain but also achieves the flatness in the wavelength region.

In the final part, a broadband hybrid two-stage fiber amplifier, which is constructed by a C-band EDFA and a C-band SOA in serial scheme, is investigated experimentally. Here, we only use a 3 m long erbium-doped fiber (EDF) serving as a preamplifier to increase the gain and reduce the noise figure. Therefore, the proposed hybrid amplifier achieves a 110 nm effectively amplification of 1500 to 1610 nm from S- to L-band. Moreover, the output performance of gain and NF in the proposed fiber amplifier has also been discussed.

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