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# Simultaneously Gain-Flattened and Gain-Clamped Erbium Fiber Amplifier[1]

**C. H. Yeh[a, *], T. T. Huang[b], M. C. Lin[c], C. W. Chow[c], and S. Chi[b, c]**

[a] *Information and Communications Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu, 31040 Taiwan*

[b] *Department of Electro-Optical Engineering, Yuan Ze University, Chungli, Taoyuan, 32003 Taiwan*

[c] *Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, 30010 Taiwan*

*e-mail: Depew@itri.org.tw

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**Abstract**—In this paper, we propose and demonstrate a simple erbium amplifier module based on an erbium-doped fiber amplifier (EDFA) and an erbium-doped waveguide amplifier (EDWA) in serial, having gain-flatted (GF) and gain-clamped (GC) functions simultaneously. In first proposed GF amplifier scheme, the maximum gain variation of 2.5 dB can be observed in the effective range of 1528 to 1562 nm and the entire gains are above 35 dB with the input signal power of –30 dBm. Hence, we investigate second scheme by optical feedback method in the proposed fiber amplifier achieving gain-flattened (GF) and gain-clamped (GC) efficiencies simultaneously. Thus, the maximum gain variations of ±0.8 and ±1.8 dB can be obtained in the operating range of 1530 to 1564 nm, when the input signal powers are –16 and –40 dBm, respectively. Moreover, the dynamic gain profile can be adjusted and dynamic input power range is also measured based on the proposed GF and GC fiber amplifier.

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## 1. INTRODUCTION

Due to the nature of erbium-doped fiber (EDF), the gain curve of erbium-doped fiber amplifier (EDFA) displayed the non-flatness and input-dependent behaviors in the effective gain range. Therefore, gain-flattened (GF) and gain-damped (GC) EDFAs play a key role in wavelength division multiplexed (WDM) optical communications where dynamic channels adding-dropping or abrupt breakdown of the other signal channels can occur. Thus, optical feedback schemes based on a lasing mechanism are a simple and effective way to achieve constant gain characteristics regardless of input power variations [1, 2]. In addition, the gain profiles of EDFAs can be flattened were also reported, such as by doping the material composition in the erbium-doped fiber (EDF) [3], pr using optical filters to compensate for the variations in the gain spectrum [4–10]. Furthermore, many different kinds of optical filters have been demonstrated for the GF fiber amplifier, including long-period fiber gratings (LPFG) [4, 5], fiber Bragg gratings (FBG) [6], fiber acousto-optic (AO) tunable filters [7, 8], Mach-Zehnder (M-Z) filters [9], and a split-beam Fourier filter [10] etc. However, these techniques would whittle down the original gain values in the effective operating range due to these optical filters were applied in their proposed amplifier schemes [4–10]. And to extend the operating bandwidth, S-band EDFA based depressed-cladding design with gain flattened and clamped functions has also studied [11].

In this study, we propose two erbium fiber amplifier modules to retrieve gain-flattened (GF) and gain-clamped (GC) functions simultaneously. Based on the past GF technologies [4–10], these methods would cause the loss and the gain degradation of their proposed GF amplifiers. However, our proposed GF amplifier does not cause the loss and reduce gain. Contrarily, the amplifier can enhance the gain value in effectively wavelength range. As a result, the proposed amplifier not only can flatten the gain curve but also enhance the gain value.

## 2. EXPERIMENTS AND RESULTS

First of all, the proposed gain-flattened two-stage erbium amplifier in serial scheme, which is constructed by an EDWA and an EDFA, is illustrated in Fig. 1. The first stage and second stage are EDWA and EDFA. The EDWA, which is manufactured via two-step ion-exchange process, has the advantage of inheriting the known properties of the EDFA, such as low noise figure, slight polarization dependence, and no crosstalk between WDM channels. And all optical performances are measured when the laser pump diode current equals to 440 mA at room temperature. Besides, optical isolators can reduce backward amplified spontaneous emission (ASE) and improve noise figure performance, and

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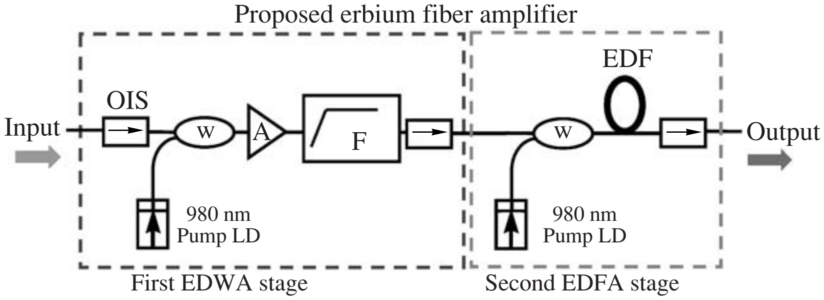

**Fig. 1.** The proposed gain-flattened erbium fiber amplifier module using two-stage EDWA and EDFA in serial. W: 980/1550 nm WDM coupler; A: waveguide gain media; F: pump kill filter; OIS: optical isolator; EDF: erbium-doped fiber; EDWA: erbium-doped waveguide amplifier.

the pump kill filter is utilized to eliminate 980 nm pump power and keep 1550 nm signal pass. To measure the proposed fiber amplifier, a tunable laser source (TLS) is used to probe the gain and noise figure spectra observing by an optical spectrum analyzer (OSA) with a 0.05 nm resolution.

Figure 2 displays the gain and: noise figure spectra of the original EDWA module for 0, –15, and –30 dBm input signal power, respectively, in an operating range of 1528 to 1562 nm. When the input signal power is 0 dBm, the gain and noise figure are larger than 10.8 dB and smaller than 7.7 dB, respectively, in the wavelengths of 1528 to 1562 nm are retrieved, as shown in Fig. 2. In addition, 36 dB maximum gain and 6.2 dB noise figure are observed at 1532 nm, and the noise figure curve is distributed between 5.3 and 6.7 dB in the wavelengths of 1528 to 1562 nm when the input signal power is –30 dBm, and the maximum gain difference of 8.5 dB is also retrieved in Fig. 2. As a result, the EDWA has the larger noise figure, comparing with conventional EDFA (3–5 dB), due to the nature of erbium waveguide media.

The second EDFA stage is consisted of 10 m long EDF length, a 980 nm pump laser, 980/1550 nm WDM coupler (W) and an optical isolator (OIS). The pump power of 980 nm laser is set at 80 mW. Figure 3 illustrates the gain and noise figure spectra of the original EDFA module for 0, –15, and –30 dBm input signal powers, respectively, in the operating range of 1528 to 1562 nm. When the input signal power is 0 dBm, the entire gain is larger than 13.5 dB and the noise figure distributes from 6.1 to 6.9 dB in the wavelengths of 1528 to 1562 nm. While the input signal power is –30 dBm, 37.3 dB maximum gain and 5.4 dB noise figure are measured at the wavelength of 1532 nm, and 14 dB maximum gain difference is also retrieved over the wavelength region of 1528 to 1562 nm, as shown in Fig. 3. Moreover, the noise figure curve distributes

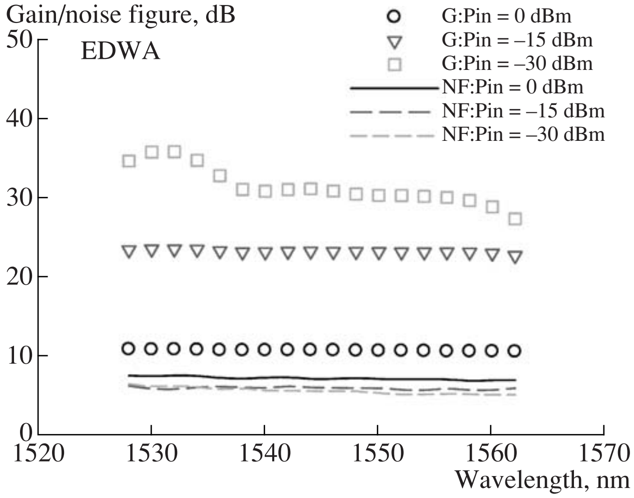

**Fig. 2.** Gain and noise figure spectra of the original EDWA module for 0, –15, and –30 dBm input signal power, respectively, in an operating range of 1528 to 1562 nm.

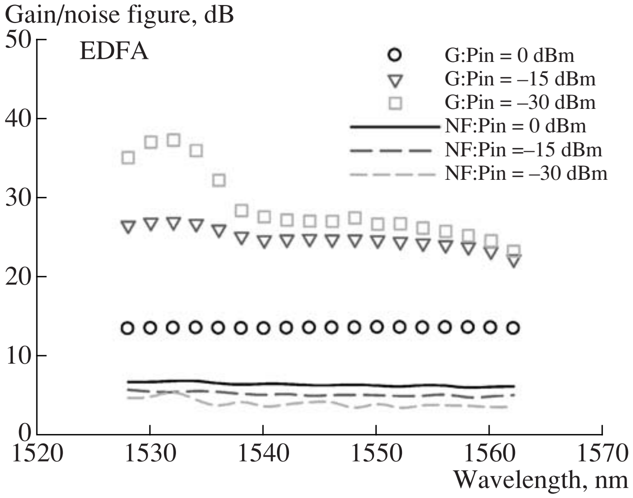

**Fig. 3.** Gain and noise figure spectra of the original EDFA module for 0, –15, and –30 dBm input signal power, respectively, in an operating range of 1528 to 1562 nm, when the pump power of 980 nm LD is set at 80 mW.

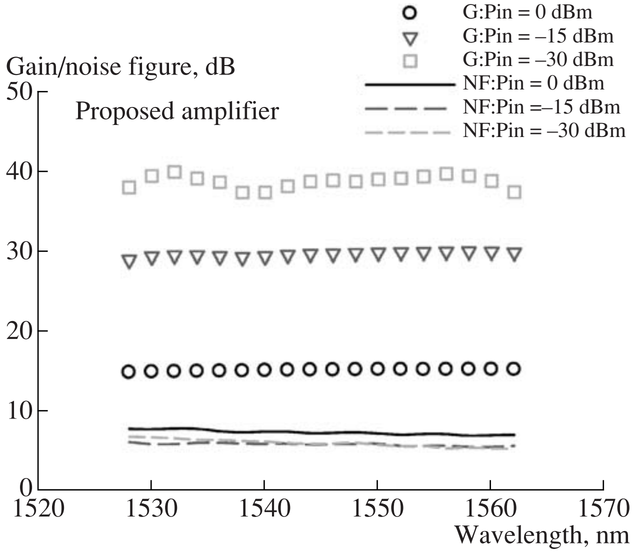

**Fig. 4.** The gain and noise figure spectra of the proposed GF amplifier for 0, –15, and –30 dBm input signal powers, respectively, in the operating range of 1528 to 1562 nm.

from 3.5 to 5.4 dB for –30 dBm input signal power over the operating range.

In order to obtain the gain-flattened erbium fiber amplifier, a two-stage erbium-based amplifier module in serial is illustrated in Fig. 1. Based on gain saturation operation and optimal length of EDF applied in second EDFA, the proposed fiber amplifier can enhance the gain value and also obtain the flatter gain profile. Thus, Fig. 4 shows the gain and noise figure spectra of the proposed gain-flattened amplifier for 0, –15, and –30 dBm input signal powers, respectively, in the operating range of 1528 to 1562 nm. For 0 dBm input signal power, a maximum gain variation of 0.4 dB is obtained and the gain can be larger than 14.9 dB in the wavelength bandwidth of 1528 to 1562 nm. Figure 4 presents two maximum gains of 40.1 and 39.8 dB at 1532 and 1556 nm, respectively, and the maximal gain variation of ±1.3 dB is also retrieved for –30 dBm input signal power in the same operating range. From the experimental results, the proposed erbium amplifier not only can increase the entire gain of >37 dB in the wavelengths of 1528 to 1562 nm, but also can maintain gain curve flatness with the maximum variation of ±1.3 dB for –30 dBm input signal power. In Fig. 4, the entire noise figure is distributed from 5.2 to 7.7 dB at the same operating conductions in the wavelengths of 1528 to 1562 nm under different input signal powers. Generally, the gain-flattened fiber amplifiers used the various optical filters to filter the redundant ASE to maintain the flattening behavior. It would cause the gain decreasing and noise figure increasing slightly [4–10]. Compared with the past studies, the proposed amplifier does not use any filter inside amplifier and achieves gain flattening and enhances gain value simultaneously.

Then, in order to obtain the gain clamping function in the proposed amplifier module simultaneously, an optical injection technology is used in the new proposed scheme, as shown in Fig. 5. To obtain the gain and noise figure profiles under various saturated wavelengths with different injection power forward into the amplifier by self-injected method. In this experiment, three lasing saturated tones, which are set at 1533, 1539, and 1545 nm, respectively, are selected forward injected into the amplifier to clamp the gain curve. And the three lasing wavelengths have 5 and 13 dB power attenuation by adjusting the variable optical attenuator (VOA) in Fig. 5. Therefore, the gain and noise figure spectra of the proposed GC EBFA with –30 dBm input signal power under different saturated tones in an operating range of 1530 to 1570 nm are shown in Figs. 6a and 6b. In Figs. 6a and 6b, when the 1545 nm saturated tone is injected the amplifier, it would cause the larger gain degradation. With increase of injection power or lasing wavelength shift, the gain curve will produce the larger degradation, as shown in Fig. 6. Besides, Figs. 6a and 6b show that the smaller and larger gains are distributed at the shorter and longer wavelengths, respectively. Figure 6a displays two maximum gains of 19.4 and 25.2 dB at 1534 and 1558 nm with 5 dB power attenuation, and the noise figure are also between 6.2 to

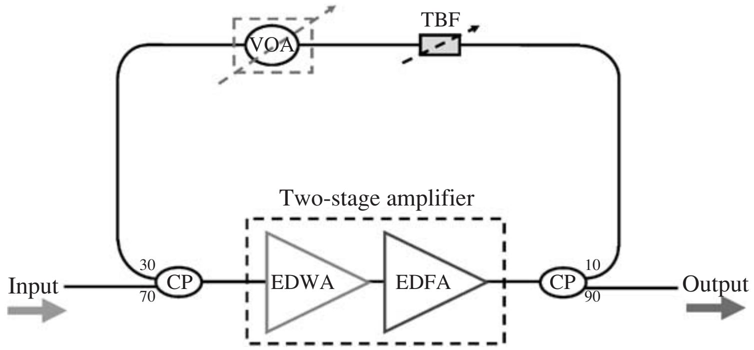

**Fig. 5.** The proposed gain-clamped and gain-flattened EBFA module based on an EDWA and EDFA by forward feedback method.

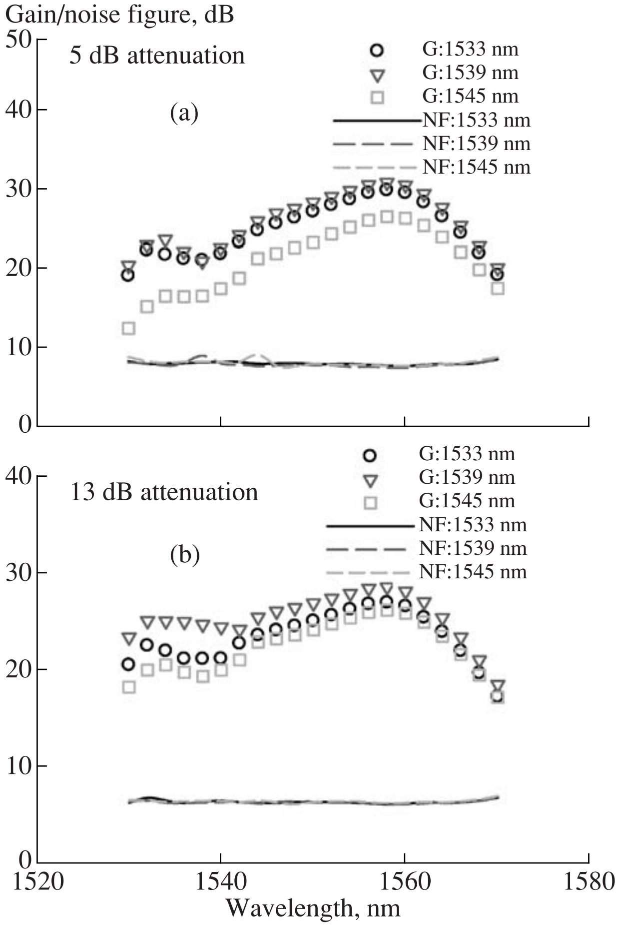

**Fig. 6.** Gain and noise figure spectra of the proposed GC EBFA with –30 dBm input signal power under different saturated tones of 1533, 1539, and 1545 nm in an operating range of 1530–1570 nm with (a) 5 and (b) 13 dB attenuation, respectively.

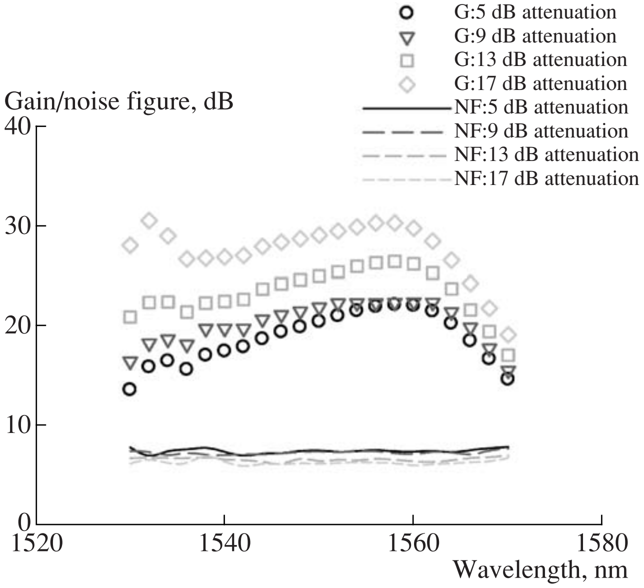

**Fig. 7.** Gain and noise figure spectra of the proposed GC EBFA with –30 dBm input signal power under the saturated tones of 1539 nm in an operating range of 1530 to 1570 nm under different power attenuations of 5, 9, 13, and 17 dB, respectively.

7.4 dB in the wavelengths of 1530 to 1570 nm when the saturated tone is 1539 nm. Figure 6b also shows two maximum gains of 25.1 and 28.5 dB at 1532 and 1558 nm with 13 dB power attenuation, and the noise figure are between 6.1 and 6.8 dB in the wavelengths of 1530 to 1570 nm, when the saturated tone is 1539 nm. When the forward injection power is decrease, the variation of gain value will be reduced gradually. As a result, the injection wavelength location and injection power not only affect the gain value but also resolve the clamping performance of GC amplifier. According to the past reports [2, 12, 13], the common gain clamped EDFAs by optical feedback technology would produce the noise figure degradation increasing 1.0–2.5 dB. Thus, compared with Figs. 2 and 6, the degradation noise figure of <0.7 dB is retrieved and measured when the optical feedback method is applied in the proposed amplifier with –30 dBm input signal power in the wavelength range of 1530 to 1570 nm. As a result, the gain curve can be dynamically adjusted and controlled for different applications using the different injection power level and various saturated wavelength position into the amplifier.

Based on the measured results of Fig. 6, we can obtain the dynamic gain profile by setting the different injected saturated tone and varying the injection power. Hence, for example, we set the test input signal power at –30 dBm into the GC amplifier and select a saturated tone at 1539 nm by varying the VOA to achieve the dynamic gain spectrum. Thus, Fig. 7 shows the gain and noise figure spectra under different attenuations of 5, 7, 9, 11, 13, 15, and 17 dB, respectively, in the wavelengths of 1530 to 1570 nm. When the attenuations are 5 and 17 dB, the observed maximum gains are 22.3 and 30.7 dB (noise figures are 7.5 and 6.3 dB) at 1558 and 1534 nm, respectively, in the operating range.

In accordance with above results, the proposed GC amplifier shows the better gain and noise figure curves when the saturated tone is 1539 nm, as shown in Figs. 6a and 6b. Thus, we select a saturated wavelength at 1539 nm forward injected into the amplifier module for achieving the GC performance. Figure 8 presents the gain and noise figure versus the different power of input signal at the input wavelength of 1542 nm under different power attenuations of 5, 7, 9, 11, 13, 15, and 17 dB, respectively, for the proposed GC amplifier. In Fig. 8, the gain will be kept constant at the input signal power of <–10 dBm when the power attenuation of <9 dB, with 30 dB dynamic input power range from –10 to –40 dBm for gain clamping. The obtained gain value can be above 18 dB and the noise figure degradation is ~1.3 dB at –10 dBm input signal power with 5 dB power attenuation. Besides, when the input signal

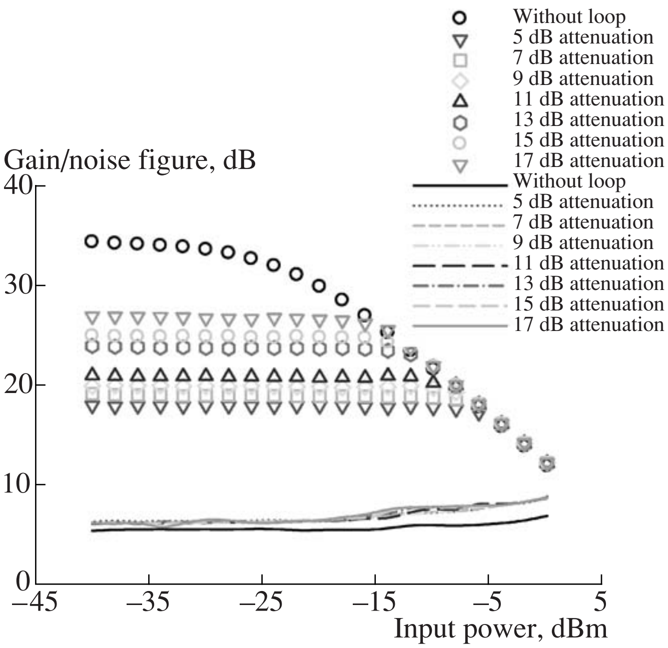

**Fig. 8.** Gain and noise figure versus the different power of input signal at the input wavelength of 1542 nm under different power attenuations of 5, 7, 9, 11, 13, 15, and 17 dB, respectively, for the proposed GC erbium amplifier.

power is –30 dBm, the noise figure degradation is between 0.8 and 1.0 dB under different power attenuations of 5, 7, 9, 11, 13, 15, and 17 dB, respectively. When the power attenuation is adjusted to 17 dB and the input power of <–16 dBm, the smallest gain can be kept constant and above 26.4 dB and the noise figure is measured below 7 dB, as shown in Fig. 8.

According to the above experimental results, we set the saturated tone and power attenuation at 1539 nm and 17 dB into the proposed amplifier, respectively. Figure 9 presents the gain and noise figure profiles of the proposed amplifier in the wavelengths of 1530 to 1564 nm, while the input signal power Pin = –16 and –40 dBm. Therefore, when the properly operating condition is achieved, the better GC and GF function in the proposed amplifier can be also observed and measured, as shown in Fig. 9. In Fig. 9, the maximum gain variations of ±0.8 and ±1.8 dB are observed when the input signal powers are –15 and –40 dBm, respectively, in an operating range of 1530 to 1564 nm. The maximal gain difference of 2.7 dB is also retrieved at 1556 nm in the dynamic input power range of –16 to –40 dBm over the operating range, as also illustrated in Fig. 9. Besides, the noise figure of the amplifier is between 6 and 7 dB over the operating bandwidth. As mentioned-before, the proposed fiber amplifier with optical feedback method can easily obtain the GC and GF operations simultaneously under properly operating conditions.

To demonstrate the performance of the proposed erbium amplifier module, a bit error rate (BER) is measured in this experiment. A 1539 nm saturated tone with 17 dB injection power attenuation of the structure is used; in the proposed erbium amplifier. A test input signal at 1542 nm is modulated by a 2.5 Gbit/s non-return-to-zero (NRZ) pseudorandom binary sequence 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 amplifier, characterizing the transmitter and receiver. A 2.5 Gbit/s opti-

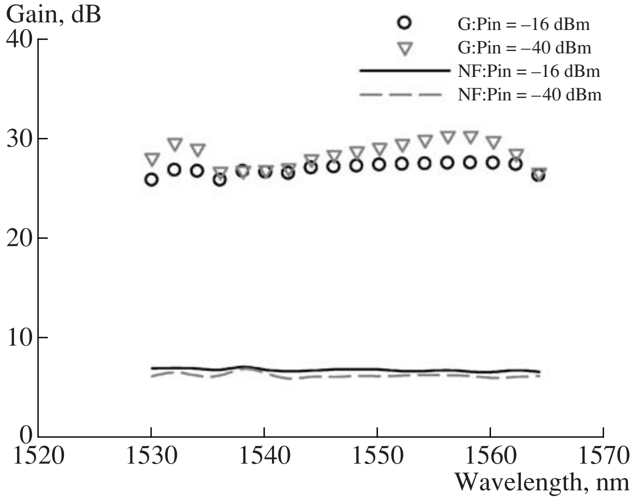

**Fig. 9.** The gain and noise figure profiles of the proposed amplifier with optical feedback method in the wavelengths of 1530 to 1564 nm, while the input signal power Pin are –16 and –40 dBm, respectively, and the saturated tone and power attenuation are set at 1539 nm and 17 dB.

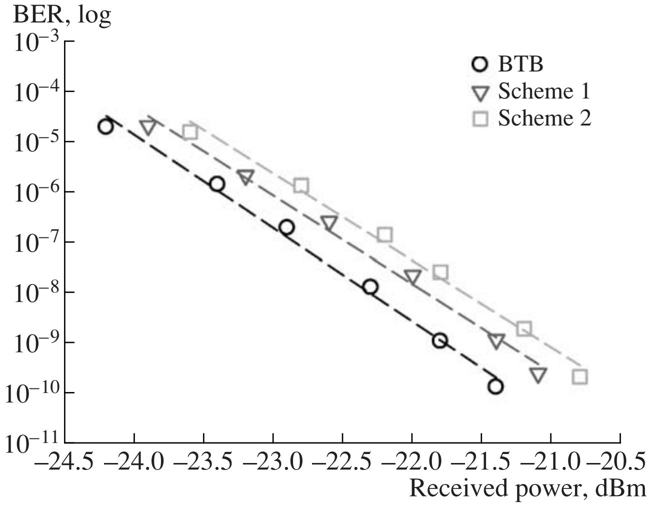

**Fig. 10.** BER curves at a test signal of 1542 nm in a 2.5 Gbit/s NRZ system when the injection power attenuation is 17 dB for the two proposed erbium amplifier schemes in Figs. 1 and 5.

cal receiver is used to measure the proposed amplifier performance. Figure 10 show the measured BER curves of the two proposed amplifiers against the received power for the back-to-back-type and the test signal through the proposed amplifier schemes in Figs. 1 and 5, respectively. The observed power penalties are small than 0.4 and 0.7 dB at the BER of $10^{-9}$, respectively, at the two proposed amplifier schemes.

## 3. CONCLUSIONS

In conclusion, we have proposed land demonstrated a simple erbium amplifier module based on an EDFA and an EDWA in serial, having GF and GC functions simultaneously. In first proposed GF amplifier scheme, the maximum gain variation of 2.5 dB can be observed in the effective range of 1528 to 1562 nm and the entire gains are above 35 dB with the input signal power of –30 dBm. Hence, we investigate second scheme by optical feedback method in the proposed fiber amplifier achieving GF and GC efficiencies simultaneously. Thus, the maximum gain variations of ±0.8 and ±1.8 dB can be obtained in the operating range of 1530 to 1564 nm, when the input signal powers are –16 and –40 dBm, respectively. Moreover, the dynamic gain profile can be adjusted and dynamic input power range is also measured based on the proposed GF and GC fiber amplifier.

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