Optics Communications 386 (2017) 31–36

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The effect of ASE reinjection configuration through FBGs on the gain and noise figure performance of L-Band EDFA

Fırat Ertaç Durak*, Ahmet Altuncu

Photonics Technologies Application and Research Center, Department of Electrical and Electronics Engineering, Dumlupınar University, Kütahya 43100, Turkey

ARTICLE INFO

Keywords:
Erbium doped fiber amplifier
Fiber Bragg grating
Gain improvement
L-band EDFA

ABSTRACT

In this study, we present the gain and noise figure performance improvement in L-band erbium-doped fiber amplifier (L-EDFA) provided by amplified spontaneous emission (ASE) reinjection through different configurations of 1533 nm band FBGs. The experimental results are compared with a single-stage bidirectionally pumped conventional L-EDFA design. It is shown that when the forward and/or the backward ASE noise is partly reinjected to L-EDFA using a double/single 1533 nm fiber Bragg gratings (FBG), the gain and noise figure performance of L-EDFA increases depending on the FBG configuration. The best gain and NF performance in our L-EDFA was achieved by reinjection of forward and backward ASE through FBG1 and FBG2 leading to an 4.5 dB increase in gain and 1 dB decrease in NF at 1585 nm and −30 dBm input signal power. The results show that both FBGs must be used at the same time to improve gain and NF performance in L-band EDFAs.

1. Introduction

Long-wavelength band erbium-doped fiber amplifiers (L-EDFAs) have recently seen more attention to supply for increasing demand of data transmission capacity. The optical amplification in L-band in addition to C-band allows to upgrade the capacity of dense wavelength division multiplexing systems (DWDMs) with a further 45 nm bandwidth addition (1565–1610 nm) [1]. However, L-band lies at the tail of the erbium amplification window where the pump conversion efficiency (PCE) is low. The poorer EDFA gain in L-band relative to C-band can in principally be increased by using longer lengths and relatively heavier erbium doped active fibers. Several different amplification methods have been proposed in order to increase PCE enabling a higher gain per unit fiber length in L-band [1–11]. A significant gain enhancement was achieved through an external C-band (1550–1560 nm) seed signal injection [1,3]. Similarly in order to improve, control and flatten the gain in L-band, the unused forward and/or backward ASE noise is reinjected to L-EDFA using narrowband Fiber Bragg Grating (FBG), reflective filters [4–6] or wideband fiber mirror reflectors [7,8]. A double-pass or dual stage configuration was also used to get a higher gain and noise figure performance in L-EDFA [5,6,9–11].

In this paper, the gain enhancement provided in L-EDFA through ASE reinjection at 1533 nm using a single or double FBG at different configurations is experimentally demonstrated and compared with the conventional single-stage bidirectionally pumped L-EDFA performance. The C-band EDFA designs using FBGs were previously investigated to provide a high gain and gain clamping feature [12–14]. Also, a double C-band FBGs were used to accurately control and flatten gain spectrum of a two-stage L-EDFA based on gain clamping [4]. To the best of the authors' knowledge, none of the previous studies exhibits a comprehensive result on the gain and noise figure performance improvement of L-EDFAs provided by a single and double FBGs operating at 1533 nm. We have observed that when the forward and/or backward ASE noise in C-band is partly reinjected to EDFA using a single or double FBGs, this reinjected ASE signal serves as a secondary pump source for further amplification in L-band. Therefore, a part of forward and/or backward propagating C-band ASE energy at the highest intensity wavelength of 1533 nm is transferred to L-band resulting an increase in gain and decrease in NF of L-band EDFA. In addition, the ASE reinjection mechanism at C band 1533 nm using front and/or end FBGs provides a significant gain and NF performance improvement with respect to the conventional L-EDFA design. Specifically, EDFA gain at 1565 nm increases up to 8 dB and NF decreases up to 5 dB.

2. The principle and experimental setup

In order to control gain, NF, and gain flatness in L-band EDFA, a lasing resonance cavity with Fabry-Perot (F-P) configuration is made up of using a couple of FBGs reflecting partly backward and forward

* Corresponding author.
E-mail addresses: firat.durak@dpu.edu.tr (F.E. Durak), altuncu@dpu.edu.tr (A. Altuncu).

http://dx.doi.org/10.1016/j.optcom.2016.11.009
Received 5 September 2016; Received in revised form 4 November 2016; Accepted 7 November 2016

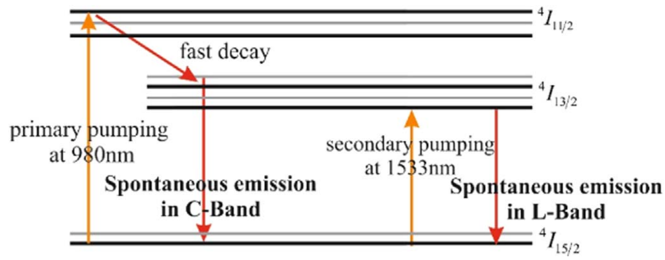

Fig. 1. Er^{3+} Energy level diagram.

ASE noise (FBG1 and FBG2). The lasing wavelength is determined by the center reflection wavelength of the fiber Bragg gratings. In such an L-EDFA design, the input signals will not only be amplified using external pump sources but also be amplified using a secondary pumping effect generated by lasing resonance in F-P cavity structure of L-band EDFA.

Based on the F-P laser controlled EDFA theory [14], assuming that the length of EDF is L and the signal wavelength is λ, then the controlled gain $G(\lambda)$ can simply be expressed in a closed form as

$$G(\lambda) = e^{\{[\alpha(\lambda)+g^*(\lambda)]\overline{n}-[\alpha(\lambda)+l(\lambda)]\}L} \tag{1}$$

where α, g^* and l are the absorption coefficient, emission coefficient and background loss of EDF, respectively. $\overline{n} = (1/L)\int_0^L n(z)dz$ is the average population inversion over the lasing cavity. For a laser controlled EDFA, the average population inversion can directly be derived from the lasing condition without the knowledge of the actual optical power distribution along the cavity length. In F-P configuration, the effective cavity loss L_c in decibels per unit length is [13]

$$L_c = \frac{(-10\log\sqrt{r_1 r_2} + \delta_c)}{L} \tag{2}$$

where r_1 and r_2 are the reflectivities of the FBGs, δ_c is the total of splices and FBG insertion losses. It is obvious from Eq. (2) that the effective cavity loss is mainly determined by the grating reflectivities and splice/insertion losses. According to Ref. [14], the average population inversion in a laser controlled EDFA can be expressed as

$$\overline{n} = \frac{\alpha(\lambda_B) + l(\lambda_B)}{\alpha(\lambda_B) + g^*(\lambda_B)} + \frac{L_c}{4.34\gamma[\alpha(\lambda_B) + g^*(\lambda_B)]}, \tag{3}$$

where λ_B is the FBG center reflection wavelength, γ is 2 for F-P configuration [14]. $\overline{n}$ is a function of the effective cavity loss L_c, the lasing wavelength λ_B and is independent of pump wavelength. In an L-band EDFA, lasing oscillation provided by a couple of FBG inserted at both sides can lead to two significant results. Firstly, in a F-P laser-controlled EDFA, an effective gain control can be provided by having a low average population inversion. This means a strong saturation in EDFA leading to a high NF and a low gain flatness. In order to do that, a longer lasing wavelength and a lower cavity loss must be chosen. On the contrary, to reduce NF and to improve gain flatness, a relatively high average population inversion must be maintained. This may be achieved by using a relatively short lasing wavelength or a high cavity loss for suitable EDF length [14]. However, the gain of the EDFA decreases significantly. Therefore, a compromise must be made between a high controlled gain, low noise figure and high gain flatness.

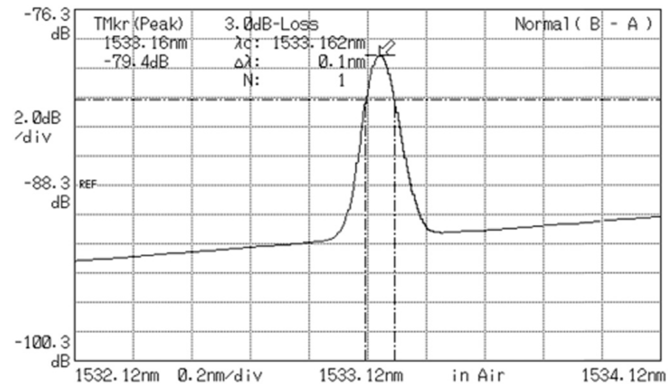

Fig. 3. The FBG reflection spectrum.

As shown in Fig. 1, the second significant effect in F-P laser controlled L-band EDFA using FBGs, is that 980 nm pump light can produce a strong C-band ASE noise at the input and output parts of the long length of erbium doped fiber due to the ion transitions between the energy levels of $^4I_{13/2}$ and $^4I_{15/2}$. A strongly amplified lasing signal at 1533 nm between the FBGs, can provide extra energy to L-EDFA by behaving a secondary pumping source [15]. Thus, a combination of both effects maintained for an optimized L-band EDFA can lead to a relatively better performance in terms of high gain, low noise figure and high flatness. Regarding the primary pumping wavelength, L-EDFA pumped at 980 nm can obtain a better performance than L-EDFAs pumped at 1480 nm to achieve good gain control with a high population inversion.

The experimental setup of a bidirectionally pumped L-EDFA with front (FBG1) and end (FBG2) to characterize the effect of ASE reinjection configuration is shown in Fig. 2. In this setup, a tunable laser source (Santec TLS-200) following with a variable optical attenuator was used as the L-band signal source. L-EDFA was pumped forward at 974 nm and backward at 976 nm. Two isolators were used at the input and output of the L-EDFA to suppress undesired lasing oscillations. The isolators and wavelength division multiplexer (WDM) couplers used in the setup are wideband at C/L-band signal wavelengths and their insertion losses are smaller than 0.2 dB. The erbium doped fiber (LIEKKI™ Er30-4/125) used was 20 m long and its numerical aperture is 0.2, the cutoff wavelength is 960 nm, the core radius is 1.85 µm, ion-concentration is 1.9e25 ion/m^3, background loss at 1200 nm is 23 dB/km, and emission loss at 1530 nm is 30 dB/m. As its spectrum given in Fig. 3, the center wavelength of the FBGs (λ_B) used is 1533 nm, the reflectivity is 95% and 3 dB linewidth is 0.1 nm which was tested using a stable ASE source. The amplified signal at the L-EDFA output was observed with an Anritsu MS9710B optical spectrum analyzer (OSA), and the gain and NF measurements were performed systematically with an 0.1-nm resolution. The maximum pump power injected in L-EDFA was 240 mW in total with equal powers in both directions. The temperature during the experiments was kept at 24 ± 1 °C and the setup was placed on a stable platform to avoid from the unexpected mechanical vibrations.

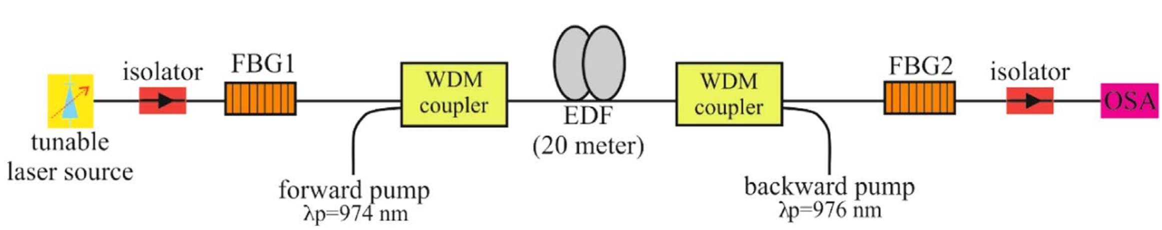

Fig. 2. The experimental setup.

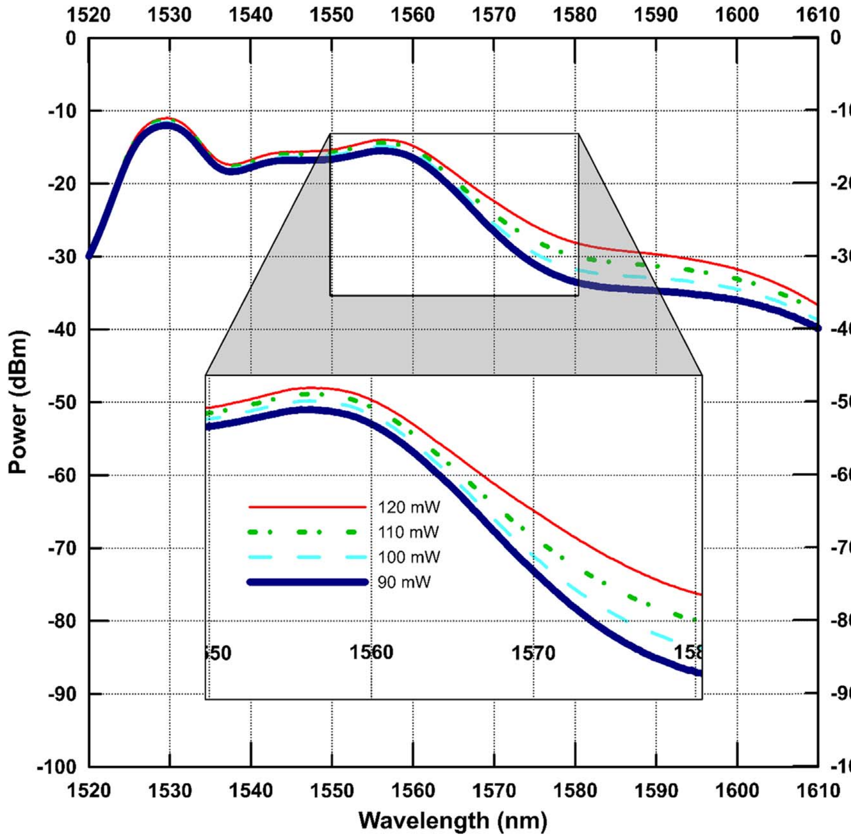

Fig. 4. Forward ASE spectra of L-EDFA for four different total pump powers.

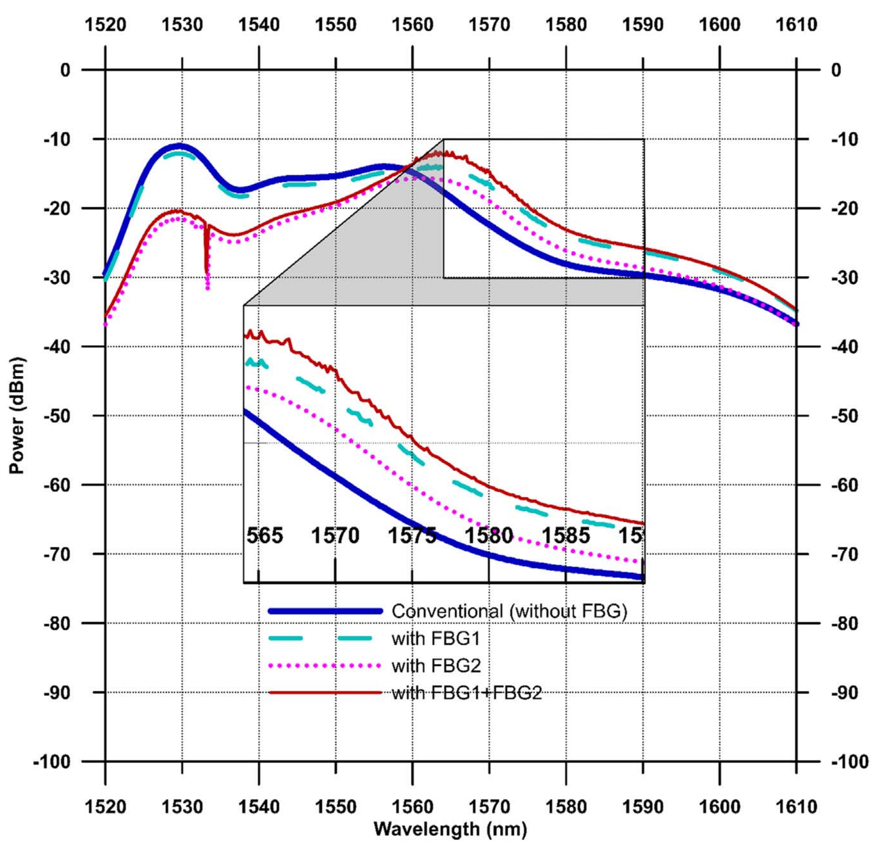

Fig. 5. The comparison of forward ASE spectra in L-EDFA with FBG1, FBG2, FBG1+FBG2 and its comparison with the conventional L-EDFA design without FBG.

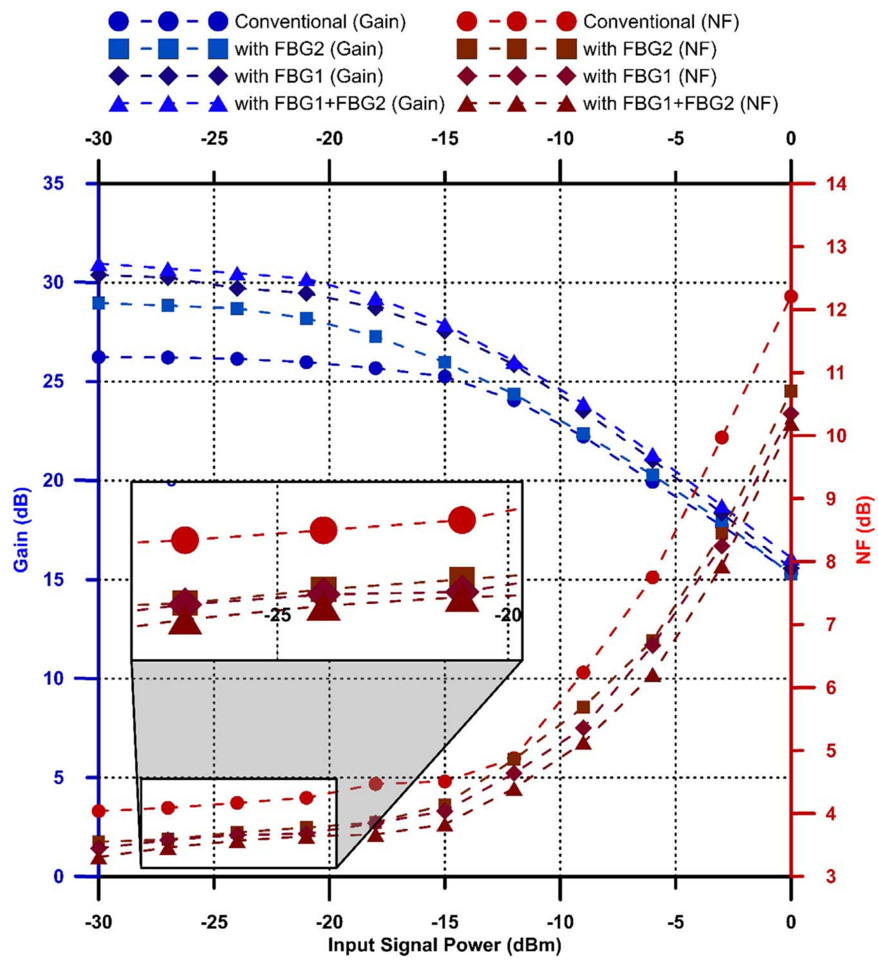

Fig. 6. Gain and NF variations as a function of input signal power in L-EDFA for different FBG configurations at 1533 nm and a conventional L-EDFA design without any FBG.

3. Results and discussion

Using the experimental setup shown in Fig. 2, the effect of FBG insertion at front and/or end of L-EDFA on the improvement of the gain and noise figure performance were investigated and compared with the conventional bidirectionally pumped L-EDFA design with no FBGs. Firstly, the forward ASE spectra were obtained for the conventional L-EDFA design for four different pump powers. It can be seen in Fig. 4 that the forward ASE in L-band EDFA increases with the increasing pump power applied equally at both directions. However, the measured forward ASE power at L-band is as much as 15 dB greater than the C-band ASE power.

Fig. 5 shows the comparison of forward ASE spectra in L-EDFA with FBG1, FBG2 and FBG1+FBG2 and its comparison with the conventional L-EDFA design without FBGs. In this measurement, the forward and backward pump power were kept at 120 mW and no input signal was applied. When the forward and/or backward ASE noise was reinjected to the L-EDFA, the pumping energy could be converted more efficiently to L-band signal. A part of C-band ASE noise reinjected at 1533 nm using FBG1 at the front side and/or FBG2 at the end side was strongly reamplified in the second part of long length EDF and used as a secondary pumping source to enhance the amplification efficiency in L-band. From Fig. 5, it can be seen that the level of the forward ASE power spectral density at 1570 nm increases about 7.95 dB at maximum when the FBG1 and FBG2 are inserted to L-EDFA.

Fig. 6 shows the gain and NF variations as a function of input signal power in L-EDFA for three different L-EDFA design with FBG and conventional L-EDFA design without any FBG. In this experiment, the input signal power was varied from −30 to 0 dBm. It can be noticed from Fig. 6 that the gain and NF performance of the L-EDFA increases significantly due to the secondary pumping effect of ASE reinjection through FBG1 and/or FBG2 compared to the conventional L-EDFA design. The gain improvement was 2.7 dB, 4.16 dB and 4.73 dB at −30 dBm input signal power and 240 mW total pump power with FBG2, FBG1 and FBG1+FBG2, respectively. Fig. 6 also shows that the amplifier NF increases with the input signal power of higher than −15 dBm due to strong saturation effects for all of the configurations. The NF values were less than 4 dB for the input signal powers of less than −15 dBm. When the forward and backward ASE at 1533 nm is reinjected using FBG2 and FBG1, in this case, the best gain and NF performance could be obtained. An input signal with a high power can stimulate more erbium ions and consequently population inversion is more heavily depleted at the input part of the EDF [16]. Therefore, reinjection of C-band ASE noise is able to further increase the secondary pumping effect. Thus, the gain and noise figure performance of L-EDFA improves significantly comparing with the conventional design. We also observed that the performance improvement provided is significantly higher with FBG1 compared to the configuration with FBG2.

Fig. 7 shows the measured gain and NF spectra of L-EDFA for different FBG configurations and for the design without FBG. The measurement was realized for the input signal wavelength between 1550 and 1585 nm with an input signal power of −30 dBm and a total pump power of 240 mW. The spectral gain and NF measurements was limited to 1585 nm for L-band, due to unavailability of the tunable laser source beyond it. It can be seen from Fig. 7 that when the ASE noise at 1533 nm is reinjected to the L-EDFA using a FBG in either at front or end of L-EDFA, the gain significantly increases and NF

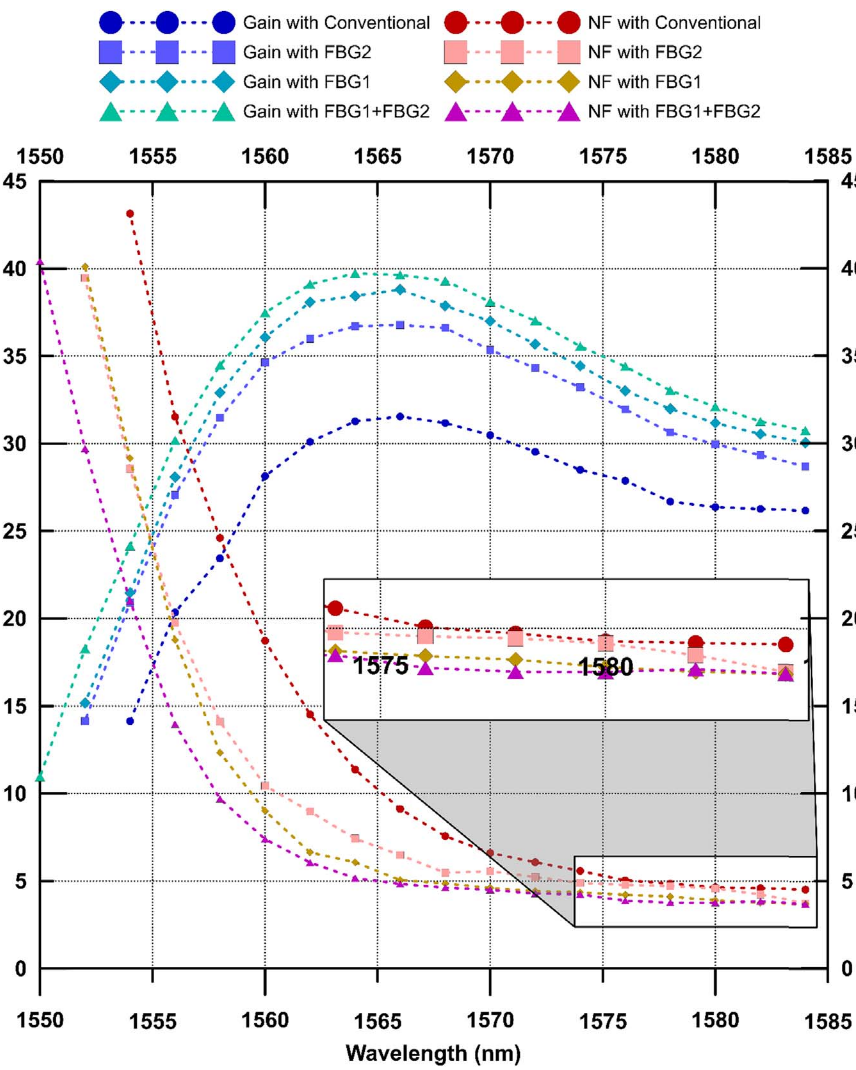

Fig. 7. Gain and NF spectra of L-EDFA for different FBG insertions at reflecting 1533 nm and a conventional L-EDFA design without FBG.

moderately decreases. The gain in L-EDFA with the insertion of both FBG1 and FBG2 to partly reinject forward and backward ASE was resulted in a higher performance with respect to the conventional design giving rise to a maximum gain increase of 9.01 dB. All of the configurations have almost given the highest gains at 1565 nm with a moderate NF values. From the measured output ASE spectrum, the L-band EDFA with FBG1+FBG2 is estimated to provide an approximately 40-nm gain bandwidth between 1570 and 1610 nm for saturating signal powers (≥−15 dBm). In the L-EDFA configuration with FBG1+FBG2 only, NF remains under 5 dB between 1565 nm and 1585 nm. The best NF performance in this configuration was obtained at 1585 nm as 4 dB. As a result, L-band EDFA design with FBG1+FBG2 can provide the highest gain and NF performance which is a good candidate to be used in L-band DWDM systems.

4. Conclusion

In this study, the effect of FBG insertion configuration on L-EDFA performance was investigated experimentally. A substantial improvement in gain and noise figure performance was achieved in L-EDFA using FBG1 and FBG2 together. The L-band forward ASE power has increased up to 7.95 dB depending on the FBG configurations. The performance of the L-EDFA designs with FBG1 and/or FBG2 were compared with the conventional L-EDFA design without FBG. The best performance in our L-EDFA at 1585 nm for an input signal power of −30 dBm was achieved by reinjection of forward and backward ASE at 1533 nm through FBG2 and FBG1 resulting a 4.5 dB increase in gain and 1 dB decrease in NF. The NF values were less than 4 dB for the input signal powers of less than −15 dBm when the forward and backward ASE at 1533 nm are reinjected using FBG2+FBG1. In conclusion, the L-EDFA design with FBG1+FBG2 can be used as a line amplifier in L-band DWDM communication systems due to giving a significant improved gain and noise figure performance.

References

[1] A. Altuncu, A. Başgümüş, Gain enhancement in L band loop EDFA through C band signal injection, IEEE Photonics Technol. Lett. 17 (2005) 1402–1404.
[2] S.W. Harun, T. Subramaniam, N. Tamchek, H. Ahmad, Gain and noise figure performances of L-band EDFA with an injection of C-band ASE, J. Teknol. 40 (2004) 9–16.
[3] H. Chen, M. Leblanc, G.W. Schinn, Gain enhanced L-band optical fiber amplifiers and tunable fiber lasers with erbium doped fibers, Opt. Commun. 216 (2003) 119–125.
[4] J. Yang, X. Meng, C. Liu, Accurately control and flatten gain spectrum of L-band erbium doped fiber amplifier based on suitable gain-clamping, Opt. Laser Technol. 78 (2016) 74–78.
[5] M.S. Zainudin, N.A.M.A. Hambali, G.C. Seong, M.S.A. Hurera, N. Roshidah, M.H.A. Wahid, M.M. Shahimin, A.Z. Malek, Comparative characteristics between L-Band EDFA, L-Band EDFA utilising single FBG and dual stage L-Band EDFA utilising dual FBG configurations, Appl. Mech. Mater. 815 (2015) 348–352.
[6] C.L. Chang, L. Wang, Y.J. Chiang, A dual pumped double-pass L-band EDFA with high gain and low noise, Opt. Commun. 267 (2006) 108–112.
[7] A.A.A. Bakar, M.A. Mahdi, M.H. Al-Mansoori, S. Shaari, A.K. Zamzuri, Single-stage

gain-clamped L-Band EDFA with C-Band ASE saturating tone, Laser Phys. 19 (2009) 1026–1029.
[8] T.C. Liang, S. Hsu, The L-band EDFA of high clamped gain and low noise figüre implemented using fiber Bragg grating and double-pass method, Opt. Commun. 281 (2008) 1134–1139.
[9] N.Md Yusoff, A.F. Abas, S. Hitam, M.A. Mahdi, Dual-stage L-band erbium-doped fiber amplifier with distributed pumping from single pump laser, Opt. Commun. 285 (2012) 1383–1386.
[10] J. Yang, X. Meng, C. Liu, C. Liu, Gain-flattened two-stage L-band erbium-doped fiber amplifier by weak gain-clamped technique, Opt. Eng. 54 (3) (2015) 036107.
[11] M. Yücel, Fuzzy logic-based automatic gain controller for EDFA, Microw. Opt. Technol. Lett. 53 (11) (2011) 2703–2705.
[12] J. Yang, Y. Ma, Y. OuYang, C. Liu, J. Zhang, A Comprehensive study on gain stabilization of Er-doped fiber amplifier in C-band with uniform fiber Bragg grating-pair, IN: Proceedings of the International Symposium on Photonics and Optoelectronics, vol. 9233, 2014, 92331F–1/F-5.
[13] A. Yu, M.J. O'Mahony, Properties of gain controlled erbium doped fibre amplifiers by lasing, Electron. Lett. 31 (16) (1995) 1348–1349.
[14] A. Yu, M.J. O'Mahony, Design and modeling of laser-controlled erbium-doped fiber amplifiers, IEEE, J. Sel. Top. Quantum 3 (1997) 1013–1018.
[15] L. Zhu, W. He, Y. Zhang, F. Luo, M. Dong, A high flattening C+L band broadband source based on single pump and the same erbium-doped fiber, Optik 125 (2014) 4659–4662.
[16] M.H. Al-Mansoori, A.S. Al-Qasmi, K.M. Al-Abri, W.S. Al-Ghaithi, M.A.A.Younis, Wideband EDFA Utilizing Short-length High Concentration Erbium-doped Fiber, in: Proceedings of the IEEE 5th International Conference on Photonics, 2014, 201-2013.