Improvement of Gain and Noise Figure in Double-Pass L-Band EDFA by Incorporating a Fiber Bragg Grating

L. L. Yi, L. Zhan, J. H. Ji, Q. H. Ye, and Y. X. Xia

***Abstract*—An obvious improvement on both the gain and noise figure (NF) is demonstrated in the new double-pass L-band erbium-doped fiber amplifier (EDFA) with incorporating a fiber Bragg grating (FBG). Compared with the conventional L-band EDFAs, the gain is improved by about 6 dB in the new configuration for a 1580-nm signal with an input power of -30 dBm at 60 mW of 980-nm pump power. It is important that the NF is greatly reduced in the new configuration, as the FBG greatly compresses the backward amplified spontaneous emission. For the economical utility of pump power and erbium-doped fiber length, such a configuration may be a very competitive candidate in the practical applications of L-band EDFAs.**

***Index Terms*—Circulator, double-pass configuration, erbium-doped fiber amplifier (EDFA), fiber Bragg grating (FBG), L-band.**

I. Introduction

With the rapid growth of the Internet and data traffic, it has been becoming more and more important to utilize the long wavelength band (L-band) of the wavelength-division-multiplexing (WDM) systems. The L-band erbium-doped fiber amplifier (EDFA) has been viewed as a natural extension of the conventional band (C-band) EDFA for increasing the channel capacity of the systems. Compared with C-band EDFAs, L-band EDFAs have intrinsically flat gains. By integrating L-band EDFA in parallel with C-band EDFA, a gain bandwidth of $\sim$80 nm has been achieved [1].

However, L-band EDFAs are relatively inefficient on the gain, as the operating wavelengths are far from the peak emission band of Er^{3+} ion. To improve the gain of L-band signal, several methods have been reported, such as C-band light assistant pumping [2], utilizing unwanted backward amplified spontaneous emission (ASE) [3], [4], incorporating a fiber Bragg grating (FBG) to reflect a port of ASE into erbium-doped fiber (EDF) [5], and using double-pass configuration [6], [7]. Although these methods improve efficiently the gain of L-band, they need a high pump power or several pump laser diodes (LDs) [7], or even lead to a high noise figure (NF) [6]. Due to the high cost or the degraded NF, these configurations may not be competitive candidates in practical projects.

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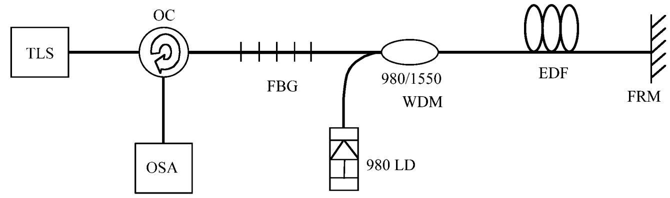

Fig. 1. Schematic diagram of the suggested L-band EDFA.

In this letter, a novel double-pass configuration with incorporating an FBG is introduced to improve the L-band gain and NF. In this configuration, a part of the C-band backward ASE is reflected into erbium-doped fiber (EDF) by an FBG as the mediating pump, and the forward L-band signal is reflected back into the EDF by a fiber reflector mirror (FRM) to realize the double-pass amplification. By comparing with the other three configurations, including the single-pass configuration without FBG, single-pass configuration with FBG and conventional double-pass configuration without FBG, it was experimentally demonstrated that a higher gain can be obtained in the new configuration at a low pump power. It is important that the NF is greatly improved in our new configuration in comparison with the conventional double-pass configuration.

II. Experiment

The used optimal experimental setup is shown in Fig. 1. In the configuration, the FBG reflects 90% of 1553-nm C-band ASE with a 3-dB bandwidth of 0.2 nm into the EDF as the mediating pump to amplify the L-band signal. The FRM reflects back the signals, the unabsorbed completely 1553-nm C-band light into the EDF to amplify the L-band signal again. An optical circulator (OC) routes the amplified signal into an optical spectrum analyzer (OSA). For test, a tunable laser source was used to input the L-band signal. In the experiment, a 70-m-long EDF of 240-ppm erbium ion concentration was used, and the power of 980-nm pump LD was set at 60 mW.

To understand easily the advantage of the new configuration, we also measured the results of the other three configurations. These configurations are defined as follows: Type 1 is the single-pass configuration without FBG, which is obtained by replacing, respectively, the FRM and the OC by an isolator and taking away the FBG from Fig. 1; Type 2 is the single-pass

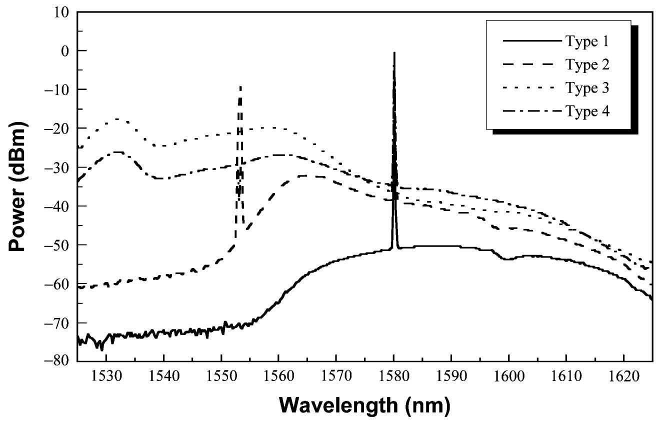

Fig. 2. Output spectra of four types of L-band EDFA at -20 dBm of 1580-nm input signal.

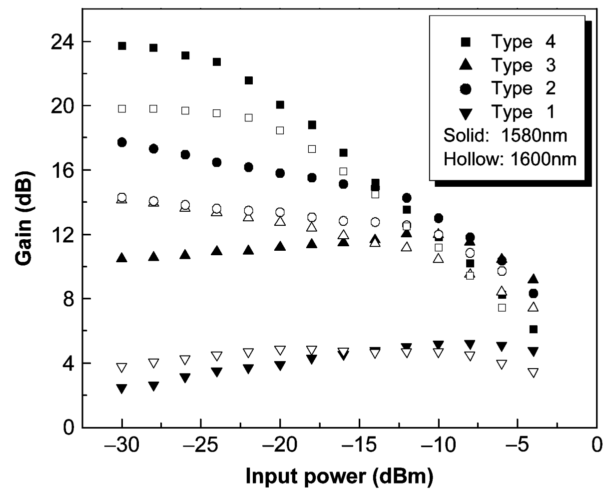

Fig. 3. Gain against input signal power. In the figure, the solid symbols show the gains at 1580-nm wavelength and the hollow symbols show the ones at 1600-nm wavelength.

configuration with an FBG, which is realized by only replacing, respectively, the FRM and the OC by an isolator from Fig. 1; Type 3 is the conventional double-pass configuration without FBG, which is gained by taking away the FBG from Fig. 1; and Type 4 is the new double-pass configuration with an FBG, which is our optimal configuration, as shown in Fig. 1. In Types 1 and 2, the OSA was connected to the second isolator, and in Types 3 and 4, it was connected to the third port of the OC. In the experiment, the results for all configurations were measured on the same condition.

III. Results and Discussion

Fig. 2 shows that the optical output spectra of the four configurations at -20 dBm of 1580-nm input signal, in which, the solid, dashed, dotted, and dashed–dotted lines represent the output spectrum in the Types 1, 2, 3, and 4, respectively. The output powers at 1580 nm in Types 1, 2, 3, and 4 are -16.06, -4.19, -8.97, and 0.04 dBm, respectively. It is obvious that the gain in Type 1 is quite low, which is just about 4 dB, as the pump power here is low. In Type 2, the FBG reflects a part of 1553-nm ASE into the EDF as the secondary pump. The gain at 1580 nm is enhanced by $\sim$12 dB in comparison with that in Type 1, but the output power at 1553 nm is quite strong, which is as high as -9.36 dBm. That will impact the reception of the L-band signal. Though the output power at 1553 nm can be completely translated into the L-band amplified signal if increasing the EDF length, the method is not economical. Type 3 takes advantage of the double-pass technology to amplify the L-band signal, but the background C-band ASE is too strong. As a result, the NF of the L-band signal is degraded [6]. It is easily seen that from Fig. 2, Type 4 integrates the advantages in Types 2 and 3. The gain at 1580 nm can be as high as 20 dB, and the residual power at 1553 nm passing once the EDF is reflected by the FRM into the EDF and absorbed again by the EDF, so the power at 1553 nm does not exist in the output spectra. It is important that the backward ASE level is $\sim$9 dB lower than that in Type 3, as the 1553-nm light reflected into EDF compresses the backward ASE. It will be useful to achieve a low NF in this configuration as well as a high gain.

Fig. 3 shows that the gains at 1580 and 1600 nm in four types of L-band EDFA vary with the input signal power, in which, the solid symbols show the gains at 1580-nm wavelength and the hollow symbols show the ones at 1600-nm wavelength. In Type 1, the gains at both 1580 and 1600 nm are as small as below 6 dB for all input powers. When a small signal power is input, the gains increase abnormally with the increase of the input power owing to the fact that the small signal power is mostly absorbed in the long EDF. When the input power is large enough, the gain variation with input power is normal due to the saturation effect. From Fig. 3, both Types 2 and 3 can enhance the gain of L-band signal efficiently. Compared with Type 1, the gain at 1580 nm for -30-dBm input power is enhanced 11.5 dB in Type 2, and 5.7 dB in Type 3. Apparently, the performance of Type 4 is optimal, in which, the gains of up to 23.7 dB at 1580 nm and 20.1 dB at 1600 nm were obtained at -30 dBm of input signal. Compared with Type 1, the gain is improved 21.2 dB at 1580 nm and 16.0 dB at 1600 nm. Compared with Types 2 and 3, there is also an improvement of about 6 and 13 dB on the gain at 1580 nm, respectively.

From Fig. 3, the difference of gain among different types is very obvious when a small signal power is input. However, the gain difference begins to become a blur when the input signal power exceeds about -15 dBm, because the gain begins to get saturated. It means that Type 4 cannot show its superiority to improve efficiently the saturated output power. Above about -7 dBm of input power, Type 4 is the third in gain level. This means that in the WDM situation, the other structures are better than the proposed structure. However, as it can realize a high small-signal gain using a low pump power and a short EDF length, such a configuration is an economical and useful candidate in the practical applications, such as in-line and preamplifiers.

Fig. 4 shows that the gains and NFs of four types of L-band EDFA change with the signal wavelength at -20 dBm of input signal, in which, the solid symbols show the gains and the hollow symbols show the NFs. As shown in Fig. 4, Type 1 has the best gain equalization, but the pump conversion efficiency is very low and the gain is just about 4.5 dB. In Type 3, using the double-pass technology, the configuration can get a flat gain of

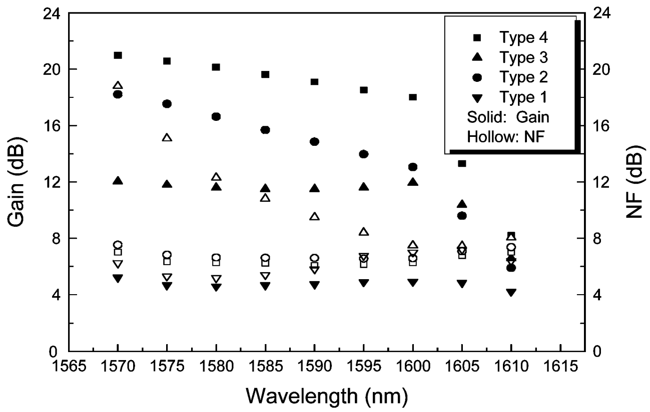

Fig. 4. Gain and NF versus signal wavelength. In the figure, the solid symbols show the gains and the hollow symbols show the NFs.

∼12 dB from 1570 to 1600 nm. From Fig. 4, it is obvious that the gain performance of double-pass configuration is superior to that of single-pass configuration, but the gain in Type 3 is still somewhat small. However, incorporating an FBG to reflect ASE into the EDF can efficiently enhance the signal gain [5]. In Types 2 and 4, the 1553-nm ASE reflected into the EDF by the FBG is amplified in the first portion of EDF, and then the amplified 1553-nm light is used to amplify the L-band signal as secondary pump in the later portion of EDF. Furthermore, in Type 4, utilizing the FRM, the ASE reflected into the EDF by the FBG is fully used to amplify the L-band signal, and the signal is amplified twice in the double-pass configuration. Such a configuration can get a high gain of about 20 dB, as well as the gain equalization is also acceptable.

As shown in Fig. 4, Type 3 shows the worst NF among the four types of EDFA. Especially, the NF is quite high at the shorter side of the L-band, as the backward ASE in the conventional double-pass EDFA is very strong [6]. In this configuration, the NF increases quickly with the decrease of the input L-band signal wavelength, since the short-wavelength L-band signal is closer to the strong backward ASE, as shown in Fig. 2. The NF in Type 1 is lowest because the L-band ASE level is lowest. In Types 2 and 4, the NFs are nearly equal and quite low, as the 1553-nm light reflected into the EDF by the FBG greatly compresses the backward ASE. It is clearly seen from Fig. 4 that the NF varies from 6.0 to 7.5 dB at the flat-gain region from 1570 to 1600 nm. Such a new double-pass EDFA as Type 4 achieved an improvement of about 1–10.0 dB on the NF over the flat-gain region in comparison with those of the conventional double-pass EDFA.

In all, considering the gain and NF synthetically, the performance of Type 4 is optimal. Such an L-band EDFA not only can provide a high gain and a low NF compared with the conventional ones, but also its cost is even more competitive due to the economical utility of pump power and EDF. It will be a very useful and competitive candidate in the practical applications.

IV. Conclusion

A novel double-pass L-band EDFA with incorporating an FBG has been demonstrated, in which, both the L-band gain and NF are improved. Utilizing 60-mW pump power of a 980-nm LD and 70-m EDF of the 240-ppm erbium ion concentration, a 23.7-dB gain was obtained for a 1580-nm signal with an input power of −30 dBm, and the NF is as low as about 6.5 dB. The gain was enhanced by at least 6 dB compared with the conventional L-band EDFA at −30 dBm of 1580 input signal; the NF was greatly reduced as well. For the perspective of economical usage of pump power and EDF length, this method may play an important role in the development of practical L-band EDFAs.

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