Low Noise-Figure Gain-Clamped L-Band Double-Pass Erbium-Doped Fiber Ring Lasing Amplifier With an Interleaver

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

Abstract—**A new design of all-optical gain-clamped L-band double-pass (DP) erbium-doped fiber amplifier (EDFA) has been proposed and demonstrated, in which the input port and the odd-channel output port of an interleaver are connected with the DP configuration EDF through a circulator to form lasing ring cavity for clamping gain, and the even port is utilized to export the amplified signals. The low noise figure can be achieved because the lasing power copropagates with the signals, and it is exported separately from the amplified signal thanks to interleaver. Meanwhile, the fiber Bragg grating incorporated in DP configuration suppresses the backward amplified spontaneous emission generation, and therefore improves efficiently the gain and lowers the noise figure. In such a way, the clamped gain of 16.3 dB with a variation below 0.2 dB and noise figure below 5 dB are achieved in the new L-band all-optical gain-clamped EDFA.**

Index Terms—**Erbium-doped fiber amplifier, gain clamping, interleaver, L-band, optical communication.**

I. INTRODUCTION

WITH the recent explosive growth of the telecommunication requirements, new optical transmission bandwidths with amplifiers are desired to satisfy the ever increasing capacity demand of dense wavelength-division multiplexed (DWDM) systems. Nowadays, the conventional wavelength band (C-band) transmission window (1530–1560 nm) has been extended into the long wavelength band (L-band) (1570–1610 nm) [1], [2]. Meanwhile, the DWDM networks basically require optical amplifiers to maintain constant gain when wavelength channels are added or dropped. To satisfy the requirement of broadband transmission in DWDM systems, the gain clamping (GC) is an important characteristic for L-band erbium-doped fiber amplifiers (EDFAs), as well as for C-band EDFAs. It is possible that the performances of EDFAs are independent of the input power of signals and the number of used channels in DWDM systems.

To date, various approaches of gain-clamping have been proposed and demonstrated for both C-band and L-band EDFAs. Mostly, the gain clamping in EDFAs can be achieved through two kinds of methods. One is the electrical control technique [3], such as fast pump current control to maintain appropriate population inversion level in two-stage EDFA by detecting the powers of input signals. In such way, the amplifier is usually complicated and the fast variation on drive current may shorten the life of high- power pump laser diodes. The other is the all-optical gain control technique [4]. A simple and effective way to clamp the gain is to utilize the lasing mechanism by using a couple of gratings at the EDF ends [5], [6] or by forming an optical ring to establish lasing oscillation [7], [8]. However, in most works, the low noise figure (NF) and the signal output without lasing power cannot be satisfied simultaneously in the all-optical GC lasing amplifiers. To overcome this problem, we have proposed and demonstrated a novel C-band GC-EDFA, in which the low NF and the signal output without lasing power can be simultaneously achieved incorporating an interleaver in the ring cavity [9]. On the other hand, 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 L-band gain, several methods have been reported [10]–[12]. Of them, the double-pass (DP) configuration has demonstrated that it can improve efficiently the L-band gain, but subject to a high NF due to strong backward amplified spontaneous emission (ASE) [12]. Following this problem, we reported a new DP configuration incorporating a fiber Bragg grating (FBG) to enhance the gain while lowering the NF [13].

In this paper, we propose and demonstrate a novel configuration of L-band all optical GC-EDFA with a low NF, which is integrated with the advantages both of the fiber-ring lasing configuration with an interleaver and of the DP configuration incorporating an FBG. In our new L-band GC-EDFA, the input port and the odd-channel output port of interleaver are connected with a DP configuration EDF through a circulator to form the fiber ring cavity. An FBG is incorporated in the DP configuration to enhance the gain and lower the NF [13]. The even-channel output port is used to output the signal. In such a way, the amplified signals are exported separately without the lasing power, as the signal wavelengths are different from those of lasing power. Here, the interleaver also plays the role of a filter, which induces the ASE power output from odd-channel port to form lasing oscillation. As the lasing suppresses the generation of ASE, and the lasing power can be filtered from the output signals by the interleaver, a low NF can be obtained. Finally, a new L-band GC-EDFA with a clamped gain of 16.3 dB and a low NF of less than 5 dB was demonstrated.
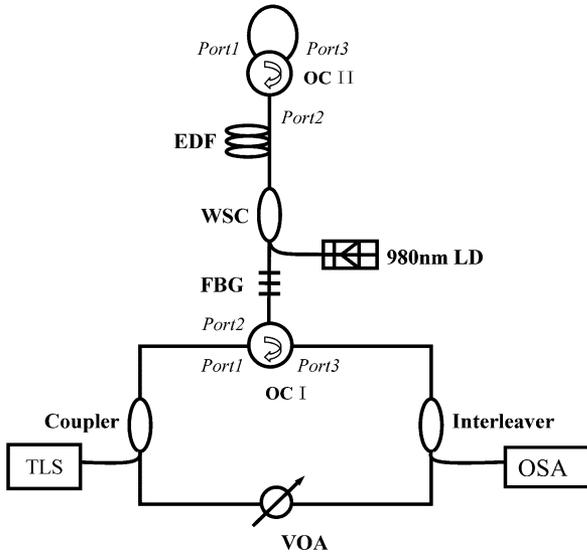
Fig. 1. The schematic configuration of the new L-band all-optical gain-clamped EDFA.

II. Experiment

Fig. 1 shows the scheme of the L-band GC-EDFA in this study. A 90:10 coupler inputs 90% signal power into the fiber-ring cavity. Optical circulator I (OC I) is utilized to define the propagation of the signals and lasing power with the same direction. The signal light propagates in from port 1 to port 2 and then out from port 2 to port 3. Port 1 and port 3 of the circulator II (OC II) are connected in order to let the signal pass again through the erbium-doped fiber (EDF), which is 80 m long with 240-ppm erbium ion concentration. Here, OC II acts as fiber reflection mirror. A 1550/980-nm wavelength selective coupler (WSC) combines 90-mW laser from a 980-nm laser diode (LD) into the EDF as pump. The FBG with the center wavelength of 1553 nm and the 3 dB bandwidth of 0.2 nm slices a portion of the backward C-band ASE fed back into the EDF to amplify the signal [10]. The interleaver is such a filter that separates DWDM signal channels into two groups with twice the wavelength spacing, and lets the odd-channel/even-channel signal group exported separately from the odd/even port. In the experiment, a 100/200-GHz interleaver is used to slice the continuous ASE from EDF into two reverse-shape spectrums with 1.6 nm wavelength spacing. The ASE from the odd port is fed back into fiber-ring cavity through the 10:90 coupler to establish the lasing oscillation. The insertion loss of the interleaver is about 1.5 dB at the L-band. The even port of the interleaver is connected with an optical spectrum analyzer (OSA) to measure the gain, spectrum, and NF of the amplified signals. In order to control the gain, a variable optical attenuator (VOA) is applied in the cavity to modify the cavity loss. In the experiment, a tunable laser source (TLS) connected with a VOA is employed as the input signal source.

III. Results and Discussion

Fig. 2 shows the output spectra of the amplified signals from the even-channel port of the interleaver in our new GC-EDFA with a 22.2 dB loss of VOA. Fig. 2(a) is composed of Figs. 2(b)–(d). The measured power of 1580.576 nm output signal is −13.65, −3.74, and 6.93 dBm, respectively, responding to the input signal power of −30 [Fig. 2(b)], −20 [Fig. 2(c)], and −8 dBm [Fig. 2(d)]. With the input signal power increase from −30 to −20 dBm, the gain is 16.35 and 16.26 dB, respectively. They are almost equal, because these input signals locate in the gain clamping range. This result indicates that the gain was clamped at ∼16.3 dB when the cavity loss was 22.2 dB. Nevertheless, the gain of the −8 dBm input signal power is 14.93 dB due to the gain saturation when the input signal power exceeds −10 dBm. In the gain clamping range of the input signal power below −10 dBm, the gain does not vary regardless of the input signal power change. Fig. 2 also shows the effect of the interleaver, which slices the continuous ASE into two reverse-shape spectrums. In Fig. 2, the ASE spectrum exported from the even-channel port exhibits that the continuous ASE sliced into peak and vale with a 1.6 nm period.

To indicate the gain-clamping characteristic of EDFA under different signal powers, the gain and NF against the input signal power are shown in the Fig. 3, in which the solid symbols represent the gain and the hollow ones for the NF. In the measurement, the 1580.576 nm light is input as the probe signal. In Fig. 3, the triangles represent the results with the fiber-ring cavity with 22.2 dB loss of VOA (type A), and the circles for the result with 12.1 dB loss (type B). To indicate the importance of the fiber-ring cavity for gain-clamping, we also present the results without the fiber-ring cavity (type C). In Fig. 3, the squares show the result of type C, which is directly detected from port 2 of OC when the fiber ring is disconnected at the position of VOA. From Fig. 3, with the VOA loss of 22.2 dB, the clamped gain of about 16.3 dB is achieved until signal power increases to −10 dBm. Beyond −10 dBm, the signal gain decreases gradually as input signal power increases further. When the VOA loss changes to 12.1 dB, the clamped gain is measured at 10.1 dB when the signal power is below −6 dBm. With the cavity loss decrease, the clamped gain decreases while the GC range of input signal power turns longer, because the average population inversion fixed by the lasing power turns lower. Without fiber ring, the gain of type C always decreases with the increase of signal power. At the same input signal power, the gains of types A and B are lower than that of type C. This is caused by the lasing expense for gain clamping and the insertion loss of interleaver. During the GC range of type A or type B, gain does not change while the input signal power changes. Less than 0.2 dB gain variations in the GC range are possibly caused by the measurement error or the fluctuation on the lasing power. The clamped gain of type A is different from the clamped gain of type B, since the average inversion population is determined by the lasing power, which can be modified through changing the loss of the fiber-ring cavity. Up to here, the experimental results indicate that the new L-band EDFA exhibits a good performance on the GC characteristic for the single channel input signal. Because of the lack of the multichannel L-band signal source, we cannot continue to test the results with the multichannel input signals. However, as is well known, the EDF is a homogenous broadening gain medium. The tested GC characteristic using the single input signal with different power, is applicable to indicate
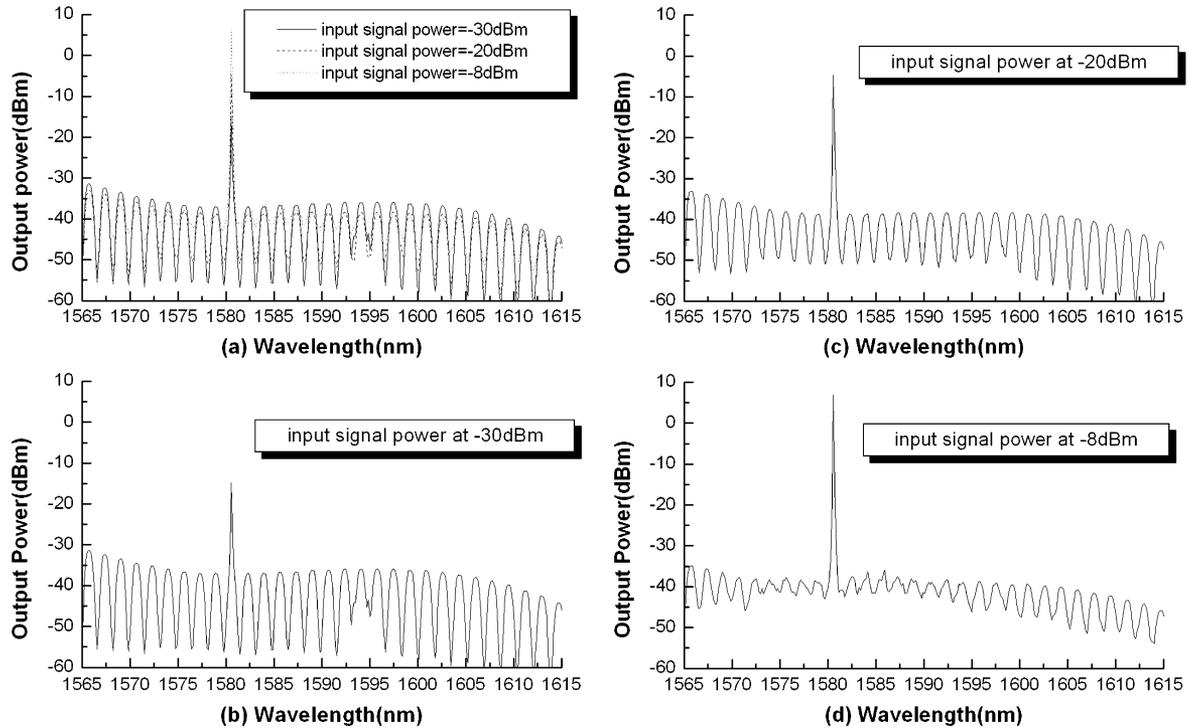
Fig. 2. The output spectra of the amplified 1580.576 nm signals when the loss of VOA= 22.2 dB. (a) The solid line represents −30 dBm signal input, the dashed line −20 dBm, and the dotted line −8 dBm. (b) The output spectra of the 1580.576 at −30 dBm signal input. (c) The output spectra of the 1580.576 at −20 dBm signal input. (d) The output spectra at −8 dBm signal input.
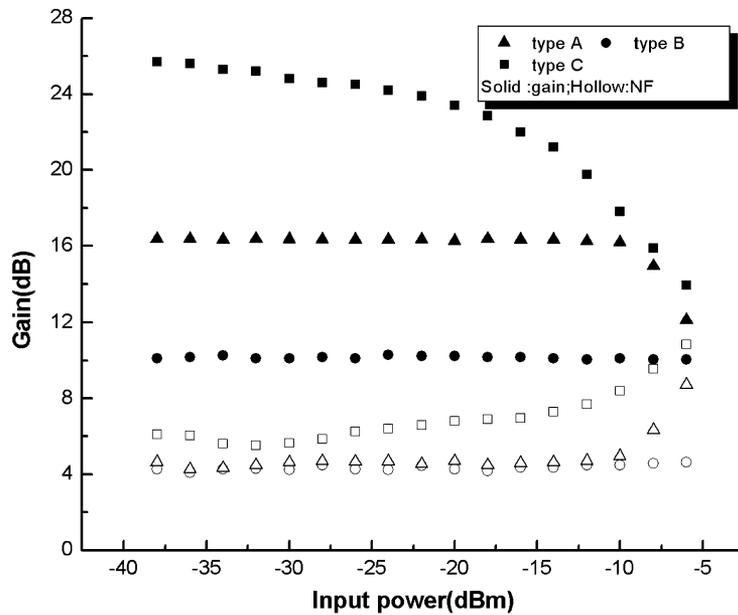

Fig. 3. Gain and NF versus input signal power at 1580.576 nm at different lasing cavity losses. In the figure, the solid symbols show the gains and the hollow symbols show the NFs.

the performance on add/drop signal in the multichannel DWDM system.

As shown in Fig. 3, the NFs of types A, B, and C are 4.68, 4.27, and 6.8 dB, respectively, when −20 dBm is the input signal power. The different NFs result from the different cavity losses, which correspond to 22.2 dB, 12.1 dB, and infinite cavity loss (the cavity off). Commonly, the NF of the countertraveling lasing configuration is bigger than that of the cotraveling config-

uration [14]. In our configuration, the lasing power propagates in the same direction with the signal. This leads to the improvement of NF at first. For the cotraveling lasing system, the NF exhibits a different behavior opposite to that in the countertraveling system [15]. In the cotraveling configuration, the lasing power entering the input end of the active medium plays a more important role to suppress the backward ASE generation at this end. The less the cavity loss is, the stronger lasing power will
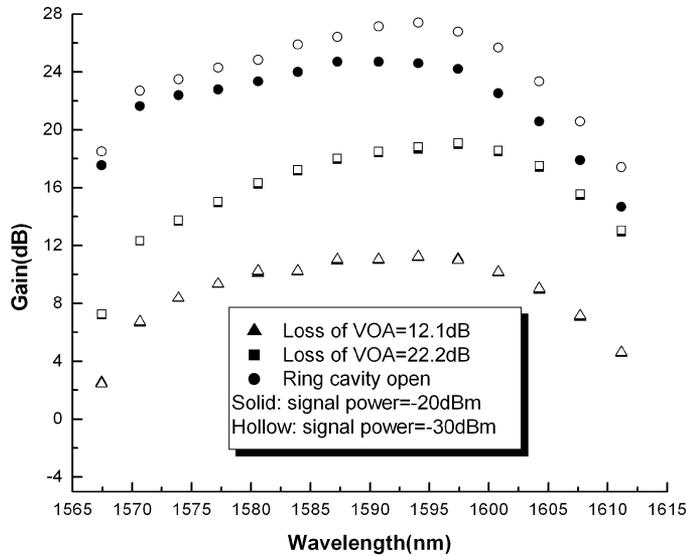
Fig. 4. Gain against input signal wavelength at different cavity losses. In the figure, the solid symbols and the hollow symbols represent the − 20 and −30 dBm input signal power, respectively.

be generated. The lasing power efficiently suppresses the backward ASE and therefore restores the population to a higher level. Thus, the less the cavity loss is, the smaller the NF that will be achieved. Certainly, to lower the NF in this way is based on the expense of the reduced gain. The NF of type C is obviously higher than types A and B at the same input signal power. Especially, when the input signal power is bigger than −24 dBm, the difference is more obvious. This is contributed to the effect of the interleaver, which confines a portion of the ASE into lasing power in the cavity, and then separates the lasing power for the output signals. Here, the NFs of all types are relatively lower than the one in conventional DP L-band EDFA, because the incorporated FBG strongly suppresses the backward C-band ASE generation in the DP configuration [13].

Fig. 4 shows the gain against the wavelength of input signals at different VOA losses. In Fig. 4, the squares and the triangles stand for the results when the VOA loss = 22.2 and 12.1 dB, respectively, and the circles for the case of the cavity off. The solid symbols represent the input signal power = −20 dBm and the hollow for −30 dBm. From Fig. 4, owing to the effect of gain clamping, the gain curves of the input signal power at − 30 and −20 dBm are almost overlapped in the whole L-band spectrum, for both the cases of 22.2 and 12.1 dB VOA loss. When the ring cavity is cut off, the gain of the −30 dBm input signal power is higher than that of the −20 dBm input signal power. It is obvious that the gain changes with the input signal power when the ring cavity is cut off. Such an EDFA is not suitable for the DWDM systems.

Compared with those of the conventional DP EDFA, the NF in type A is quite low, which is below 5 dB in the mainly gain-clamping range. Meanwhile, the gain equalization of type A does not greatly degrade. Synthetically considering gain and NF, the performance of type A is best optimized. Such an L-band GC EDFA not only can provide a higher gain but also performs a low NF. In the experiment, the C-band circulator was used in

the scheme, because of the lack of the L-band circulator. That leads to a 6 dB insertion loss or more, which is dependent on the wavelength. If an L-band circulator was used, we believe that the proposed L-band GC-EDFA would perform a higher gain and a lower NF. This scheme may be a competitive candidate in the practical applications. It should be pointed out that the demonstrated L-band GC-EDFA is only suitable for the 200-GHz-spacing DWDM optical communication system, because of the application of 100/200-GHz interleaver. However, if other kinds of interleavers (for example, 25/50- or 50/100-GHz interleaver) take the place of the 100/200-GHz interleaver, the proposed design of L-band EDFA can be used in an alternative (50- or 100-GHz spacing) DWDM system.

IV. CONCLUSION

In conclusion, a novel L-band all-optical GC EDFA is proposed and experimentally demonstrated, which is integrated with the advantages both of the fiber-ring lasing configuration with an interleaver and the DP configuration with incorporating an FBG. A low NF can be achieved in the new design because the lasing power through the odd-channel port of interleaver clamps the average population inversion at a lower level, and strongly suppresses the backward ASE generation. Meanwhile, the interleaver filters out the lasing power and a portion of ASE from the amplified signal and lets the amplified signals export from the even port. In addition, the FBG in the DP configuration improves the gain and lowers the NF. Eventually, an L-band GC-EDFA with gain of 16.3 dB and NF of about 4.6 dB is demonstrated when the ring cavity loss set at 22.2 dB. Through modifying the specification of interleaver, the proposed configuration may be applicable for all kinds of DWDM optical communication systems.

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