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Investigation of Amplifying Mechanism in an L-Band Erbium-Doped Fiber Amplifier Pumped by a 980 nm Pump

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For a more detailed understanding of the mechanism of an L-band erbium-doped fiber amplifier, we investigated 980 nm absorption, signal amplification and forward and backward amplified spontaneous emission along the erbium-doped fiber. In addition, we compared performances of the erbium-doped fiber amplifier with and without a fiber Bragg grating.

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I. INTRODUCTION

L-band (1570 nm ~ 1605 nm) erbium-doped fiber amplifiers (EDFAs) have a flat-gain bandwidth above 30 nm without a gain-flattening filter. Hence, by using L-band EDFAs in conjunction with C-band EDFAs, the capacity of wavelength division multiplexing (WDM) transmission systems can easily be doubled. Recently, WDM transmission systems operating at terabits per second were demonstrated by using both C-band and L-band EDFAs. [1]- [4] In addition, extended L-band erbium-doped fiber (EDF) that moves the gain region of EDF to 1620 nm has been reported, and the gain bandwidth of L-band EDFAs is extended. [5] In many transmission systems 1480 nm pump laser diodes (LDs) are typically used in L-band EDFAs for better amplifying characteristics in this band. However, using 980 nm LD in EDFAs is very profitable in terms of price, electricity consumption, thermal effect and noise figure. A highly efficient L-band EDFA was reported in which a noise figure below 3.9 dB was obtained by using a 980 nm pump LD. [6]

Because of the difference in the gain coefficient of the EDF with wavelength, L-band EDFAs generally require EDF that is almost ten times longer than the EDF of C-band EDFAs. When an EDFA is pumped by a 980 nm LD, the unpumped region of L-band EDFAs occurs in the EDF because of the high absorption coefficient in EDF at 980 nm. As a result, the amplification mechanism of the signal in L-band EDFAs is different from that in C-band EDFAs because the signal in the C-band is amplified by the pump energy over the entire length of EDF.

Recently, simulators for L-band EDFA have been reported. [7] However, the reliability of such simulators is still low for L-band EDFAs. The simulators typically emphasized the output characteristics rather than the mechanism. In order to optimize the design for L-band EDFAs, we must understand the characteristics of the output signal as well as the progress and interactions of the pump, the signal and the amplified spontaneous emission (ASE).

In this paper, we measured the absorption of the 980 nm pump, amplification of signal, forward ASE and backward ASE along the EDF to understand the mechanism of L-band EDFAs. We focused on the progress of the backward ASE, which affects population inversion, and the forward ASE, which is needed to amplify signals in L-band EDFA. In addition, we compared performances of an EDFA with and without a fiber Bragg grating (FBG).

II. RESULTS AND DISCUSSION

1. The setup and measurement of the experiment

Fig. 1 shows a diagram for the measurement setup to study the mechanism of an L-band EDFA pumped by a 980 nm LD. The single stage L-band EDFA consists of a 980 nm pump LD and 55 m of EDF (erbium concentration of +800 ppm), which is spliced with 0.9 m, 2.2 m, 2.2 m, 7.5 m, 15 m and 27.2 m. We measured the characteristics at 1580 nm for three different

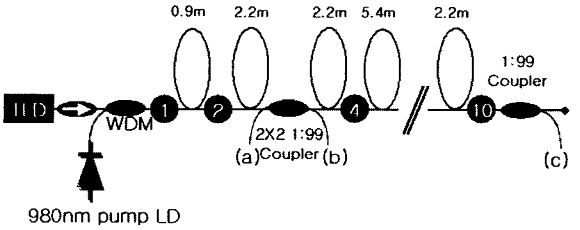


FIG. 1. The experimental setup for the operational principle of the L-band EDFA pumped by a 980 nm pump LD. The 980 nm pump LD power was 150 mW.

input signal levels of -20 dBm, -10 dBm and 0 dBm. After locating the 2 × 2 1:99 coupler at a specific position among positions (1) to (10), we measured the 980 nm pump absorption, the forward ASE spectrum and the signal power. At 1% tab (a), we measured the backward ASE spectrum. The insertion loss of the 1:99 coupler into the EDF loss was 0.2 dB, which is not significant in analyzing the results. We monitored the output spectrum at 1% tab (c) to confirm that all the measurements were done at a similar experimental condition. For all the present measurements, the variation of the output spectrum was maintained below 0.9 dB.

2. The operational principle of an L-band EDFA

Fig. 2 shows that almost 980 nm pump power was absorbed at 15 m of EDF. Therefore, the unpumped region exists in the L-band EDFAs with the long EDF. Consequently, analysis of the signal amplification process at the unpumped region in an L-band EDFA is important. Fig. 3(a) shows the forward ASE spectrum along the EDF. Forward ASE, which was generated and amplified in the pumped region by the pump power, was ultimately absorbed in the unpumped region of the EDF. Because the absorbed C-band ASE caused the population inversion and gave gain into the L-band, the L-band signal was amplified even in the unpumped region. From this result, we understand that the amplification of the L-band signal was due not only to the 980 nm pump power but also to the C-band ASE. On the other hand, the backward ASE was progressively amplified in the opposite direction of signal from the exiting part of the EDF. Because a short EDF for a C-band EDFA has no unpumped region, the forward and backward ASEs are amplified to a similar power in a short EDF. However, if the EDF is long, the backward ASE grows larger than the forward ASE. [8] The backward ASE was amplified more greatly than the forward ASE at the beginning of the EDF in Fig. 3(b). The experimental results reveal that the reason why the characteristic of L-band EDFAs is poor is consumption of pump power in amplifying the backward ASE which is mostly in the C-band of high gain.

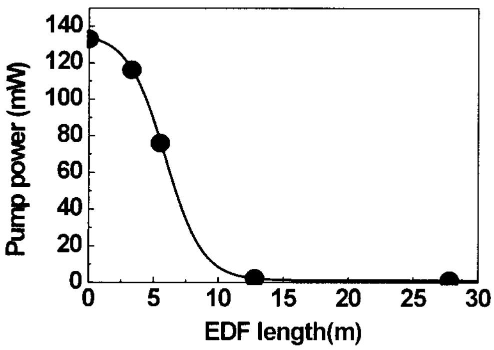


FIG. 2. Pump absorption along the EDF.

3. The efficient L-band EDFA pumped by a 980 nm pump LD

To increase the efficiency of L-band EDFAs, an

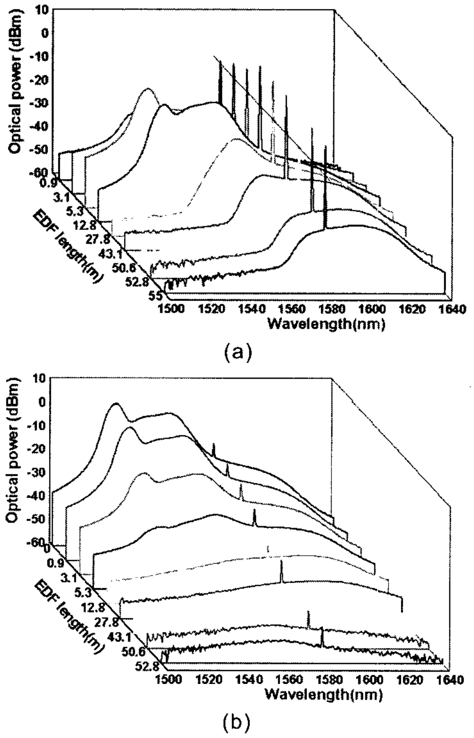


FIG. 3. (a) The forward ASE spectrum along the EDF (an upper line indicates -10 dBm) (b) The backward ASE spectrum along the EDF.

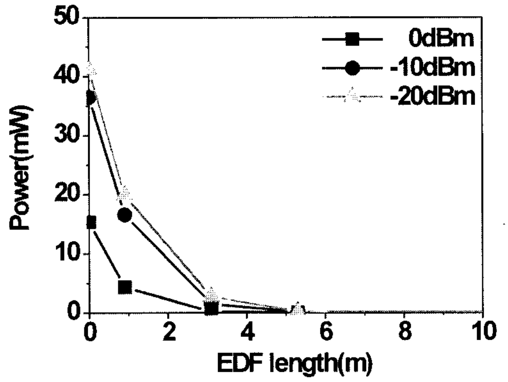


FIG. 4. The backward ASE power along the EDF.

isolator may be inserted in EDF to prevent the backward ASE from amplifying. This method may prevent amplification of the backward ASE, but it is inefficient because a significant pump loss occurs when the isolator is inserted. [9]

Another method tries to increase the total input, makes the population inversion of the EDF low and so prevents the backward ASE from amplifying significantly. Fig. 4 shows the backward ASE power along the EDF at different L-band input levels. When the input signal power changes by -20 dBm, -10 dBm and 0 dBm, the backward ASE power decreases gradually by 41.2 mW, 36.5 mW and 15.4 mW, respectively.

As the input power increased, the population inversion of the EDF decreased. In this case, the forward ASE that is mostly in the C-band and contributes to the L-band amplification decreased, together with the backward ASE. Therefore, the amplification efficiency of signals in the L-band decreased. However, if the total input is increased by using an additional C-band signal, only the backward ASE will be reduced. Because an additional C-band signal was greatly amplified and reabsorbed in the EDF so as to give extra gain to the L-band signal, the amplification efficiency of the L-band signal increased. An external signal or internal ASE can be used to add the C-band signal. [10]- [12]

Among the methods that use ASE inside an EDFA, the method that employs an FBG is very simple in configuration. [11] Fig. 5 shows a diagram of an L-band EDFA with an FBG. The FBG reflects 90% of the 1545 nm light with a 3 dB bandwidth of 0.2 nm. Part of the C-band backward ASE from the pumped EDF was reflected by the FBG and it then reentered the EDF. The 1545 nm ASE reflected by the FBG was -2 dBm. Therefore, the backward ASE amplification was decreased because the low population inversion of the EDF caused by the increase of the total input.

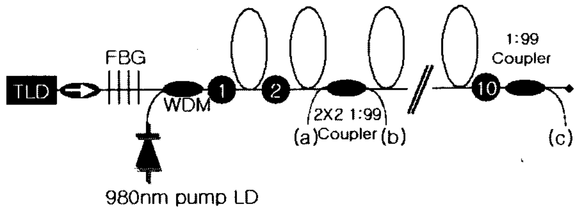
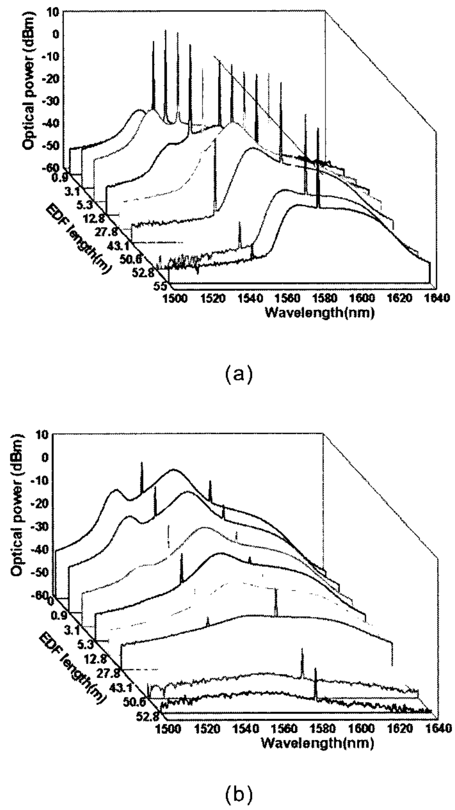


FIG. 5. The experimental setup for the efficient L-band EDFA with an FBG pumped by a 980 nm pump LD.

Fig. 6(a) shows the forward ASE spectrum along the EDF. The ASE reflected by the FBG were inputted and amplified strongly in the EDF by the 980 nm pump power. In the unpumped region, because the strongly amplified forward C-band ASE was absorbed by the EDF, the absorbed C-band ASE acted as a mediating pump for the L-band signal. Fig. 6(b) shows the backward ASE spectrum along the EDF. The total power of the backward ASE decreased significantly.

By calculating the signal power and the ASE power from the spectrum at an input of -10 dBm, we observed a gain improvement of the signal by using the



(a)

(b)

FIG. 6. (a) The forward ASE spectrum along the EDF (an upper line indicates -10 dBm). (b) The backward ASE spectrum along the EDF.

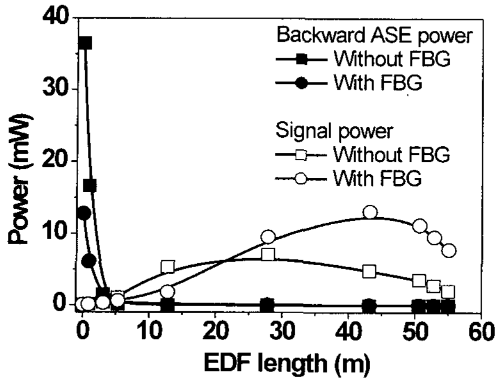


FIG. 7. The backward ASE power and signal power variation along the EDF.

FBG. In Fig. 7, without the FBG, the backward ASE was +15.6 dBm. However, with the FBG, the backward ASE was +11 dBm. Without the FBG, the amplification of the signal ended at 27 m of EDF but, with the FBG, it ended at 43 m of EDF and the L-band signal power increased by 4.3 dB.

When the FBG was inserted, the amplification of signal was smaller than that of the signal without the FBG, from the front part of EDF, because of the low population inversion in the EDF caused by the increase of the total input. After the amplification of the L-band signal by the reabsorbed C-band ASE to 43 m, the signal was absorbed by the very low inverted EDF and so the power decreased.

III. CONCLUSION

To understand the mechanism of L-band EDFAs pumped by a 980 nm pump, we configured a single-stage L-band EDFA with a 980 nm pump and employed a 2 × 2 1:99 coupler to measure the pump power, the amplification of the signal and the forward and backward ASE spectra along the EDF.

We analyzed the mechanism of L-band EDFAs by dividing into pumped and unpumped regions. In the pumped region, the signal was amplified by the pump power. In the unpumped region, the signal was amplified by absorption of the amplified forward C-band ASE. Because the forward ASE was smaller than the backward ASE at the front part of the EDF, the efficiency of typical L-band EDFAs pumped by 980 nm LD was low. On the other hand, configuration with a FBG enabled a very simple and efficient L-band EDFA, by reducing the detrimental backward ASE and increasing the C-band ASE power to provide gain in the L-band along the EDF.

In conclusion, we have experimentally demonstrated the mechanism of L-band EDFAs. We expect the presented results to be useful in making good simulators for L-band EDFAs, which are not perfect at this time.

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