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Double-Pass Two-Stage EDFA with Gain-Flattening Filters

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The optical gain and noise figure improved double-pass two-stage EDFA using a mirror, circulator, and gain-flattening filters is proposed. By double passing the pump light and removing the ASE propagating into the input part, the signal gain of 5 dB and noise figure of 2.1 dB are improved compared to the conventional single- and double-pass EDFA. With gain-flattening filters in the second stage of EDFA, we obtain an improved flat gain with a gain flatness less than 1 dB over 33-nm wavelength range at the 980-nm pump power of 86 mW.

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I. INTRODUCTION

Erbium-doped fiber amplifiers (EDFA's) have been intensively studied for wavelength-division-multiplexing (WDM) transmission systems. The optical amplifier gain and added noise are two fundamental characteristics affecting the communications signals. In the transmission systems, removing of amplified spontaneous emission (ASE) noises, which are essentially generated from EDFA's, is very important. Various devices, such as filters, isolators, and tapered structures, have been used to reduce the noise figure (NF) and to increase the gain of EDFA's [1-4]. Reflective type EDFA's using a mirror and an optical circulator were proposed to achieve a better utilization of wasted pump energy [5]. This double-pass EDFA doubled the gain coefficient compared to that of a single-pass one. However, its NF is worse than that of single-pass EDFA's. As the NF depends on a high population inversion in the input end of the erbium-doped fiber (EDF), ASE at this part of the EDF is especially undesirable. A double-pass two-stage EDFA using an optical circulator placed within the length of EDF was proposed, and it achieved a NF improvement of 2 dB compared to the conventional double-pass EDFA [6]. In this paper, we demonstrate a double-pass two-stage EDFA with enhanced signal gain and NF. Using a gold-coated mirror to reflect the pump and amplified signal light, and a midway circulator to remove the backward ASE, the proposed EDFA achieves about 5 dB higher gains and 2.1 dB lower NF than the conventional single- and double-pass EDFA. We show that by inserting band-rejection filters in the second stage of the EDFA, a significant improvement on the signal gain can be achieved. It is also shown that the gain improvement at 980 nm pump is much higher than that of the EDFA at 1480 nm pump. The pump light cannot traverse the circulator for a 980-nm pump, thus we use WDM couplers to allow the pump light to bypass the circulator and enter the second stage. With gain-flattening filters (GFF's) based on a microbending long-period fiber grating (LPFG) in the second stage of the EDFA [7], we obtain an improved flat gain with a gain flatness of 0.5 dB over a bandwidth of 33 nm.

II. EXPERIMENTS AND RESULTS

The schematic structure of the double-pass two-stage EDFA is shown in Fig. 1. The lengths of the EDF are 5 m and 10 m for the first and second stage of the EDFA, respectively. The circulator inserted between two stages prevents the forward and backward ASE from propagating into the first stage. The ASE, which becomes large and causes saturation near the input end of the EDF, degrades the noise characteristics. By removing the ASE, the NF can be significantly reduced. A gold-coated mirror is incorporated at the end of EDF. Amplified signal, ASE, and residual pump are reflected. The optical gain is highly dependent on the length of the EDF. So, the double-pass EDFA's have higher signal gain than the single-pass ones. Here the circulators are operated at the wave-

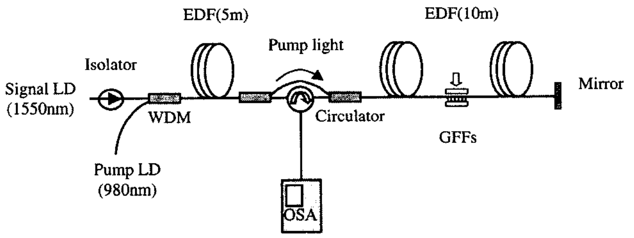

FIG. 1. Schematic of the double-pass two-stage EDFA.

length of 1550 nm. By incorporating the 980/1550-nm WDM couplers on both sides of circulator, the 980-nm pump offering the benefit of the gain improvement can be used.

The gain and NF characteristics of the 1550-nm signal against pump power are measured by varying the pump power from 20 to 112 mW for three cases as shown in Fig. 2. The double-pass two-stage EDFA achieves about 5 dB higher signal gain than the single-pass EDFA. This is mainly attributed to its longer EDF length. The gold-coated mirror reflects the pump and the amplified signal light, and has a reflection ratio of about 83 %. Moreover, the NF performance is improved by more than 2.1 dB compared to the double-pass EDFA. This is due to the rejection of the ASE propagating into the first stage by using a mid-way circulator.

It has been shown that it is possible to increase optical gain and NF with filters in the conventional single-pass EDFA. Fig. 3 shows the optical gain improvement of the double-pass two-stage EDFA as a function of the normalized filter position in the second stage of the EDFA. We show that by inserting a band-rejection filter in the double-pass EDFA, the optical gain improvement at the signal wavelength of 1550 nm is obtained by using 980 and 1480 nm pump, respectively. It is also shown that the gain improvement at 980 nm pump is much higher than that of an EDFA at 1480 nm pump, as shown in Fig. 3. The band-rejection filter with center wavelength of around 1531 nm, where the ASE is at its maximum, is inserted in the second stage EDFA. So both the forward and backward ASE generated during amplification can be reduced, and therefore the optical gain and pump efficiency are increased. The optimum filter position is found to be from 50 to 100 % of the second stage in the double-pass two-stage EDFA.

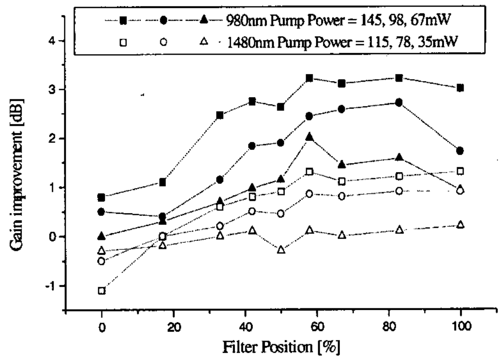

FIG. 3. Gain improvement as a function of filter position in the second stage of EDFA.

Fig. 4 shows the measured signal gain and NF spectra of the EDFA with and without gain-flattening filters (GFF's). Input signal and 980 nm pump power are −35 dBm and 86 mW, respectively. Our GFF's based on microbending LPFG [7] are inserted in the second stage of the EDFA. This filter, which is very simple and inexpensive, has desirable characteristics for gain flattening of the EDFA. We can easily tune the center wavelength and the depth of the notches by mechanically adjusting the grating period and the pressure, respectively. When designing our GFF's to obtain the gain flatness, we can control the center

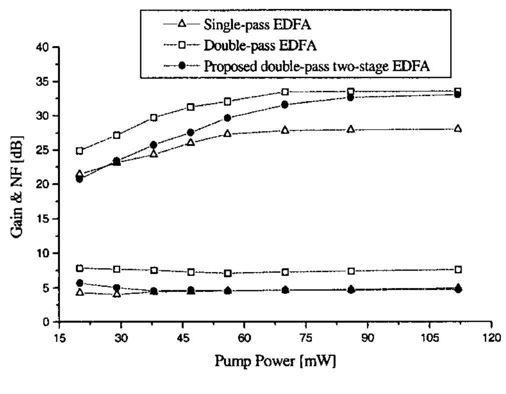

FIG. 2. Signal gain and noise figure against pump power.

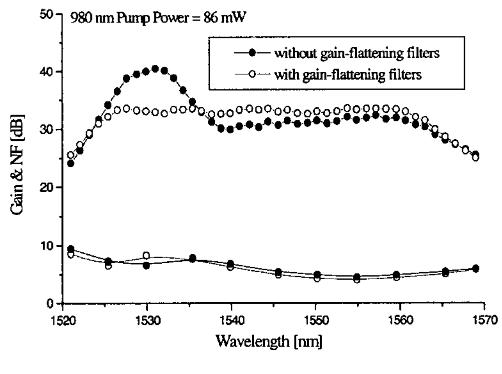

FIG. 4. Gain and noise figure spectra with and without gain-flattening filters.

wavelength and the depth of the notches according to the bandwidth and amplitude of the gain spectrum. The gain variation is less than 1 dB over the wavelength range from 1525 to 1558 nm. The optical gain and NF improvements are about 2.5 dB and 0.4 dB at the wavelength range of 1538 to 1560 nm, compared with those of the EDFA without GFF's.

III. CONCLUSION

We have demonstrated that significant optical gain and NF improvements can be achieved by using a double-pass two-stage EDFA. Using a gold-coated mirror to reflect the pump and amplified signal light, and a midway circulator to remove the forward and backward ASE, this EDFA has achieved about 5 dB higher gains and 2.1 dB lower NF than the conventional single- and double-pass EDFA. With GFF's based on microbending LPFG's in the second stage of the EDFA, we have obtained an improved flat gain with the gain variation less than 1 dB over 33 nm at a 980-nm pump power of 86 mW.

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