Double-pass high-gain low-noise EDFA over S- and C+L-bands by tunable fundamental-mode leakage loss

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Abstract: We demonstrate a high-gain low-noise double-pass tunable EDFA over S- and C+L-bands by discretely introducing fundamental-mode leakage loss in a 16-m-long standard C-band Er^{3+}-doped fiber. The amplified spontaneous emission at the wavelengths of longer than 1530 nm can be substantially attenuated by the ASE suppressing filters to maintain high population inversion and to squeeze out the optical gain for S-band signals. When the filters are disabled, the gain bandwidth immediately returns back to the C+L-bands. Under S-band operation, a 37 dB small signal gain and a minimum 4.84 dB noise figure at 1486.9 nm are achieved with a 980 nm pump power of 154 mW.

OCIS codes: (260.2030) Dispersion; (060.2410) Fibers, erbium; (060.2320) Fiber optics amplifiers and oscillators; (999.9999) Fundamental-mode cutoff

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1. Introduction

S-band (1480 ~ 1530 nm) amplification for coarse WDM or Tri-band (1310/1490/1550-nm) networks has been an important research topic recently. In the literature, the Tm-doped fluoride-based fiber [1], Raman fiber [2, 3], and Er^{3+}-doped fiber (EDF) [4-11] have been utilized to obtain S-band amplification. Among these approaches, the Tm-doped and Raman fibers are always facing the problems of low gain efficiency and the requirement of high pump power. In contrast, the silica-based EDF approach seems to be a better candidate for S-band amplification due to its high gain efficiency, low ASE noise, and compatibility to conventional C- and L-band EDF amplifiers (EDFAs). The S-band amplification in EDF occurs through the stimulated emission from energy level $^4I_{13/2}$ to $^4I_{15/2}$, which is composed of manifold Stark components in amorphous glass. The Stark splitting at $^4I_{13/2}$ and $^4I_{15/2}$ multiplet gives rise to optical gain not only for the S-band but also for the C- and L-bands and the population inversion over $^4I_{13/2}$ multiplet can be easily reached through 980 nm or 1480 nm pumping. The 980 nm pumping is featured with a high population inversion over short fiber distance to achieve a good noise figure (NF) whereas the 1480 nm pumping is advantageous to higher quantum efficiency over long fiber range to scale up the output power. Compared with the 1480 nm, the 980 nm pumping can achieve a higher energy population distribution at $^4I_{13/2}$ multiplet and is thus capable of providing stronger optical gain for the S-band signals. However, the absorption and emission cross sections of EDF have a strong overlap in S-band and, moreover, the energy population of erbium ions at $^4I_{13/2}$ and $^4I_{15/2}$ multiplet follows the Boltzmann distribution in thermodynamic equilibrium, which makes the sublevels with lower energy have a higher population of ions [12]. As a result, the S-band gain in EDF is much more difficult to be achieved than in C- and L-bands. If the EDF can be highly population inverted (inversion rate > 70%), the net emission cross sections become positive in S-band but the optical gain in S-band is still unavailable due to the strong homogeneous broadening effects. In order to obtain S-band gain, the requirements of a high inversion rate at $^4I_{13/2}$ multiplet (high Er^{3+}-doping density can cause ion pairs to deteriorate the inversion rate and must be avoided) and the suppression of C+L-band amplified spontaneous emission (ASE) must be simultaneously satisfied. Arbore *et al.*, utilized a 27-m-long depressed-cladding Al-codoped EDF under a 980 nm pump power of 260 mW to attenuate the ASE at the wavelengths of longer than 1530 nm and demonstrated a 32 dB small signal gain near 1500 nm [5]. The Al codoping in core can enhance the EDF to come along with a wider and flatter gain profile [13]. Also, an EDF with a depressed inner cladding can make the fundamental-mode guiding lights with the wavelengths of longer (shorter) than the cutoff wavelength have effective indices of lower (higher) than that of the outer silica cladding. Thus, the longer wavelengths suffer strong leakage loss while the shorter wavelengths can be well confined to propagate in core with negligible loss [14]. The cutoff wavelength is determined by the wavelength whose propagation constant matches to that of a radiation mode and it can be employed as distributed ASE filtering in EDF. The cutoff wavelength can be moved by varying the spooling diameter of winding EDF and thus the gain bandwidth can be tuned to span S-band or the shorter spectral regime [4, 8-11]. However, the cutoff efficiency (slope of roll-off curve) degrades as the spooling diameter decreases [10,15] so that the S-band gain would be somewhat suppressed while the cutoff wavelength is tuned to be around 1530 nm to attenuate the C+L-band ASE [10]. Nevertheless, the small signal gain at 1490 nm was only about 25 dB with a NF of around 7 dB over 1480 ~ 1490 nm under the -25 dBm signal input power condition in a double-pass amplifier configuration [9]. Moreover, a special designed depressed-cladding fiber must be required.

In contrast, a high cutoff efficiency fundamental-mode leakage loss filter can be achieved based on material dispersion discrepancy between core and cladding [16]. The filters had been utilized in an EDFA to realize amplification over S- and C + L-bands [17]. The filters can significantly suppress the C+L-band ASE to accomplish a high population inversion in S-band. When the filters are temperature-tuned to be disabled, the filters play as all-pass filters and thus the amplification immediately returns back to the C+L-band. In this paper, we employ the high-cutoff-efficiency fundamental-mode leakage-loss filters in standard C-band silica-based EDF with a double-pass EDFA configuration to achieve a high-gain low-noise S-band EDFA. A 37 dB small signal gain and a 4.84 dB NF are achieved at 1486.9 nm (S-band). In addition, the gain spectra can be extended to the C+L-band based on this tunable double-pass EDFA consisting of a 16-m-long standard silica-based C-band EDF under a 980 nm pump power of 154 mW.

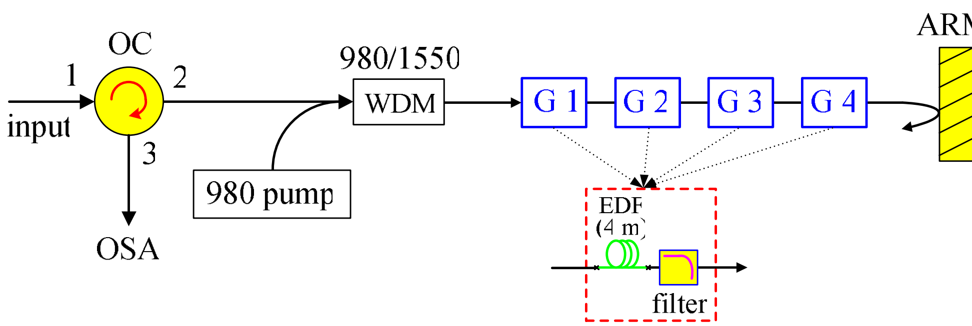

Fig. 1. Experimental set-up of the double-pass EDFA spanning S- and C+L-bands.

2. Fabrication and experiments

The experimental set-up of the double-pass EDFA is shown in Fig. 1, where the tunable fused-tapered fundamental-mode leakage loss filters with the use of Cargille index liquid (n_D = 1.456) [18] can provide a sharp filter skirt and a deep stopband rejection efficiency (> 50 dB) as shown in Fig. 2(a). The details of fabrication for the filters have been addressed in reference 17. From Fig. 2(a), the cutoff wavelengths of the four filters are very close to each other, which is crucial to correctly separate the stopband for C+L-band ASE and the passband for pump and S-band signal lights. The maximal difference among the cutoff wavelengths is measured to be 5.8 nm and the average gradient of the roll-off curves at 28.1°C from 1370 ~ 1415 nm is -1.04 dB/nm, which is four times larger than that of the depress-cladding EDF [5]. Unlike the cutoff efficiency will be degraded when the bending radius decreases to a smaller value than 14 cm in depressed-cladding EDF [5], the cutoff efficiency of our four filters is remained almost the same even when the cutoff wavelength is tuned far over a few hundreds nanometers [16]. The insertion losses of the filters in air at 1550 nm are measured typically below 0.6 dB. The four filters are discretely located within a 16-m-long standard silica-based

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C-band EDF (EDFH0790: Prime Optical Fiber Corporation) while the 980 nm pump light and the desired signal are multiplexed and launched into the EDF. A filter is used for every 4-m-long EDF to form a gain stage in which the signal amplified spectrum is reshaped to restrain into the desired wavelength region before the signal entering the next gain stage. Hence, the EDFA is composed of four gain stages (G1 ~ G4) as shown in Fig. 1. An all-reflection-mirror (ARM) is used at the end of G4 while an optical circular (OC) is used in the front of the 980/1550 WDM coupler to convey the output amplified signals to optical spectrum analyzer (OSA).

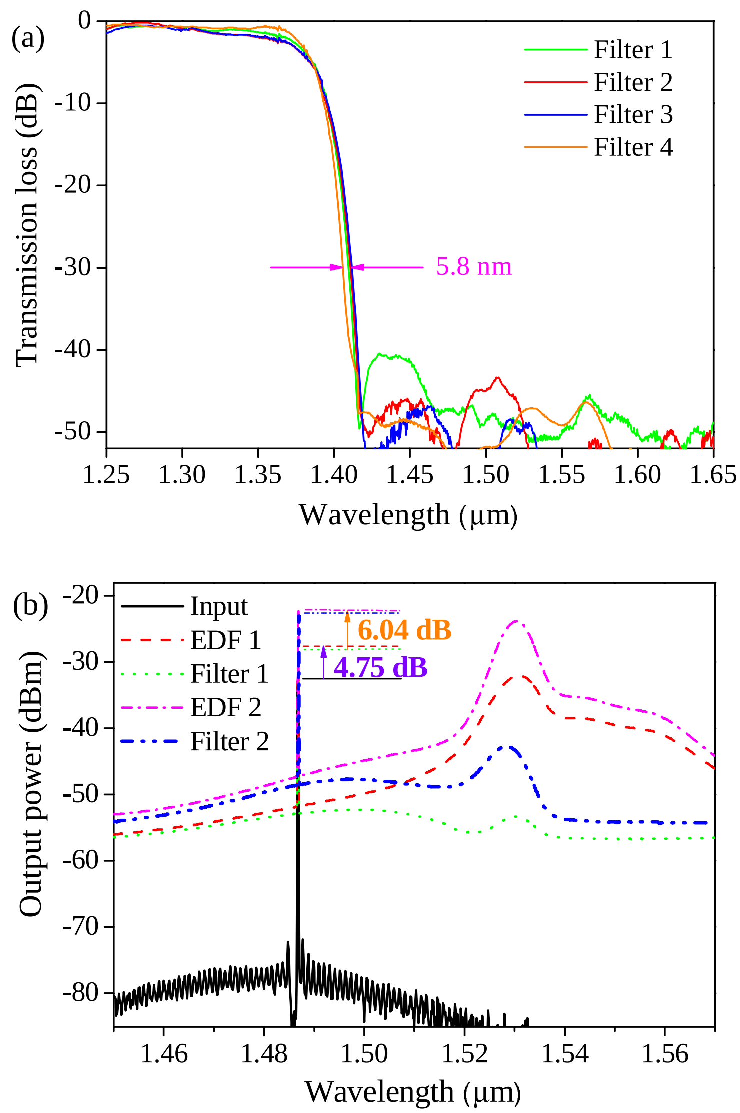

Fig. 2. (a). Spectral responses of the tapered fiber fundamental-mode cutoff filters using Cargille liquid (n_D = 1.456) at 28.1°C (RES: 1 nm). (b) Evolution of the gain spectra under S-band operation from the output of the different stage of the filters and EDFs (RES: 0.1 nm).

In this double-pass EDFA, there are some unavoidable optical losses to degrade the gain efficiency of the amplification. First, the splicing loss between the SMF-28 (Corning) and the EDF (POFC) is about 0.35 dB for each splicing point due to the mismatch of the numerical aperture (NA) between SMF-28 (NA = 0.13) and EDF (NA = 0.2). Thus, there are 16 points

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to cause total 5.6 dB loss for double-pass configuration. Second, the 980/1550 WDM coupler and the ARM can respectively induce 0.4 dB and 0.9 dB loss while the S-band signal (1486.9 nm) passing through/reflecting from them for each time. Finally, the OC is designed for C-band operation and thus the induced loss at 1486.9 nm is measured to be 4.1 dB for the signal traveling from port 1 to port 3. In order to investigate the influences of C+L-band ASE suppression on the variations of S-band gain, the evolution of gain spectra is investigated by each gain stage as shown in Fig. 2(b) based on the single-pass and forward-pumping scheme. First of all, the input signal is recorded and a 4-m-long EDF is then added to achieve 4.75 dB gain, measured by an OSA under the resolution bandwidth (RES) of 0.1 nm, for the S-band signal. Second, a short-pass filter is added and then temperature-tuned to suppress of the C+L-band ASE shown in Fig. 2(b). Again, this filtered signal enters another 4-m-long EDF to acquire 6.04 dB gain for S-band signal. Following the steps repeatedly until two gain stages are connected, the S-band signal is found to grow up gradually. Thus, a high-gain low-noise S-band amplification should be achievable for this double-pass EDFA and the final measured results will be presented below.

3. Results of measurements

To investigate the amplification characteristics in S- and C+L-bands, a 980 nm pump laser with 154 mW fiber-pigtailed output power is launched into the EDF through a 980/1550 WDM coupler in a forward pumping scheme. Subsequently, the input signals in S-, C-, and L-bands are respectively launched into the EDF with an output power of -33 dBm. The high cutoff efficiency fundamental-mode leakage loss filters in the 16-m-long EDF can discretely suppress the unwanted ASE in the C+L-bands and pass the S-band signal and 980 nm pump wavelength. The input signal spectra (P_i) and amplified output signal spectra (P_o) in S-bands at 30.9°C and in C+L-band at 40°C are shown in Fig. 3(a) under 0.1 nm RES. In S-band, the small signal gain at 1486.9 nm is measured to be around 32 dB while in C+L-bands the maximal signal gains at 1549.6 and 1589.4 nm were measured to be 43 dB and 17.8 dB, respectively. At 30.9°C, the S-band output signal power gradually increased with increasing pump power, similar to the evolution of gain spectra in Fig. 2(b), because the C+L-band ASE is discretely and substantially suppressed every 4-m-long EDF. Actually, the small gain at 1486.9 nm can reach 37 dB or more when the 5.6 dB splicing losses are neglected since in principle the splicing losses can be avoided by directly tapering the EDFs as the short-pass filters. The optical losses coming from the 980/1550 WDM coupler, ARM, and OC can be further avoided by using the suitable fiber components designed for S-band wavelengths operation. By doing so, the S-band gain at 1486.9 nm could probably be greater than 43 dB for this double-pass EDFA.

At 30.9°C, the input power of 1486.9 nm signal is varied to measure the gain and NF, as shown in Fig. 3(b). With the 980 nm pump power of 154 mW, the S-band gain changes from 32 dB to 4 dB as the signal input power varying from -33 dBm to -2.5 dBm. The gain compression of 3 dB small signal gain value determines the saturation signal power. Thus, the saturation signal power was about -19 dBm while the saturation output power was +9.91 dBm, which corresponds to a 6.36% power-conversion efficiency and is mainly limited by the absorption of 16-m-long EDF. In Fig. 3(b), the NF varies from 4.84 dB to 8.7 dB with increasing signal input power. By estimation, under the -25 dBm signal input power, the NF is about 5.3 dB and the signal gain is about 31.2 dB at 1486.9 nm wavelength. Obviously, our double-pass EDFA can achieve not only a higher signal gain than other S-band EDFAs [5-10] but also have a lower NF than theirs. For the S-band EDFAs using depressed cladding EDF, the cutoff efficiency is not as high as our fundamental-mode cutoff filters so that the C+L-band ASE can not be efficiently attenuated to make the S-band wavelengths obtain high gain efficiency and low NF. In contrast, in small signal regime, the low-noise S-band amplification in our EDFA is ascribed to the strong suppression of the forward and backward C+L-band ASE by the high cutoff efficiency fundamental-mode leakage loss filters to achieve the high population inversion in S-band. Nevertheless, under the fixed 980-nm pump power of 154 mW, the high population inversion in S-band may be easy to be deteriorated in the EDF when

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the signal input power gradually grows up. As previously mentioned, the 980-nm pump power can be significantly absorbed over short fiber distance to achieve a low NF [19]. The 154 mW 980 nm pump power is enough to achieve high population inversion through the entire EDF in small signal regime. However, when the input signal power gradually grows up, the pump power is substantially depleted in the beginning of EDF due to the larger stimulated emission rate of signals. Thus, the population inversion is quickly deteriorated in the rest of EDF and which will decrease the net cross section in S-band much faster than in C-band [19]. Consequently, the gain will be strongly robbed by the C+L-band ASE generated in the EDF between two adjacent filters and which makes the population inversion in S-band become even worse. Hence, the available optical gain is not sufficient to support the S-band signal to keep going amplified when the signal power gradually increase to beyond a certain value, say -10 dBm, where the gain is reduced to be around 15 dB while the NF goes up to 7 dB or so. Since a higher signal power can easily lowers the population inversion by increased stimulated emission, our double-pass EDFA is easier to saturate in contrast to the C-band EDFA [20]. In order to achieve a higher saturation output power and a smaller NF for S-band signals, it is advantageous to uniformly distribute optical pump power over the entire EDF with distributed high-cutoff-efficiency fundamental-mode leakage loss by a bidirectional pumping scheme. For this EDFA under C+L-band operation at 40°C, the NF for 1549.6 nm is 16.59 dB which is much higher than that in single-pass configuration since the backward ASE can not be blocked and thus the NF is seriously downgraded.

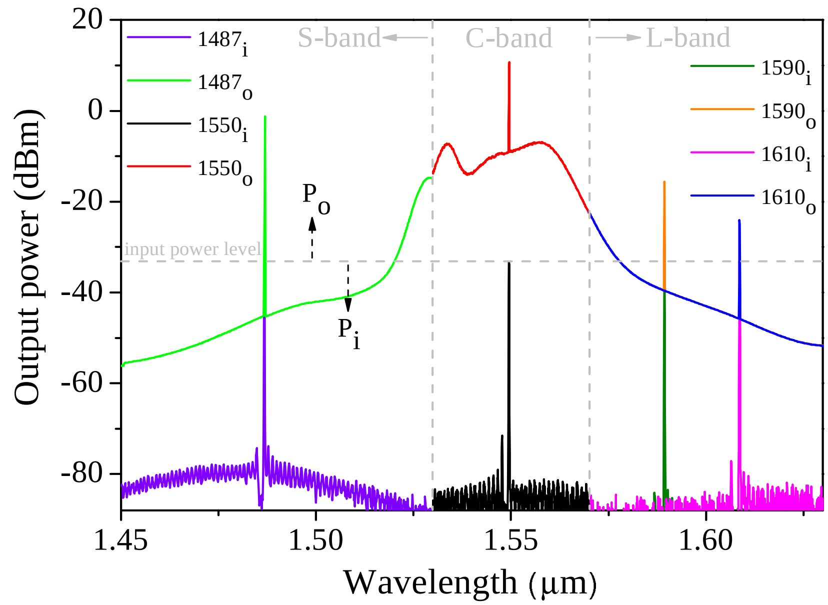

Fig. 3(a). Amplification characteristics of the signals in S-band at 30.9°C and in C+L-bands at 40°C (RES: 0.1 nm). P_i and P_o are input and output signal spectra, respectively.

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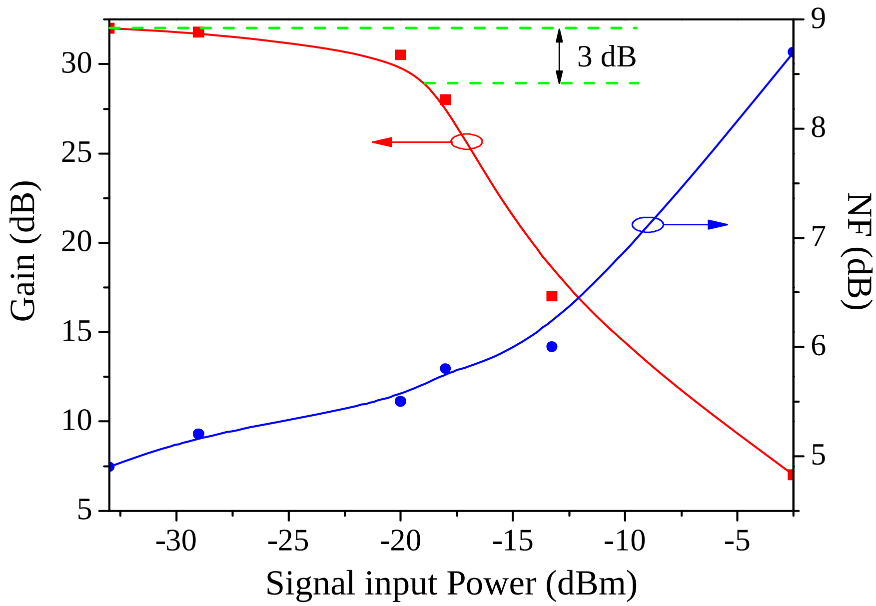

Fig. 3(b). Gain and noise figure spectra under S-band operation at 1486.9 nm wavelength.

4. Conclusion

We have demonstrated a high-gain low-noise tunable double-pass EDFA over S- and C+L-bands by using high cutoff efficiency fundamental-mode leakage loss filters discretely located in a 16-m-long standard silica-based C-band EDF. These tunable filters can substantially suppress the C+L-band ASE to achieve S-band gain and thus the gain bandwidth of our EDFA can be temperature-tuned to cover S- and C+L-bands over 1490 ~ 1610 nm. With a 980 nm pump power of 154 mW, the small signal gain at 1486.9 nm (S-band) can be above 37 dB whereas the noise figure can be as low as 4.84 dB. The highest gain in C- and L-bands can be greater than 40 dB and 17 dB, respectively. The saturation gain and saturation output power in S-band can be further improved by uniformly distributing optical pump power over the entire EDF with distributed high-cutoff-efficiency fundamental-mode leakage loss via a bidirectional pumping scheme. A high-bandwidth EDFA simultaneously covering S+C+L-band can be achieved based on a parallel EDF structure.

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