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Option of EDFAs for WDM Long-Haul Transmission Systems: Gain Flattening With or Without a Gain Equalizer

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We have investigated gain flattening of EDFA systems with or without a gain equalizer for WDM long-haul transmission using a re-circulating EDFA loop. Without a gain equalizer, gain variation as small as 2.9 dB was achieved over the 10-nm band of a 100 cascaded EDFA system by the inversion principle. With a gain equalizer based on all-fiber acousto-optic tunable filters, two different configurations of EDFAs were tested. For a single- stage EDFA scheme, the 21-nm band has shown 3.8 dB of gain variation at 17.4 ~ 20.3 dB of OSNRs after the 100th stage of EDFAs. For a dual-stage EDFA scheme, a wider bandwidth of 34 nm has shown 3.6-dB variation after 40 cascaded EDFAs.

I. INTRODUCTION

Ever increasing demand on transmission capacities including Internet traffic and digital video services asks for high-speed optical transmission systems. To cope with such challenges, extremely high-capacity transmission systems beyond a terrabit per second have recently been demonstrated by adapting wavelength-division multiplexing (WDM) technologies. [1,2] Erbium-doped fiber amplifiers (EDFAs) have been playing a key role to achieve wide bandwidths for WDM such as 40 nm over 600 km [1] or 55.6 nm over 400 km [2]. However, for the longer distances (2,500 km ~ 12,000 km), the available gain bandwidths of EDFAs are still limited to 20 nm even with gain equalizers (GEQs) [3-5].

In this article, we have characterized and compared two EDFA systems (named EDFA$_1$ and EDFA$_2$) with different gain-flattening methods for WDM long-haul transmission. EDFA$_1$, gain flattened without a gain equalizer, showed a 10-nm bandwidth after 100 cascaded EDFAs. Although the 10-nm bandwidth is not wider than the previous reports [4,5], the simple structure that does not require any GEQ and the resulting merits of high reliability and low cost make that EDFA more feasible in the real world. On the other hand, EDFA$_{2S}$ (EDFA$_{2S}$ for a single- stage scheme and EDFA$_{2D}$ for a dual-stage scheme), gain flattened with a gain equalizer based on all-fiber acousto-optic tunable filters (AOTFs) [7], showed a 21-nm bandwidth after a 4,600 km transmission or a much wider 34-nm bandwidth after 3,300 km. These results suggest that the gain-flattening method using the active GEQ, i.e., AOTF, will be a good candidate to achieve wider gain bandwidths of WDM long-haul transmission systems.

II. EXPERIMENTAL SETUP

Long distance transmission was simulated by a re-

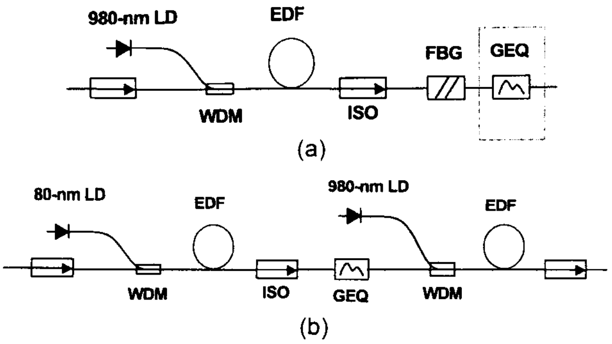

FIG. 1. Schematics of (a) EDFA$_1$ without a GEQ or EDFA$_{2S}$ with a GEQ and (b) EDFA$_{2D}$.

circulating EDFA loop, which consisted of two acousto-optic modulators, a 3-dB coupler, 3.4-km delay line of single-mode fiber (SMF) and a variable attenuator [8]. A delay pulse generator was used to synchronize two optical switches with an optical spectrum analyzer. Gains, noise figures (NFs), and optical signal-to-noise ratios (OSNRs) were measured by a probe signal with two saturating tones. The saturating powers were set to simulate the number of channels in each gain bandwidth.

Fig. 1(a) illustrates a schematic diagram of EDFA$_1$ (without a GEQ) or EDFA$_{2S}$ (with a GEQ) and Fig. 1(b) shows that of EDFA$_{2D}$.

The Fiber Bragg grating (FBG, center wavelength: 1531 nm, 20-dB bandwidth: 10 nm) in Fig. 1(a) was a common section of EDFA$_1$ and EDFA$_{2S}$ to reject the amplified spontaneous emission (ASE) near the 1530-nm band, originating from the first stage. Each EDFA included a different EDF (Er^{3+} concentration: 300 ppm, absorption coefficient: 3.7 dB/m at 1530 nm) lengths, 17 m for EDFA$_1$ and 22 m for EDFA$_{2S}$. For both of EDFA$_{2S}$ and EDFA$_{2D}$ the gain equalizer based on all- fiber acousto-optic tunable filters was added to flatten unequal gain spectra [7]. The pump wavelength was 980 nm and the pump powers were 100 mW for EDFA$_1$ and 70 mW for EDFA$_{2S}$.

Since the loss of optical power from the GEQ decreased the net gain of EDFA$_{2S}$, a dual-stage configuration with a mid-way GEQ, EDFA$_{2D}$ (Fig. 1(b)), was used when higher gain operation was required. Moreover, because FBG was not used in that scheme, the 1530-nm band was available with the GEQ. The EDF length was 22 m for the first stage and was 17 m for the second stage. Each stage was pumped with 100 mW of 980-nm LD. In addition, a mid-stage isolator was inserted to reject the counter propagating ASE from the second stage. Some key features of our EDFAs, which include configurations and parameters such as EDF lengths and pump powers, are tabulated in Table 1.

III. EDFA$_1$: GAIN-FLATTENED EDFA WITHOUT GEQ

Al-codoped EDFs have inherently flat-gain spectra. The flat-gain spectra can be obtained by controlling the population inversion of Er^{3+} ion, i.e., by adjusting EDF lengths or pump powers at pre-determined input signal levels [8]. This implies that WDM long-haul transmission could be possible by using gain-flattened EDFAs without a GEQ. All of the WDM long-haul (beyond 2,500 km) systems reported, so far, have utilized gain equalizers, whether passive or active. We have tested how far WDM signals can be transmitted without experiencing a severe gain excursion, say less than 5 dB, for the transmission system with EDFAs, gain flattened only by the inversion principle.

At -3.9 dBm of signal input power, EDFA$_1$ had gain flatness of 0.3 dB (19.0 ~ 19.3 dB) over 1543 nm ~ 1559 nm. Noise figures were as small as 4.3 ± 0.2 dB. The total power of two saturating tones, positioned at 1548 nm and 1554 nm, was set to −4.2 dBm and the power of the probe signal was −15 dBm. Those powers were designed to simulate −15 dBm x 13 channel. The repeater spacing was set to 83 km, considering 0.23

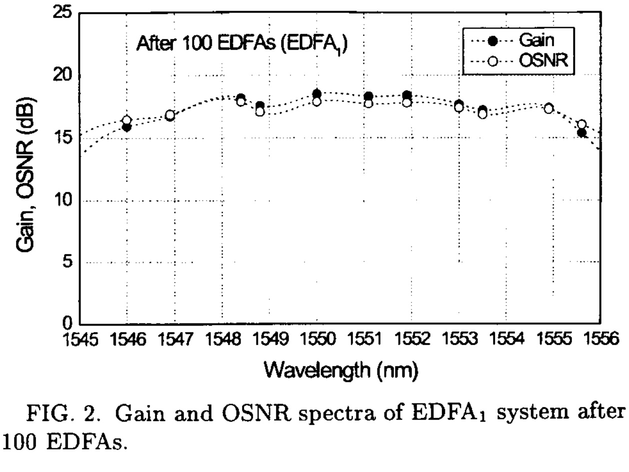

FIG. 2. Gain and OSNR spectra of EDFA$_1$ system after 100 EDFAs.

TABLE 1. Key features of EDFAs.

	Scheme	FBG employment	GEQ employment	EDF length(m)	Pump Power(mW)
EDFA$_1$	single stage	yes	no	17	100
EDFA$_{2S}$	single stage	yes	yes	22	70
EDFA$_{2D}$	dual stage	no	yes	22/17	100/100

dB/km loss of SMF, to make the loss to be 19.1 dB. Fig. 2 shows the gain and OSNR spectra when the signals were transmitted through 100 cascaded EDFAs, corresponding to 8,300 km.

The gain variation over 10 nm was 2.9 dB and less than 0.15 % of the system total gain, 1,910 dB. In addition to this small gain excursion, OSNRs were larger than 16 dB throughout the band. Further increase of transmission distance up to 12,450 km degraded the gain variation only a little, by 4.2 dB. Although the OSNRs became slightly reduced to 14 ~ 16.3 dB, larger values could be attained with the lower-gain operation, typically used in ultra-long submarine systems. Considering the fact that this simple structure without any gain equalizer means improved reliability, EDFA_1 should be a good candidate of in-line amplifiers for an ultra-long- haul WDM transoceanic system.

IV. EDFA$_2$: GAIN-FLATTENED EDFA WITH A GAIN EQUALIZER

Various gain-flattening filters for equalizing EDFA gain have been developed. Long- period grating filters, Mach-Zehnder filters, and AOTFs are good examples, which have been widely used in WDM long-haul transmission systems [3–6]. However, the usable gain bandwidths in these reports were still less than 20 nm. To extend the gain bandwidth of cascaded EDFAs, all-fiber AOTFs [7] have been used as a gain equalizer and a 37-nm bandwidth of 40 cascaded EDFAs has been successfully demonstrated [9]. However, with slight changes in the configuration of the EDFAs with AOTFs, we have realized longer transmission distances without sacrificing much of the gain bandwidths.

The schematic diagram of EDFA_{2S} was the same as that of EDFA_1 in Fig. 1(a) except for the active GEQ enclosed by a dotted line in the figure. Since the loss of the GEQ decreased the net gain of EDFA_{2S}, EDFA_{2S} was utilized for low-gain operation. On the contrary, since the mid-way GEQ in EDFA_{2D}, illustrated in Fig. 1(b), did not affect the net gain as much as the GEQ in EDFA_{2S}, EDFA_{2D} was utilized for high-gain operation. The gains, NFs, gain bandwidths, and input signal powers of EDFA_{2S} are summarized in Table 2.

For comparison, those values for EDFA_1 were also included. Signal gain of EDFA_{2D} was higher than that of EDFA_{2S} by ~ 9 dB and NF was almost the same. Due to FBG in EDFA_{2S}, the 1530- nm band was out of flat-gain bandwidth. More information on the operating conditions for long- distance transmission was tabulated in Table 3.

The saturating tones were located at appropriate wavelengths to properly cover the flat-gain bandwidth. Repeater spacing was 45.7 km for EDFA_{2S} system and 83.9 km for EDFA_{2D} system.

Fig. 3(a) shows the gain and NF spectra of EDFA_{2S} system after the transmission of 4,600 km, corresponding to 100 EDFAs. Over a 21-nm bandwidth, with the ASE rejection of 1530-nm band and retaining the flatness of the 1550-nm band by AOTFs, quite a small gain variation of 3.8 dB, 0.38 % of the system total gain, was achieved. The OSNRs were large enough to be 17.4 ~ 20.3 dB, suitable for long-haul systems. When the signals were transmitted through 9,100 km, corresponding to 150 EDFAs, OSNRs decreased to 14.3 ~ 18.5 dB, but the gain variation was still within 5 dB over the 20-nm bandwidth.

By including the 1530-nm band with the careful adjustment of GEQ, EDFA_{2D} had a much larger usable bandwidth of 34 nm after 3,300-km transmission, with small gain variations of 0.47 % (Fig. 3(b)). Reasonable values of OSNR as 15.6-17.8 dB were achieved. What makes this EDFA noticeable is the fact that 34-nm of flat-gain bandwidth of the single EDFA was fully retained even after 40 cascaded EDFAs. We believe that the gain equalizing method using dynamic AOTF is promising in maintaining the flatness for long-haul sys-

TABLE 2. Gain, noise figure, and gain bandwidth of EDFAs.

	Gain(dB)	NF(dB)	Wavelength range(nm)	Total input signal power(dBm)
EDFA_1	19.0 - 19.3	4.1-4.5	1543 - 1559	-3.9
EDFA_{2S}	10.1 - 10.8	4.9 - 5.6	1540 - 1567	-1.1
EDFA_{2D}	19.3-19.6	4.8 - 5.7	1530 - 1565	-2.6

TABLE 3. Experimental conditions of EDFAs.

	Saturation tone			
	Wavelength (nm)	Total Power (dBm)	Probe Power(dBm)	Sapcing(km)
EDFA_1	1548, 1554	-4.2	-15	83(19.1)
EDFA_{2S}	1548, 1559	-1.2	-13	45.7(10.5)
EDFA_{2D}	1531,1554	-3.0	-19	83.9(19.3)

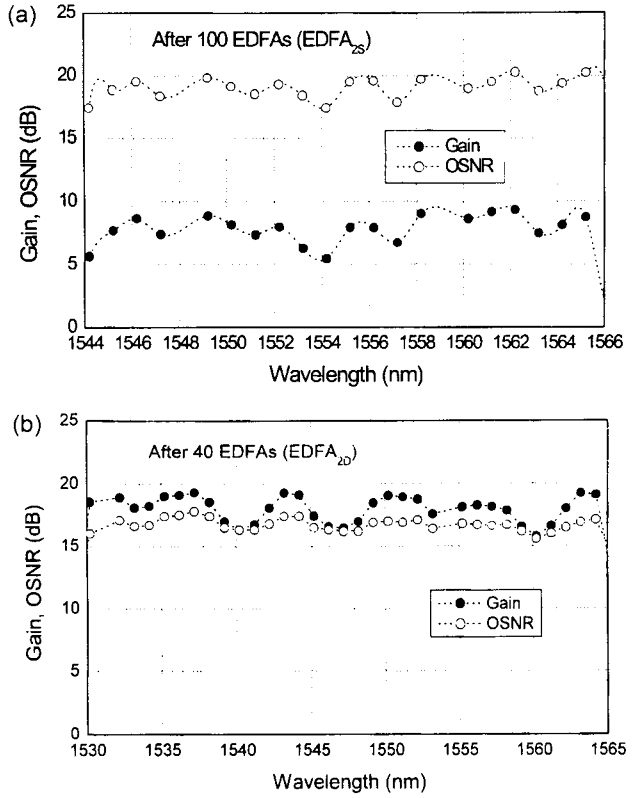

FIG. 3. Gain and OSNR of (a) $EDFA_{2S}$ system after 100 EDFAs and (b) $EDFA_{2D}$ system after 40 EDFAs.

tems. Although the GEQ was operated manually for this work, automatic control by an electronic circuit with feedback of monitored output signal was demonstrated already [10].

V. DISCUSSIONS

Two figures of merit (FOM) can be introduced in order to compare different EDFA systems. FOM_1 is to represent the gain flatness of the system total gain over the gain bandwidth,

$$FOM_1 = \Delta G/(G \times BW)(nm^{-1}). \qquad (1)$$

Here ΔG is the gain variation, G is the system total gain, and BW is the gain bandwidth. FOM_2 is defined as the product of transmission distance and signal gain bandwidth,

$$FOM_2 = BW \times Distance(Knm - km). \qquad (2)$$

TABLE 4. FOM_1 and FOM_2 of EDFAs.

	Gain bandwidth (nm)	Distance (km)	FOM_1 (nm^{-1})	FOM_2 (K nm-km)
$EDFA_1$	10	8,300	0.015	83
$EDFA_{2S}$	21	4,600	0.018	96
$EDFA_{2D}$	34	3,300	0.014	114

Table 4 shows FOM_1 and FOM_2 for the three EDFA systems.

It is interesting that values of FOM_1 are comparable to each other, meaning that each EDFA system has similar flatness in spite of different gain excursions over the system total gain (0.15 ~ 0.47 %). In addition, the values of FOM_2 are also nearly the same. Hence, the usable gain bandwidth of three types of EDFAs decrease linearly with distance under the condition of constant FOM_2. The experimental results are summarized as:

i) The gain variations over the system total gain were less than 0.5 % for all EDFA systems.
ii) FOM_1s, the flatness figures of merit in cascaded EDFAs, were 0.014 ~ $0.018nm^{-1}$.
iii) FOM_2s, the bandwidth-distance products, of the scheme were nearly the same such as 83 ~ 111K nm-km.

VI. CONCLUSION

We have investigated and compared the EDFA systems, gain flattened with or without a gain equalizer, in various transmission distances. Although their gain bandwidths and transmission distances could not be maximized simultaneously, each system had good properties for specific applications. The $EDFA_1$ system without a GEQ can retain 10 nm of inherently flat band over 8,300 km. Considering the enhanced reliability due to its simple structure, $EDFA_1$ can be recommended as an in-line amplifier for ultra long-haul transmission systems like transoceanic systems. To achieve the wider gain bandwidths, a dynamic and flexible gain equalizer based on AOTFs was employed for $EDFA_{2S}$, a single-stage EDFA and for $EDFA_{2D}$, a dual-stage EDFA. Over 4,600 km of transmission distance, 21-nm gain bandwidth was available with $EDFA_{2S}$ system. Wider bandwidth of 34 nm was available after 3,300 km of transmission distance in $EDFA_{2D}$ system. These EDFAs had the advantage of the broader gain bandwidth at the expense of the transmission distance. All of the above EDFA systems showed good properties in terms of FOM_1 and FOM_2 as summarized in Table 4.

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