Actively Gain-Flattened Erbium-Doped Fiber Amplifier Over 35 nm by Using All-Fiber Acoustooptic Tunable Filters

Hyo Sang Kim, Seok Hyun Yun, Hyang Kyun Kim, Namkyoo Park, and Byoung Yoon Kim

Abstract—**We demonstrate an actively gain-flattened erbium-doped fiber amplifier (EDFA) using an all-fiber gain-flattening filter with electronically controllable spectral profiles. A good gain flatness (<0.7 dB) over a broad wavelength span (>35 nm) is achieved for a wide range of operational gain levels as well as input signal and pump powers.**

Index Terms—**Erbium materials/devices, optical fiber amplifiers, optical fiber communication, optical fiber filters, tunable filters, wavelength-division multiplexing.**

CONSIDERABLE efforts have been devoted to the realization of gain-flattened erbium-doped fiber amplifiers (EDFA's) over a wide spectral range for large-capacity wavelength-division-multiplexed (WDM), optical communication systems. As a result, the usable gain bandwidth of EDFA's has been increased significantly over the past few years with the help of new glass compositions [1] and/or gain flattening filters [2]. Furthermore, an active control to maintain a fixed population inversion level utilizing an optoelectronic feedback loop [3] or an all-optical feedback loop [4] made it possible to maintain the gain flatness even when the input signal parameters change. However, most of the gain flattened EDFA's demonstrated so far produce the flat gain characteristics only for a predetermined gain level, and show undesirable gain tilt when the gain level changes. Efforts were made to expand the gain dynamic range [5], [6], but with only a limited optical bandwidth of 10 nm. An adaptive EDFA which can maintain the optimum gain flatness over a broad optical bandwidth and a wide range of gain levels, is highly desirable in WDM systems to cope with the changes in operating conditions due to, for example, link loss change, pump deterioration, channel add/drop, and network reconfigurations.

In this letter, we demonstrate a very flexible dynamic gain equalization of an EDFA based on an all-fiber active filter with electronically controllable spectral profiles [7] as a mid-stage gain flattening element. A good gain flatness (<0.7 dB) over a broad wavelength span (>35 nm) is achieved for a wide range of operational gain levels as well as for a variety of input signal and pump powers.

A complex filter profile is required to flatten an uneven EDFA gain, which exhibits large peaks with different widths around 1530 and 1560 nm. It was demonstrated that the combination of three Gaussian shaped passive filters can produce a flat gain over a 30-nm wavelength range [8]. In this letter, an active filter which can produce six different sinc-function-type notch profiles with variable center wavelengths and rejection ratios was used as a midstage gain-flattening device in a dual-stage EDFA. The gain flattening filter consists of two all-fiber acoustooptic tunable filters (AOTF's) [7], [9] in series, as shown in Fig. 1(a). Each AOTF was driven by three radio frequency (RF) signals at different frequencies and amplitudes that produce acoustooptic mode conversion from the fundamental mode to different cladding modes. This approach eliminates the detrimental coherent crosstalk present in $LiNbO_3$-based AOTF's [10], [11]. The 3-dB bandwidths of AOTF1 were 3.3, 4.1, and 4.9 nm for the couplings to the cladding modes $LP_{12}^{(cl)}$, $LP_{13}^{(cl)}$, and $LP_{14}^{(cl)}$, respectively. For AOTF2, they were 8, 8.6, and 14.5 nm for the couplings to the cladding modes $LP_{11}^{(cl)}$, $LP_{12}^{(cl)}$, and $LP_{13}^{(cl)}$, respectively. The minimum separations of notches produced by single RF driving frequency were ~50 nm for AOTF1 and ~150 nm for AOTF2, respectively, so that only one notch for each driving frequency falls into the gain-flattening range (35 nm). The large difference between the two AOTF's were due to the difference in fiber outer diameters. The polarization splitting in the center wavelength of the notches as ~0.2 nm for the AOTF1 and ~1.5 nm for the AOTF2. The relatively large polarization dependence in AOTF2 is mainly due to the unwanted core ellipticity and residual thermal stress in the fiber, that can be reduced to a negligible level by using a proper optical fiber. The AOTF1 and the AOTF2 were used for the control of the EDFA gain shape around the wavelengths of 1530 and 1555 nm, respectively. The background loss of the gain flattening filter was less than 0.5 dB, which was mainly due to splicing of different single-mode fibers used in the two AOTF's. Adjusting the frequencies and voltages of the applied RF signals, we could control the positions and depths of the notches with great flexibility. The RF's were in the range between 1 and 3 MHz.

Manuscript received January 12, 1998; revised February 13, 1998. This work was supported in part by the Opto-Electronic Research Center, which is funded by the Korea Science and Engineering Foundation, and Donam Systems Inc.

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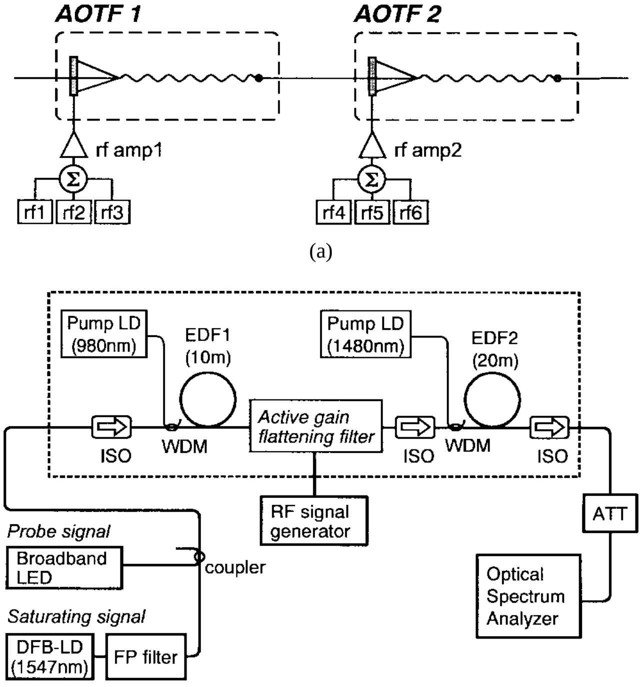
Publisher Item Identifier S 1041-1135(98)03816-6.



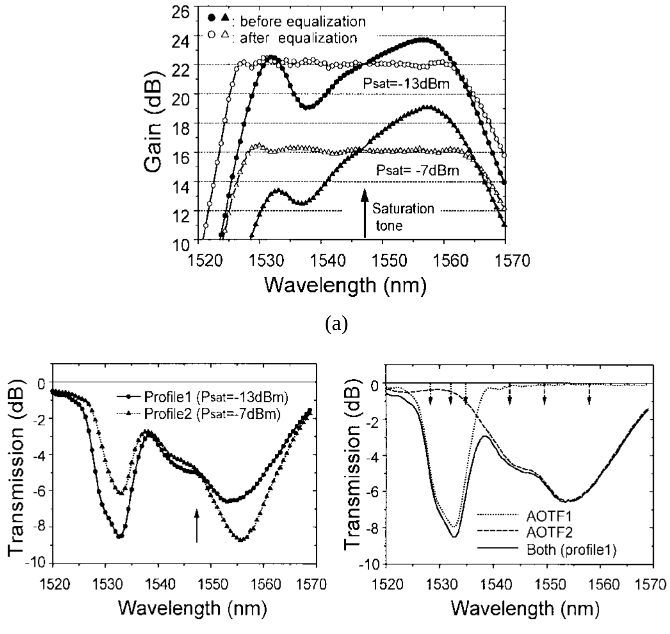
(a)

(b)

Fig. 1. (a) All-fiber acoustooptic gain flattening filter. (b) Schematic of experimental setup. A dual stage EDFA (inside the dotted box) and the measurement setup are shown. RF1–RF6: RF signal sources, RF amp1–RF amp2: RF power amplifiers, EDF: erbium-doped fiber, WDM: wavelength-division-multiplexing coupler, ISO: isolator, ATT: 10-dB attenuator.

Fig. 1(b) shows a schematic of a dual-stage EDFA employing the active gain flattening filter, along with a test setup. A 10-m-long EDF pumped by a 980-nm laser diode and a 24-m-long EDF pumped by a 1480-nm laser diode were used as the first and the second stage amplifiers, respectively. The peak absorption coefficients of both EDF's were ~2.5 dB/m at 1530 nm. The gain flattening filter described earlier was inserted between the two stages along with an isolator. Total insertion loss of the filter and the isolator was less than 0.9 dB. Six synthesizers and two RF power amplifiers were used to drive the filter.

Gain profiles of the EDFA were measured using a saturating signal at the wavelength of 1547.4 nm and a broad-band light-emitting diode (LED) probing signal [12]. The saturating signal from a distributed feedback (DFB) laser diode was launched into the EDFA after passing through a Fabry–Perot filter (optical bandwidth: 3 GHz, extinction ratio: 27 dB) to suppress the sidelobes of the laser diode. The total power of the probe signal in 1520–1570-nm range was −27 dBm, which is much smaller than that of the input saturating signal ranging from −13 to −7 dBm used in this letter. Noise figures were obtained from the gain and power spectrum of amplified spontaneous emission (ASE). No attempt was made to exclude spectral-hole burning (SHB) effects due to the saturating signal around 1547.4 nm. The pump power in the first stage was fixed to be 20 mW, that produced a ~10-dB gain in the first stage at 1547.4 nm for the input saturating signal of −10 dBm. The pump power for the second stage of the EDFA was varied to tune the gain level of the amplifier.



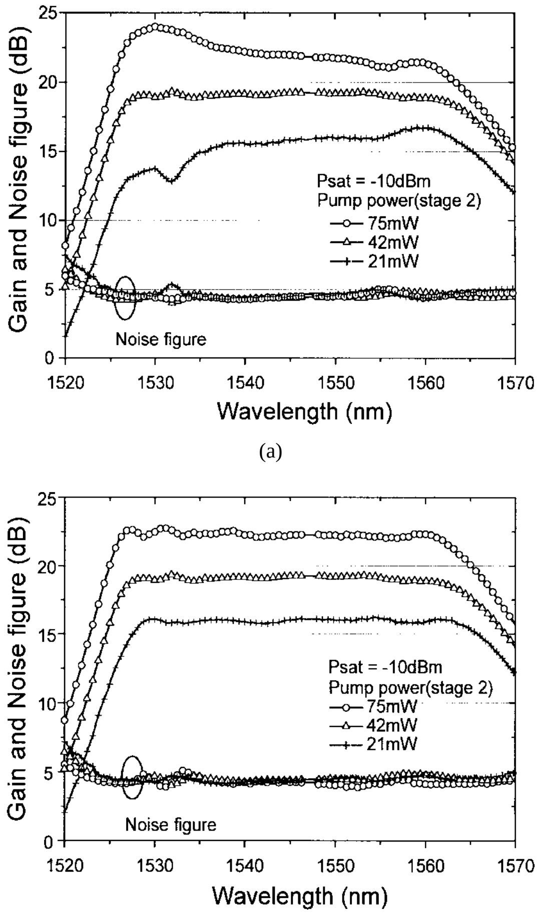
(a)

(b) (c)

Fig. 2. (a) Gain profiles before (filled) and after (open) equalization at two different saturating signal powers. Circles and triangles are the EDFA gains for the saturating tone of −13 and −7 dBm, respectively. (b) Filter profiles (Profile 1 and Profile 2) needed for the gain equalizations for different powers of the saturating signal. P_{sat}: saturating signal power. (c) Filter profiles produced by AOTF1, AOTF2, and combined to form Profile 1. The arrows indicate the center wavelengths of the notches.

Fig. 2(a) shows gain profiles before and after the gain flattening for two different saturating signal powers of −13 and −7 dBm when the second-stage pump power was 42 mW. The gain excursions before flattening were larger than 5 dB. By adjusting the filter profile, flat gain profiles within 0.7 dB were obtained over 35 nm for both cases. The flat gain region is shifted slightly toward the shorter wavelength for higher gain level, which is due to the intrinsic gain characteristics of the EDF. Fig. 2(b) shows filter profiles that produced the flat gain profiles shown in Fig. 2(a), where Profile 1 and Profile 2 are for the cases of saturating tones of −13 and −7 dBm, respectively. For the measurements, EDF1 was used as an ASE source, while the second pump diode (1480 nm) was turned off. The ASE signal leaked out of the second WDM coupler was monitored and the signals obtained when the filter was on and off were compared to yield the filter response. The attenuation coefficients for Profile 1 and Profile 2 at the saturating signal wavelength were 5.0 and 4.9 dB, respectively, and the average attenuation over the 35-nm range (1528–1563 nm) was ~5 dB in both cases. The total RF electrical power consumption of the filter was less than 500 mW. Profile 2 could be obtained from Profile 1 by adjusting mainly the depths of notches, although fine adjustments of center wavelengths of notches within 0.5-nm range slightly improved the gain flatness. Fig. 2(c) shows the filter profiles of AOTF1 and AOTF2 used to form Profile 1, and also the locations of center wavelengths of six notches.

Since the filter is driven by multiple acoustic frequencies, small amount of coherent crosstalk may be produced as described in [7]. In order to measure the level of coherent



(a)

(b)

Fig. 3. (a) Gain tilt due to pump power changes in a gain-flattened EDFA designed for a fixed gain level of 19 dB. (b) Flat gain profiles at various operating gain levels, which were achieved by adjusting the gain flattening filter.

crosstalk, light from the DFB laser used for the saturating tone ($\lambda = 1547.4$ nm) was transmitted through the filter and the output was monitored by a photodetector and an RF spectrum analyzer. The electrical power ratio of the ac to dc component was measured as the coherent crosstalk [7] and was less than -33 dB. Similar results were obtained at the wavelength of 1530 nm.

In order to demonstrate the gain flatness for different gain levels, the following experiments were carried out. First, we flattened the gain profile for 19 dB of gain at a total input signal power of -10 dBm as shown in Fig. 3(a). When we changed the pump power to increase or decrease the gain level by 3 dB for the -10-dBm saturating signal, an undesirable gain tilt of 3.5 dB in the 35-nm range was observed. The results shows what is expected from a passively gain flattened EDFA's. We could recover the gain flatness within 0.7 dB for 16 and 22.5 dB of gain levels by readjusting the gain flattening filter, as shown in Fig. 3(b). The noise figures were less than 5 dB at both gain levels. The experimental results clearly show that the gain flatness of the actively controlled EDFA can be maintained over a wide-wavelength range for varying gain levels. Although the gain flattening filter was used as a mid-stage filter in a dual-stage EDFA in this letter, it can also be employed for the equalization of EDFA chains. When used in combination with proper passive filters, such as long period grating filters, the number of notches and control parameters as well as the electrical power consumption may be reduced further to produce similar results.

We have demonstrated a dynamic gain equalization of EDFA's by using all-fiber AOTF's driven at multiple RF frequencies. By adjusting the filters' spectral profiles electronically, we have obtained a gain flatness of <0.7 dB over 35-nm wavelength range at various levels of gain as well as input signal and pump power.

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