Dynamic Erbium-Doped Fiber Amplifier Based on Active Gain Flattening with Fiber Acoustooptic Tunable Filters

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***Abstract*— We describe the first demonstration of a dynamic erbium-doped fiber amplifier (EDFA) based on automatic feedback control of active gain equalizing filters. The filters are all-fiber acoustooptic tunable filters capable of generating controllable filter shapes. Wide dynamic-range gain/power control is achieved with $<$0.6-dB signal ripple over 30 nm in various operating conditions. We also show, by numerical simulation, an important advantage of the dynamic EDFA over a conventional EDFA in cascaded structures.**

IN WAVELENGTH-DIVISION-MULTIPLEXING (WDM) communications networks, the operating conditions for erbium-doped fiber amplifiers (EDFA's) can change due to various reasons such as active channel routing and system reconfiguration. Therefore, it becomes necessary that an EDFA be designed to cope with the varying operating conditions. For wide-band WDM systems, the use of gain equalizing filters (GEF's) is essential to equalize both the signal power and the signal-to-noise ratio (SNR) of multiple channels over a wide spectral bandwidth. Passive GEF's, however, can only flatten the gain at a predetermined operating condition. Therefore, an EDFA utilizing a passive GEF had to employ a variable attenuator for automatic power control of an EDFA with respect to, for instance, link loss change [1], [2]. However, this scheme not only has a difficulty in precisely matching the filter profile, but also has a limited dynamic range unless large optical power is lost in the attenuator. To overcome these difficulties, many researchers have sought active GEF's for flexible dynamic EDFA design [3]–[5]. However, their application to gain flattening has been realized only by manually controlling the filter profiles.

In this letter, we describe the first demonstration, to our knowledge, of a dynamic EDFA based on automatic control of an active GEF [6]. An electronic feedback loop automatically adjusts the profile of the active GEF and the pump power to equalize output signal powers to a desired value. The dynamic EDFA can cope with variations in operating conditions that are frequently encountered in practical WDM networks, such as optical add/drop multiplexing (OADM), link loss change, and readjustment of output power/gain levels. We also show an important advantage of the dynamic EDFA over conventional passively flattened EDFA's in the transmission line using cascaded EDFA's.

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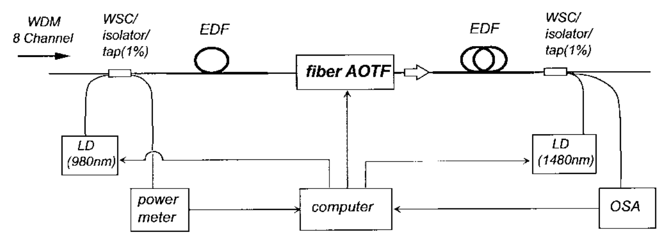

Fig. 1. Experimental setup of the dynamic EDFA. WSC: wavelength selective coupler.

Fig. 1(a) shows the schematic experimental setup of the dynamic EDFA. The optical part is a conventional two-stage amplifier with a mid-stage GEF. The electric feedback loop is comprised of a monitoring system and a main control unit. A small fraction, 1%, of the input signal light is tapped and directed to a power meter to measure the total input power entering the EDFA. The output of the EDFA is also tapped to monitor the output spectrum with a conventional optical spectrum analyzer. The feedback control of an active GEF necessitates the output spectrum monitoring that would be also essential for efficient system management [7]. A computer was used to process the monitored data and to control the GEF and pump laser diode controllers. The pump power control is for both gain clamping and gain level adjustment. The active GEF was tandem all-fiber acoustooptic tunable filters (AOTF's) [4]. The AOTF is based on mode conversion from the core mode to the dissipating cladding modes by periodic microbends formed by acoustic waves. The acoustic wave is generated by a piezoelectric transducer and launched to a single-mode fiber (SMF) by using a silica glass horn. Each AOTF was operated with three RF signals at different frequencies. Each RF signal produces an individual notch in the transmission spectrum of the AOTF. By tuning the frequencies and voltages of the six RF signals, the overall filter profile can be controlled to match a very complex shape needed for gain flattening of an EDFA [8]. In the experiment, the computer controlled only the voltages of the radio-frequency (RF) signals, and the frequencies of the RF signals were fixed to specific preset values for simplicity. It turned out that the voltage feedback

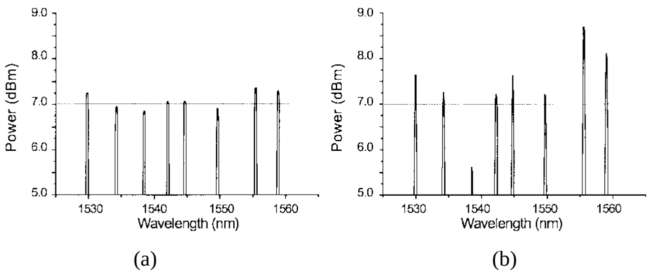

Fig. 2. Output signal channel spectra (a) with and (b) without gain flattening.

control was sufficient for the EDFA to respond to various operating conditions successfully as described in the following. Better feedback algorithm for system implementation is under study.

The erbium-doped fiber (EDF) used in the experiment had a peak absorption coefficient of 3.5 dB at 1529 nm. The first stage used a 12-m-long EDF with a forward pump at 980 nm. The gain and noise figure of the first stage were 16.4 and 4.7 dB, respectively, on average in the wavelength range between 1530 and 1560 nm at the total input power of −6 dBm. The second stage consisted of a 24-m-long EDF pumped in the backward direction with a 1480-nm laser diode.

The performance of the EDFA was tested with eight-channel WDM signals distributed between 1529 and 1559 nm over a 30-nm bandwidth. Fig. 2(a) shows a typical output spectrum of the EDFA, measured and calibrated from the monitored data. The input signal power per-channel was −15 dBm, and the output signal power was equalized to 7 dBm in this measurement (the total input and output powers were −6 dBm and 16 dBm, respectively). The peak-to-peak power variation and the noise figure were less than 0.6 and 5 dB, respectively. The polarization-dependent gain was about 0.5 dB at the worst signal channel, which is due to polarization dependence of our present AOTF, but can be improved. The time taken for one cycle of the feedback loop was about one second, mainly due to the scan time of the optical spectrum analyzer and slow communications between the computer and other instruments. The tuning speed of the AOTF itself is much faster (<100 μs), and the pump power control can be done in a few microsecond time scale [2]. Therefore, with proper spectrum monitoring system [7] and electric circuits, the response time of the dynamic EDFA can be greatly reduced. Fig. 2(b) shows the output spectrum at the same operating conditions as in Fig. 2(a) but when the AOTF was turned off. The power variation was larger than 3 dB without gain flattening.

We tested dynamic capabilities of the EDFA with respect to various operating conditions. Fig. 3(a) shows the response of the EDFA to variations of the number of input signals. Such variations can occur in dynamic OADM operation. It is clearly seen that when the input signals in six out of eight channels were turned off, the output power level remained constant with a power variation less than 0.6 dB. Fig. 3(b) demonstrates the EDFA's capability of maintaining constant output power level (at 5 dBm in this example) for two different input signal powers of −15 and −23 dBm, respectively. The corresponding gain levels were 20 and 28 dB, respectively. The different

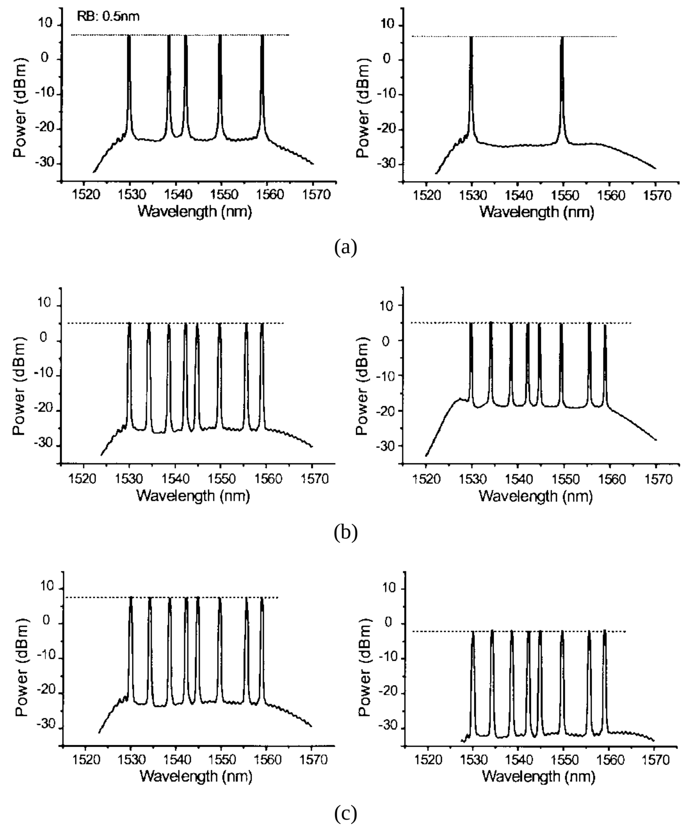

Fig. 3. Output spectra of the dynamic EDFA under varying operating conditions. (a) Channel drop. (b) Input power change. (c) Output power level change.

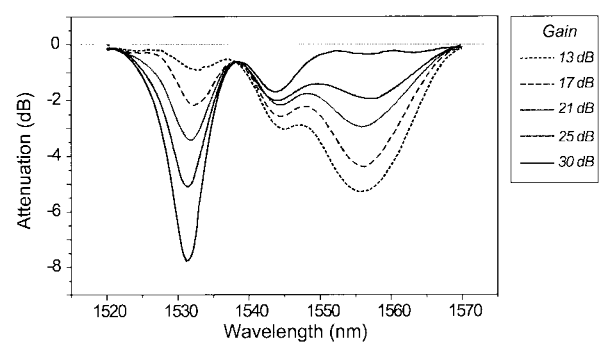

Fig. 4. Automatically generated filter profile of the AOTF for the best flatness at various gain levels.

noise levels are the consequence of the large gain difference of 8 dB. The output power variation was less than 0.6 dB in both cases. The EDFA also showed good performance under readjustment of the output power level. For an input signal power of −15 dBm, the output power level could be changed from −2 to 8 dBm over a wide dynamic range of 10 dB, as shown in Fig. 3(c). Thirty iterations of the feedback loop were sufficient for the EDFA to respond to any situations demonstrated in Fig. 3.

The dynamic range of the present EDFA was primarily limited by the finite output power of the pump lasers (120 mW). The flexibility of the filter profile control can offer much wider dynamic range. Fig. 4 shows the AOTF profiles determined by the feedback loop for the best gain flatness at five different gain

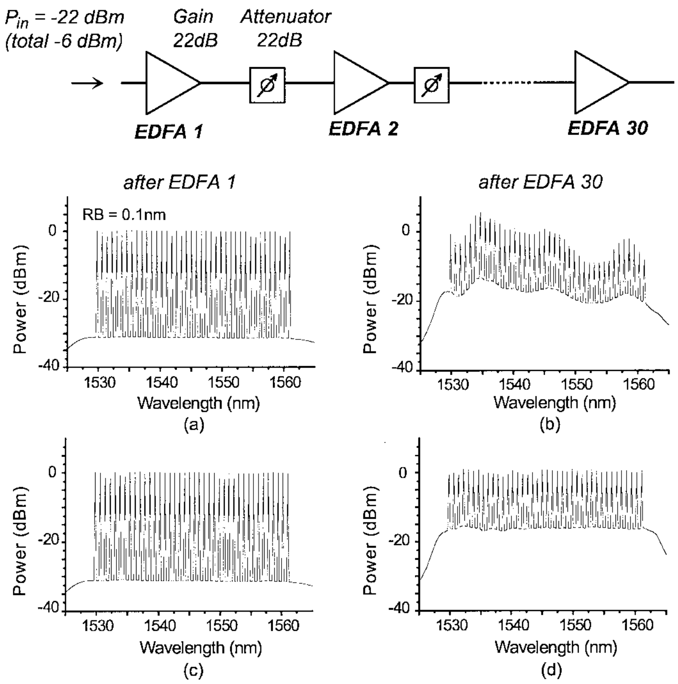

Fig. 5. Simulation results of 40-ch WDM signal propagation along cascaded EDFA's with passive GEF's [(a) and (b)] and active GEF's [(c) and (d)], showing the self-healing effect of dynamic EDFA's.

levels between 13 and 30 dB. For this measurement, a small input signal power of −25 dBm was used.

In cascaded conventional EDFA's employing passive GEF's, the ripple in the signal power grows approximately linearly in decibel scale as a function of the number of EDFA's the signal propagates through. However, in the dynamic EDFA chain, the growth of the ripple can be much slower because of its self-adjusting capability. We have confirmed this prediction with a computer simulation of a transmission link consisting of thirty identical EDFA's and attenuators, as shown in Fig. 5. First, EDFA's employing passive GEF's were considered. We assumed that each EDFA employed an identical set of passive GEF's. In real systems, however, the profiles of the GEF's would not be the same for all amplifiers, which can slow down the growth of the signal ripple. The passive GEF's in our simulation were chosen such that the individual EDFA exhibits the power excursion less than 0.6 dB over 32-nm wavelength range [Fig. 5(a)]. After the 10th and 30th EDFA's the power excursion increased to 5.5 and 15.7 dB, respectively [Fig. 5(b)]. The SNR was 11.4 dB for the worst channel after the 30th EDFA. We then replaced the passive GEF's with active GEF's in the simulation. In contrast to the experimental EDFA, the EDFA's in the simulation employed automatic feedback loops that controlled both the positions and depths of the active GEF's for better gain flatness. In this case, the power variation was 0.6 dB after the first EDFA, 0.8 dB after the second EDFA, and only 2.2 dB after the 30th EDFA, as shown in Figs. 5(c) and (d). The worst SNR after the 30th EDFA was 15.7 dB, a several-decibel improvement over the case of passively flattened EDFA's. These results show an important advantage of the dynamic EDFA, meaning that one can cascade more EDFA's for a given receiver sensitivity or that the required gain flatness on individual dynamic EDFA may not be as tight as that of the passively flattened EDFA for uses in the cascaded structure.

In conclusion, we have described the first demonstration of a dynamic EDFA based on automatic active gain flattening. The dynamic EDFA offers a number of advantages over conventional passively flattened EDFA and will be useful in WDM communications systems and networks.

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