Dynamic Power-Equalized EDFA Module Based on Strain Tunable Fiber Bragg Gratings

Shien-Kuei Liaw, Keang-Po Ho, *Member, IEEE,* and Sien Chi

***Abstract*— An adaptive power-equalized erbium-doped fiber amplifier (EDFA) module is proposed and experimentally demonstrated by using strain tunable fiber Bragg gratings (FBG's). In a demonstration for a five-channel wavelength-division-multiplexed (WDM) system, the EDFA module can effectively reduce the power variation from 11 dB to 0.3 dB. Measured power penalty for 2.5-Gb/s data is less than 0.5 and 1.1 dB for 5 and 17 dB of signal attenuation by tunable FBG's, respectively. The power-equalized EDFA module can find wide applications in WDM lightwave transmission systems.**

***Index Terms*—Erbium-doped fiber amplifier, power equalization, strain tunable fiber Bragg grating, wavelength-division multiplexing.**

I. Introduction

To COMPENSATE for fiber loss, an erbium-doped fiber amplifier (EDFA) is one of the key devices in wavelength-division-multiplexed (WDM) transmission systems and can provide an optical network with almost unlimited coverage [1]. However, the EDFA has a nonuniform gain spectrum that restricts its usable amplifier bandwidth. The slight variations in the gain profile yield different amplifications for different channels. This may mount up to a substantial difference in signal power and signal-to-noise ratio (SNR) among channels after many cascading EDFA's [2]. The situation exacerbates when allowing slight input power variations among different channels, for example, due to channel add–drop in optical networks. It is thus of tremendous interest to develop a dynamic power equalization scheme for the EDFA to accommodate the dynamic natural of optical networks. Some passively gain-flattening techniques [3]–[5] were proposed to provide equal gain among WDM channels. Previous dynamic equalization schemes include demultiplexing and inserting variable attenuator for each channel [6], an acoustooptic tunable filter [7] or a complicated control circuit [8]. This paper reports a dynamically power equalization scheme for EDFA using low-cost, strain tunable fiber Bragg gratings (FBG's) to provide variable attenuation for individual channels. The EDFA module can achieve equal output power, to a certain extent, for all WDM channels regardless of the variations in operating conditions and/or input power levels.

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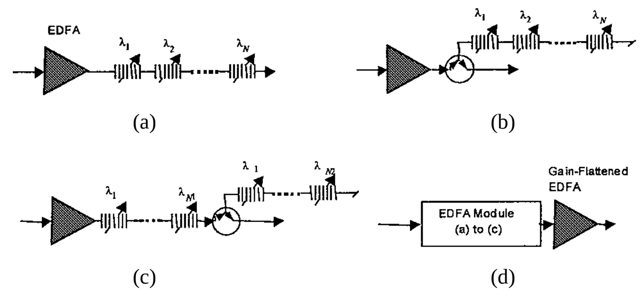

Fig. 1. Possible schematic diagrams of the power-equalized EDFA module: (a) pass-through type, (b) reflection type, (c) hybrid type and (d) high output power type.

II. Principles

Fig. 1 shows four possible schematic diagrams of the power-equalized EDFA modules using strain tunable FBG's. Fig. 1(a)–(c) are the pass-through, the reflection and the hybrid types, respectively. The operating principle of these EDFA modules is simply by tuning each individual FBG to an appropriate position to attenuate the corresponding WDM signal proportionally using the band-edge of the EDFA. The wavelength offset $(\Delta\lambda)$ between each Bragg wavelength and channel signal is from 0.0 to about 1.0 nm. The attenuation values are larger for the strong signals and smaller for the weak signals. For operation with larger range and higher output power, another regular gain-flatten EDFA shown in Fig. 1(d) can be placed after one of the modules of Fig. 1(a)–(c). The EDFA for Fig. 1(a) and (c) must have an output optical isolator to block reflection light back into the EDFA gain module. No optical isolator is needed for EDFA in Fig. 1(b) because of the interport isolation of three-port optical circulator (OC).

In this letter, the EDFA module of Fig. 1(a) is investigated and demonstrated. Beside low-cost, the module of Fig. 1(a) has the advantage that the in-line loss of all WDM channels is identical. Fig. 1(b) has the advantage that the ASE in the wavelength region of one to several nanometers away from the WDM channels will be strongly reduced due to the filtering of FBG's. Because the FBG usually operates in reflective mode, no strain is required for the FBG's in Fig. 1(b) if all WDM channels already have equal output power before the FBG-chain. As in-line loss increase with number of FBG's, the structure of Fig. 1(d) can be used to compensate for the loss induced by FBG's when large channel numbers are used.

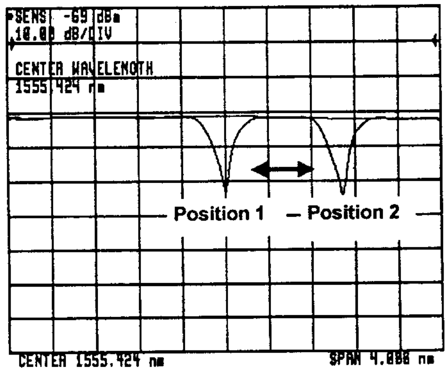

Fig. 2. The transmission spectra of a strain tunable FBG at position 1 of 1555.4 nm without strain, or at position 2 of 1556.5 nm with strain.

Tunable FBG is essential for the EDFA modules in Fig. 1. Strain tuning of FBG's have been demonstrated [9], [10] by stretching or compressing the FBG's. Usually, strain tunable FBG is the same as a regular FBG in structure. The central wavelength shift for an applied longitudinal strain ε is given by

$$\Delta\lambda = \lambda(1 - p_e)\varepsilon \qquad (1)$$

where p_e is the photoelastic coefficient given by

$$p_e = 1/2n^2\{p_{12} - \nu(p_{11} + p_{12})\} \qquad (2)$$

where p_{12} and p_{11} represent the components of the strain-optic tensor, n is the core refractive index and ν is the Poisson's ratio. Fig. 2 shows the transmission spectrum of one tunable FBG with two tuning points of 1555.4 nm without strain and 1556.5 nm with some strain. The reflectivity of the FBG is over 99% and the 10- and 20-dB bandwidth are 0.25 and 0.6 nm, respectively. When the WDM channel locates between the two tuning points, the tunable FBG can attenuate the optical power up to 20 dB. This dynamic range is enough for most system applications.

Piezoelectric ceramic transducer (PZT) may be used for strain tuning with response speed up to 10 KHz which is fast enough for most operation. As a reference, the response time of SONET restoration is 50 ms. When applying several voltages to the PZT, the central wavelength of FBG can be tuned about one nanometer away from its original central reflective wavelength. Temperature control and linear feedback circuit are needed to reduce the wavelength jitter of FBG's induced amplitude modulation. Since most FBG's change so rapidly in wavelength, a tolerable hysteresis, e.g., 1 dB, can be used to avoid power modulation due to feedback loop noise.

III. Experiment Demonstration

A five-channel equalized EDFA module in Fig. 1(a) configuration is demonstrated using strain tunable FBG's. Fig. 3(a) shows the input signals before the EDFA module. The wavelengths of the five input channels are ranging from 1550.7 to 1559.5 nm. A large input power variation of 11 dB is intentionally used to demonstrate the power-equalization function of the EDFA module. Fig. 3(b) is the transmission characteristic of the five tunable FBG's observed with EDFA amplified spontaneous emission (ASE). The Bragg wavelengths of FBG's are already located at, or tuned to the appropriate wavelengths for power equalization. Fig. 3(c) shows the output signals after the FBG-chain. The result shows that almost the same output power for all five WDM channels with a variation less than 0.3 dB. Without affecting the operational principle, the large signal attenuation shown in Fig. 3(c) is due to the high insertion of one abnormal FBG in the experiment. And the power spectrum of Fig. 3(c) is measured after a 5:95 coupler, or has different signal level to that in Fig. 3(a).

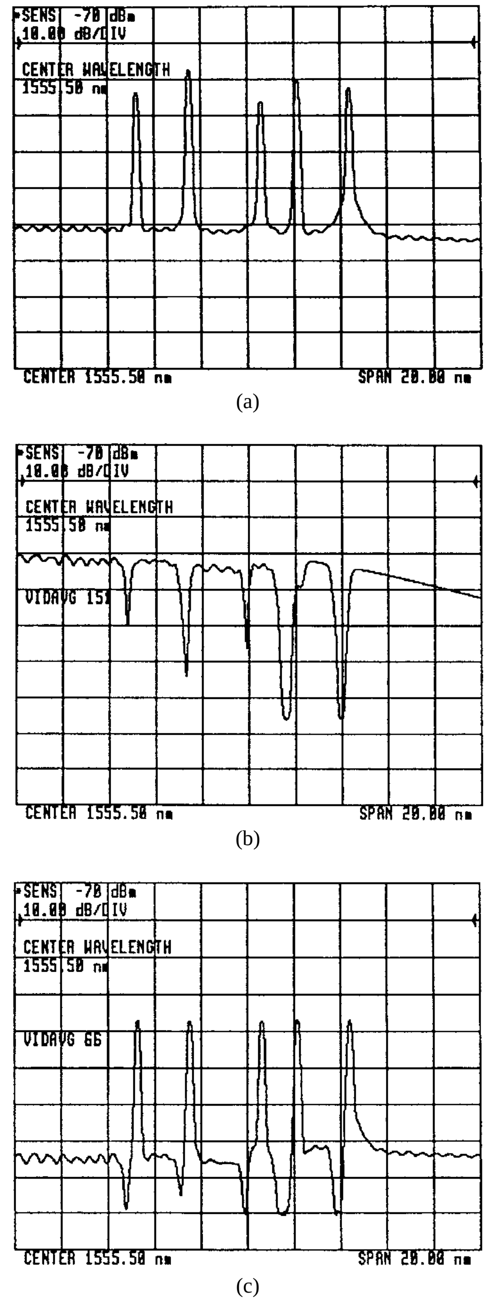

Fig. 3. The EDFA module is used for a five-channel WDM system. Spectra of the (a) five input signals before the FBG-chain, (b) transmission characteristic of these FBG's, and (c) five output signals after the FBG-chain. Note that the reference power levels in (a) and (c) are different.

Some WDM channels pass through the "slope" of the FBG's notch filter. To verify if the signals attenuated by tunable

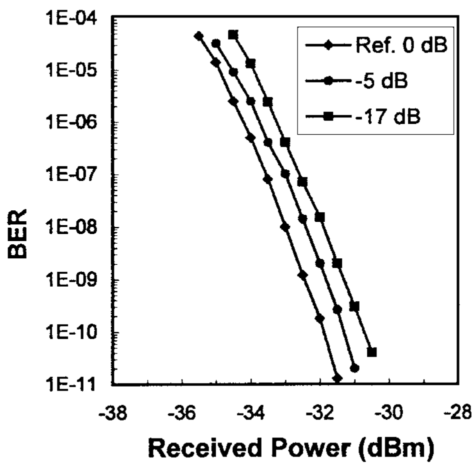

Fig. 4. Measured BER of the power-equalized EDFA module by offsetting the central wavelength between one tunable laser and one strain tunable FBG. The signal attenuation levels were 0, 5, or 17 dB, respectively.

FBG's may induce any power penalty due to nonuniform spectral response of FBG, one 1.55-μm band tunable laser source and one symmetric FBG were used. The central wavelength offset between the tunable laser and center wavelength of the FBG was varied from 0.0 to 1.2 nm, resulting with maximum attenuation of 21 dB. Fig. 4 shows the bit-error-rate (BER) measurement for a 2.5-Gb/s $2^{23}-1$ pseudorandom bit sequence (PRBS) externally modulated lightwave transmission system including the power-equalized EDFA module. Three attenuation values of 0, 5, and 17 dB for the tunable laser source were measured. Comparing to 0 attenuation case, for a BER of 10^{-9}, power penalty induced by the EDFA module are only 0.6 and 1.1 dB for a 5 and 17 dB of signal attenuation, respectively. The power penalty may mostly attribute to the imperfect filtering of the FBG "slope," especially for the 17-dB attenuation case because of its higher nonuniformity. In addition, the 17-dB attenuation case has smaller signal-to-ASE ratio.

IV. Conclusion

A dynamic power-equalized EDFA module is proposed and demonstrated using strain tunable FBG to attenuate the output power of each WDM channel proportionally. Small power penalty of less than 0.5 and 1.1 dB for a 5- and 17-dB signal attenuations were observed due to nonuniform filtering by the "slope" of notch filter. The power-equalized EDFA module can find vast applications in WDM optical networks.

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References

[1] J. M. P. Delavaux and J. A. Nagel, "Multistage erbium-doped fiber amplifier designs," *J. Lightwave Technol.*, vol. 13, pp. 703–720, 1995.
[2] O. K. Tonguz and F. A. Flood, "Gain equalization of EDFA cascades," *J. Lightwave Technol.*, vol. 15, pp. 1832–1841, Oct. 1997.
[3] S. Chi and J.-C. Dong, "Gain flattened for WDM system by using fiber Bragg gratings in EDFA," in *OFC'1998*, San Jose, CA, pp. 135, 1998, paper WG2.
[4] S.-K. Liaw and Y.-K. Chen, "Passive gain-equalization wide-band erbium-doped fiber amplifier using samarium-doped fiber," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 879–881, 1996.
[5] J.-M. P. Delavaux, D. M. Baney, D. J. DiGiovanni, and Y. K. Park, "BOA: Balanced optical amplifiers," in *OFC'1993*, San Jose, CA, 1993, pp. 79–82, postdeadline paper PD 19-1.
[6] F. Shehadeh, R. S. Vodhanel, M. Krain, C. Gibbons, R. E. Wagner, and M. Ali, "Gain-equalized, eight-wavelength WDM optical add-drop multiplexer with an 8-dB dynamic range," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 1075–1077, 1995.
[7] H. S. Kim, S. H. Yun, H. K. Kim, N. Park, and B. Y. Kim, "Actively gain-flattened erbium-doped fiber amplifier over 35 nm by using all-fiber acoustooptic tunable filters," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 790–792, 1998.
[8] S. Y. Park, H. K. Kim, G. Y. Lyu, S. M. Kang, and S.-Y. Shin, "Dynamic gain and output power control in a gain-flattened erbium-doped fiber amplifier," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 787–789, 1998.
[9] J. Bryce, G. Yoffe, Y. Zhao, and R. Minasian, "Tunable, gain-clamped EDFA incorporating fiber Bragg grating," *Electron. Lett.*, vol. 34, pp. 1680–1681, 1998.
[10] M. G. Xu, A. T. Alavie, R. Maaskant, and M. M. Ohn, "Tunable fiber bandpass filter based on linearly chirped fiber Bragg grating for wavelength demultiplexing," *Electron. Lett.*, vol. 32, pp. 1918–1919, 1996.