

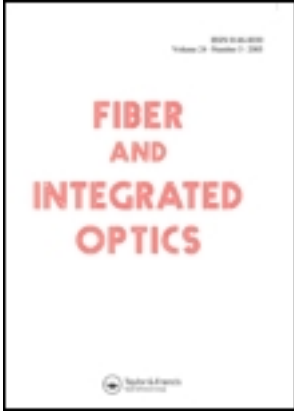
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# Gain-Flattened Optical Limiting Amplifier Modules for Wavelength Division Multiplexing Transmission

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*By integration of a bidirectional erbium-doped fiber amplifier and a three-port optical circulator with several fiber Bragg gratings (FBGs), two gain-flattened optical limiting amplifier (OLA) modules are proposed and experimentally demonstrated. They rely on the use of central wavelength misalignment and bending loss methods, respectively. They can effectively cover the whole useful 1.55- $\mu\text{m}$  band. Both modules can provide gain-flattening characteristics over a large input dynamic range. The FBGs-integrated OLA configuration has potential application in wavelength division multiplexing lightwave communication systems.*

**Keywords** erbium-doped fiber amplifier, fiber Bragg grating, flattened gain, optical limiting amplifier, wavelength division multiplexing

Because of the features of wide bandwidth and high gain, erbium-doped fiber amplifiers (EDFAs) are revolutionizing both the long-distance and distribution-based multichannel lightwave transmission systems in the 1.55- $\mu\text{m}$  band. They are often used to compensate for the fiber attenuation and network splitting losses. Furthermore, optically amplified systems allow a manifold increase in total capacity by supporting the use of wavelength division multiplexing (WDM) [1]. However, the nonuniform gain curve of the EDFA is one of the major problems for multichannel lightwave transmission systems with cascading EDFAs. The strong wavelength-dependent gain profile and saturation characteristics of EDFAs lead to rapid accumulation of interchannel power variation and large differences in the optical signal-to-noise ratio (SNR) among channels. These problems may cause significant system penalties when the interchannel power spreads are beyond the receiver dynamic range. This will result in the SNRs of some channels being too low to be detectable.

To date, various external and intrinsic approaches have been proposed to equalize the EDFA nonuniform spectral gain curve [2-7]. Recently, we discussed

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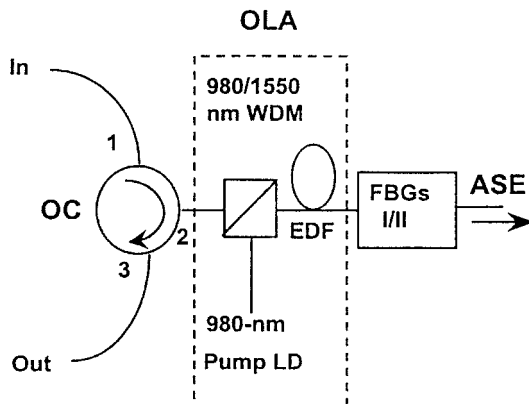
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the feasibility of two simple and passive techniques using a samarium-doped fiber (SDF) [8] and fiber Bragg gratings (FBGs) [9] in the EDFA as equalizers. In this paper, we proposed and experimentally demonstrated two gain-flattened optical limiting amplifier (GF-OLA) modules for multichannel transmission. Both are achieved by integration of an EDFA, a three-port optical circulator (OC) with several FBGs corresponding to the transmitted signals. The designs of the GF-OLA modules are based on the principles of central wavelength misalignment and fiber bending loss. Both methods can effectively equalize the gain variation among channels in WDM transmission systems. Meanwhile, they can strongly reduce the amplified spontaneous emission (ASE) [10] several nanometers away from transmitted signals due to the narrow-band filtering feature of FBGs. In both single-channel and WDM systems, the GF-OLA can provide a nearly constant output power for a large input signal dynamic range and a high saturated output power because of the dual-pass amplification characteristic of the OLA. Thus, fiber span and link budget can be increased [11].

### Characteristics of GF-OLA Modules

Figure 1 shows the common configuration of the proposed GF-OLA modules consisting of a three-port OC, a bidirectional EDFA (Bi-EDFA) without any optical isolator, and several FBGs with central-reflective wavelengths designed to match the transmitted signals. The FBGs are used to equalize the multichannel signals and to reduce the ASE. The Bi-EDFA was constructed by a section of erbium-doped fiber (EDF) and one 980/1550 nm WDM coupler. The EDF was pumped by an 80-mW, 980-nm laser diode and had a saturated power of 10.5 dBm. The length, absorption coefficient at 1532 nm, and numerical aperture (NA), core, and cladding diameters of the homemade EDF are 10 m, 5.8 dB/m, 0.21, 5.0  $\mu\text{m}$ , and 125.0  $\mu\text{m}$ , respectively. The three-port OC provides about 50-dB isolation for the EDFA at both the input and output ports. The Bi-EDFA with its dual-pass amplification scheme acts as an OLA. The FBGs inside the GF-OLA modules are operated as reflective mirrors, and the input signals are amplified, filtered, and



**Figure 1.** Common configuration of the proposed GF-OLA modules, consisting of a three-port optical circulator, a bidirectional EDFA, and several FBGs: OLA, optical limiting amplifier; FBGs I/II, the first or the second module of the fiber Bragg gratings.

reflected by the FBG chain and then amplified again. The gain efficiency of the OLA is equivalent to that of the two cascading EDFAs when the launched power is small.

To verify the OLA characteristic, in Figure 2 we compare the output power characteristic against the input power of the proposed single-channel GF-OLA module with a conventional EDFA at the wavelength of 1549.8 nm. The conventional EDFA was constructed by adding two optical isolators with 55-dB isolation and 0.8-dB insertion loss to both ends of the Bi-EDFA. The dynamic ranges of the proposed GF-OLA and a conventional EDFA are 30 and 9.0 dB, respectively, when they use the same pumping power of 80 mW. The “optical limiting amplifier” means that an amplifier can keep a constant saturated output power over a large dynamic range. The dynamic range is defined as the input power difference (in dB) between the corresponding full-saturated and half-saturated (i.e., 3 dB lower) output powers.

### Operating Principles of GF-OLA Modules

Figure 3 shows an example of a general WDM system. A WDM multiplexer (MUX) combines five digital channels at the transmitter, and a WDM demultiplexer (DMUX) separates all channels at the receiver. There are several EDFAs in the system, with some spools of single-mode fiber (SMF) inserted between two EDFAs. The EDFAs are used to compensate for the fiber loss. Five channel signals of  $\lambda_1 \sim \lambda_5$  with the same input power are launched into the WDM MUX, boosted by an EDFA, and then transmitted along the fiber link. The unflattened gain characteristics of saturated EDFAs will result in power level variation among these signals. However, when one of the two proposed GF-OLA modules is used in the system, the power level of these signals can be equalized at the output port of the GF-OLA module or the common port (i.e., Pt. Y in Figure 3) of the WDM DMUX.

For the first kind of GF-OLA module, as shown in Figure 4a, the misalignment value  $\Delta\lambda_i$  (nm) for signal  $i$  (where  $i = 1, 2, 3, 4,$  or  $5$ ) is defined as the central wavelength difference between the spectrum of distributed feedback laser $_i$  (DFB $_i$ ) and the reflective peak of the FBG $_i$ . In this case, the misalignment values are adjusted according to the relation of  $\Delta\lambda_5 > \Delta\lambda_4 > \Delta\lambda_3 > \Delta\lambda_2 > \Delta\lambda_1$ , assuming that the FBGs have the same transfer shape and reflectivity. Thus the wavelength

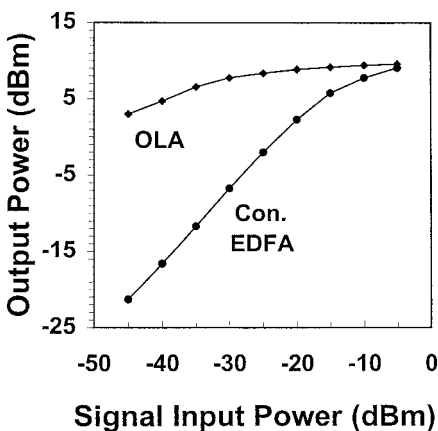
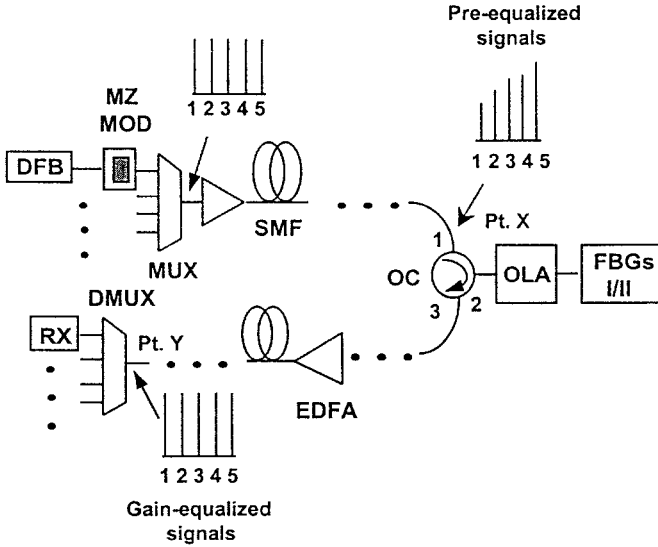
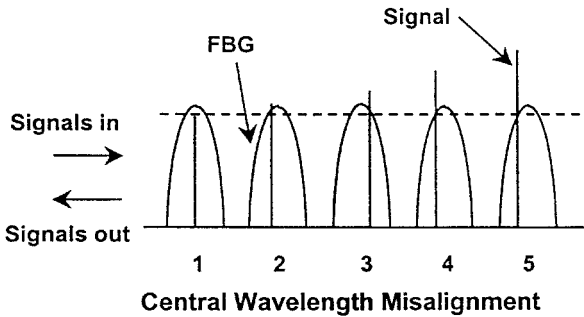


Figure 2. Output power versus input power for the proposed GF-OLA module and the conventional EDFA.

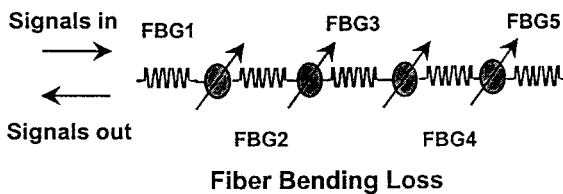


**Figure 3.** General WDM system: DFB, distributed feedback laser; MUX/DMUX, multiplexer/demultiplexer; MOD, modulator; SMF, single-mode fiber.

misalignment induced signal attenuation (dB) for  $\lambda_5$  is largest and reduces subsequently for those of  $\lambda_4$ ,  $\lambda_3$ ,  $\lambda_2$ , and  $\lambda_1$ . The misalignment values can be dynamically adjusted simply by temperature tuning of the DFB laser(s) or straining the FBG(s). Using this method, some WDM channels are likely to pass through the “edge” region instead of the central reflective region of the FBGs. An FBG was used, for example, to measure the signal attenuation versus wavelength misalign-



(a)



(b)

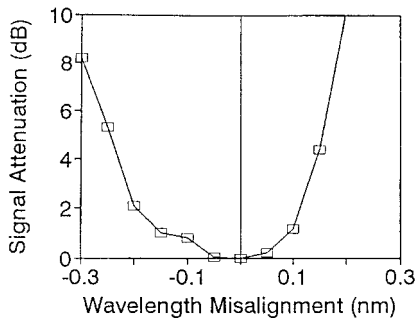
**Figure 4.** Operating principles of the two proposed GF-OLA modules, one based on the (a) central wavelength misalignment and (b) bending loss method.

ment between a DFB laser and an FBG, and the result is shown in Figure 5a. The FBG used here has a central reflective wavelength at 1549.8 nm with 95% reflectivity, and 3-dB bandwidth of 0.25 nm that is slightly unsymmetrical. The slope ( $y/x$  value) of the curve will change from smooth to steep for  $\Delta\lambda > 0.2$  nm. Because the transfer function of many commercial or homemade FBGs is not flat and perfect around their central reflected wavelength, too large a wavelength misalignment value  $\Delta\lambda$  may induce unavoidable power penalties, which is mainly due to the imperfect FBG filtering and the ASE.

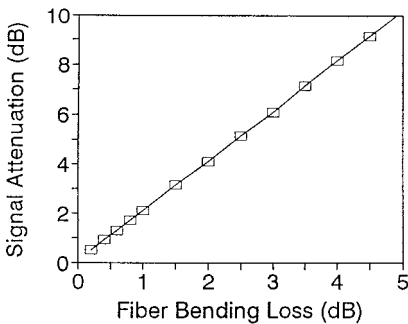
Figure 4b indicates the second kind of the proposed GF-OLA module by using the bending loss method for signals gain-equalization. By using this approach, the FBG<sub>1</sub>, FBG<sub>2</sub>, FBG<sub>3</sub>, FBG<sub>4</sub>, and FBG<sub>5</sub> should be located from left to right inside the GF-OLA module, as shown in Figure 1. The bending attenuation of each section of SMF located between every two adjacent FBGs can be dynamically adjusted. Figure 5b shows the signal attenuation (dB) versus the fiber bending loss (dB) for a specific FBG. The slope of the curve is about 2, since the proposed GF-OLA module is a dual-pass amplification configuration for the transmitted signals. In other words, these signals are attenuated twice at each bending point of SMF, where it/they passed back and forth. For instance, the bending attenuation value between BFG<sub>3</sub> and BFG<sub>4</sub> is about 2.0 dB if a 4.0-dB power level variation should be compensated between  $\lambda_3$  and  $\lambda_4$ .

## Experimental Results and Discussion

The GF-OLA modules are applied to a five-channel WDM system to demonstrate the functions of the GF-OLA modules. Figure 6a shows the spectrum of the five input channels at the input port of the GF-OLA modules. The five input channels

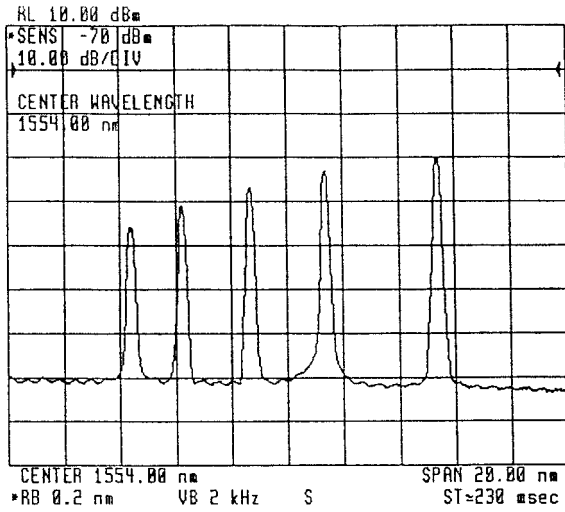


(a)

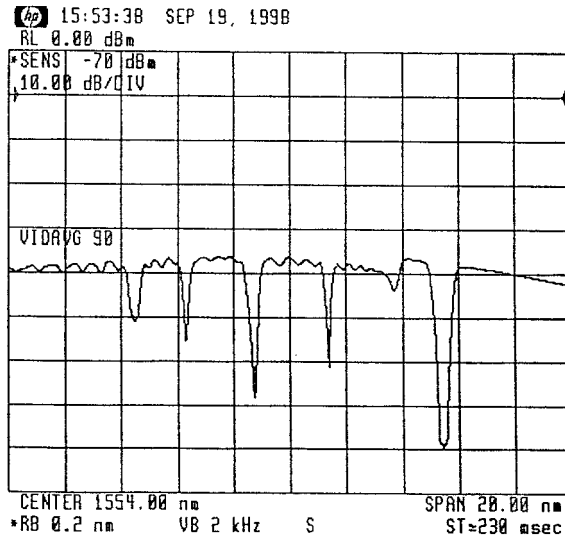


(b)

**Figure 5.** FBG used for an example to measure the signal attenuation (dB) versus (a) wavelength misalignment (nm) and (b) fiber bending loss (dB).



(a)

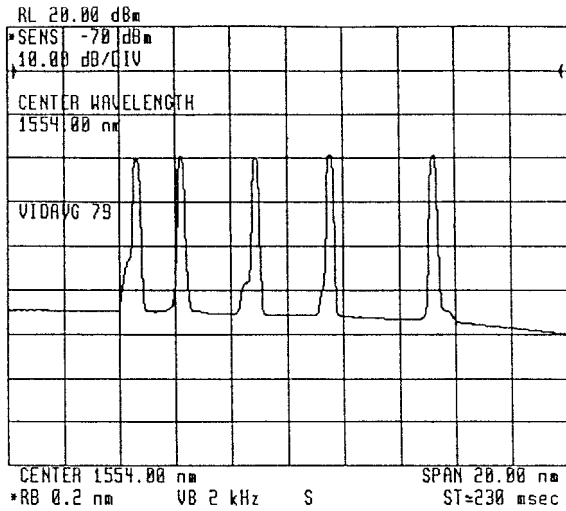


(b)

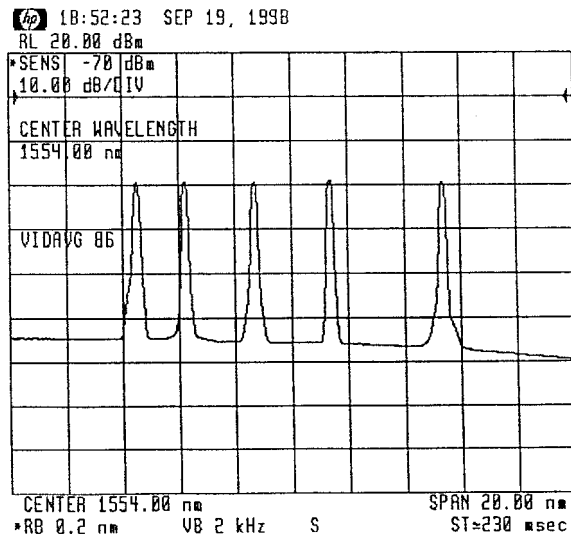
**Figure 6.** (a) Five-channel input before the GF-OLA modules. (b) Transfer function of the FBG chain.

are from 1548.5 to 1559.5 nm for a range of about 11 nm with unequal input powers of 16.0-dB variation. Figure 6b is the transfer function of the FBG chain with reflectivity ranging from 93 ~ 99.99%, designed to match the central wavelengths of the five channels. As shown in Figure 6c, the GF-OLA module provides almost the same output power for all five WDM channels with a variation of less than 0.6 dB at the output port of the module when the method of central wavelength misalignment was used. In that case, the misalignment values are 0.0, 0.12, 0.15, 0.2, and 0.25 nm for  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ , and  $\lambda_5$ , respectively, for equalizing the signals. As shown in Figure 6d, when the bending loss method was used to equalize the five signals, the output spectrum is similar to that of Figure 6c with a





(c)



(d)

**Figure 6.** (cont.) Five-channel outputs using the methods of (c) central wavelength misalignment and (d) bending loss.

gain variation of only 0.5 dB. The results confirm the feasibility of the GF-OLA modules. In Table 1 we summarize and compare the features of these two GF-OLA modules.

## Conclusion

By integration of a Bi-EDFA and a three-port OC with several FBGs, two GF-OLA modules are proposed and experimentally studied for gain flattening the multichannel signals in WDM systems containing cascading EDFAs. These two

**Table 1**  
Summary features of two GF-OLA modules

	Central wavelength misalignment	Fiber bending loss
Measured unit ( $X$ axis)	nm	dB
Simple design	yes	yes
Temperature tuning of DFBs/FBGs	yes	no
Dynamically adjustable	yes	yes
FBG sequence necessary	no	yes
ASE filtering feature	yes	yes
Dual-pass amplification	yes	yes

DFB, distributed feedback (laser); FBG, fiber Bragg gratings; ASE, amplified spontaneous emission.

modules rely on the use of central wavelength misalignment and fiber bending loss. Either of the GF-OLA modules can gain flatten the WDM channels and provide a larger input dynamic range to increase the link budget and fiber span than can a conventional EDFA. The GF-OLA modules can also find important applications in high-speed ( $\geq 10$  Gb/s per channel) WDM transmission systems while replacing FBGs with chirped fiber gratings for fiber chromatic dispersion compensation [12] as well as for signals gain-flattening purposes.

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## Biographies

**Shien-Kuei Liaw** received his BSEE degree from the National Taiwan University and his MSEE degree from the National Tsing-Hwu University, Taiwan, in 1988 and 1993, respectively. From 1993 to 1997 he was a member of the technical staff at Applied Research of Chung-Hua Telecommunication Laboratories in Yang-Mei, Taiwan. In 1996 he was a resident visitor at Bellcore, Red Bank, New Jersey, for a period of 6 months. Currently, he is pursuing his Ph.D. degree at the National Chiao-Tung University, Taiwan. His research interests include optical fiber communications, fiber amplifiers, and fiber Bragg gratings and their related applications.

**Sien Chi** received his BSEE degree from the National Taiwan University and his MSEE degree from the National Chiao-Tung University, Taiwan, in 1959 and 1961, respectively. He received his Ph.D. degree in electrophysics from the Polytechnic Institute of Brooklyn in New York in 1971, after which he joined the faculty of the National Chiao-Tung University, where he is currently a professor at the Institute of Electro-Optical Engineering. From 1972 to 1973 he chaired the Department of Electrophysics; from 1973 to 1977 he directed the Institute of Electronics; from 1977 to 1978 he was a resident visitor at Bell Laboratories, Holmdel, New Jersey. From 1985 to 1988 he was the principal advisor with the Hua-Eng Wire and Cable Company, the first manufacturer of fibers and fiber cables in Taiwan, developing fiber making and cabling technology; and from 1988 to 1990 he directed the Institute of Electro-Optical Engineering. He was the symposium chair of the International Symposium of Optoelectronics in Computers, Communications and Control in 1992, which was co-organized by National Chiao-Tung University and SPIE. In 1993 he received the Distinguished Research Award sponsored by the National Science Council, Taiwan, ROC. His research interests are optical fiber communications, optical solitons, and optical fiber amplifiers. Dr. Chi is a member of the Chinese Optical Engineering Society and a fellow of the Optical Society of America and the Photonics Society of Chinese-Americans.