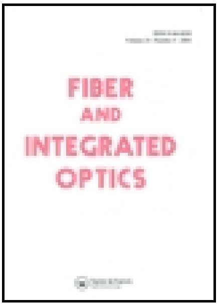

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We proposed and experimentally demonstrated two power-equalized erbium-doped fiber amplifier (EDFA) modules using fiber Bragg gratings (FBGs) with various reflectivities for individual channels. The transmission type power-equalized EDFA module is low-cost for its simple design, while the reflection type power-equalized EDFA module can suppress most of the amplified spontaneous emission noise. Both consist of a bidirectional EDFA, a set of FBG chains with suitable reflectivities, and an optical isolator / optical circulator. They can find potential applications in wavelength division multiplexing lightwave transmission systems.

Keywords erbium-doped fiber amplifier, fiber Bragg grating, lightwave transmission, power equalization, wavelength division multiplexing

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To compensate for fiber attenuation and network splitting losses, high-gain and wide-bandwidth erbium-doped fiber amplifiers (EDFAs) are essential for optical networks and long-haul wavelength division multiplexing (WDM) transmission links in the 1.55-μm band [1]. However, EDFA should have uniform gain for WDM lightwave transmission, especially for systems with many EDFAs cascaded. Otherwise, nonuniform EDFA gain may cause significant system penalties when the interchannel power spreads beyond the receiver dynamic range and the signal-to-noise ratios (SNRs) of some weak channels are too small. Previous works were proposed to equalize the nonuniform EDFA spectral gain curve [2–7]. They included a complicated control circuit [2], a high aluminum doped fiber [3], an erbium-doped fluoride fiber [4], demultiplexing and inserting a variable attenuator for each channel [5], a section of samarium-doped fiber [6], or fiber Bragg gratings (FBGs) written in erbium-doped fiber (EDF) [7]. Another previous work proposed gain equalization WDM channels using a short-period grating for EDFA covering several nanometers of the wavelength region [8]. In this paper, short-period FBGs with various reflectivities are used to construct power-equalized EDFA modules, including both transmission and reflection types. The EDFA modules consist of a set of low-cost, regular FBG or chirped fiber grating chains matching the WDM signals, an EDF, as well as an optical isolator (or an optical circulator, OC). An experiment was investigated to demonstrate the power equalization of a four-WDM-channel system by using a reflection type EDFA module.

Theoretical Analysis and Operating Mechanism

Two proposed power-equalized EDFA modules are based on the use of photo-imprinted FBGs with various reflectivities. The reflectivity of each FBG is designed and precisely controlled during the fabrication process. As is shown in Figure 1*a* for the transmission type power-equalized EDFA module, it consists of a single-stage amplifier followed by an optical isolator and the FBG chain. Without FBGs, the input power level for λ_1 is assumed to be the largest, and those of λ_2, $\lambda_3, \ldots, \lambda_N$ ($N = 11$ in Figure 1) reduce subsequently with 1 dB variation for every adjacent channel. All of the N WDM channel signals pass through the FBG chain and then continue their forward propagation with power equalization. Meanwhile, the signals at $\lambda_1, \lambda_2, \ldots, \lambda_{N-1}$ are reflected partly by FBG_1, $\text{FBG}_2, \ldots, \text{FBG}_{N-1}$, respectively, to proportionally attenuate the power of channels having power levels higher than that of λ_N. One optical isolator is inserted between the EDF and the FBG chain to block the reflected signals and amplified spontaneous emission (ASE) back to the EDF. The reflections are due to FBGs, connectors, and Rayleigh backscattering. As is shown in Figure 1*b* for the reflection type power-equalized EDFA module, it consists of an OC and FBG chain and a single-stage amplifier. The EDF can be located at either port 1 or port 3 of an OC. The N WDM signals are reflected and power-equalized by the FBG chain and then continue their forward propagation. Meanwhile, the signals at λ_1, $\lambda_2, \ldots, \lambda_{N-1}$ may partly penetrate FBG_1, $\text{FBG}_2, \ldots, \text{FBG}_{N-1}$, respectively, to attenuate the channels that have power levels higher than that of λ_N with lowest power. By integration of a three-port OC with the FBG chain, the ASE in the wavelength region from 1 nm to several nanometers away from the WDM channels will be strongly reduced due to the filtering of FBGs. In other words, the FBGs also function as ASE filters for WDM channels.

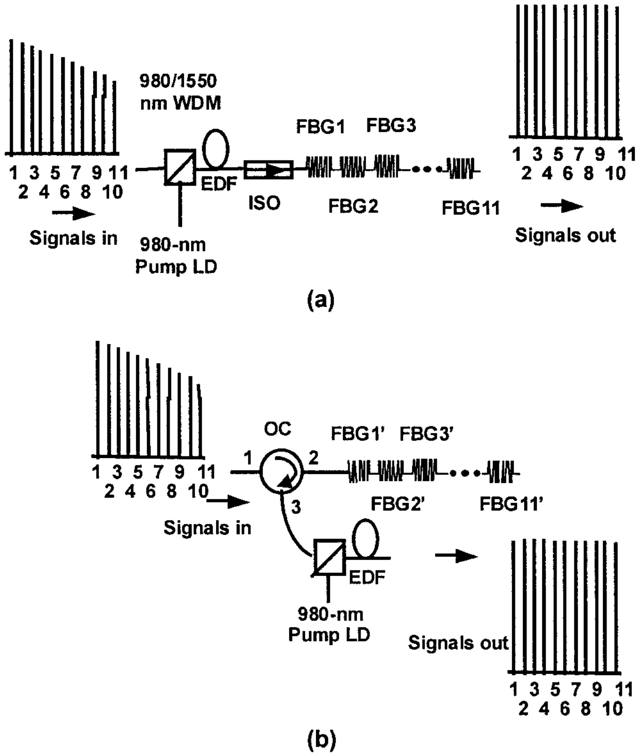


Figure 1. Schematic diagram of the power-equalized EDFA modules using (*a*) transmission type and (*b*) reflection type FBG chains for an 11-WDM channel system. EDF, erbium-doped fiber; FBG, fiber Bragg grating; ISO, optical isolator; OC, three-port optical circulator.

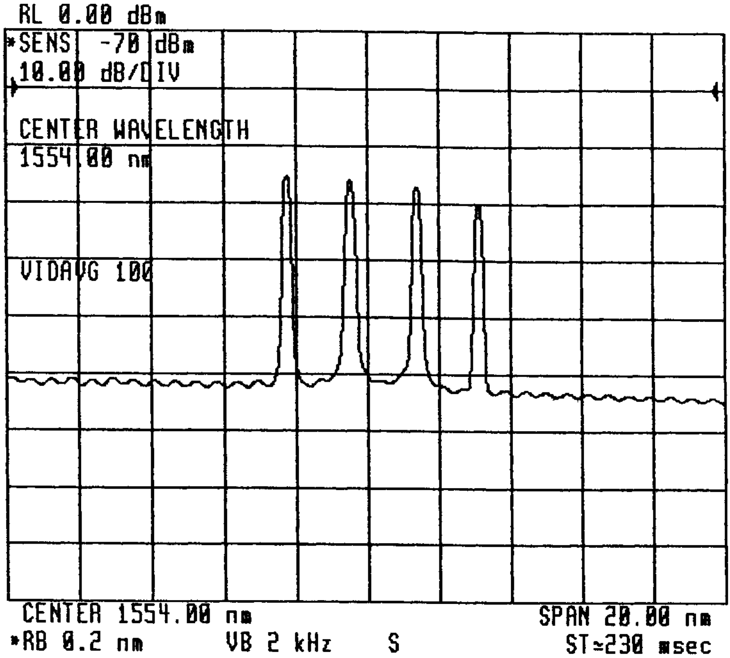
For both the transmission and reflection types FBG chains, the FBGs are designed to have different reflectivities to equalize the powers of the WDM channels. Signal attenuation for each channel depends on the reflectivity written on the corresponding FBG_i ($1 \leq i \leq N$). The total loss attributed by the power-equalized EDFA modules includes the connection/splicing loss, in-line loss of FBGs, insertion loss of the optical isolator/OC, and the loss induced by the reflectivity of the corresponding regular FBG_i. To save costs, one 1×2 coupler (50:50, for example) can be used to replace the three-port OC.

For the transmission type power-equalized EDFA module, if the in-line loss of FBGs is negligible, the reflectivities ($R_1, R_2, R_3, \ldots, R_N$) of FBG_1, FBG_2, FBG_3, $FBG_3, \ldots, FBG_N$ can be designed such that $R_1 > R_2 > R_3, \ldots, > R_N$ according to the relation

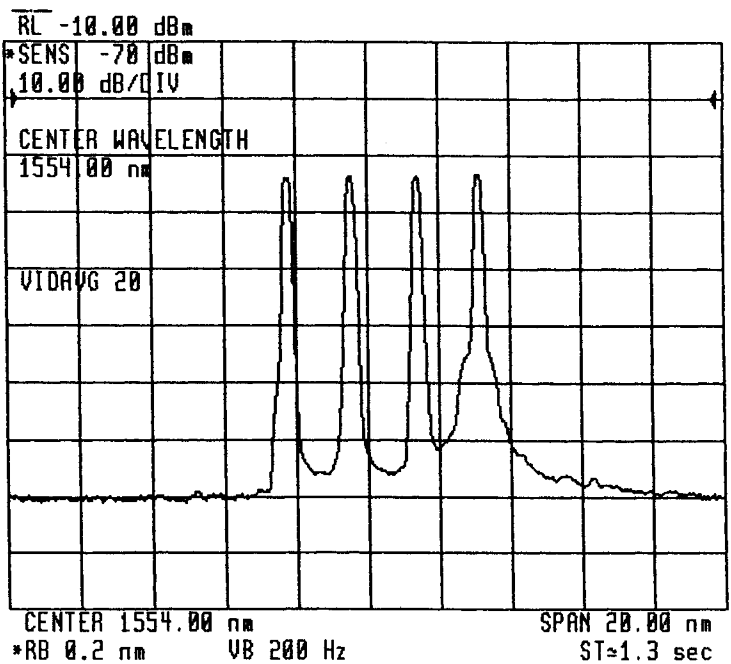
$$\text{Signal Attenuation } L \text{ (dB)} = -10 \log (1 - R_i) \tag{1}$$

where R_i denotes the reflectivity of FBG_i ($1 \leq i \leq N$) and ranges from 10.0% (for R_N) to ~ 90% (for R_1) in this example. The calculated result is shown in Figure 2*a*.

Similarly, for the reflective type power-equalized EDFA module, the reflectivities of FBG_1, FBG_2, $FBG_3, \ldots, FBG_N$ can be designed such that $R_1 < R_2 <$



(a)



(b)

Figure 2. Calculated results of the signal attenuation (dB) versus fiber Bragg grating reflectivity (R%) for the (a) transmission type and (b) reflection type power-equalized EDFA modules.

$R_3, \ldots, < R_N$ with the relation

$$\text{Signal Attenuation } L\ (\text{dB}) = -10 \log (R_i) \tag{2}$$

where R_i denotes the reflectivity of FBG_i ($1 \leq i \leq N$) and ranges from ~ 10.0% (for R_1) to 99.9% (for R_N) in this example. From the above equations, we see that any FBG can easily be used to attenuate the optical power of its corresponding channel from 0.0 to 10.0 dB. This operating range is large enough for most WDM system applications. To further increase the practical operation range in WDM channels, three methods are proposed to achieve the requirement. They are by cascading (1) two sets of transmission type FBG chains, (2) two sets of reflection type FBG chains, or (3) the hybrid type FBG chains containing one set of transmission type and one set of reflection type FBG chains.

Experiment and Results

To demonstrate the feasibility of a power-equalized EDFA module, one reflection type power-equalized EDFA module is demonstrated for a four-WDM channel system rather than an *N*-WDM channel system. The four WDM channels cover the wavelength range of 1551.7–1557.1 nm with channel spacing of 1.8 nm. The reflectivity of these regular FBGs ranges from 70.0% (rather than the theoretical value of 31.5% because the in-line loss of FBGs is not negligible) to 99.9%. The 3 dB bandwidth of these regular FBGs ranges from 0.15 to 0.25 nm. The temperature coefficient of these FBGs is about 0.015/°C. No amplitude modulation was observed due to wavelength jitter, since the temperature variation is less than ± 1.0°C during measurement. Figure 3 shows optical spectra of four WDM channels taken from a reflection type FBG chain (*a*) before port 1 of the OC, with a power variation of 5.0 dB, and (*b*) after port 3 of the OC but before the gain medium, with a power variation of only 0.3 dB. Note that the output power was taken before the gain medium for insertion loss measurement. The reference power levels in Figures 3*a* and 3*b* are 0.0 and −10.0 dB, respectively. The signal wavelength of 1557.1 nm (λ_4) with the lowest power level of −20.0 and −23.5 dB before and after the FBG chain corresponds to a total 3.5 dB loss, most of which is attributed to the OC insertion loss and FBG in-line loss.

Discussion

Compared with using one broadband filter per EDFA for gain equalization, the proposals in our work have some advantages. First, they can simultaneously realize the power equalization among WDM channels and fiber chromatic dispersion by replacing regular fiber Bragg gratings with chirped fiber gratings (CFGs) for individual channels, for both the reflection and transmission modules. However, a chirped broadband filter could not realize this function. Second, if the input power levels among channels are arbitrarily nonuniform and/or the gain shapes among the EFDAs are different from one another, it will be very complicated to fabricate this kind of broadband filter for covering the entire wavelength range. Nevertheless, it is simpler to design the FBGs with various reflectivities to match the optimum condition regardless of the variations in operating conditions and/or input power levels. Third, the residual ASE noise can be suppressed by using the reflection type EDFA module containing the regular FBG /CFG chain, rather than by using a transmission broadband filter. Also, based on the International Telecommunications Union (ITU) proposal of 200 (or 100) GHz of channel spacing, wavelengths could be fixed with accuracy and union. It does not matter if the short-period FBGs (filters) could cover the whole operating region.

Considering the two curves of signal attenuation versus FBG reflectivity in Figures 2 *a* and 2 *b*, the slope ($\Delta y/\Delta x$) will be much more sensitive to reflectivity at

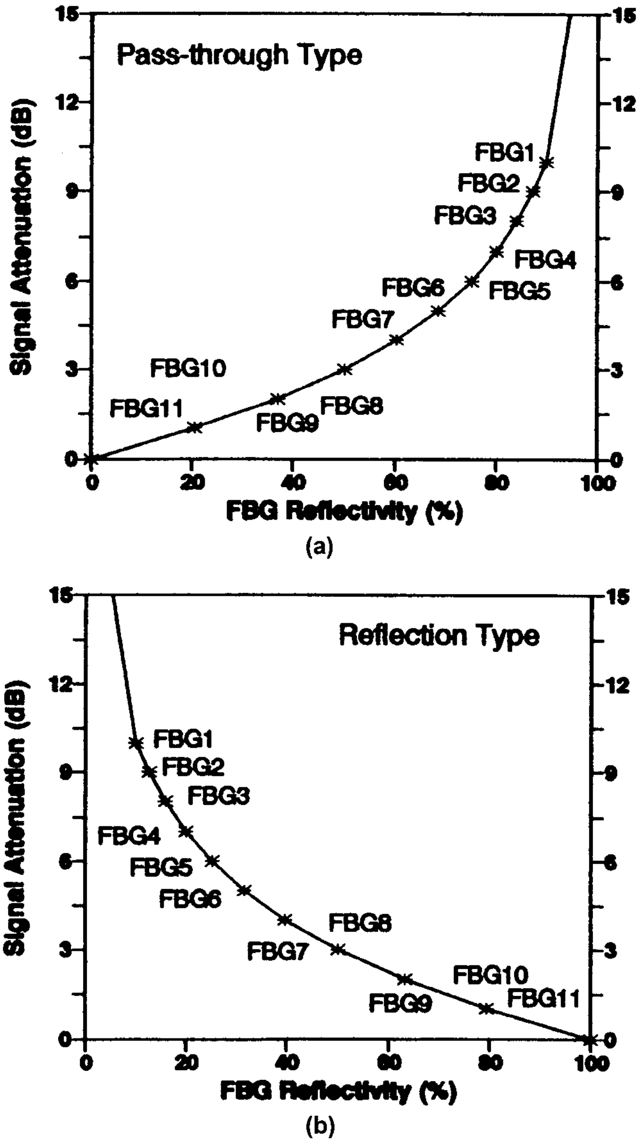


Figure 3. Optical spectra of a four-WDM channel system (*a*) before port 1 and (*b*) after port 3 of the OC using the reflection type power-equalized EDFA module. The figure was grafted before the erbium-doped fiber for power level comparison. Note that the reference power levels in Figures 3 *a* and 3 *b* are 0.0 and −10.0 dB, respectively.

the region where the $\Delta y/\Delta x$ value is high. The reflectivities should be precisely controlled during the fabrication process because even a small reflectivity change (ΔR) will induce a nonnegligible change in the signal level (dBm). For the transmission type EDFA module, the channels with low power levels ($\lambda_N, \lambda_{N-1}, \lambda_{N-2}, \ldots$) are easier to adjust. For the reflection type EDFA module the channels with large power levels ($\lambda_1, \lambda_2, \lambda_3, \ldots$) are easier to adjust.

To simplify the fabrication processes and reduce the in-line loss of the FBG chains, the sinc-sampled FBGs [9] may be potential candidates for the proposed EDFA modules. By using the continuous grating fabrication technique, the time taken to write the grating chain is short. Packaging and temperature demands are also reduced because these gratings are effectively contained within the same length of fiber. According to theory, the reflectivity of each channel could be precisely controlled.

Conclusion

By integration of a piece of EDF, and an optical isolator or OC, a set of FBG/CFG chain of appropriate reflectivities, two power-equalized EDFA modules are proposed. The reflection type EDFA module was experimentally demonstrated with the additional feature of ASE suppression. The output power levels are equalized among the WDM channels by using the FBG/CFG chain with various reflectivities regardless of the input power levels. The transmission type power-equalized module is low-cost for its simple design. The reflection type power-equalized EDFA module can suppress most ASE noise. Both types of power-equalized EDFA modules are easy to fabricate and can find useful application in WDM lightwave transmission systems and optical networks.

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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-Hua University, Taiwan, in 1988 and 1993, respectively. From 1993 to 1997 he was a member of the technical staff at the Applied Research of Chung-Hwa Telecommunication Laboratories in Yang-Mei, Taiwan. In 1996 he was a resident visitor at Bellcore, Red Bank, New Jersey, for period of 6 months. He is currently a PhD student at the National Chiao-Tung University, Taiwan. His research interests include optical fiber communications, erbium-doped fiber amplifiers, fiber Bragg gratings and their related applications.

Keang-Po Ho (S'91–M'95) received the B.S. degree from National Taiwan University, China, in 1991 and the M.S. and Ph.D. degrees from the University of California at Berkeley in 1993 and 1995, respectively, all in electrical engineering.

From 1992 to 1995, he was a Research Assistant in the Department of Electrical Engineering and Computer Sciences of the University of California at Berkeley, where he conducted research in communication systems, optical communication, communication theory, digital signal processing, and image and video transmission. During the summer of 1994, he was with IBM T. J. Watson Research Center, Hawthorne, NY, where he worked on optical networks. From 1995 to 1997, he was a Research Scientist with Bellcore, Red Bank, NJ, and since 1997, he has been an Assistant Professor with the Department of Information Engineering of the Chinese University of Hong Kong. His interests include combined source-channel coding, optical communication systems, multimedia communications, broadband access, and communication theory.

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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 PhD in electrophysics from the Polytechnic Institute of Brooklyn, New York, in 1971 and he joined the faculty of the National Chiao-Tung University, where he is currently a professor 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 Wires and Cables Company, the first manufacturer of fibers and fiber cables in Taiwan, developing fiber making and cabling technology; and from 1988 to 1990 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 coorganized by the National Chiao-Tung University and SPIE. In 1993 he received the Distinguished Research Award sponsored by the National Science Council, Taiwan. His research interests are optical fiber communications, optical solitons and optical fiber amplifiers. Chi is a member of the Chinese Optical Engineering Society and fellow of the Optical Society of America and the Photonics Society of Chinese-Americans.