



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Optics Communications 222 (2003) 207–212

OPTICS
COMMUNICATIONS

www.elsevier.com/locate/optcom

Characteristics of the erbium doped fiber amplifier with polarization mode dispersion compensation

Jeng-Cherng Dung*, Sien Chi, Chia-Chu Chen

Institute of Electro-Optical Engineering, National Chiao Tung University, 1001, Ta Hsueh Road, Hsinchu, Taiwan, ROC

Received 8 January 2003; received in revised form 18 April 2003; accepted 12 May 2003

Abstract

We have experimentally demonstrated the characteristics of the reflective type erbium-doped fiber amplifier (R-EDFA) which is composed of a circulator and a Faraday rotator mirror. It is shown that the gain spectrum of the R-EDFA is shifted to longer wavelength when compared with that of the conventional single-pass EDFA. For the R-EDFA, the forward pumping is better than the backward pumping in gain and noise figure. Besides, the reflective structure can be used as a broad band light source because its ASE spectrum is wider and the output power is higher. We also show that, by using the reflective type configuration, the polarization dependent gain is reduced and the polarization mode dispersion of EDF can be completely compensated but the polarization mode dispersion from the circulator is still survived.

© 2003 Elsevier Science B.V. All rights reserved.

Keywords: Erbium doped fiber amplifier; Polarization mode dispersion; Polarization dependent gain

1. Introduction

Owing to its statistical nature, the polarization mode dispersion (PMD) appears to be a complex phenomenon limiting the performance of transmission system. As the bit rates increase (40 Gbit/s and higher), the PMD is becoming a major system impairment [1–3]. The erbium-doped fiber amplifiers (EDFAs) are indispensable tools for providing optical amplification in 1.5 μm fiber transmission

systems because of its excellent characteristics such as wide band, high gain, high saturation output, and low noise. However, EDFAs still have a few drawbacks arising from the polarization nature of the light [4]. The erbium-doped fiber (EDF) exhibits a difference of refractive index for the orthogonal polarization state, called birefringence, which results in the PMD of EDFA. The maximum tolerable PMD value of transmission system should remain below about 10% of bit duration. The polarization dependent gain (PDG) is another drawback due to the anisotropic gain saturation in EDFAs [5]. The effect originates from the microscopic anisotropy of the erbium-ion susceptibility. The PDG results in undesirable fluctuation of the

* Corresponding author. Tel.: +886-3-5731824; fax: +886-3-5716631.

E-mail address: jcdung@mail.nctu.edu.tw (J.-C. Dung).

signal-noise-ratio (SNR) at the output and degrades the performance. Therefore, PMD compensation and PDG reduction are important topics for enabling satisfactory transmission in a high bit rates transmission system with EDFAs [6,7].

The use of a Faraday rotator mirror (FRM) to stabilize the state of polarization (SOP) in the re-tracing path without maintaining the SOP of signal has been known to be simple and effective [8,9]. The FRM, having a 45° single-pass rotation and reflector mirror, reflects the light in the orthogonal polarization state regardless of the incident state. The reflected light then makes a second pass through the amplifier. As a result, the SOP in the backward direction is orthogonal to that in the forward direction everywhere regardless of any fiber birefringence. In this paper, we present the characteristic of a reflective type erbium-doped fiber amplifier (R-EDFA) employing a circulator and a FRM. The gain spectrum of the R-EDFA is shifted to longer wavelength when compared with that of the conventional single-pass EDFA. In the R-EDFA, the forward pumping is better than the backward pumping and the optimum length is about 2/3 of the optimum length of single-pass EDFA. The reflective structure can be used as a broad band light source because its amplified spontaneous emission (ASE) spectrum is wider and the output power is higher. By using the reflective type configuration, the polarization mode dispersion of EDFA is almost compensated and the polarization dependent gain is reduced.

2. Numerical modeling

The EDFA can be modeled as a homogeneously broadened two-level system. The spectra of the absorption cross-section (σ_a) and emission cross-section (σ_e) of the Al co-doped EDFA are shown in Fig. 1. The ASEs are assumed to be the optical beams of effective frequency bandwidth $\Delta\nu_k$ centered at the wavelength $\lambda_k = c/\nu_k$ to resolve the ASE spectrum. Under the steady-state condition, the equations to describe the spatial development of the pump power (P_p), signal power (P_s), and ASE power (P_k , $k = 1, \dots, N$) in the EDFA can be written as [10]:

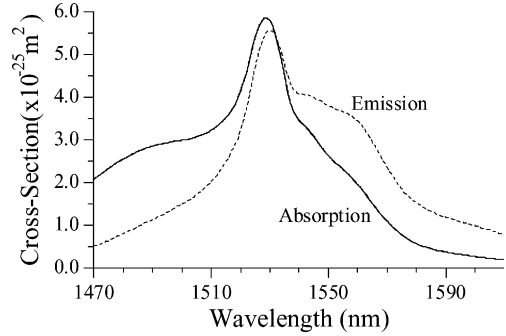


Fig. 1. The absorption cross-section and emission cross-section of an Al co-doped EDFA.

$$u^\pm \frac{dP_p^\pm}{dz} = (\sigma_{ep}N_2 - \sigma_{ap}N_1)\Gamma_p P_p^\pm, \quad (1)$$

$$u^\pm \frac{dP_s^\pm}{dz} = (\sigma_{es}N_2 - \sigma_{as}N_1)\Gamma_s P_s^\pm, \quad (2)$$

$$u^\pm \frac{dP_k^\pm}{dz} = (\sigma_{ek}N_2 - \sigma_{ak}N_1)\Gamma_k P_k^\pm + 2\sigma_{ek}N_2\Gamma_k h\nu_k \Delta\nu_k - \alpha_{ip}P_k^\pm, \quad (3)$$

where N_1 and N_2 are the population densities of the ground level and metastable level, σ_{ej} , σ_{aj} , Γ_j , α_p , and $h\nu_j$ are the emission cross-section, absorption cross-section, confinement factor, intrinsic fiber loss, and photon energy, respectively. The superscript (\pm) designates the optical beam propagating along $\pm z$ direction and $u^\pm = \pm 1$. The coupled Eqs. (1)–(3) are numerically solved with the absorption cross-section (σ_a) and emission cross-section (σ_e) given in Fig. 1. We use 5601 points to sample the ASE spectrum, which corresponds to the spacing of $\Delta\lambda = 0.025$ nm.

3. Experimental setup

Fig. 2(a) shows the experimental R-EDFA using forward pumping configuration. An optical circulator places between the isolator and the wavelength division multiplexing coupler connected to one end of EDF. The optical signals generated from tunable laser input the EDF from port 1 to port 2 of the optical circulator. After optical signal has been amplified during transmission in the EDF,

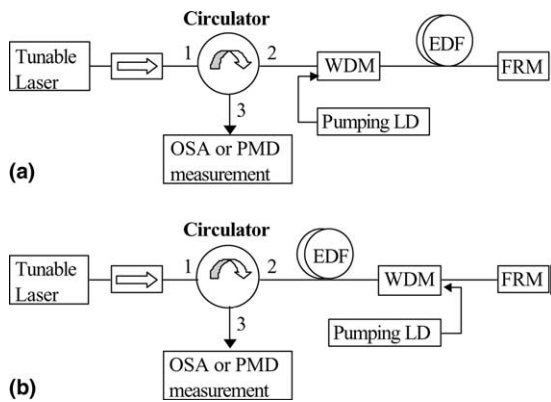


Fig. 2. The R-EDFA configuration using (a) forward pumping, (b) backward pumping.

the FRM at the other end of EDF reflects back the signals in the orthogonal polarization state. Then the signal is amplified in the EDF again and exits from port 2 to port 3 of the circulator. The reflectivity of the FRM is 95%. The optical circulator has a loss of about 0.7 dB and an isolation of over 47 dB. About 200 mW pump power is launched into the EDF from a 980 nm laser diode. The EDF we used is an Al co-doped fiber with a core radius of 1.44 μm and an NA of 0.223. The erbium concentration is $8.55 \times 10^{24} \text{ m}^{-3}$. We measure the signal gain and the noise figure characteristics of both the reflective type configurations and the single-path one which could be easily modified from the reflective type ones by replacing the end FRM with an optical isolator. The backward pumping configuration is shown in Fig. 2(b). The characteristics of the backward pumping will be compared with that of the forward pumping. The initial length of the EDF we used is 15 m which is the optimum length of the single-pass with -10 dBm input signal and 200 mW pump power.

4. Results and discussion

The measured results of forward pumping by scanning the wavelength of input signal with intensity of -10 dBm are shown in Fig. 3. We measure signal gain and noise figure characteristics of both the reflective type configuration and the

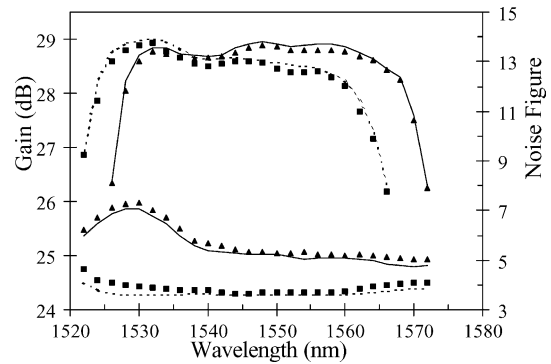


Fig. 3. The measured gain and noise figure of forward pumping; dotted line, numerical result of 15 m single-path EDFA; solid line, numerical result of 11 m R-EDFA; (■) measured results of 15 m single-path EDFA; (▲) measured results of 11 m R-EDFA.

single-path one with 15 m EDF. The numerical results of the 15 m single-path and the 11 m reflective type are also shown in Fig. 3. We cut-back the EDF to measure the characteristics of the R-EDFA with different lengths of EDF. Among all the gain results of different lengths R-EDFA, the optimum length of EDF is about 11 m, so the amplified length is 22 m. By comparing the gain results of the 11 m reflective type with those of the 15 m single-path, the gain spectrum of the reflective type is broader and smoother. The gain values of the R-EDFA exceed those of the single-pass EDFA at the signal wavelength longer than 1538 nm. It is noticed that the spectrum of the reflective type is shifted to longer wavelength about 8 nm. The characteristics are mainly attributed to the longer amplifying EDF length of the reflected type. However, its noise figures of the R-EDFA are 1.2 dB higher than those of the single-pass EDFA over the whole wavelength regime because the backward strongly amplified signals and the reflective ASE due to FRM make the population inversion in the input of EDF low. Fig. 4 shows the gain and noise figure of the backward pumping EDFA. The signal gain of the backward pumping R-EDFA appears to be 1 dB lower than that of the forward pumping one. The noise figure performance is higher than 2 dB over most of the measured wavelength regime. Thus, the forward pumping configuration is more suitable to

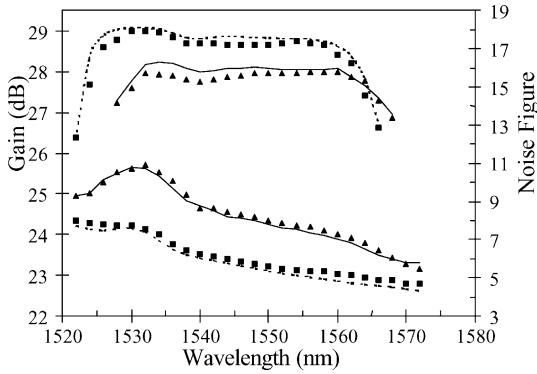


Fig. 4. The measured gain and noise figure of backward pumping; dotted line, numerical result of 15 m single-path EDFA; solid line, numerical result of 11 m R-EDFA; (■) measured results of 15 m single-path EDFA; (▲) measured results of 11 m R-EDFA.

the R-EDFA. Besides, we also find that there is another merit for the reflective structure. With 15 m EDF and 50 mW pump power, Fig. 5 shows the ASE spectrums of the single-pass and the reflective type. The total output ASE powers are 7.04 and -0.63 dBm for the reflective type and the single-pass, respectively. Hence, the reflective structure can be used as a broad band light source because its ASE spectrum is wider than that of the single-pass.

We use the Poincaré sphere method to measure the PMDs of the single-pass EDFA and the R-EDFA with a FRM [11,12]. The tunable laser of fixed polarization state is used as a light source.

We tune the wavelength of light source and measure the stokes vector of polarization state after EDFA with polarimeter to obtain the PMD values. Fig. 6 shows the stokes vector S_2 versus input wavelength. From the stokes vector measurements, the PMD values are 0.97 and 0.074 ps for the single-pass EDFA and the R-EDFA with a FRM, respectively. Therefore, with a FRM in the R-EDFA, the PMD is nearly compensated but survives 0.07 ps. If we replace a FRM with a reflective mirror in the reflective EDFA, the PMD is 1.37 ps because the changes of EDF length should result in different PMD value.

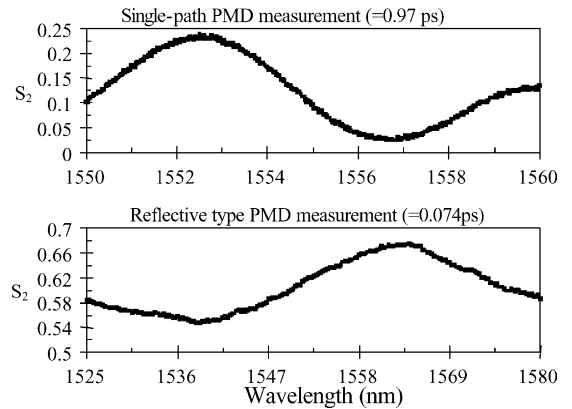


Fig. 6. The measurement of stokes vector S_2 versus input wavelength to obtain the PMD values.

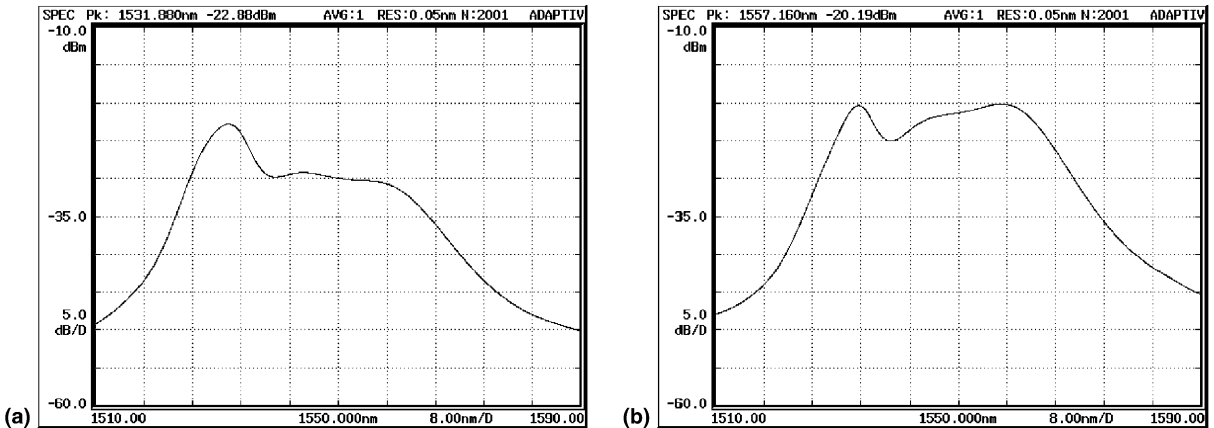


Fig. 5. The ASE spectrums of (a) single-pass and (b) reflective type with 15 m EDF and 50 mW pump power.

Employing a circulator and a FRM in EDFA, it has been demonstrated that the PMD can be compensated both in the circulator and in the EDF [9]. We will investigate it further. We measure the PMD of the R-EDFA with different EDF lengths. The results are shown in Fig. 7, the PMD values for different EDF length are around 0.07 ps. For comparison, we measure the PMD of a circulator, from port 1 to port 2 and reflecting by FRM then exiting from port 3, and the value is 0.07 ps. Therefore, the survived PMD value of the R-EDFA is all from the circulator. It is apparent that the reflecting signal by FRM will not pass through port 2 to port 1 again. So the input and output paths of the circulator are different and the PMD of a circulator cannot be compensated. Thus, using a FRM in the R-EDFA, the PMD of EDF is completely compensated and the PMD from the circulator is still survived. Furthermore, when we find a circulator which has the same PMD value and the parallel principal states within both port 1 ⇒ port 2 and port 2 ⇒ port 3, the PMD value of the circulator with a FRM will be zero.

We also demonstrate a R-EDFA that incorporates a FRM to passively cancel the PDG produced by the gain anisotropy. The cancellation of PDG was demonstrated by measuring the dependence of gain on the polarization states of a saturating signal beam. The polarization states are set by placing a linear polarizer after tunable laser and

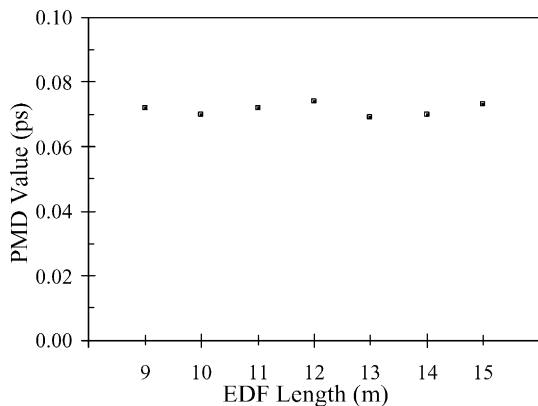


Fig. 7. The PMD values for R-EDFA with different EDF length.

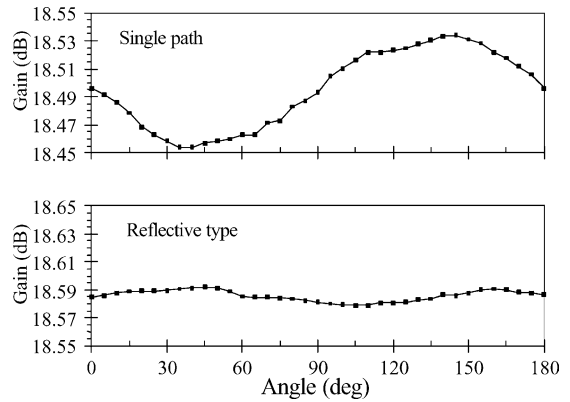


Fig. 8. The measured gains versus the input polarization states.

using polarization controller to scan the states of linear polarization. The input probe signal beam, 0 dBm at 1550 nm, is detected at the amplifier output using a power meter. The measured gains versus the input polarization states are shown in Fig. 8. The measured data points are the average values of six measurements. The PDGs of the single-path EDFA and the R-EDFA with a FRM are 0.08 and 0.017 dB, respectively. It shows clearly that the effect of reducing PDG by the FRM which reflects the signal with a 90° rotation in the EDFA.

5. Conclusions

In conclusion, we have presented the characteristics of gain and noise figure of the R-EDFA employing a circulator and a FRM. Due to the longer amplifying length of the R-EDFA, the signal gain is better but the noise figure is worse than the conventional single-pass EDFA. The gain spectrum is shifted to longer wavelength and the forward pumping is more suitable to the R-EDFA. Besides, the reflective structure can be used as a broad band light source because its ASE spectrum is wider and the output power is higher. Using a FRM in the R-EDFA, the PMD of EDF is completely compensated and the PMD from the circulator is still survived. The reflective method of suppressing PMD is an easy implement and is beneficial to reduce the PDG in EDFA lightwave transmission systems.

Acknowledgements

This research was supported by the National Science Council of ROC under Contract NSC 91-2215-E-009-054 and the Academic Excellence Program of ROC. Ministry of Education under Contract 91-E-FA06-1-4-91X023.

References

- [1] C.D. Pool, J. Nagel, in: *Optical Fiber Telecommunications IIIA*, Academic Press, New York, 1997.
- [2] D. Sobiski, D. Pikula, J. Smith, C. Henning, D. Chowdhury, E. Murphy, E. Kolltveit, F. Annunziata, *Electron. Lett.* 37 (2001) 46.
- [3] N.Y. Kim, D. Lee, H. Yoon, J. Park, N. Park, *IEEE Photon. Technol. Lett.* 14 (2002) 104.
- [4] H. Taga, N. Edagawa, S. Yamamoto, S. Akiba, *J. Lightwave Technol.* 13 (1995) 829.
- [5] M.G. Taylor, *IEEE Photon. Technol. Lett.* 5 (1993) 1244.
- [6] C.R. Giles, *Electron. Lett.* 30 (1994) 976.
- [7] C. Francia, F. Bruyère, J.P. Thiéry, D. Penninckx, *Electron. Lett.* 35 (1999) 414.
- [8] A.D. Kersey, M.J. Marrone, M.A. Davis, *Electron. Lett.* 27 (1991) 518.
- [9] S. Yamashita, K. Hotate, M. Ito, *J. Lightwave Technol.* 14 (1996) 385.
- [10] E. Desurvire, *Erbium-Doped Fiber Amplifiers*, Wiley, New York, 1994.
- [11] D. Andresciani, F. Culti, F. Matera, B. Danino, *Opt. Lett.* 12 (1987) 844.
- [12] Y. Namihira, K. Nakajima, *Electron. Lett.* 30 (1994) 1157.