Gamma-ray irradiation effects on dynamic gain of erbium-doped fiber amplifiers

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Experiments were made of the gamma-ray irradiation effect on the dynamic performance of erbium-doped fiber amplifiers (EDFAs). The frequency responses of EDFAs before and after irradiation are dependent on radiation dose and modulation frequency. The ac gain of EDFA with irradiation effect was also simulated, and our simulations are in agreement with the experimental results.

Keywords: erbium-doped fiber amplifier, gamma-ray irradiation.

1. Introduction

The features of erbium-doped fiber amplifiers (EDFAs) are continuously improved because of their great importance in optical communication systems. Much work has been carried out on their gain optimization. Environmental effects on the performance of fiber systems are important in fiber communication and sensor applications [1–7]. The effect of core impurity such as Al and Ge on the irradiated EDF loss has been reported [1–3]. The static gain of EDFA has also been studied in a space radiation environment [4–6]. However, little is known about the radiation effects on dynamic gain of EDFA. In this paper, we report the gamma-ray irradiation effects on the dc gain and the frequency response of EDFA.

2. Experiments

Two types of commercial EDFs were used in our experiment. EDF #1 has a core diameter of 2.95 μm, cutoff wavelength of 878 nm, background loss <8 dB/km at 1550 nm, dopant peak absorptions of 6.5 dB/m at 980 nm and 8.3 dB/m at 1535 nm.

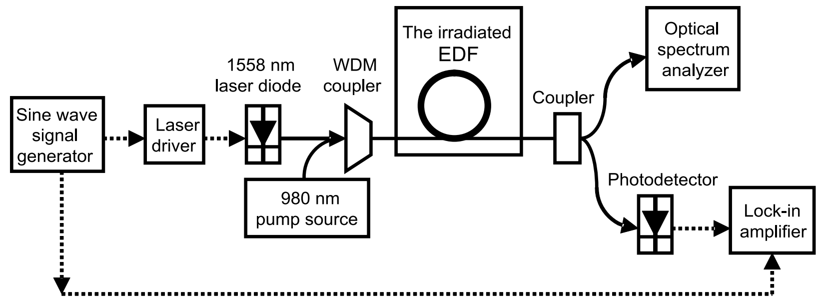

Fig. 1. Measurement of the dc and ac gain of EDFA before and after irradiation.

EDF #2 has a core diameter of 2.17 μm, cutoff wavelength of 910 nm, background loss of 7.7 dB/km at 1550 nm, dopant peak absorptions of 10 dB/m at 980 nm and 1530 nm. Those EDFs were irradiated by gamma-ray from a Co^{60} radiation source at a dose rate 0.34 krad/min. Total doses of 1 krad and 10 krad were applied to those EDFs. The characteristics of EDFAs were studied before and after gamma-irradiation. The measurement setup of EDFA dynamics is shown schematically in Fig. 1. The static gains can be obtained from optical spectrum analyzer (OSA), while the dynamics are obtained using a lock-in amplifier.

Figure 2**a** shows the static gain versus input pump power before and after irradiation for EDF #1 with 5 m length and 255 μW input signal. It shows that the gain decreases due to gamma-irradiation. The gain reduction depends on the pump power. The gain reduction due to 10 krad irradiation is 0.85 dB at 8 mW pump power and increases to 1.4 dB at 16 mW. Furthermore, we show the signal power dependence of the gain reduction in Fig. 2**b** for EDF #2. At 10 mW pump power, the decrement for the signal of 64 μW is 1.5 dB due to 10 krad irradiation, which is larger than 0.9 dB for the signal of 292 μW. Those results are in agreement with [5].

In Figures 3**a** and 3**b**, the magnitude and phase of the ac gain before and after irradiation is plotted as a function of modulation frequency for EDF #1 with 8.2 mW

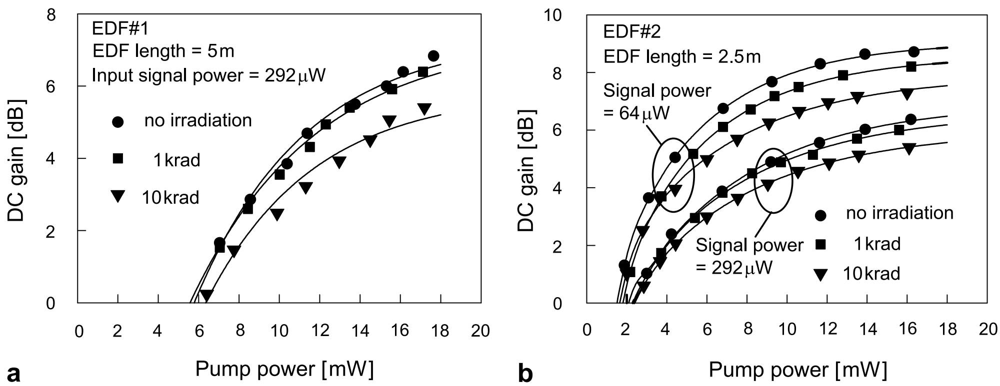

Fig. 2. Dc gain as a function of pump power for 1 krad and 10 krad irradiation EDF #1 (**a**), EDF #2 (**b**).

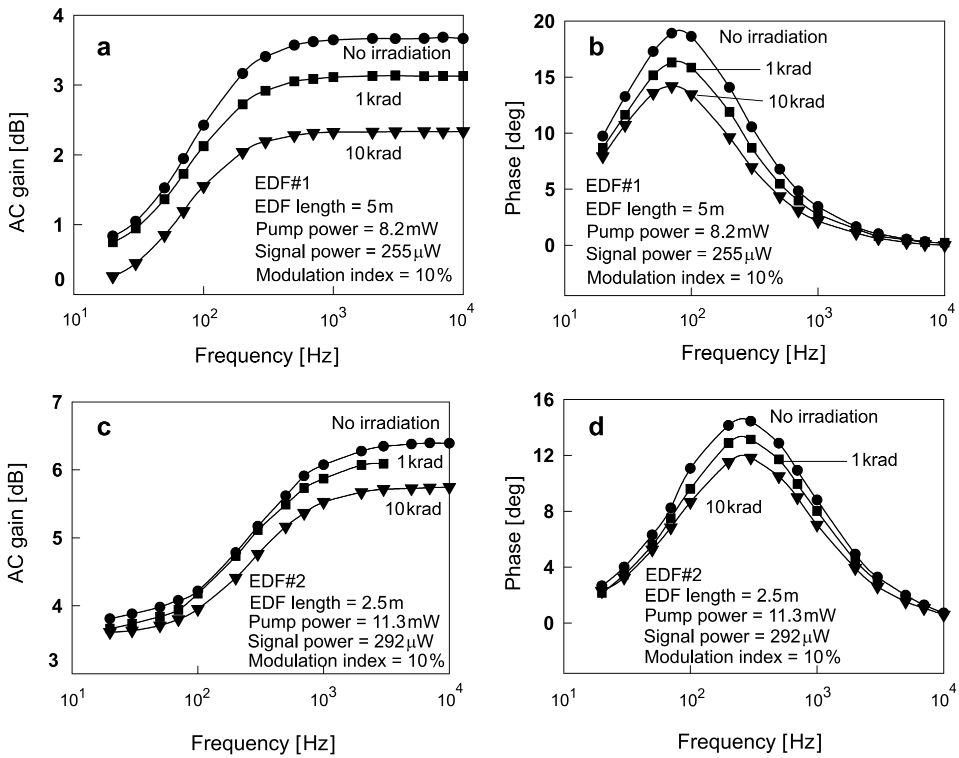

Fig. 3. Magnitude and phase of the EDFA ac gain before and after irradiation: magnitude for EDF #1 (**a**), phase for EDF #1 (**b**), magnitude for EDF #2 (**c**), phase for EDF #2 (**d**).

input pump power, 255 μW input signal, and 10% modulation index. Figures 3**c** and 3**d** show the frequency response for EDF #2 with 11.3 mW input pump power and 292 μW input signal. By those experimental results, we have some findings for the ac gain reduction. *i*) The ac gain reduction is more pronounced at greater radiation dose; *ii*) It is larger at greater modulation frequency; *iii*) The peak phase decreases with radiation dose.

3. Simulations and discussion

Assume that the excited-state absorption can be neglected and the wavelength dependence of group velocity can be ignored. In a co-pumped two-level EDFA system, let the optical beams propagate through the EDF of length L. At the location z and time t, the rate equation for the population $N_2(z, t)$ at the metastable level and the evolution equations of optical powers can be written as [8]

$$\left(\frac{1}{\tau} + \frac{\partial}{\partial t}\right) N_2(z, t) = \sum_{k=1}^{M} \left[N_t \sigma_k^a - N_2(z, t) \sigma_k^{ae} \right] \Gamma_k P_k(z, t) \tag{1}$$

$$\frac{\partial P_k(z,t)}{\partial z} = \left[\Gamma_k \sigma_k^{ae} N_2(z,t) - \Gamma_k \sigma_k^a N_t - \alpha_k\right] P_k(z,t) \tag{2}$$

where $P_k = P_k'/h\nu_k A$, P_k' is the power of the k-th optical beam; ν_k is the optical frequency; h is Planck's constant; N_t is the erbium density in the fiber core of effective area A; Γ_k is the overlap factor of the k-th beam; τ is the fluorescence lifetime of the metastable level; $\sigma_k^{ae} = \sigma_k^a + \sigma_k^e$, σ_k^a and σ_k^e are respectively the absorption and emission cross-sections at the wavelength λ_k; α_k is the radiation-induced loss; $k = p, s$ for the pump (p) and signal (s) beams.

We consider a forward 8 mW 980 nm pump EDFA with 5 m EDF length and 250 μW input signal power at 1558 nm. Other parameters used are: $N_T = 7.7\times10^{24}$ m^{-3}, $\tau = 10$ ms, $A = 2.5\times10^{-11}$ m^2, $\sigma_s^a = 2.4\times10^{-25}$ m^2, $\sigma_s^e = 3.8\times10^{-25}$ m^2, and $\sigma_p^a =$ $= 2.0\times10^{-25}$ m^2 [8]. After the EDF is irradiated with a total dose of 10 krad, we assume $\alpha_s = 0.09$ dB/m and $\alpha_p = 0.4$ dB/m [5]. For 1 krad irradiation, $\alpha_s = 0.03$ dB/m and $\alpha_p = 0.1$ dB/m [5] are used in our simulation. Our simulations, the magnitude and phase of the ac gain before and after irradiation, are shown in Figs. 4**a** and 4**b**. The frequency response is dependent on radiation dose and modulation frequency can also be obtained, and our simulations are in agreement with the experimental results.

In Figures 3**a** and 4**a**, the simulated magnitudes of the EDFA ac gain are higher than the experimental magnitudes. In Figures 3**b** and 4**b**, the simulated peak phases of the EDFA ac gain are located at 30 Hz modulation frequency, and the experimental peak phases are located at 70 Hz. The simulation parameters of the EDF could not match completely with the actual parameters. However, the total dose of radiation influences the magnitudes and peak phases of the EDFA ac gain, as shown in Figs. 5**a** and 5**b**, and the same trends can be obtained for the experiments and the simulations. For 10 krad irradiation, the variations between experiments and simulations are larger. The higher radiation-induced losses for 10 krad irradiation could be assumed. In

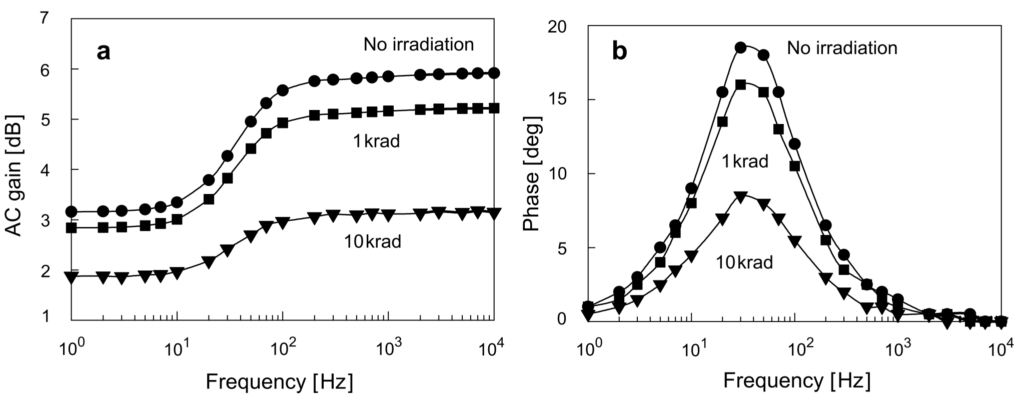

Fig. 4. Simulation of the frequency response of EDFA with irradiation effect: magnitude (**a**), phase (**b**).

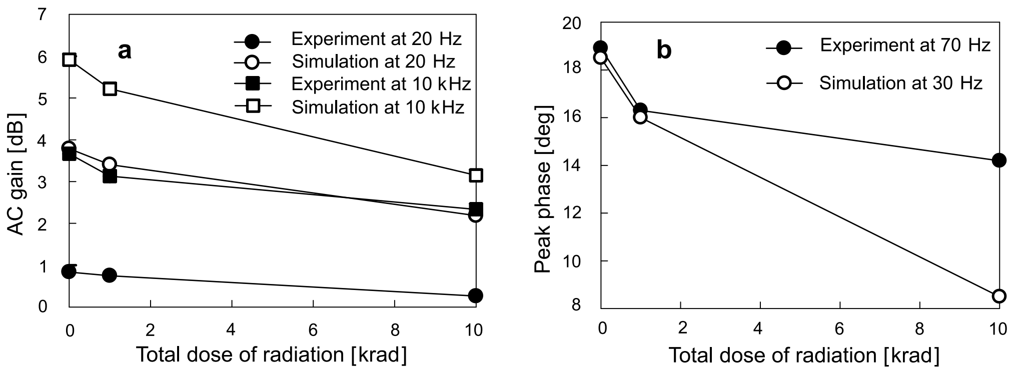

Fig. 5. Comparing experiments and simulations: magnitude of the ac gain at 20 Hz and 10 kHz (**a**), peak phase of the ac gain (**b**) *vs*. total dose of radiation.

addition, the amplified spontaneous emission of EDFA was not considered in our simulations, which could also be one of the factors responsible for the differences between experiments and simulations.

4. Conclusions

We had presented the dynamic gain of EDFA under gamma-ray irradiation. The two kinds of EDFs were used in our ac gain experiment of EDFA before and after irradiation. It is found that the ac gain reduction and the peak phase of EDFA dynamics are dependent on radiation dose and modulation frequency. The EDFA dynamics with irradiation effect were also simply simulated through the numerical calculation. The dynamic analyses of EDFA under gamma-ray irradiation are helpful to understand the transient behavior of the optical communications or sensors in a radiation environment.

Acknowledgements – The authors would like to thank Prof. Chou Chien of the Department of Medical Radiation Technology, Yang-Ming University, Taiwan, for his assistance with the irradiation experiment.

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Received January 5, 2010
in revised form June 8, 2010