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Radiation effects on the gain of thulium doped fiber amplifier: Experiment and modeling

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ABSTRACT

The optical elements which are placed in orbits around the earth can experience harsh radiation environments that originate from trapped-particle belts, cosmic rays and solar events. Therefore, it is crucial to study the effect of those events on the fiber amplifier devices. In the present paper, the thulium doped fiber amplifier (TDFA) has been irradiated by a neutron beam of different doses for various exposure times from an Am-241/Be-9 neutron source. The gain of the TDFA has been calculated theoretically and recorded after and before irradiation. The calculated results by the proposed model are in good agreement with the experimental ones. It indicates that the gain of TDFA deteriorates after being irradiated by a neutron dose. The gain of irradiated TDFA reduced to 17.1 dB at a dose of 720 Gy.

1. Introduction

The increasing in optical transmission capacity encouraged active researchers to expand the signal band. Recently, the S-band of wavelength ranges from 1460 to 1530 nm attracted a lot of attention as a candidate for the next generation communication band because of its low fiber loss and low dispersion close to C-band [1]. The thulium doped fiber amplifier (TDFA) is one of the most promising candidates, because it can cover almost the entire S-band and achieve high gain, high efficiency and low noise [2].

Radiation reduced the light-output and creates attenuation in optical emitters, detectors, amplifiers and couplers. However, as these components can often be set up in remote, shielded environments, they will not be considered in the present study [3]. Radiation exposure may induce color centers which affect the performance of the amplifier fiber by decreasing the small gain through absorption of the pump signal gain and the amplified signal which in turn decreases the output power [4].

In the present paper, we will expose the thulium doped fiber amplifier (TDFA) to a beam of neutrons emitted from Am-241/Be-9 neutron source in the Nuclear Laboratory, Faculty of Science, King Abdulaziz University, Jeddah. The effect of the neutron irradiation of different doses on the optical properties of the TDFA has been studied.

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2. Experimental method

The TDFA is pumped by a pump laser diode (wavelength 980 nm). The input power is varied from −40 dB to 5 dB. The pump light and signal light are lunched into the inputs of a wavelength division multiplexing (WDM) coupler as in Fig. 1. The TDFA is exposed to a neutron beam emitted from an Am-241/Be-9 neutron source of 5 Ci activity for different exposure times 1, 10, 20, and 30 days. The neutron source was calibrated by Amersham Ind., UK in 1987. The neutron spectrum in Fig. 2 indicates that Am/Be neutron energies range from about 2 MeV to 10 MeV and that approximately 23% of neutrons are of energies below 1 MeV [5]. The average neutron energy was taken to be 4.5 MeV as in [6].

The neutron emission rate from the source and its tolerance, the source strength, the half life, the peak thermal neutron flux, the capsule type, the source composition, and the moderator are listed in Table 1.The source mixture is doubly encapsulated in a vacuum melted stainless steel (grade AIS1.316) sealed by argon arc welding. A typical percentage composition is: C (0.004%); Mn (1.59%); P (0.011%); S (0.008%); Si (0.37%); Cr (16.96%); Ni (3.61%); Mo (2.29%); and Fe (65.16), [6]. Fine powder of AmO_2 is mechanically mixed with powdered Be (initial cluster size of 50 pmm) and compressed into cylindrical pellet (density 1.3 g/cm^3). The source is embedded in a Plexiglas and Lucite: $C_5H_8O_2$; density = 1.18 g/cm^3; A = 100.117 [8].

The overall diameter, overall height and wall thickness of the source are 30, 60 and 1.2 mm, respectively, as in Fig. 3a and b, [6, 7]. The measurements were carried out at the Nuclear Radiation Laboratory at the Physics Department, King Abdulaziz University, Jeddah, Saudi Arabia. The TDFA was counted at 5 cm from

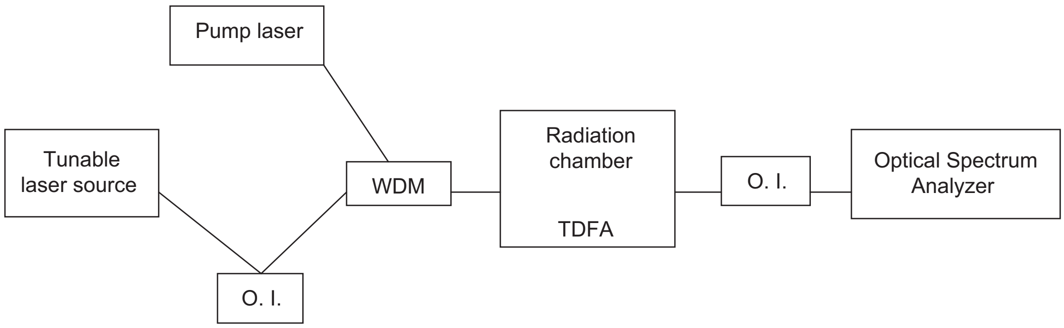

Fig. 1. TDFA experimental setup. (OI: optical isolator.)

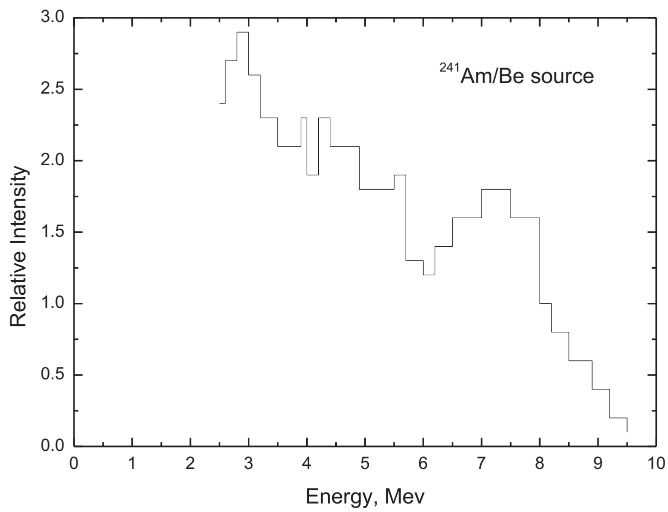

Fig. 2. The neutron spectrum Am-241/Be-9 [5].

the center of the neutron source. The emitted gamma rays from the neutron source has been shielded by 10 cm thickness lead bricks surrounded the source from all sides [9].

The neutron doses from the source were measured by a neutron monitor (Nuclear Enterprise, UK NM2) to be 24, 240, 480 and 720 Gy, respectively. This monitor was provided by the Radiation Safety Committee in King Abdulaziz University.

3. Mathematical method

The main transitions in energy levels for Tm^{+3} ions in fluoride are 0.48 μm, 0.8 μm, 1.47 μm, 1.9 μm, and 2.3 μm, as it has been shown in the thulium ion energy diagram, Fig. 4. In the present work, we focus on the stimulated emission from $^3H_4$ to $^3F_4$ for 1.4 μm band amplification. This method first excites the ground-state $^3H_6$ ions above the lower level ($^3F_4$) of the amplifying transition by one wavelength pumping and then excites the lower level ions above the upper level ($^3H_4$) of the amplifying transition by the same wavelength. The refractive index of the core of the fiber under the radiation effect could be calculated using Ref. [10].

The rate equation for the ion populations at each level are expressed as follows [11]:

$$\frac{dN_o}{dt} = -(W_{p01}+W_{s01}+W_{8a}+W_{18a})N_o+(A_{10}+W_{18e})N_1 + (A_{30}+W_{8e})N_3 \tag{1}$$

$$\frac{dN_1}{dt} = -(W_{p01}+W_{s01}+W_{18a}) + N_o-(A_{10}+W_{p13}+W_{s13}+W_{18e})N_1 + (A_{31}+W_{p31}+W_{s31})N_3 \tag{2}$$

$$\frac{dN_2}{dt} = W_{8a}N_o+(W_{p13}+W_{s13})N_1-(A_{31}+A_{30}+W_{p31}+W_{s31}+W_{8e})N_3 \tag{3}$$

where W_{p01} and W_{s01} are the pump and signal absorption rates by ground state ions, W_{p13}, and W_{s13} are the absorption rates in pump and signal band at the excited state. W_{p31} and $W_{s31}$are the emission rates in pump and signal band at the excited state. $W_{8a,18a}$ and $W_{8e,\ 18e}$ are the transition rates of amplified spontaneous emission (ASE) at wavelengths 800 and 1800 nm. A_{ij} is the spontaneous transition rate from level i to level j and N_t is the thulium ion concentration. The parameters used in the numerical simulation have been estimated by Scott et al. [11] and listed in Table 2.

If we assume that the TDF has zero background loss, we can define Tm^{+3} gain spectrum as follows [2]:

$$G(\lambda)=10\ \ \log\left\{\exp\int_0^l(\sigma_e N_2(z)-\sigma_a N_1(z))\Gamma_s dz\right\} \tag{4}$$

which can be simplified to [2]

$$G(\lambda)=4.3429\{(\overline{N_1}+\overline{N_2})(\sigma_e\times R-\sigma_a(1-R))\}\Gamma_s L \tag{5}$$

where σ_e is the stimulated emission cross section, σ_a is the absorption cross section, $\overline{N_1}$ is the average Tm^{+3} population of the lower level ($^3F_4$) for amplification per unit length, $\overline{N_2}$ is the average Tm^{+3} population of the lower level ($^3H_4$) for amplification per unit length,

$$\overline{N_1}=\frac{1}{L}\int_0^L N_2(z)dz \tag{6}$$

$$\overline{N_2}=\frac{1}{L}\int_0^L N_1(z)dz \tag{7}$$

The signal mode overlap factor with Tm^{+3} ion distribution, Γ_s is given by

$$\Gamma_s=(1-e^{-R^2/w^2}) \tag{8}$$

where r is the core radius and w is the spot size.

The noise figure could be calculated using [12]

$$NF=\frac{P_{ASE}}{h\gamma\Delta\gamma G}+\frac{1}{G} \tag{9}$$

where P_{ASE} is the noise power and it is equal $2n_{sp}h\gamma\Delta\gamma(G-1)$

4. Results and discussion

As the radiation is not a reversible process, the performance of the TDFA must be tested before it is exposed to the radiation. Fig. 5 shows the gain of the TDFA as a function of the wavelength. The solid line represents the experimental data, whereas, the symbols are for the present calculations for the wavelength in nanometers. Fig. 5 also shows the variation of the noise figure (NF) for all the wavelengths before the irradiation using Eq. (9). At wavelength