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Black box model and theoretical model investigation of gamma irradiated Yttria-alumina-silicate erbium doped fiber amplifier at 1540 nm

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A new method for calculating the gain of gamma irradiated Yttria- alumina silicate erbium doped fiber amplifier (GIEDFA) is purposed using a black box model (BBM) and compared with theoretical model at wavelength 1540 nm. Two important parameters which α and $P_{\max}$ are introduced in (BBM) and are also almost independent of wavelength 1540nm at the fixed radiation dose. Applying the BBM, we can estimate the gain in the wavelength of 1540nm easily, only by the parameters of α, $P_{\max}$ and the small-signal gain in corresponding wavelengths. The BBM gives a very good agreement results with the theoretical model, which affords a new way to characterize the gain deterioration characteristics of EDFA in radiation environment.

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1. Introduction

The transmission characteristics of optical fiber are very much influenced in radiation environment due to generation of radiation induced defect centers by ionization and atomic displacement within the molecular bonding network of silica (SiO2) glass [1, 2]. Radiation dose, dose rate and composition of fibers are the most important factors in the radiation effect on the EDFAs. A lot of teams have paid more attention to this field in recent years. The team of Griscom firstly proposed an origin of power-law dependence of concentration on dose and gave us a concise theory to explain the relationship between the radiation dose and the performance parameters of fibers [3]. Another two teams also reported the experiment results of gamma and proton radiation effect on EDFAs [4, 5].

In addition, experiment researchers further study on improving the radiation tolerance of the fiber amplifiers by direct nano-particle deposition technology or doping some ions in fibers [6-8]. In the last two decades much research work has been conducted to study the radiation effects on optical fibers for the purposes of: using fibers as the information transmission system under high radiation environments where the radiation resistance of the fibers is a key issue; and exploring the possibility of using this effect to fabricate fiber optic radiation sensors under various radiation environments, such as in nuclear waste tanks, nuclear reactors and radiation therapy, where higher loss in fibers due to the radiation field is favored.

The fibers that have been tested for sensing are mainly lead glass; Ge doped silica and pure silica fibers. The radiation effects on P-doped silica bulk materials and fibers have been reported and the absorption mechanism has been analyzed after high dose X-ray irradiation [9].

Erbium-doped fiber amplifier EDFA constitutes a subject of intensive research because of its application in many prospective telecommunication systems operating around 1.5 μm. It produces high powers and pulses energies. EDFAs are applied in optical communication system because of their attractive characteristics such as: high gain, wide optical bandwidth, high output saturation, near quantum noise, low insertion losses, high reliability and compactness, polarization independence, etc. The background environment plays a role in the variation of the systems normal parameters. For example, undersea cables are exposed to an accumulation dose in the range of 2.5rad and 25rad during the work life. Erbium doped fiber amplifier (EDFA) is proving to be one of the most important recent developments in the field of the optical fiber technology [10].

In the present study a black box model (BBM) and theoretical model comparison are introduced to characterize the gain of gamma irradiated Yttria alumina silicate erbium doped fiber amplifier at wavelength 1540 nm. The cross sections of absorption and emission of the glass doped are calculated for both cases, which the normal environment and gamma irradiated case, the BBM give a good agreement results with the theoretical model, which affords a new way to characterize the gain deterioration characteristics of EDFA in radiation environment.

2. Theory

2.1 Theoretical model

The refractive index of EDF can be expressed as a function of temperature T, operating optical signal wavelength and irradiation fluencies of rays as the following formulas [11, 12]:

$$n_o = A(T,\gamma) + \frac{B(T,\gamma)\lambda^2}{\lambda^2 - C(T,\gamma)} + \frac{D(T,\gamma)\lambda^2}{\lambda^2 - E} \quad (1)$$

The refractive index along the fiber length varies periodically in the form

$$n(z) = n_o + n_1(z)cos\left[\frac{2\pi}{\Lambda} + \Phi(z)\right] + n_2E^2(z) \quad (2)$$

where E(z) is the electric field, n_o is the average refractive index change of the fiber core, $n_1(z)$ is the amplitude of periodic index change, n_2 is the nonlinear Kerr coefficient, Λ is the Bragg period and Φ(z) describe the phase shift.

The absorption and emission cross sections could be calculated for EDFA using [13]

$$\sigma_{a,e} = \frac{\lambda^2}{8\pi n^2 \tau \Delta\upsilon} g_{a,e}(\lambda) \quad (3)$$

where $g_{a,e}$ is the normalized absorption and emission line shape function (Gaussian line shape), Δν is the band width of the line shape, τ life time of the atoms in the meta-stable state and n is the refractive index of the medium.

Considering for simplicity the three energy levels of erbium reduced to two levels, the propagation equations for pump, signal and amplified spontaneous emission (ASE) powers can written as [14-16]

$$\frac{dP_p(z,t)}{dz} = -P_p\Gamma_p\left(\sigma_a^p N_1 - \sigma_e^p N_2\right) - \alpha_p P_p \quad (4)$$

$$\frac{dP_s(z,t)}{dz} = +P_s\Gamma_s(\sigma_e^s N_2 - \sigma_a^s N_1) - \alpha_s P_s \quad (5)$$

$$\frac{dP_{ASE}(z,t)}{dz} = +P_{ASE}\Gamma_s(\sigma_e^s N_2 - \sigma_a^s N_1) + 2\sigma_e^s N_2 \Gamma_s P_{ASE} - \alpha_s P_{ASE} \quad (6)$$

Here $\sigma_a^{p,s}$ is the absorption cross section for pump and signal respectively, $\sigma_e^{p,s}$ is the emission cross section for pump and signal respectively $\Gamma_{p,s}$ is the overlap factor for pump and signal respectively and α_p, α_s are the fiber loss for the pump and signal respectively.

The gain of the amplifier is the ratio of the output power P_{out}^s to the input power P_{in}^s which is given by solving equations (4, 5 and 6) analytical result in [16]:

$$G = \exp(-\alpha_s L) \times exp\left[\frac{h\nu_s}{P_{in}^s}\left(\frac{P_p(0) - P_p(L)}{h\nu_p} + \frac{P_s(0)}{h\nu_s}(G-1) - \frac{P_{ASE}^+(L)}{h\nu_s}\right)\right] \quad (7)$$

The typical EDFA parameters used in calculation of the gain for normal environment, at 240 Gy and 400 Gy dose of gamma radiation are given in Tables 1, 2 and 3.

2.2. Black box model

We find that Zhang has advanced a black box model for the gain of erbium-doped fiber amplifiers in the wavelength of 1540–1560 nm in normal environment [17]. The black box model is an empirical formula, and it is based on the assumption of gain tilt function [17-20]. The gain behavior with input signal power can be described by the formula [17]:

$$G = \frac{G_o}{1+\left(\frac{P_{in}}{P_{sat}}\right)^\alpha} = \frac{G_o}{1+\left(\frac{G_oP_{in}}{P_{max}}\right)^\alpha} \quad (8)$$

G_o and G are the small- signal gain and the saturated gain for a given input signal power P_{in}, respectively, α and P_{max} are two unknown parameters which characterize the gain saturation. $P_{max} = G_o P_{sat}$, representing the maximum output power of the amplifier. The parameters α and P_{max} can be calculate using the fitting methods for normal environment and irradiated gamma.

Table 1. Typical EDFA parameters used in calculation for normal environment.

Parameter	Symbol	Value	Unit
EDFA length	L	15	m
Core radius	a	1.346	μm
Er density	ρ	2.4×10^{25}	m^{-3}
Numerical aperture	NA	0.3618	
refractive index of the fiber core	n	1.46	
Host glass material	Silica-based		
Pump-fiber overlap factor	Γ_p	0.4	
Signal-fiber overlap factor	Γ_s	0.4	
Signal absorption cross section	σ_a^s	5.1×10^{-25}	m^2
Pump absorption cross section	σ_a^p	0.75×10^{-25}	m^2
Signal emission cross section	σ_e^s	5.22×10^{-25}	m^2
Pump emission cross section	σ_e^p	0.19×10^{-25}	m^2
Pump wavelength	λ_p	980	nm
Signal Wavelength	λ_s	1540	nm
Background loss at pump wavelength	α_p	0.25	dB/Km
Background loss at signal wavelength	α_s	0.25	dB/Km
life time of Er ions	τ	10.3	ms
output ASE power	$P_{ASE}(L)$	0.15	mW
Co-dopants	yttria/Alumina		

Table 2. Modified EDFA parameters used in calculation for gamma irradiated at 240 Gy.

Parameter	Symbol	Value	Unit
refractive index of the fiber core	n	1.4813	
Signal absorption cross section	σ_a^s	4.51×10^{-25}	m^2
Signal emission cross section	σ_e^s	4.62×10^{-25}	m^2
Background loss at pump wavelength	α_p	0.75	dB/Km
Background loss at signal wavelength	α_s	0.75	dB/Km
Nonlinear term	n_2	2.5×10^{-20}	m^2/W

Table 3. Modified EDFA parameters used in calculation for gamma irradiated at 400 Gy.

Parameter	Symbol	Value	Unit
refractive index of the fiber core	n	1.4815	
Signal absorption cross section	σ_a^s	4.08×10^{-25}	m^2
Signal emission cross section	σ_e^s	4.17×10^{-25}	m^2
Background loss at pump wavelength	α_p	0.77	dB/Km
Background loss at signal wavelength	α_s	0.77	dB/Km
Nonlinear term	n_2	2.5×10^{-20}	m^2/W

3. Results and discussion

In our calculation we chose two operating doses of gamma irradiation which 240 Gy and 400 Gy [17], the normalized line shape function for cross section calculation was chosen as Guassian line shape, which matched with experimental cross section data [21]. The cross section of absorption and emission gamma irradiated Yttria-alumina silicate erbium doped fiber amplifier are calculated respectively according to equations 1-16 and the corresponding values of them at wavelength 1540 nm are represented in Tables 2 and 3 for the two operating doses of gamma irradiation which 240 Gy and 400 Gy.

Using the equations in 1-8 in our model we can represent the change in the core refractive index for Yttria-alumina silicate erbium doped fiber plotted against the gamma irradiation doses as in Fig. 1. There is a slight increase in the core refractive index with the gamma dose variation from 0 to 1 MGy, where the fiber cable maintained at room temperature and the signal wavelength in the erbium window for telecommunications (1.54 µm).

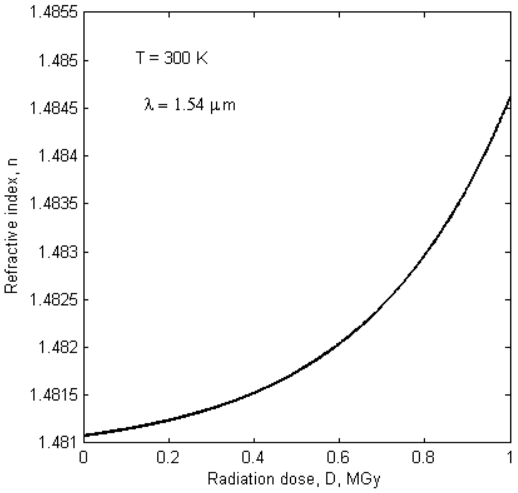

Fig. 1. Change in core refractive index against gamma irradiation dose.

Fig. 2 shows the predicted data for the gain of Yttria-alumina silicate erbium-doped fiber amplifier against the input power, for normal environment and for gamma irradiated at 240 Gy and 400 Gy, according to the theoretical model calculation t 1540 nm. As in the Fig. 2, the gain is constant for input power from (-60 dBm to +5 dBm) for both normal ad irradiated environment, also the figure shows that the effect of gamma irradiation doses make the gain decreases as the doses increase.

Fig. 3 shows the predicted data and the black box model data for the gain against the input power of our amplifier for normal environment at 1540 nm, from the figure, there is a very good agreement between BBM and theoretical model and the values of fitted parameter of BBM are given in Table 4. Fig. 4 and Fig. 5 both show a very good agreement between BBM and theoretical model for 240 Gy and 400 Gy gamma irradiated of the gain of Yttria-alumina silicate erbium-doped fiber amplifier respectively, also the fitted parameter of BBM for both 240 Gy and 400 Gy respectively are given in Table 4.

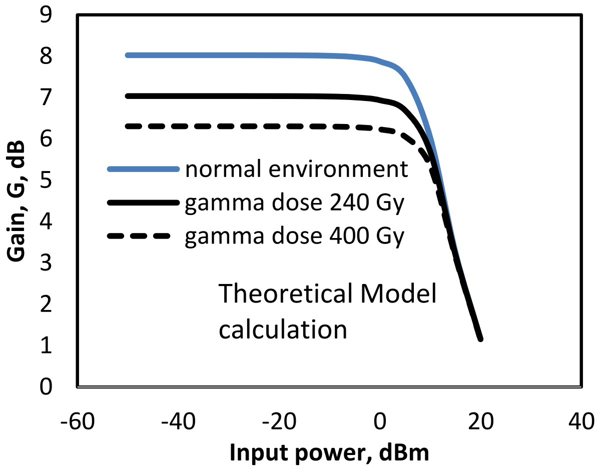

Fig. 2. Gain of Yttria-alumina silicate edfa with input power at 1540 nm for normal and irradiated gamma at 240 and 400 Gy.

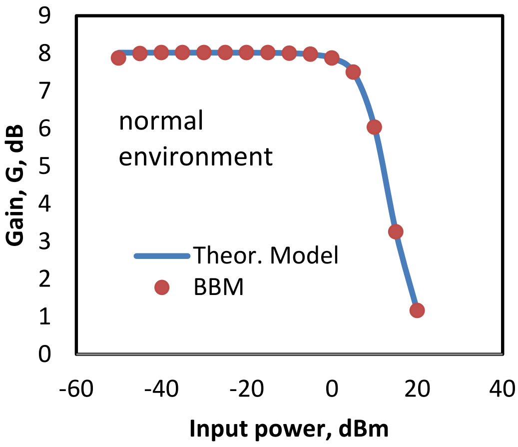

Fig. 3. Gain of Yttria-alumina silicate edfa with input power at 1540 nm for normal environment using both theoretical and black box model.

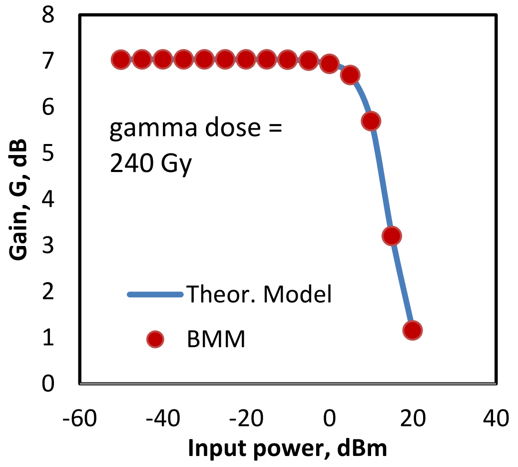

Fig. 4. Gain of Yttria-alumina silicate edfa with input power at 1540 nm for 240 Gy gamma irradiated using both theoretical and black box model.

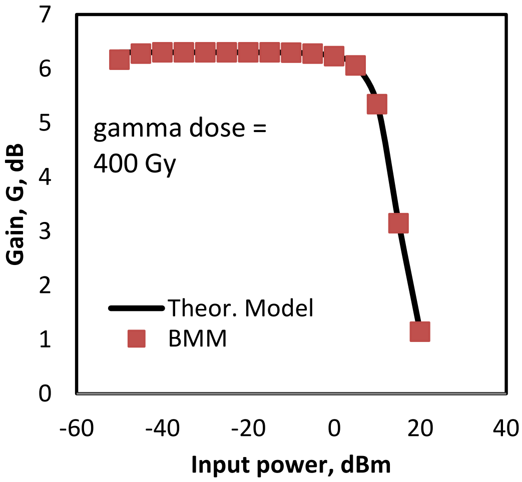

Fig. 5. Gain of Yttria-alumina silicate edfa with input power at 1540 nm for 400 Gy gamma irradiated using both theoretical and black box model.

Table 4. The unknown parameters which characterize the gain of the BMM.

Fitting parameters	Normal environment	Gamma dose at 240 GY	Gamma dose at 400 GY
α	2.45	4.44	4.2
P_{max}(dBm)	20.34	40.14	33.32

4. Conclusion

A black box model (BBM) and theoretical model comparison are introduced to characterize the gain of gamma irradiated Yttria- alumina silicate erbium doped fiber amplifier at wavelength 1540 nm. It means the parameters of α and P_{max} are also almost independent of wavelength 1540nm at the fixed radiation dose. Applying the BBM, we can estimate the gain in the wavelength of 1540nm easily only by the parameters of α, P_{max} and the small-signal gain in corresponding wavelengths. That can overcome the restriction of the measured time in radiation environment. The BBM gives a very good agreement results with the theoretical model, which affords a new way to characterize the gain deterioration characteristics of EDFA in radiation environment.

Appendix

$$A(T,\gamma) = A(\gamma)F_A(T) \qquad \text{(i)}$$

$$A(\gamma) = 1.329631 + 2.7 \times 10^{-4}\exp(\frac{\gamma}{0.319319}) \qquad \text{(ii)}$$

$$F_A(T) = 1.338922 - \frac{3.7\times10^{-4}(T-T_0)}{1.338922} \qquad \text{(iii)}$$

$$\text{Also, } B(T,\gamma) = B(\gamma)F_B(T) \qquad \text{(iv)}$$

$$B(\gamma) = 0.82863 + 7.7 \times 10^{-4}\exp(\frac{\gamma}{0.440013}) \qquad \text{(v)}$$

$$F_B(T) = 0.819562 - \frac{3.84\times10^{-4}(T-T_0)}{0.819562} \qquad \text{(vi)}$$

$$\text{With, } C(T,\gamma) = C(\gamma)F_C(T) \qquad \text{(vii)}$$

$$C(\gamma) = 0.01105 + 4.7 \times 10^{-6}\exp(\frac{\gamma}{0.391139}) \qquad \text{(viii)}$$

$$F_C(T) = 0.011127 - \frac{3.1\times10^{-6}(T-T_0)}{0.011127} \qquad \text{(ix)}$$

$$\text{Finally, } D(T,\gamma) = D(\gamma)F_D(T) \qquad \text{(x)}$$

$$D(\gamma) = 0.98481 + 1.1 \times 10^{-3}\exp(\frac{\gamma}{0.964926}) \qquad \text{(xi)}$$

$$F_D(T) = 1.055995 - \frac{2.8\times10^{-3}(T-T_0)}{1.055995} \qquad \text{(xii)}$$

And, E = constant = 100 μm^2

Where, T is the ambient temperature in K, and T_0 is the room temperature in K.

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