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The Band Width Reduction of Gamma Irradiated Erbium Doped Fiber Amplifier

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ABSTRACT

We present the wavelength and radial distribution of the core-graded index and concentration of erbium under gamma irradiated Erbium Doped Fiber Amplifier (EDFA), we considered EDFA in a two-level model under single-mode condition and weakly guided approximation, the gamma dose was chosen between 0 and 1 MGy. There is evidence to show that the irradiated core graded-index has obvious influence on the gain bandwidth of EDFA, and similarly, the radial distribution of the irradiated erbium concentration has effect on the gain bandwidth, while no effect on the gain, also a comparison between the irradiated and un-irradiated core-index and concentration of EDFA has been investigated. As a result, the gain bandwidth of irradiated EDFA is decreased than those of un-irradiated.

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INTRODUCTION

Erbium-doped fiber amplifiers (EDFAs) have received great attention over the past years due to their advantages, high gain, broadband, low noise and high efficiency. Current performance of a single fiber EDFA possesses ~35 dB gain, ~25 nm bandwidth and the lowest quantum noise threshold of ~3 dB. As a key device, EDFA configures wavelength division multiplexing systems (WDMs) in optical telecommunications, finding diverse applications in lasers, switches and a variety of nonlinear devices (Cheng Cheng, *et al*., 2013). This performance can be affect by many factors, like radiation by gamma source, which is the most energetic form of electromagnetic radiation (Taymour A. Hamdalla, 2013). 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. (M. C. Paul *et al*., 2000). In this paper the wavelength and radial distribution of the core-graded index and concentration of erbium for un-irradiated (Osama Mahran, 2010) and under gamma irradiated Erbium Doped Fiber Amplifier (EDFA) is investigated, also a comparison between the irradiated and un-irradiated core-index and concentration of EDFA has been calculated.

Theory:

The gamma radiation is affecting the core-refractive index as [(M. Medhat *et al*., 2002), (Ahmed Nabih Zaki Rashed, 2012)]. The two- level modeling of EDFA is sufficient to describe the optical power propagation in the fiber (Long Zhang *et al*., 2001), with a circularly symmetric fiber, considering radial effects; the power propagation equation in a two-level system is given by (Cheng Cheng and Min Xiao, 2005),

$$\frac{dP_k(z)}{dz} = u_k\sigma_{ek}\int_0^a i_k(r,t)n_2(r,z,t) \times [P_k(z) + mh\nu_k\Delta\nu_k]2\pi r dr - u_k\sigma_{ak} \times \int_0^a i_k(r,t)n_1(r,z,t)P_k(z)2\pi r dr - u_k I_k P_k(z) \qquad (1)$$

where P_k is the power propagated in the fiber with the frequency ν_k, each beam is traveling either in the forward ($u_k = +1$) or backward ($u_k = -1$) direction; $\sigma_{ek}(\sigma_{ak})$ is the emission cross section (absorption cross section); i_k is the normalized transverse mode intensity, $n_{1,2}$ are the populations of the ground level $^4I_{15/2}$ and the upper-level $^4I_{13/2}$, respectively, I_k is the excess fiber loss per length and $\Delta\nu_k$ is an effective noise bandwidth, $mh\nu\Delta\nu_k$ is the contribution of spontaneous emission from local n_2 population, m = 2 (for both forward and backward

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component of amplifier spontaneous emission (ASEs). In Eq. (1), the first term is the contributions from the emission and spontaneous decay, the second term is from the absorption loss, and the last one represents propagation loss in the fiber. Note that Eq. (1) has a modification from (Cheng Cheng and Min Xiao, 2005) by adding the radial distribution.

For high concentration of erbium, the rate equation for the population of the erbium upper-level $^4I_{13/2}$ can be written as follows

$$\frac{\partial n_2(r,t)}{\partial t} = \sum_k \frac{P_k i_k \sigma_{ak}}{h\nu_k} n_1 - \sum_k \frac{P_k i_k \sigma_{ek}}{h\nu_k} n_2 - \frac{n_2}{\tau} - C_{22} n_2^2 \equiv S_{ak} n_1 - S_{ek} n_2 - \frac{n_2}{\tau} - C_{22} n_2^2 \quad (2)$$

Table 1: The working parameters of the EDFA used in the modeling(Cheng Cheng and Min Xiao, 2005).

pumping power, P_p(mW)	Signal power, P_s(dBm)	Upper level lifetime, τ(ms)	Rate coefficient, C_{22} (cm^3/s)	Fiber loss, I_k(dB/m)	Refractive index difference, Δn	Core radius a (μm)	fiber length(m)
50	-30	10	1.5x10^{18}	0.03	0.0063	4.1	50

where τ is the lifetime of the metastable level, C_{22} is the coefficient of the cooperative up-conversion, $i_k = i_k(r,t)$, $n_{1,2} = n_{1,2}(r,t)$. With steady-state approximation, we have

$$n_2(r) = \frac{1}{C_{22}}\left\{\left[\left(S_{ak} + S_{ek} + \frac{1}{\tau}\right)^2 + 4C_{22}E_r(r)S_{ak}\right]^{1/2} - \left(S_{ak} + S_{ek} + \frac{1}{\tau}\right)\right\} \quad (3)$$

Table 2: the optimized values of α, β and δ of the EDFAs (Cheng Cheng and Min Xiao, 2005).

Central concentration E_{r0}(cm^{-3})	β(μm)	δ	α	pump wavelength, λ_p(nm)
6.43x10^{19}	1.846	1.820	0.108	1503.4

where the total concentration $E_r(r) = n_1 + n_2$ and the working parameters of EDFA are given in table 1 (Cheng Cheng and Min Xiao, 2005).

We use an exponential function as follows

$$E_r(r) = E_{r0} \exp\left(-\frac{r}{\beta}\right)^{\delta} \quad (4)$$

where E_{r0} is the center concentration, β and δ are the parameters optimized in (Cheng Cheng and Min Xiao, 2005) and is given in table 2. The core radius as a function of the core-refractive index is given as [4]

$$r = a\left[1 - \frac{1}{2\Delta n}\left(\frac{n_{core}^2}{n_{clad}^2} - 1\right)\right]^{1/\alpha} \quad (5)$$

where a is the fiber core radius and Δn is the relative refractive-index difference, α is also optimized parameter given in (Cheng Cheng and Min Xiao, 2005). The modeling subjects to two premises: (1) a weakly guided approximation; (2) a signal single mode condition, by choosing the refractive difference Δn = 0.0063 and the core radius a = 4.1 μm, to be consistent with the current fiber data of the Lucent. Only the positive pumping direction, i.e. u_k = +1 in Eq. (1), is implemented in the current work. Under the condition of the constant pumping power and signal power, the optical power P_k in Eq. (1) depends on seven parameters (Er_0, β, δ, α, γ, L and λp), in which L is the length of the fiber, and λp is the pumping wavelength, for constant temperature 25 C^0 and signal wavelength 1.53 μm (Cheng Cheng and Min Xiao, 2005).

The objective function used in calculation the gain and band width of EDFA [(D. S. Weile and E. Michielssen, 1997), (D.E. Goldberg,1989), (Christof Strohhöfer and Albert Polman,2001)] is given as

$$f_{obj} = \Delta(E_{r0}, \beta, \delta, \alpha, \gamma, L \text{ and } \lambda p) + \eta G_s(E_{r0}, \beta, \delta, \alpha, \gamma, L \text{ and } \lambda p) \quad (G_s > 30dB) \quad (6)$$

where Δ is the =3 dB bandwidth, G_s is the signal gain and c is introduced to balance the desired gain and bandwidth for the amplifier. Choosing different η values meet different requirements for reaching a high gain and/or a broadband, here we choose η = 0.17 nm/dB.

RESULTS AND DISCUSSION

Using the equations in (5, 6) in our model we can represent the change in the core refractive index 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 (1.53 μm).

Fig. 2 shows the change in erbium concentration with the gamma dose, the gamma radiation was changed the mechanical properties of the core, which change the refractive index and so on the concentration of the erbium.

Fig. 3 shows the effect of gamma radiation (through radial distribution) on the gain bandwidths. The signal gain was chosen in our model 33.5 dB, for unirradiated fiber, the bandwidth was 30 nm, as the cable irradiated the bandwidth of the gain begin to decrease from 26.2 nm at 0.1 MGy to 18.1 nm at 1 MGy. Based on these data, one can expected that the total erbium concentration is a key to determine gain bandwidth in the EDFA, which strongly affected by gamma irradiation.

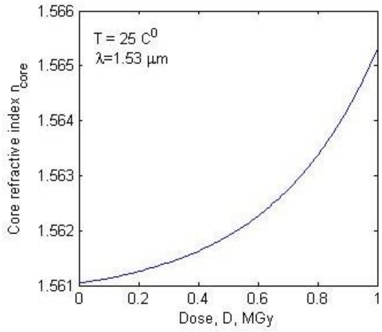

Fig. 1: Change in core refractive index against gamma irradiation dose.

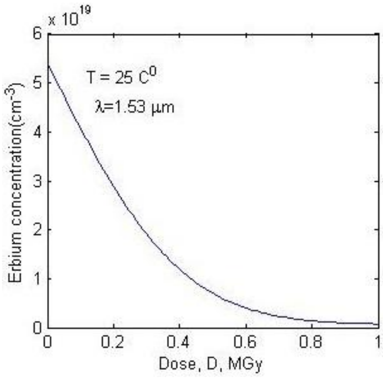

Fig. 2: Change in erbium concentration against gamma irradiation dose.

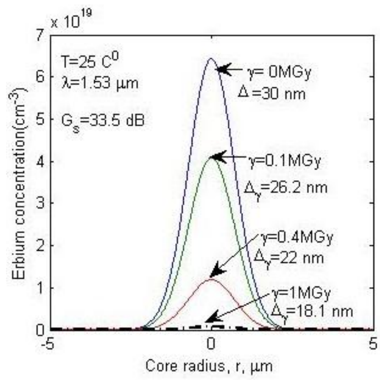

Fig. 3: The effect of gamma doses on the bandwidth of EDFA.

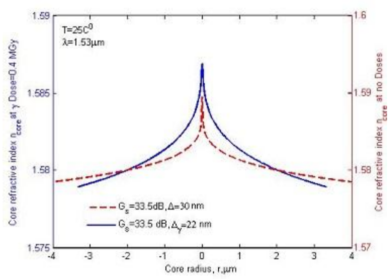

Fig. 4: Comparison of the radial profile of the unirradiated core refractive index and irradiated one at 0.4 MGy doses of gamma.

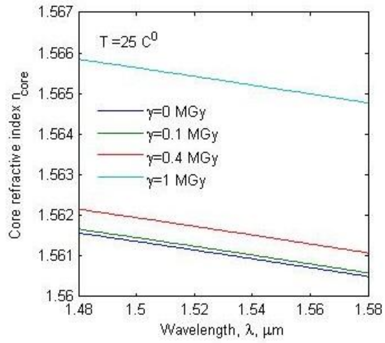

Fig. 5: The wavelength profile of the core refractive index under effect of gamma doses.

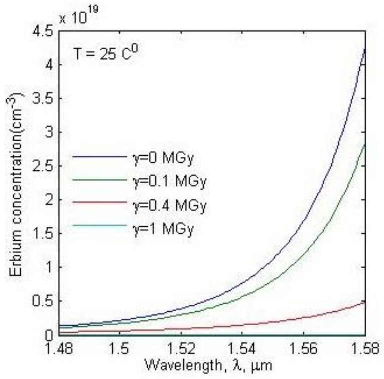

Fig. 6: The wavelength profile of the erbium concentration under effect of gamma doses.

The comparison of the radial effects of unirradiated and irradiated core refractive index on the gain bandwidth is shown in fig.4, where the EDF is irradiated at 0.4 MGy. The effect of gamma is decreasing the gain bandwidth to 22 nm but no effect on the gain of the amplifier.

The wavelength profile of both core refractive index and erbium concentration, under the effect of gamma doses is represented in fig. 5 and fig.6. no change of the gain of the amplifier under the effect of gamma irradiation, but the effect only on the band width of the amplifier.

Conclusion:

The gain bandwidth of the erbium doped fiber amplifier plays an important role in the wavelength division multiplexing (WDM), so we must study and explain the effect of the parameters that affected this bandwidth and from these parameters, the gamma irradiation.

The radial distributions of an un-irradiated and irradiated EDFA were investigated by solving optical propagation equations and rate equations in a two-level model.

An analytical method developed to study the effect of gamma irradiation on the gain bandwidth of the EDFA through radial and wavelength distribution of the core refractive index and erbium concentration, in summary, the gamma irradiation produce defects in the EDFA performance which decrease the gain bandwidth of the amplifier, but produce no effect on the gain itself. This defect is very important to study, because we need large gain bandwidth to make better (WDM) in fiber communications.

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