ISSN: 2278 – 1323
International Journal of Advanced Research in Computer Engineering &Technology (IJARCET)
Volume 2, Issue 11 , November 2013

Modeling of Radiation Induced Attenuation and its Recovery in Optical Fibers

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Abstract*- Ge-doped-silica core optical fibers are studied. One of the most important harmful effects of radiation on optical fibers is that the radiation induced transmission loss in optical fibers. A block diagram model of the radiation induced transmission loss at 850 nm is developed by using VisSim environment. The model results show the attenuation induced absorption in optical transmitted signal. Moreover they show also the post-irradiation recovery forecasting which occurs as a result of the recombination process that take place after radiation exposure. In addition this formulated treatment provides the ability of choice the operating wavelength that achieves minimum attenuation along the optical fiber when used in radiation environments. The results are validated against published experimental work and showed good agreement.

Keywords*— Gamma radiation, Ge-doped-silica optical fiber, Radiation induced attenuation, Recovery process.

I. INTRODUCTION

Optical fibers are materials with a high refractive index used to transmit data in the form of light over long distances [1]. They have a number of well-known advantages with respect to the traditional forms of data link including [2], no electrical noise [3], ease of integration [4], and low loss of transmitting signals [5]. Moreover they are light weight, insulating characteristic, and a wide optical signal band [6]. Furthermore a considerable cost reduction is expected in constructing a communication system utilizing these optical fibers [7]. Due to these advantages optical fibers may be employed in a number of environments where they could be exposed to ionizing radiation under a wide variety of exposure conditions. In space applications, or when employed in nuclear reactor operations, high doses may be accumulated over several years [8]-[9]. However when optical fibers are used under radiation environments they have the disadvantage that an increase of the radiation induced transmission loss [10]-[24]. Moreover the degree of these losses dependent on the radiation source, dose rates, temperature, fiber material, fiber dimension, dopant concentration in the core and cladding [25]. In addition it also dependent on the composition of the silica glass, and total accumulated dose [26]. These losses can be attributed to the two basic interactions occur between the impinging radiation and the glass-atoms can be displaced by elastic scattering and electrons can be ionized. Most of the electrons freed as a result of ionization ultimately recombine with holes in the glass matrix, but some small fraction of the electrons traveling through the glass can become trapped at structural defect sites [27]-[28]. Such as E' centers, non-bridging-oxygen hole centers, per-oxy radicals, and self-trapped holes. However, the best known defect is E' center, which plays a major role in the radiation-induced transmission loss for silica optical fibers and therefore various degradation effects [29]-[34].Furthermore these defects cause absorption at the midinfrared wavelengths commonly used for data transmission (0.85, 1.3, and 1.5 pm) [27]. Among the different classes of fibers, the Ge doped is the most used type, mainly for telecommunications applications. Ge doping was first used to increase the refractive index of the inner part (core) of the fibers with respect to that of their external part (cladding) to ensure the light guiding. The fiber radiation responses, and particularly the one of Ge doped waveguides, have been widely investigated [35]-[36]. Moreover graded index (GI) fibers that are only doped with Germanium (Ge) are often designated as radiation hard [37]. Furthermore optical fibers can exhibit some recovery phenomena of the radiation induced optical attenuation [38]. Thus, it is vital to know the attenuation characteristics of the optical fibers that resulted from its exposure to ionizing radiation [16]. Consequently, we are interested with evaluation of transmission loss that enables us to calculate the degradation that occurs in optical fiber transmission characteristics under irradiation environment. In addition, it allows predicting operating wavelength and radiation harmful effects. The arising effects of radiation are indispensable in designing high-bit-rate optical communication systems. VisSim is a visual block diagram language for simulation of dynamical systems and model based design of embedded systems. It uses a graphical data flow paradigm to implement dynamic systems based on differential equation. This allows easy modeling of state based systems. In an engineering context, instead of writing and solving a system of equations, model building involves using visual "blocks" to solve the problem. The advantage of using models is that in some cases problems which appear difficult if expressed mathematically may be easier to understand when represented pictorially.

This paper is organized as follows: Section II presents the basic assumptions and modeling of radiation induced attenuation, Section III describes the model results. However section IV is devoted to conclusion.

II. BASIC ASSUMPTIONS AND MODELING OF RADIATION INDUCED ATTENUATION

In this paper a block diagram model is built by using VisSim environment to analyze radiation damage data induced by gamma radiation in Ge-doped- silica core and a pure silica cladding multimode optical fiber with a light source operates at 850 nm and radiation dose rang from 0.1-100 krad and assuming that the fiber length is short enough so that there is no loss of fiber before irradiation, no fluctuation of light sources and the sources are assumed to overfill the fiber taking into account the defect concentration, the probability of defect generation and the characteristic lifetime of the defect. In addition in this model we assume that the production rate constant and a recombination rate constant are time invariant but depend on dose, dose rate, and kinetic order. The model has also been used successfully to analyze radiation damage data of other multimode and single mode fibers. Furthermore the analyzed data on thousands of condensed matter samples and tens of relaxation phenomena have appeared to be described by a single "universal" relation [39].

$$A(t) = A_o \exp\left[-\left(\frac{t}{\tau}\right)^{\alpha}\right] \quad (1)$$

Where A(t), t, α are the measured quantity, the observed time constant, and a constant number between 0 and 1, respectively. Moreover a separate phenomenon has often been reported in the literature usually, though not always without any attempt at interpretation. This phenomenon is defect growth kinetics which can be represented by power-law model that taking the following form [40].

$$A(D) = CD^{f} \quad (2)$$

where D is the radiation dose and C, f(<l) are empirical constants. However the post-irradiation thermal decay of the attenuation has exhibited "stretched" behaviors as follows [39].

$$\frac{dA}{dt} = -RA^{n} \quad (3)$$

where R is a constant. In addition by differentiating equation (2) we will obtain an empirical growth rate equation as follows [39].

$$\frac{dA}{dt} = CfD^{f-1}D^{\bullet} \quad (4)$$

where $D^{\bullet}$ is the dose rate. Moreover we will use the rate equation that has the following form in classical nth order kinetics [39].

$$\frac{dA}{dt} = KD^{\bullet} - RA^{n} \quad (5)$$

where K and R is the production rate constant and a recombination rate constant respectively. In addition by equating the right-hand sides of equation (4) and equation (5) we will obtain the following formula for the recombination rate as follows [39].

$$R = A^{n}\left(K - CfD^{f-1}\right)D^{\bullet} \quad (6)$$

However the first order kinetic formulation for defect generation can be considered as follows [41].

$$K = \frac{dN}{dt} = aD^{\bullet} - \frac{N}{\tau} \quad (7)$$

where N, $D^{\bullet}$, τ and a is the defect concentration, the dose-rate, the probability of defect generation and the characteristic lifetime of the defect respectively. Moreover for an isothermal, constant dose-rate regime, the solution of equation (7) is a saturating exponential of the form [41].

$$N = aD^{\bullet}\tau\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \quad (8)$$

Moreover the characteristic lifetime of the defect, τ, for the case of n=1 can be represented as follows [39].

$$\tau = \frac{t}{(1-f)} \quad (9)$$

Furthermore equation (1) can be simplified as follows [39].

$$A = KD = CD^{f} \quad (10)$$

Furthermore from equation (6) we can eliminate (D and A) to obtain the following equation that illustrate the dependence of R, on K as follows [39].

$$R = K^{\frac{[f(1-n)-1]}{(f-1)}} C^{\frac{n}{(f-1)}} (1-f)D^{\bullet} \quad (11)$$

However by using the standard n' order kinetic solution for n >1 we obtain the prediction of post irradiation recovery as follows [39].

$$A(t) = A_o\left\{1 + (n-1)A_o^{n-1}Rt\right\}^{\frac{1}{(1-n)}} \quad (12)$$

Where $A_o = CD^{f}$ and R is the recombination rate constant. However the characteristic lifetime of the defect, τ, for the case of n>1 can be represented as follows [39].

$$\tau = \frac{t}{(1-f)(n-1)} \quad (13)$$

III. MODEL RESULTS

Radiation induced attenuation is the fundamental harmful effect of thermal irradiation environments on optical fibers. Consequently this model is used to evaluate the data damage and optical loss that occurs in optical fiber communication systems in thermal irradiation environment. In addition the model also provides a mean to predict the post irradiation recovery that occurs after radiation interruption. Moreover it provides the ability of choice the operating wavelength that achieves minimum attenuation along the fiber length. A light emitting diode (LED) light source was used since it is a common source for short distance multimode applications. The two wavelengths chosen, 850 nm and 1310 nm, are two conventional infrared wavelength windows used for silica fibers to reduce information (pulse) losses. The reference values of these parameters are shown in Table 1. These values of the calculations are taken from [39-41].

ISSN: 2278 – 1323
International Journal of Advanced Research in Computer Engineering &Technology (IJARCET)
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Table 1: Operating parameter's values used in the model were as the following:

Operating parameter	Symbol	Value
Radiation dose	D	0.1-100 krad
Optical signal wavelength	λ	850-1310 nm
Radiation dose rate	$\dot{D}$	0.1- 100 krad/min
probability of defect generation	a	100%.

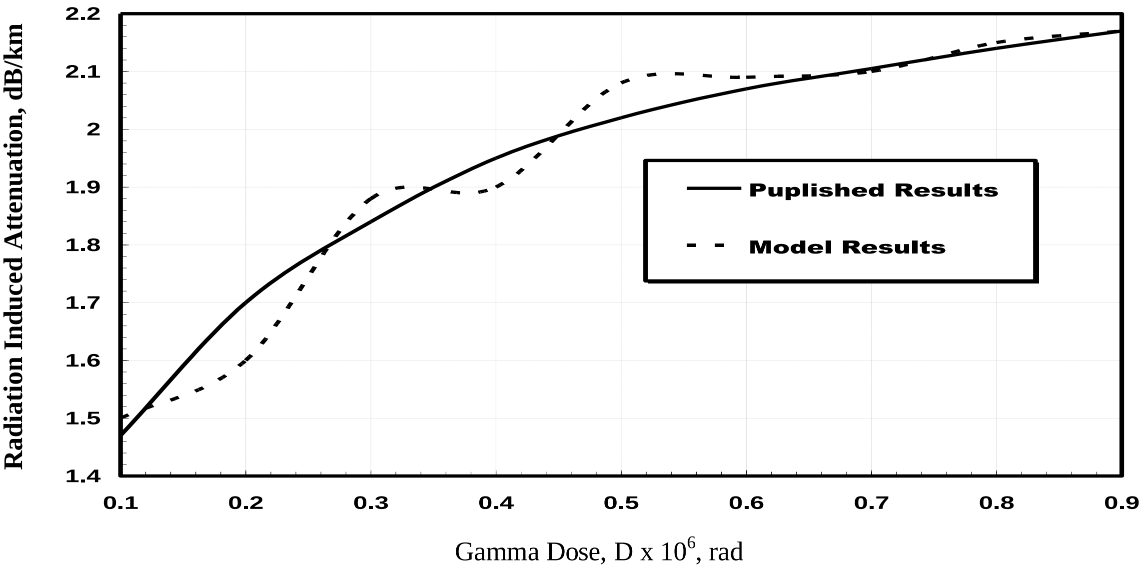

Fig.1. Variations of the radiation induced attenuation against gamma dose with operating wavelength= 850 nm and dose rate =0.1 krad/min.

In figure (1) the typical computed values for the radiation induced attenuation of a Ge-doped-silica multimode optical fiber as a function of gamma dose at 850 nm light source, and experimental values are represented in the above figure that shows a good agreement between the resulted curve and the published experimental curve.

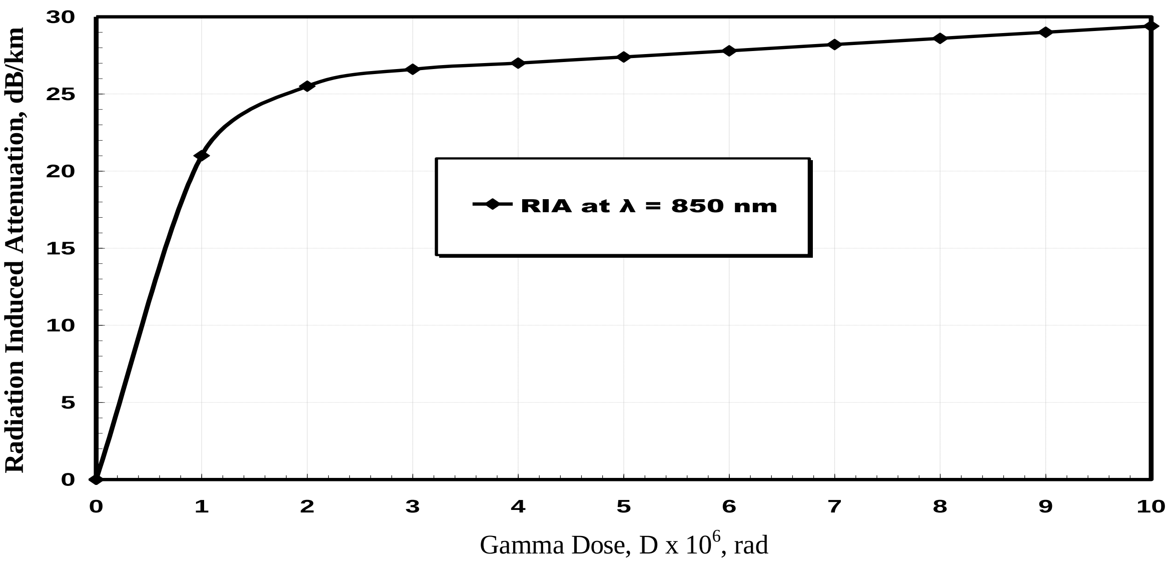

Fig.2. Variations of the attenuation against gamma dose with operating wavelength= 850 nm, dose rate =0.1 (krad/min) and probability of defect generation = 100%.

Figure (2) depicts the relation between the attenuation and radiation dose from the figure we note that radiation induced attenuation in optical fiber increases with increasing the radiation dose. This result can be accredited to the radiation creates free electrons by radiolysis that can activate pre-existing point defects that then begin to absorb photons of a specific energy. It can also create totally new point defects that are then populated by radiolysis electrons. Moreover as radiation dose increase, the point defects increase that result in increasing signal attenuation as it travels along the fiber. The reference values of power law parameters used in the model are shown in Table 2. These values are taken from [40].

ISSN: 2278 – 1323
International Journal of Advanced Research in Computer Engineering &Technology (IJARCET)
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Table 2: Fitting parameters for the power-law model in figure 2 were as the following:

Operating wavelength	850 nm	1310 nm
C	0.2384	0.0184
f	0.567	0.685

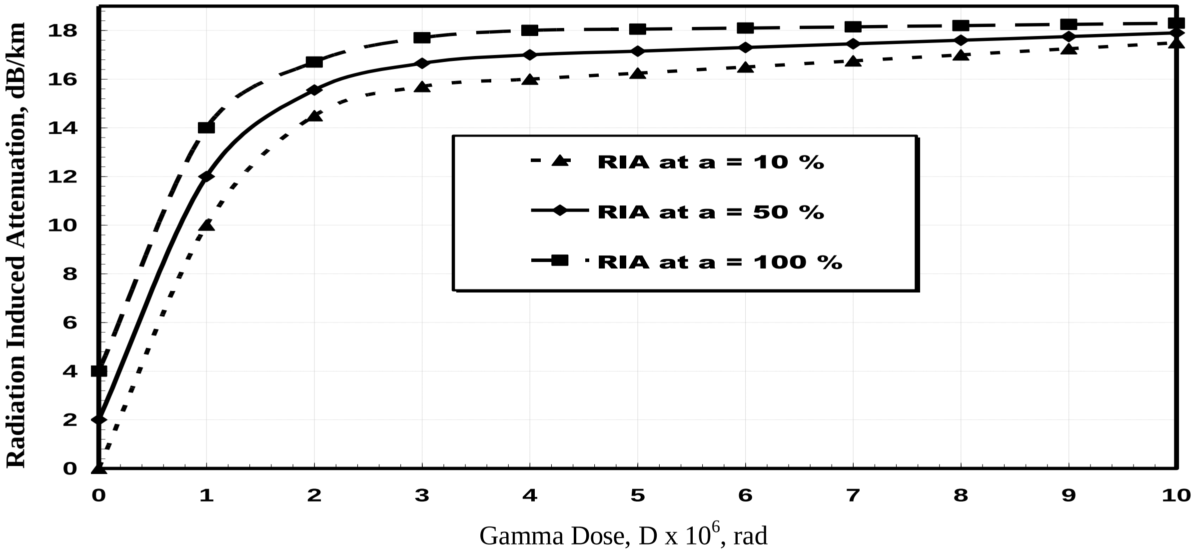

Fig.3. Variations of the attenuation against gamma dose as a function of probability of defect generation (a) with operating wavelength = 850 nm and dose rate = 0.1 (krad/min).

Figure (3) shows the relation between the attenuation and radiation dose as a function of probability of defect generation from the figure, lower signal attenuation is observed at the lowest probability of defect generation this is for the reason that these defect centers acts as absorption points of the light along the fiber length when the fiber exposure to the radiation.

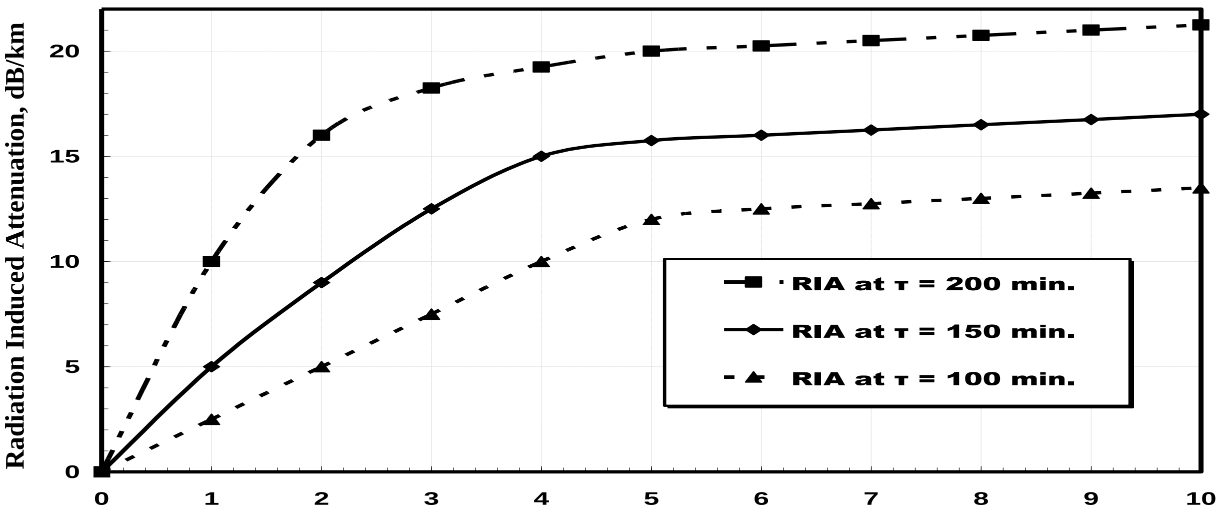

Fig.4. Variations of the attenuation against gamma dose as a function of characteristic lifetime of the defect (τ) with operating wavelength= 850 nm, dose rate =0.1 (krad/min) and probability of defect generation (a) = 100%.

Figure (4) reveals the relation between the attenuation and radiation dose as a function of characteristic lifetime of the defect from the figure, the signal attenuation increases as the characteristic lifetime of the defect increase since these defect then begin to absorb photons of the light that carry the transmitted information along the fiber length.

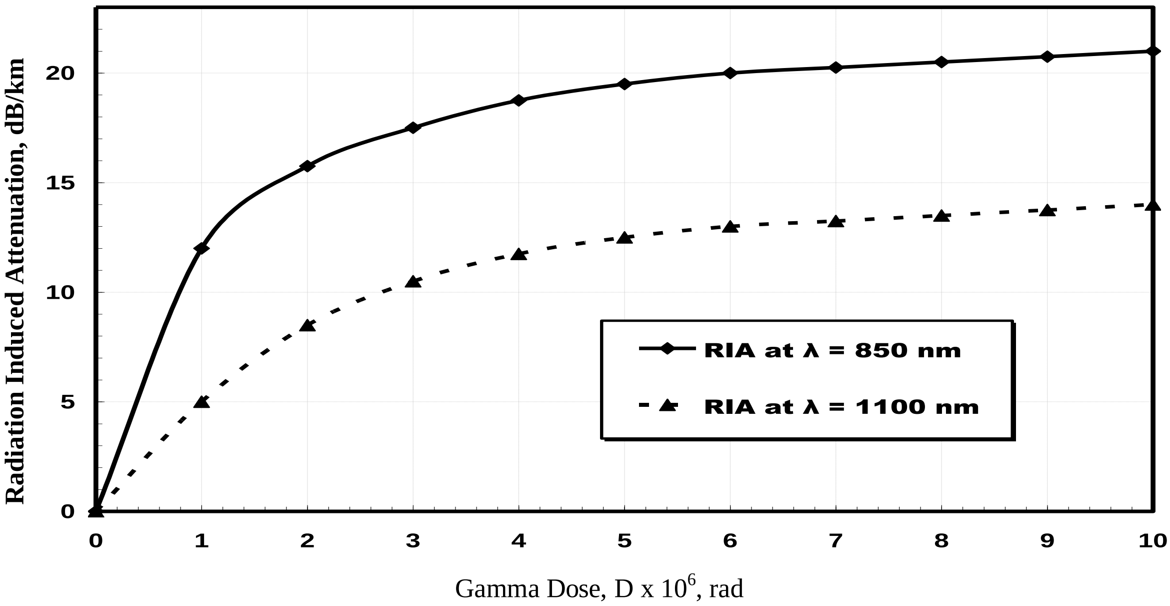

Fig.5. Variations of the attenuation against gamma dose as a function of operating wavelength (λ) with dose rate = 0.1 (krad/min) and probability of defect generation (a) = 100%.

Figure (5) shows the relation between the attenuation and radiation dose as a function of operating wavelength. From the figure, the signal attenuation increases as the wavelength decrease. Furthermore during the irradiation, the saturation in RIA growth is strongly wavelength dependent. In addition this result can be attributed to operation at short wavelength or at high frequency thus the higher frequency the higher the bandwidth which indicates that there is much more photons will be absorbed by the defect centers. Moreover for the reason that the cables at 1310 nm experience a smaller radiation- induced signal loss, this might favor the use of 1310 nm rather than 850 nm for the radiation environment.

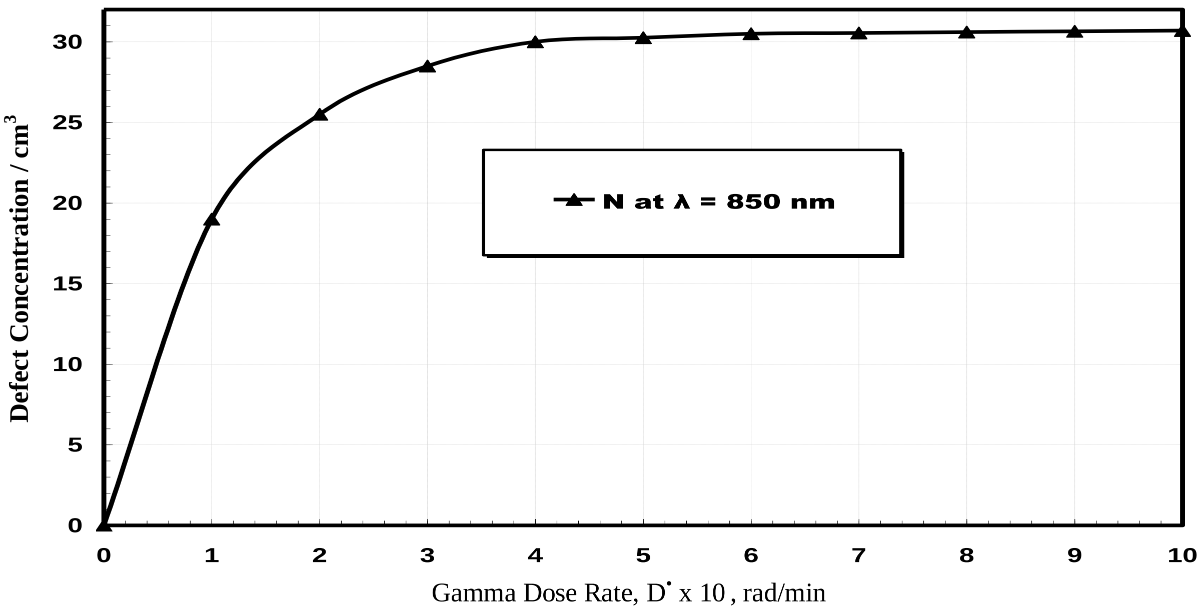

Fig.6. Variations of defect concentration against the gamma dose rate with operating wavelength= 850 nm, radiation dose = 1 Mrad and probability of defect generation = 100%.

Figure (6) shows the relation between defect concentration and radiation dose rate from the figure, as the dose rate increases the defect concentration increase. This result can be accredited to increasing radiation dose rate results in creation more free electrons by radiolysis that can activate pre-existing point defects that then begin to absorb photons of a specific energy. In addition it can also create totally new point defects that are then populated by radiolysis electrons. Moreover as radiation dose rate increase, the point defects increase which indicts increasing radiation- induced signal along the fiber.

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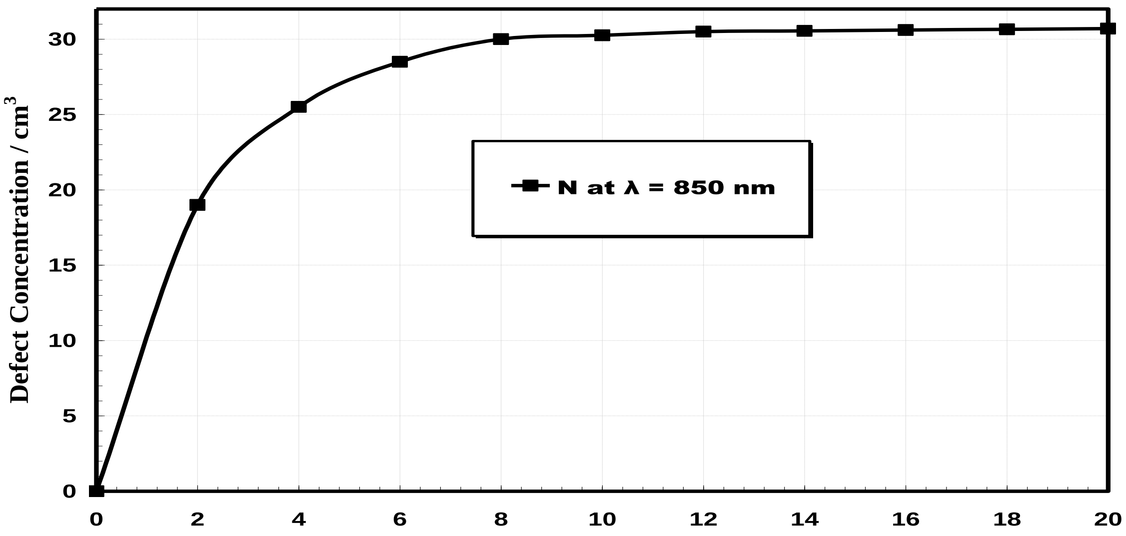

Fig.7. Variations of the attenuation against time with operating wavelength= 850 nm, dose rate = 100 krad/min, radiation dose = 1 Mrad and probability of defect generation = 100%.

Figure (7) shows the relation between defect concentration and time from the figure, there are two stages of the change of the defect concentration with the time .In the first stage the defect concentration is linearly increasing with the time until the second stage in which the saturating point is occurring at this point the defect concentration doesn't change with the time. Moreover in saturation region there is no increment of radiation- induced signal along the fiber since there is no additional point defects generation in the fiber as radiation dose increase.

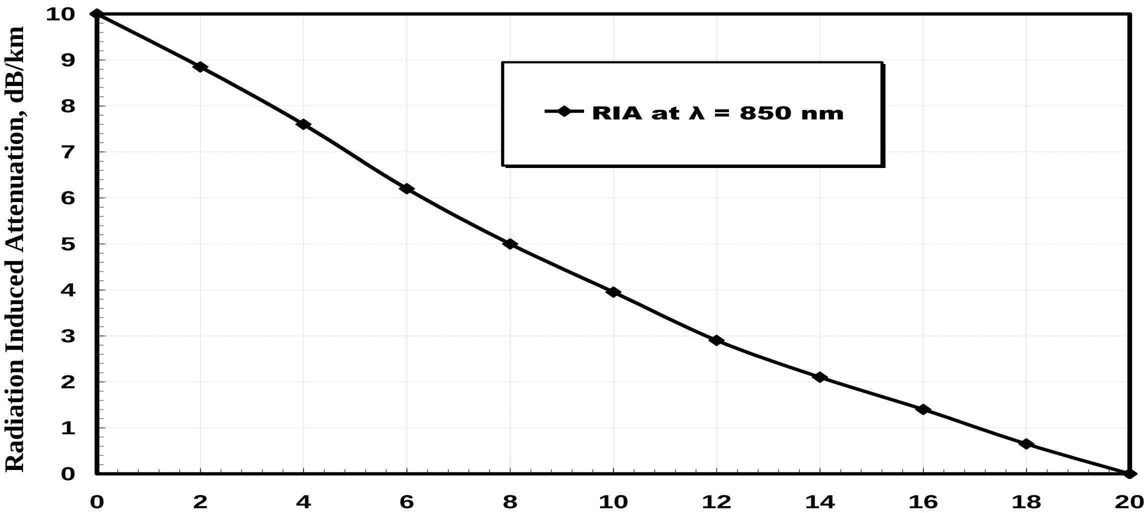

Fig.8. Variations of the attenuation recovery against time at room temperature.

Figure (8) reveals the relation between radiation induced transmission loss recovery and time, the figure shows that the transmission loss decreases after radiation interruption. This result can be accredited to the post-irradiation recovery process in which recombination between the ionized electrons and holes takes place and consequently the point defects are reduced which allows recovering partially the optical transmission characteristic of the irradiated fiber, especially if the fibers are heated at high temperature.

In general concurrent with the damage process, thermal and optical bleaching processes occur. These cause deactivation of absorption centers, for example by the liberation of a trapped charge. Activation and deactivation of absorption centers reaches equilibrium at a value of attenuation that depends on the dose rate. Attenuation will then be observed to saturate. Once irradiation has terminated activation will cease but the recovery processes will continue. This leads to the observation of short term recovery of fiber transmission. The radiation induced absorption centers continue to exist and once irradiation is resumed the attenuation levels quickly return to the saturating value as new charge carriers are created by radiolysis and start to populate the traps [41].

IV. Conclusion

In this paper a block diagram model treating the radiation induced transmission loss in Ge-doped-silica multimode optical fiber is proposed to provide a mean to control the optical properties of fibers in radiation environments. The radiation dose and the dose rate dependence of radiation induced attenuation in the optical fibers were studied by using VisSim environment. Furthermore the effect of operating wavelength shows a high contribution in the performance of the optical fiber links since operating with shorter wavelength results in attenuation increment. So the cables at 1310 nm experience a smaller radiation-induced signal loss than 850 nm under radiation condition. In addition the post-irradiation recovery follows the radiation induced transmission loss is demonstrated in order to improve maximum transmission performance when optical fibers are selected for use in a radiation field. The results are validated against the published experimental work and good agreement is observed.

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Author's Profile

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