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Modeling of Radiation Induced luminescence and How to Reduce Cherenkov Effect in Optical Fibers

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Abstract - Radiation-induced luminescence of fibers was shown to result from the Cherenkov process occurring within the fibers. In this paper we use A 'two-photon-flows' model to reveals the relation between the effect of light emission and the optical fiber parameters by using Vissim environment. This formulated treatment provides a mean to control the optical properties of fibers in radiation environments. The results are validated against published experimental work and show good agreement.

Keywords - Optical Fiber, Gamma Radiation, Light emission, Optical Communication System.

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, they are self powered [3], ease of integration [4], non-inductivity to electromagnetic noise, low loss of transmitting signals [5]. In addition they are light weight, insulating characteristic, a wide optical signal band [6]. Furthermore considerable cost reduction is expected in constructing a communication system utilizing these optical fibers [7]. Due to these advantages it is being considered for use in many systems. Many of these applications require operation in nuclear radiation environments. Hence they could be exposed to ionizing radiation under a wide variety of exposure conditions. Such as space applications, or when employed in nuclear reactor operations, high doses may be accumulated over several years. The principal response of the fibers to such conditions is a loss in transmission. This behavior has been extensively studied for a number of years [8-12]. Furthermore the other important problem is that in the presence of relativistic particles passing through the fiber, light is generated within the core [13]. This process is known as radiation-induced luminescence which could falsely be interpreted as a signal [14]. Moreover this radiation can lie within a propagating mode in the fiber and be detected as unwanted background whose intensity is dependent upon the angle between the beam and the fiber and affect the signal-to-noise ratio [13]. The radiation-induced light produced in optical fibers could be a combination of Cherenkov emission, fluorescence or luminescence depending on the type of material of the fibers utilized [15]. For pure fused silica optical fibers, this spurious light emission is predominantly shown to result from the Cherenkov process occurring within the fibers [14].Cherenkov radiation is produced when a charged particle passes through a medium of refractive index n with a velocity greater than that of light in the medium. Emission occurs only when $n\beta > 1$, where β is the ratio of the particle's velocity to the speed of light in vacuum [15]. However the radiation sensitivity of optical fibers shows up as interference by radiation-induced light emission (RLE), transient optical loss (TOL) and residual optical loss [16]. At low doses (<100 Gy), the radiation-induced light amplification in the visible region was observed [16]. The radiation-induced light amplification is a typical effect showing the dependence of optical properties on the light-intensity [16]. To solve this problem an understanding of the effect of fiber parameters on the transmission of Cherenkov radiation is needed [13]. Thus, it is important to know the non-linear optical response of the optical fibers in the irradiation environment, and how we can reduce the Cherenkov effect in those fibers. Consequently, we are concerned with evaluation of Cherenkov effect that enables us to calculate the humiliation that occurs in optical fiber transmission performance under irradiation environment. In addition, it allows improving the signal-to-noise ratio, contributes in achieving maximum usage of the communication system bandwidth, and to control the optical transmission properties of fibers in radiation environments. The arising effects of radiation induced luminescence are decisive in designing high-bit-rate optical communication systems.

This work is done by using VisSim environment. 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 luminescence, section III describes the model results. However section IV is devoted to conclusion.

II. Basic Assumptions and Modeling of Radiation Induced Luminescence

The radiation sensitivity of optical fibers shows up as interference by radiation-induced light emission (RLE), transient optical loss (TOL) and residual optical loss. In this model two silica fiber waveguides were used one of core refractive index =1.4 and the other is equal to 1.5. Operating wavelengths of the optical sources used for probing fibers are 1550 nm and 1310 nm. The propagating light is in x direction and the sources are assumed to overfill the fiber so that all mode groups are present. The lengths of the two fibers are 10 and 10.8 meter. To illustrate the non-linear optical responses of optical fibers in radiation environment we will use a "two-photon-flows" model, where I, Q, and α (I) are the propagating light intensity, light emission power, and optical losses respectively. In addition α (I) linearly dependent on the light intensity in the fiber interact with each other as shown in figure (1) [16].

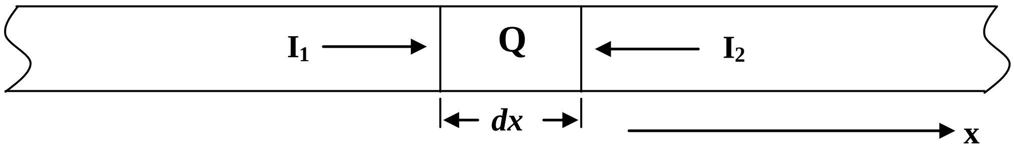

Fig.1. Optical fiber in which the light is propagating in x direction.

The optical losses α (I) is given by [16].

$$\alpha(I)=\alpha[1+k(I_1+I_2)] \quad (1)$$

where α, and k are the transient optical loss (cm^{-1}), and photon-induced absorption efficiency respectively.

The propagating light can be thought as two photon flows moving in opposite directions [16].

$$I=I_1+I_2 \quad (2)$$

where I, I_1, and I_2 are propagating light, probing light, and light emission intensities in the optical fiber (mW/cm^2) respectively. In a small piece of the fiber (length dx), the photon flows gain intensities owing to the light emission and weaken because of the optical losses [16].

$$\frac{dI_1}{dt}=V_1[Q-I_1\alpha[1+k(I_1+I_2)]] \quad (3)$$

$$\frac{dI_2}{dt}=V_2[I_2\alpha[1+k(I_1+I_2)]-Q] \quad (4)$$

where V_1, and V_2 are probing light, and light emission velocities in the optical fiber respectively. The index of refraction (n) measures the speed of light in an optical medium where the index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material itself. When light enters the fiber material (an optically dense medium), the light travels slower at a speed (V) than in air. The index of refraction is given by [17].

$$n=\frac{C}{V} \quad (5)$$

where C, V are the speed of light in the vacuum and the optical fiber respectively, C is equal to 3 $\chi 10^8$ (m/s). Thus we can write equation (5) in the following form

$$V_1=\frac{C}{n} \quad (6)$$

Emission of the light occurs only when the next condition is fulfilled [15].

$$n\beta > 1 \quad (7)$$

where β is the ratio of the particle's velocity to the speed of light in vacuum, therefore it can be represented by the following equation

$$\beta=\frac{V_2}{C} \quad (8)$$

Therefore this equation can be written as follows

$$V_2=1.25\times\frac{C}{n} \quad (9)$$

Assuming the photons maintain constant velocity as they traverse the fiber then [17].

$$V=\frac{l}{t} \quad (10)$$

In fiber optics, it is more convenient to use the wavelength of the light instead of the frequency. The conversion is [17].

$$\lambda=\frac{C}{f} \quad (11)$$

where λ, and f are the light wavelength and frequency respectively. Therefore equation (5) can be written as follows

$$V=\frac{\lambda f}{n} \quad (12)$$

where V is the speed of light in the optical fiber (m/s).

III. Results and Discussion

We have demonstrated the non-linear optical response of optical fibers in the irradiation environment. We illuminate the effect of those environments on the light emission occurring in the optical fibers and how we can reduce the Cherenkov effect in those fibers. The results showed that the key to reducing Cherenkov effect is expected in minimizing the operating wavelength or by selecting the fibers that have high refractive index. The reference values of these parameters are shown in Table 1. These values of the calculations are taken from [15-17].

Table 1: Operating parameter's values used in the model were as the following:

Operating parameter	**Symbol**	**Value**
Speed of light in vacuum	C	$3x10^8$ m/s
Operating wavelength	λ	1310-1550 nm
Optical fiber length	l	10-10.8 m
Core refractive index	n	1.4-1.5
Light emission velocity	V_2	$(2.5\text{-}2.7)x10^8$ m/s

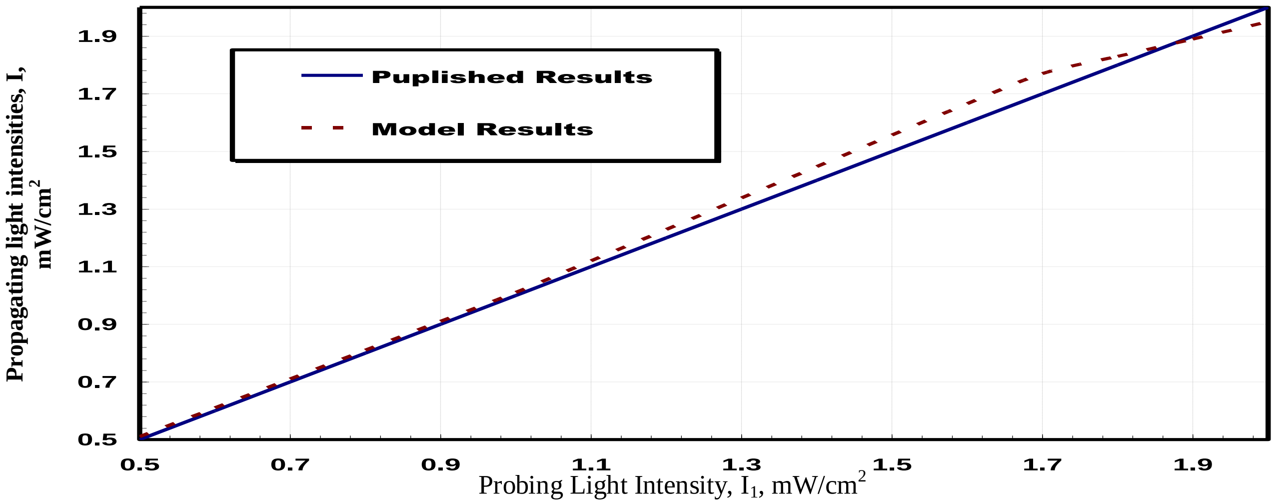

Fig.2. Variations of the probing light intensity (I_1) against propagating light intensity (I) with k=0.1

In figure (2) the typical computed values for the Phase diagram under the irradiation environment effect, and experimental values are represented in the above figure that shows a good agreement between the resulted curve and published experimental curve.

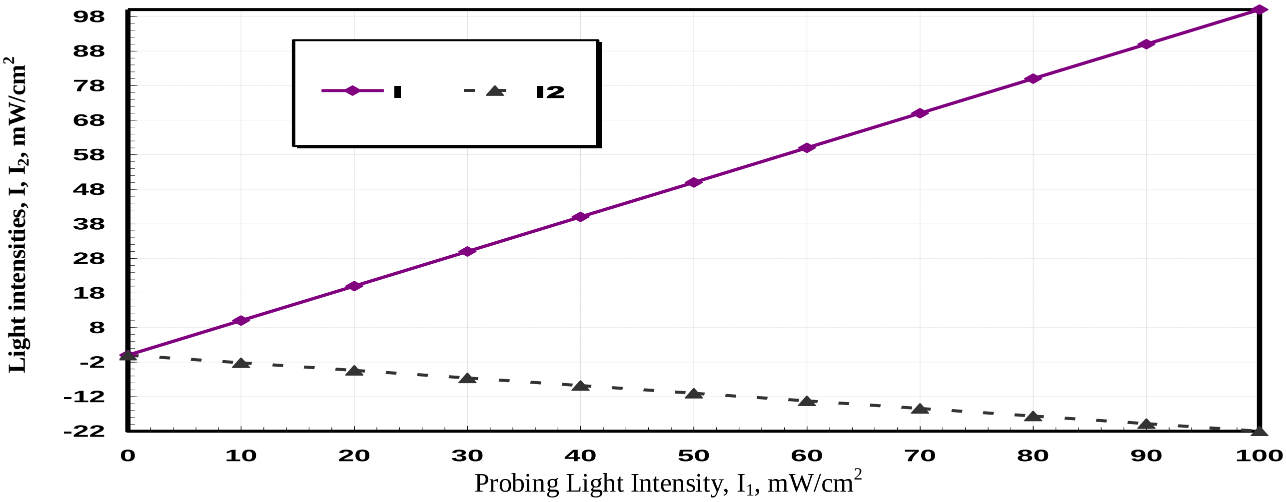

Fig.3. Variations of the probing light intensity (I_1) against propagating light intensity (I) and light emission intensity (I_2)

Figure (3) reveals the relation between the Probing light intensity (I_1), Propagating light intensity (I) and Light emission intensity (I_2) from the figure with increasing probing light intensity the light emission decreases. However the propagating light intensity increases with increasing probing light intensity. So it is become obvious that RLE depends on the probing light intensity. Moreover at the highest intensity of the probing light the light emission intensity is 1.5 times lower [16].

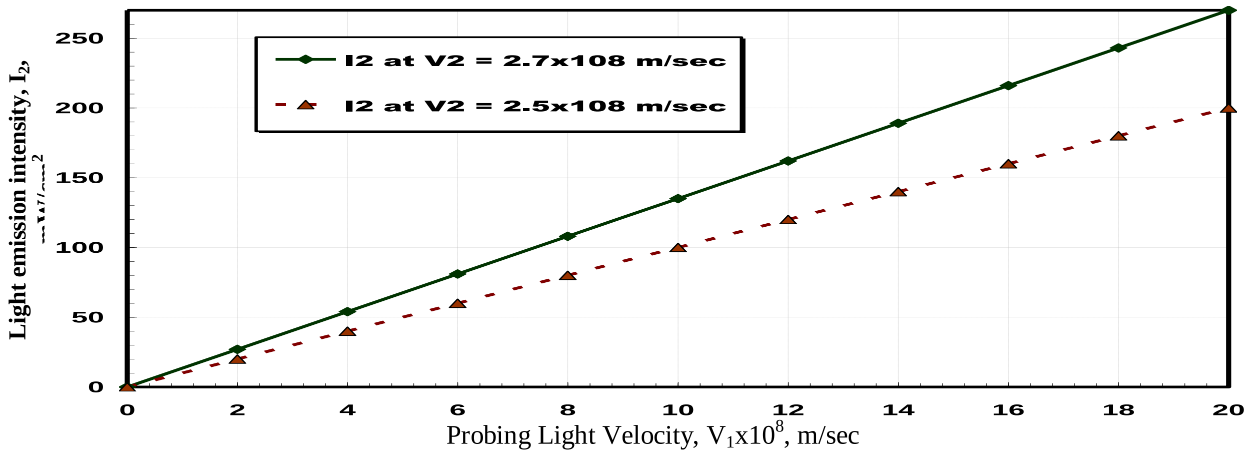

Fig.4. Variations of the light emission intensity I_2 against probing light velocity V_1 at different emission light velocities (V_2) with k=0.1

Figure (4) depicts the relation between the light emission intensity (I_2) and the velocity of the probing light (V_1), at different light emission velocities (V_2). From the figure light emission intensity (I_2) along the fiber length in the radiation environment increase as the velocity (V_2) increase. So that we need high core refractive index to reduce the emission light velocity and as a result the light emission intensity will be decrease. Furthermore this will improve the transmission performance and contributes in achieving maximum usage of the system bandwidth.

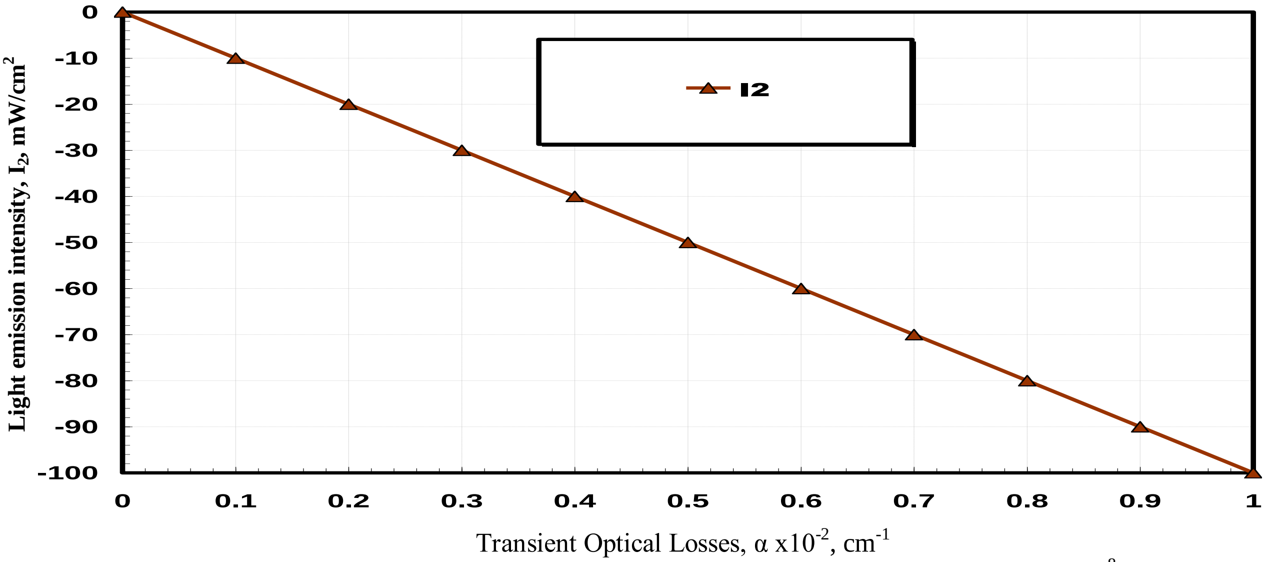

Fig.5. Variations of the light emission intensity (I_2) against the transient optical losses α with V_1=2x10^8 m/sec, V_2=2. 5x10^8 m/sec, and k=0.1

Figure (5) shows the relation between the light emission intensity (I_2) and the transient optical losses; from the figure as the optical losses increases the light emission intensity (I_2) along the fiber length in the radiation environment is decreased. Furthermore on increasing the laser intensity, the transient process becomes more pronounced, and the transient optical losses decays faster [16]. The TOL was high in the regions where the optical absorption before reactor pulses was high [16].

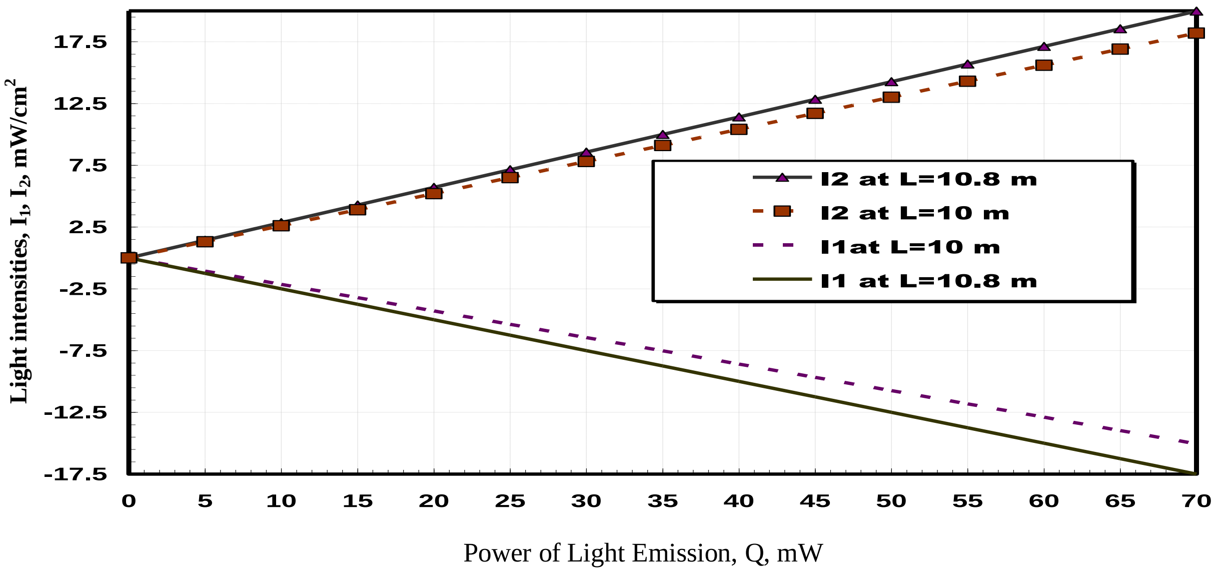

Fig.6. Variations of the light intensities (I_1, I_2) against light emission power (Q) at different optical fiber lengths (L).

Figure (6) reveals the relation between the intensities (I_1, I_2) with power of light emission (Q) at different optical fiber lengths (L), from the figure the power of light emission due to Cherenkov radiation is increased with the increasing of the light emission intensity I_2 along the fiber length in the radiation environment. At the same time we note that as the fiber length increase the intensity of I_2 increase with simultaneous decreasing of I_1. Operating with shorter fiber length will reduce the harmful effect of light emission. In addition this will increase signal-to-noise ratio that is the most important issue in any communication system.

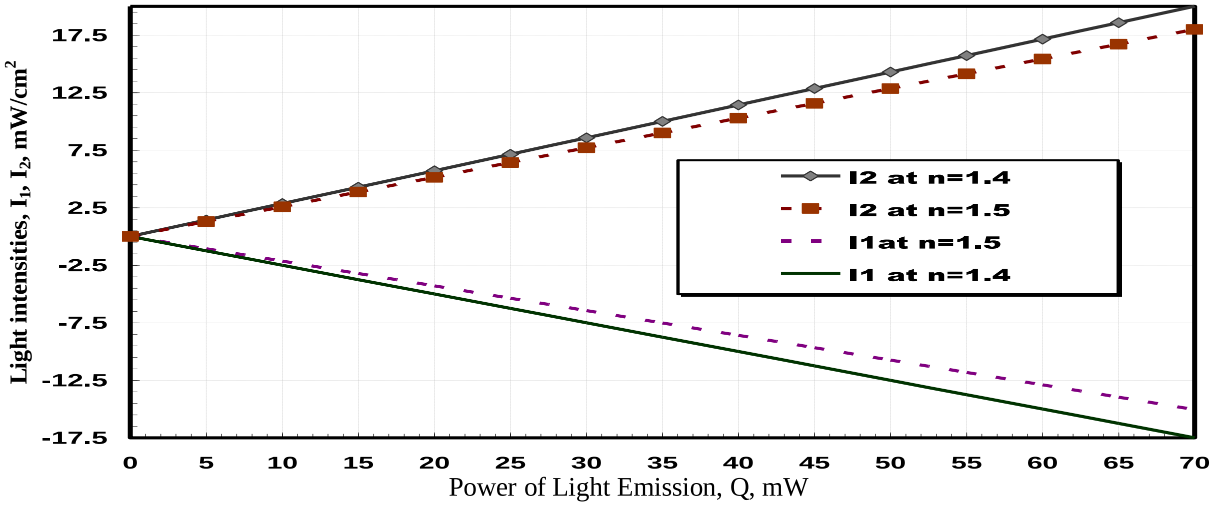

Fig.7. Variations of the light intensities (I_1, I_2) against power of light emission (Q) at different refractive indices (n)

Figure (7) reveals the relation between the intensities (I_1, I_2) with power of light emission (Q) at different core refractive index (n), from the figure the power of light emission due to radiation induced luminescence is increased with the increasing of the light emission intensity I_2. Also we note that as the refractive index of the fiber increase the intensity of I_2 decrease with concurrent increasing of I_1. Hence, the key to reducing Cherenkov capture would expect to be in maximizing (n).

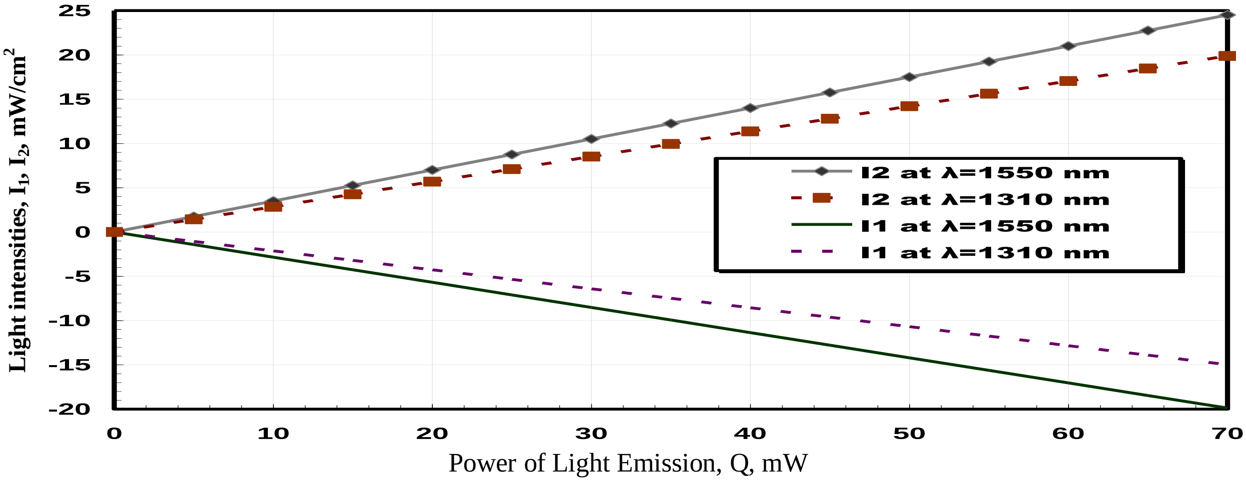

Fig.8. Variations of the light intensities (I_1, I_2) against power of light emission (Q) at different operating wavelengths (λ)

Figure (8) depicts the relation between the intensities of I_1 and I_2 with power of light emission (Q) at different operating wavelengths (λ), from the figure we note that as the operating wavelength increase the intensity of I_2 increase with immediate decreasing of I_1. So, we want to operate at short wavelength or at high frequency thus the higher frequency the higher the bandwidth. Additionally this wider bandwidth enables us to send more complex information and to improve the speed of transmission and this will improve the performance of the optical fiber communication link.

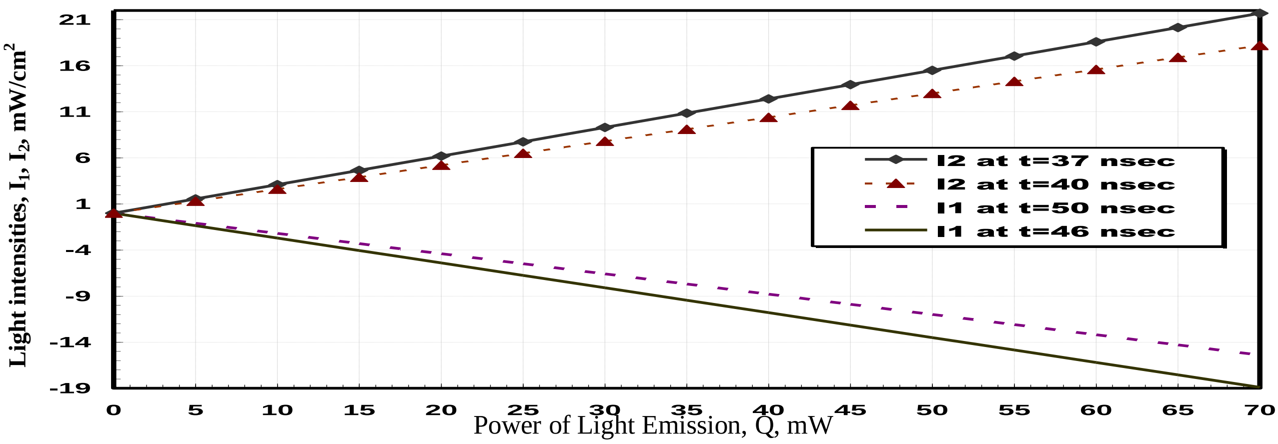

Fig.9. Variations of the light intensities (I_1, I_2) against power of light emission (Q) at different emission light traveling times (t)

Figure (9) reveals the relation between the intensities of (I_1, I_2) and the power of light emission at different emission light traveling times (t), from the figure we note that as the time of emission light traveling increase the intensity of I_2 decrease with instantaneous increasing of I_1. This is because the longer traveling time indicates higher core refractive index which interprets the reduction of emission light intensity.

IV. CONCLUSION

In this paper a block diagram model treating the radiation induced light emission is proposed to provide a mean to control the optical properties of fibers in radiation environments. The proposed treatment can be used to improve the signal- to- noise ratio. A model for "two-photon-flows" is built using VisSim environment. The obtained results show that the key to reducing Cherenkov effect would expected in minimizing the operating wavelength. In the same time this provides a wider bandwidth to send more complex information and to improve the speed of transmission. Furthermore this can be achieved by selecting the optical fibers that have high refractive index. The results are validated against the published experimental work and good agreement is observed.

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