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# Optical fibre communication cables systems performance under harmful gamma irradiation and thermal environment effects

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**Abstract:** One problem in the application of fibre optics to military systems is that nuclear (and space) radiation is known to produce colour centres in optical materials, causing a reduction of light transmission over a spectrum of wavelengths. These radiation effects could cause permanent or temporary disruption of a fibre optics transmission system. Thus, the study has investigated the harmful effects of gamma irradiation on fibre communication system links under thermal environment effects over a wide range of operating parameters. Both the ambient temperature and the irradiation dose have severe effects on the system transmission link characteristics and consequently the performance characteristics of optical communication systems. It is also to be noted that the model has deeply developed the modelling basics of transmission communication systems, which may be used to analyse total pulse dispersion, transmitted signal bandwidth, transmission bit rates, radiation induced loss and optical received power by using the soliton transmission technique after different gamma irradiation doses and irradiation times.

## 1 Introduction

Optical fibre communication systems have been considered for industrial application because of several inherent advantages of the fibres. They do not cause induction, they have low loss and provide a large bandwidth for multiplexing and they are lightweight [1]. Thus, a considerable cost reduction is expected in constructing a communication system utilising these optical fibres. In actual usage, optical fibre systems may be exposed to ionising radiations, such as in a nuclear reactor. When optical fibres are used in a radiation environment, such as in a nuclear reactor or a high energy beam accelerator, the damages caused by radiation may become a serious problem. The use of optical communications technology in radiation intensive applications has been investigated since the development of the first optical fibre. The most recent advances in fibre and communications technology have provided for new applications that require the development of radiation hardened optical fibre and components. The cost, however, of any optical system designed for use in a radiation environment is an increase in reliability risk. Systems must be designed and tested to ensure that they are capable of surviving to end of life. Along with the conventional reliability issues, such as mechanical and thermal stress, one must consider the impact of radiation effects on system survivability [2, 3]. The radiation responses of optical waveguides have been widely studied since 1970 for various radiative environments. Most of the published results are concerned with resistance to accumulated dose effects, as encountered in space [3] and nuclear industry environments. The influences of various intrinsic and extrinsic fibre parameters on their radiation responses have been previously reviewed [4]. The most radiation tolerant optical fibres for high-dose environments are those designed with pure silica cores and fluorine (F) doped claddings [5]. Depending on the application requirements, the optical properties of the amorphous silica core could be adjusted by varying the concentration of hydroxyl groups. Optical fibres with high-OH levels (ppm) are designed for transmission in the ultraviolet (UV) and visible parts of the spectrum whereas low-OH fibres are optimised for guiding near-infrared signals At a high total ionising dose of the order of 50 Mrad, these fibres show a typical radiation-induced attenuation level at 600 nm in the range of 23–35 dB/km.rad (0.55 krad/s, 323 K) [6]. Ionising radiation will induce increase in attenuation fibre optics, to a degree dependent on the fibre material and on the wavelength for which the loss is measured. In many cases, transmission will recover at rates related to the nature of the absorbing centre, on the fibre temperature and sometimes on the amount of light being transmitted. The general features of the recovery processes have been well established [7] for the more important fibre types for times up to about 104 s after irradiation. In all but the briefest irradiation events, the observed losses will be determined by a combination of absorbed dose rates and recovery rates. Thus, in order to predict the behaviour of fibre optics (in particular their maximum loss) in environments, such as space, where they may be exposed to radiation over a time

**Table 1** Coefficients of different materials based optical fibre cable system [2, 5, 7, 13]

| Coefficients | Silica glass fibre | Fluoride glass fibre |
|---|---|---|
| $A(\phi)$ | $1.329631 + 2.7 \times 10^{-4} \exp\left(\frac{\phi}{0.319319}\right)$ | $0.0765 + 1.65 \times 10^{-6} \exp\left(\frac{\phi}{5.5467}\right)$ |
| $F_A(T)$ | $1.338922 - 3.7 \times 10^{-4} (T - T_0)/1.338922$ | $0.00987 - 7.43 \times 10^{-3} (T - T_0)/0.9654$ |
| $B(\phi)$ | $0.82863 + 7.7 \times 10^{-4} \exp\left(\frac{\phi}{0.440013}\right)$ | $0.12345 + 0.0876 \times 10^{-8} \exp\left(\frac{\phi}{0.0765}\right)$ |
| $F_B(T)$ | $0.819562 - 3.843 \times 10^{-4} (T - T_0)/0.819562$ | $0.5465 - 1.8653 \times 10^{-7} (T - T_0)/0.47653$ |
| $C(\phi)$ | $0.01105 + 4.7 \times 10^{-6} \exp\left(\frac{\phi}{0.391139}\right)$ | $3.5467 + .867534 \times 10^{-4} \exp\left(\frac{\phi}{8.5432}\right)$ |
| $F_C(T)$ | $0.011127 - 3.1 \times 10^{-6}(T - T_0)/0.011127$ | $0.43567 - 0.0987 \times 10^{-3}(T - T_0)/0.35678$ |
| $D(\phi)$ | $0.98481 + 1.1 \times 10^{-3} \exp\left(\frac{\phi}{0.964926}\right)$ | $3.8659 + 21.5 \times 10^{-4} \exp\left(\frac{\phi}{3.56786}\right)$ |
| $F_D(T)$ | $1.055995 - 2.8 \times 10^{-3}(T - T_0)/1.055995$ | $3.25 - 0.59878 \times 10^{-6}(T - T_0)/2.6543$ |
| $E$ | 100 | 25.76 |
| $n_{nl}$ | $2.6 \times 10^{-20}$ m$^2$/Watt | $1.037 \times 10^{-18}$ m$^2$/Watt |
| $h_1(\phi)$ | $0.0132x/(1 + 733x) \exp\left(\frac{\phi}{0.32453}\right)$ | $0.00065 \exp\left(\frac{\phi}{1234.65}\right)$ |
| $h_2(\phi)$ | $4.8\left(\frac{T_0}{T}\right) \exp\left(\frac{\phi}{34.654}\right)$ | $0.0000876 \exp\left(\frac{\phi}{98765.54}\right)$ |
| $h_3(\phi)$ | $(0.74 + 66\Delta n)\left(\frac{T_0}{T}\right) \exp\left(\frac{\phi}{34.654}\right)$ | $0.6\left(\frac{T_0}{T}\right) \exp\left(\frac{\phi}{86.65}\right)$ |
| $h_4(\phi)$ | $4.9 \times 10^{11} \exp\left(\frac{\phi}{1.0987}\right)$ | $1.2167 \times 10^{10} \exp\left(\frac{\phi}{98.7}\right)$ |
| $h_5(\phi)$ | $48\left(\frac{T_0}{T}\right) \exp\left(\frac{\phi}{9.765}\right)$ | $71.64\left(\frac{T_0}{T}\right) \exp\left(\frac{\phi}{1.9876}\right)$ |

extending into years, it is necessary to show the nature of the recovery over a comparable period of time.

Of the hostile environments that fibre optics are likely to experience, that posed by nuclear radiation is among the worst in that the transmission losses which are then induced can be overwhelmingly large considered in terms of those normally characteristic of the fibre. The potential radiation conditions of type, flux and total exposure can vary widely from application to application [8]. One of the driving forces in promoting the use of fibre optics is their immunity to electromagnetic interference. Thus, for military users, they solve problems which would otherwise arise with the nuclear electromagnetic pulse, but on the other hand they could then be vulnerable to weapon radiation. Other potential radiation sources include reactors and the space environment. The response of a fibre to such threats will be determined primarily by its composition but will also depend on the wavelength and intensity of light being transmitted by the processing procedures, the temperature of the fibre and sometimes, on any previous irradiation history. In addition this behaviour can be a non-linear function of dose and be dose rate dependent over and above any effects because of recovery or annealing processes taking place in the fibre [9].

In the present study, a considerable amount of hard radiation effects studies on individual transmission links to a variety of radiation conditions is deeply investigated, and only little information is available on radiation tolerance at a high total dose and under gamma radiation.

## 2 Mathematical model analysis

Optical fibre has two dominant dispersion mechanisms, modal and first-order chromatic dispersions. Each of these mechanisms will be assumed to act independently and treated separately. For each mechanism, output signal bandwidth is neglected, for example, the sources are assumed to overfill the fibre so that all mode groups are present and the differential modal attenuation of the fibre is assumed to be zero. Total pulse broadening, $\Delta\tau$, because of total dispersion coefficient, $D_t$, is easily seen to be [10]

$$\Delta\tau = LD_{\mathrm{t}}(\lambda, T, \phi)\Delta\lambda \qquad (1)$$

where $L$ is the fibre cable length, $\Delta\lambda$ is the spectral linewidth of the optical source and $D_{\mathrm{t}}$ $(\lambda, T, \phi)$ is the total dispersion coefficient as a function of ambient temperature $T$, operating optical signal wavelength $\lambda$ and gamma irradiation dose $\phi$.

The refractive index of different materials based fibre cable system can be expressed as a function of temperature $T$, operating optical signal wavelength $\lambda$ and irradiation dose of gamma rays $\phi$ as the following formula [11, 12]

$$n(\lambda, T, \phi) = A(T, \phi) + \frac{B(T, \phi)\lambda^2}{\lambda^2 - C(T, \phi)} + \frac{D(T, \phi)\lambda^2}{\lambda^2 - E} \qquad (2)$$

$$\text{With} \quad A(T, \phi) = A(\phi)F_A(T) \qquad (3)$$

$$\text{Also} \quad B(T, \phi) = B(\phi)F_B(T) \qquad (4)$$

**Table 2** Proposed operating parameters for optical fibre cable under thermal gamma irradiation field [1, 5, 11, 16, 22]

| Operating parameter | Symbol | Value |
|---|---|---|
| gamma irradiation dose | $\phi$ | 0.1–1 MGy |
| ambient temperature | $T$ | 300 K–380 K |
| optical signal wavelength | $\lambda$ | 0.85 μm–1.55 μm |
| room temperature | $T_0$ | 300 K |
| source spectral line width | $\Delta\lambda$ | 0.1 nm |
| fibre link length | $L$ | 10 km |
| relative refractive index difference | $\Delta n$ | 0.005 |
| effective area | $A_{\mathrm{eff}}$ | 85 μm$^2$ |
| drive current | $I$ | 20 mA |
| germanium mole fraction | $x$ | 0.2 |
| irradiation time | $t$ | 1 hour–24 hours |

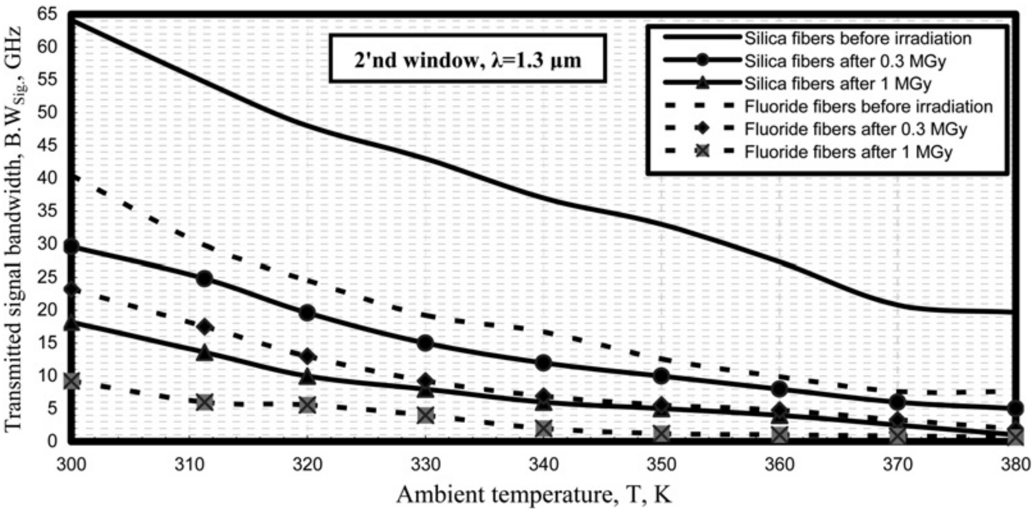

**Fig. 1** *Transmitted signal bandwidth in relation to ambient temperature and gamma irradiation dose at the assumed set of operating parameters*

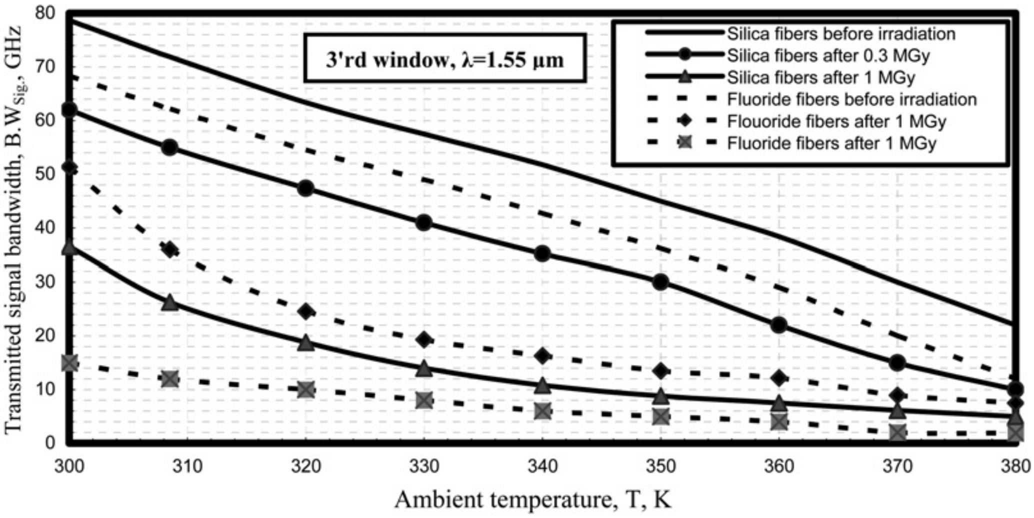

**Fig. 2** *Transmitted signal bandwidth in relation to ambient temperature and gamma irradiation dose at the assumed set of operating parameters*

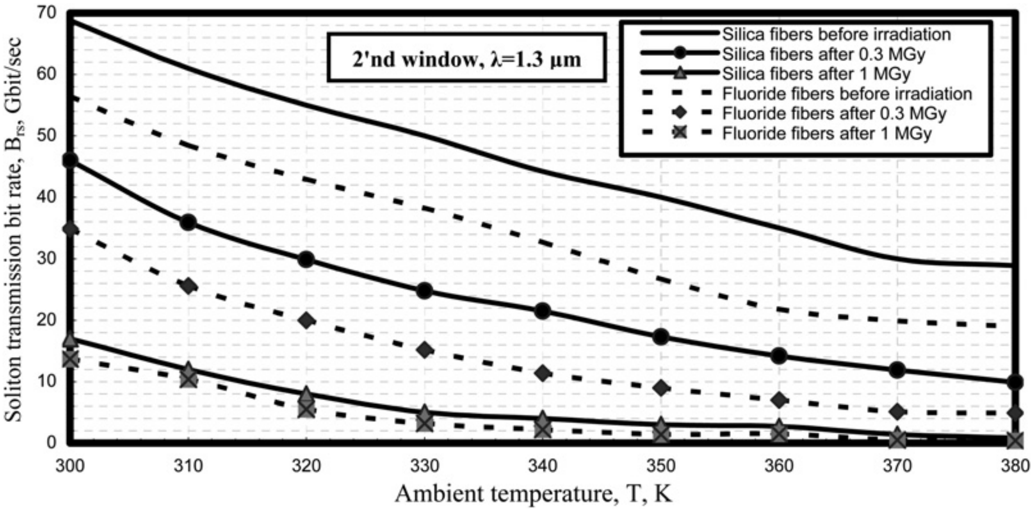

**Fig. 3** *Soliton transmission bit rate in relation to ambient temperature and gamma irradiation dose at the assumed set of operating parameters*

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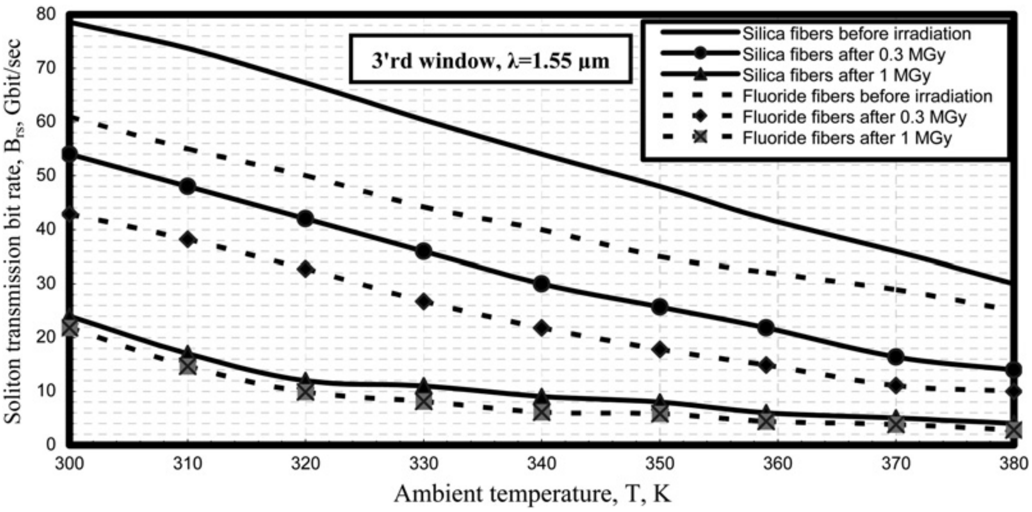

**Fig. 4** *Soliton transmission bit rate in relation to ambient temperature and gamma irradiation dose at the assumed set of operating parameters*

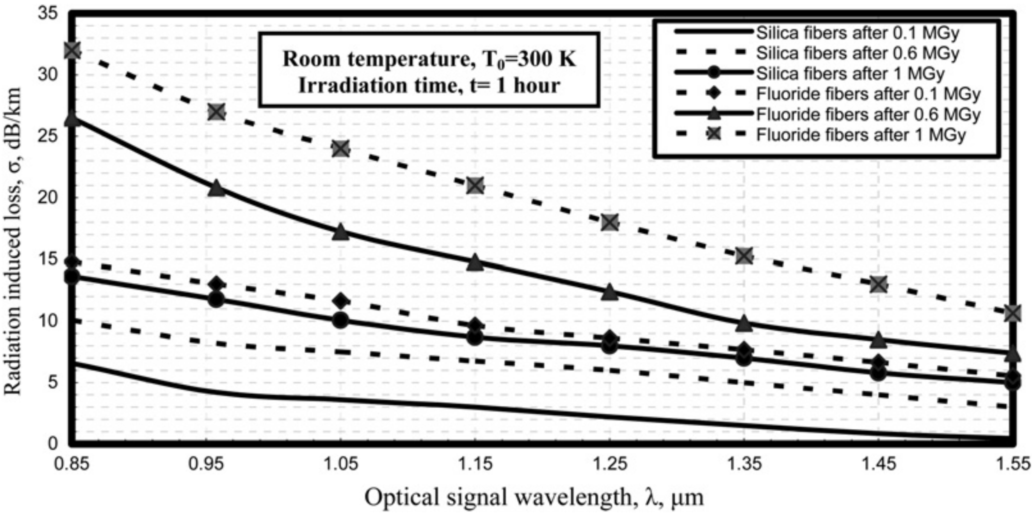

**Fig. 5** *Radiation induced loss in relation to operating optical signal wavelength and different gamma irradiation doses at the assumed set of operating parameters*

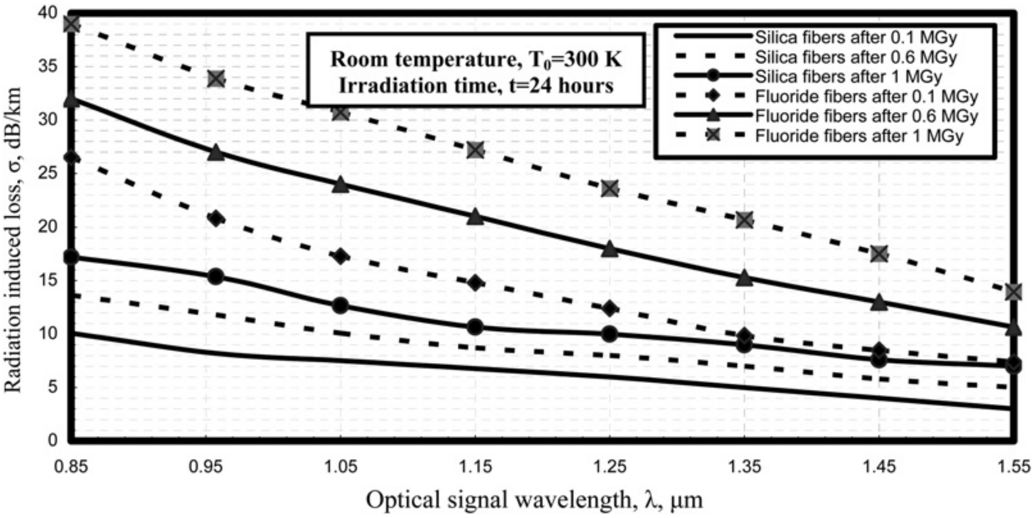

**Fig. 6** *Radiation induced loss in relation to operating optical signal wavelength and different gamma irradiation doses at the assumed set of operating parameters*

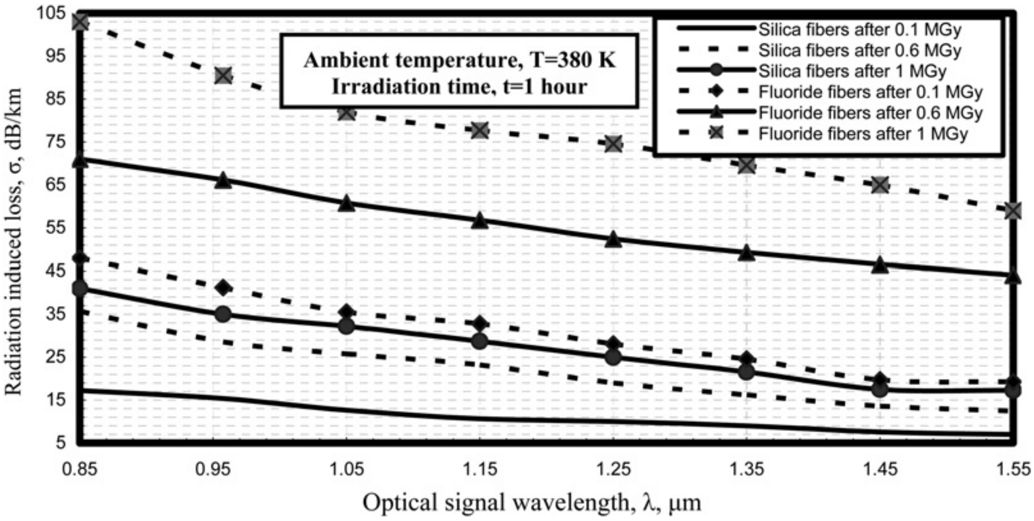

**Fig. 7** *Radiation induced loss in relation to operating optical signal wavelength and different gamma irradiation doses at the assumed set of operating parameters*

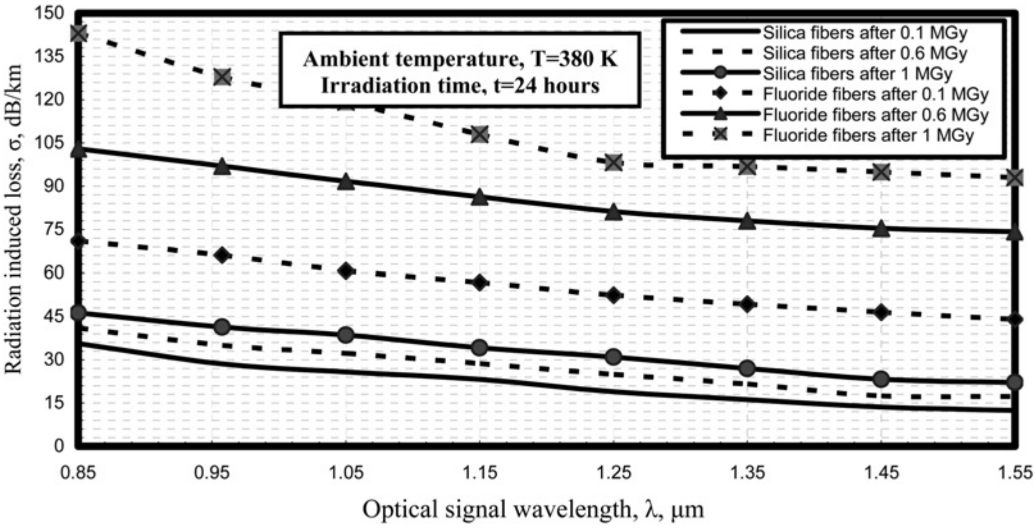

**Fig. 8** *Radiation induced loss in relation to operating optical signal wavelength and different gamma irradiation doses at the assumed set of operating parameters*

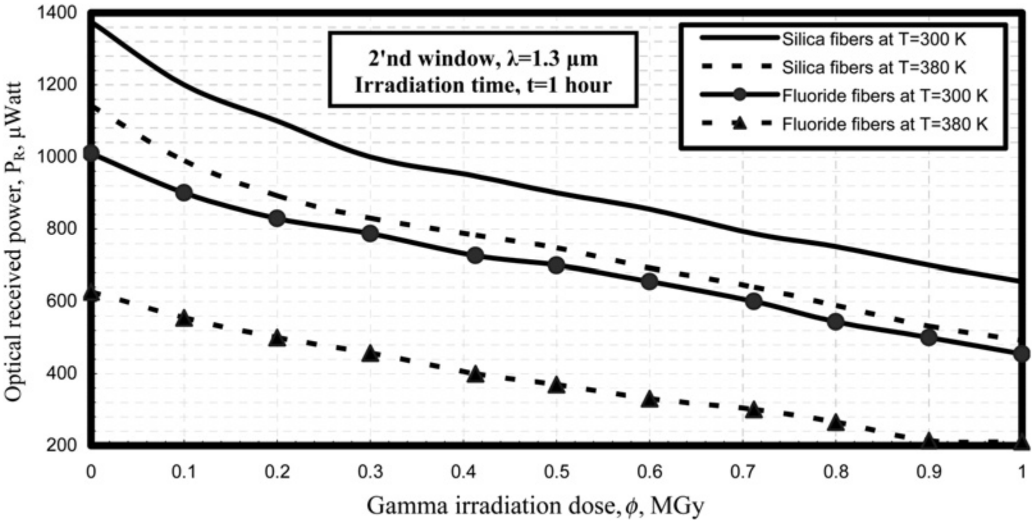

**Fig. 9** *Optical received power in relation to different gamma irradiation doses and ambient temperature at the assumed set of operating parameters*

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$$\text{With}\quad C(T,\,\phi) = C(\phi)F_C(T) \tag{5}$$

$$\text{Finally}\quad D(T,\,\phi) = D(\phi)F_D(T) \tag{6}$$

where the empirical equation coefficients of silica and fluoride glass fibres can be summarised in Table 1 where $T$ is the ambient temperature in $K$ and $T_0$ is the room temperature in $K$. The total dispersion coefficient-based standard single mode fibre that limits the transmission bit rates in optical communication system is the summation of material dispersion, $D_\text{m}$ and waveguide dispersion, $D_\text{wg}$, that is ($D_\text{t} = D_\text{m} + D_\text{wg}$) [13, 14]. The waveguide dispersion is very small and can be neglected, therefore the previous equation becomes

$$D_\text{t}(\lambda,\,T,\,\phi) \simeq D_\text{m}(\lambda,\,T,\,\phi) = -\frac{\lambda}{c}\frac{\text{d}^2 n(\lambda,\,T,\,\phi)}{\text{d}\lambda^2} \tag{7}$$

where $c$ is the speed of light ($3\times 10^8$ m/s), $\lambda$ is the optical signal wavelength and $\text{d}^2n$ $(\lambda,\ T,\ \phi)/\text{d}\lambda^2$ is the second differentiation of refractive index of different materials based fibre cable system that is analysed in [15]. In addition the transmitted signal bandwidth for fibre cable system is given by

$$BW_\text{Sig} = \frac{0.44}{\Delta\tau L} \tag{8}$$

The idea of soliton transmission is to guide the non-linearity to the desired direction and use it for our benefit. When soliton pulses are used as an information carrier, the effects of dispersion and non-linearity balance each other and thus do not degrade signal quality with propagation distance. In addition, the unique features of soliton transmission can help to solve the problem of data transmission, because the soliton data looks essentially the same at different distances along the transmission, the soliton type of transmission is especially attractive for all-optical data networking. Moreover, because of the high quality of the pulses and return-to-zero nature of the data the soliton data is suitable for all-optical processing.

The power forward current curves of different types of vertical cavity surface emitting laser (VCSEL) devices were given in [16], with remarkable non-linearity, whereas in [17] it was depicted in linear fashion. Based on the data of [18], the following non-linear thermal relations for the set of the selected devices were carried out

$$P(I,\,T) = p_0 + p_1 I + p_2 I^2, \quad \text{mWatt} \tag{9}$$

where the set of parameters $\{p_0,\ p_1$ and $p_2\}$ are polynomial functions of ambient temperature $T$.

$$p_0 = 0.73 - 0.00169T + 0.000345T^2 \tag{10}$$

$$p_1 = 2.5 - 0.0072T + 0.0002T^2 \tag{11}$$

$$p_2 = -7.3 - 0.002T + 0.000065T^2 \tag{12}$$

The power of VCSEL under the effects of thermal irradiation fields can be expressed in the following formula

$$P(I,\,T,\,\phi) = P(I,\,T)F_p(\phi) \tag{13}$$

where $F_p(\varphi)$ is a function of the gamma irradiation dose $\phi$, can be expressed as follows

$$F_p(\phi) = 1 + \alpha_1\,\phi + \alpha_2\,\phi^2 \tag{14}$$

where the set of the empirical coefficients of $\alpha_1 = 0.0005$, $\alpha_2 = -0.001$. In any infinitesimal segment of fibre, dispersion on one hand and non-linearity of the refractive-index on the other hand produce infinitesimal modulation angles, which exactly compensate reciprocally in the sense that their sum is an irrelevant constant phase shift. Under such conditions the pulse shape is the same everywhere. The soliton waveform can be used with a peak power under the effects of irradiation fluence, temperature and threshold current [19]

$$P(I,\,T,\,\phi) = \frac{\lambda^3 D_\text{t}(\lambda,\,t,\,\phi)A_\text{eff}}{12.7cn_\text{nl}\tau_0^2} \tag{15}$$

where $n_{nl}$ is the non-linear Kerr coefficient, $\lambda$ is the operating optical signal wavelength in μm and $A_\text{eff}$ is the effective area of the fibre in $\mu\text{m}^2$. Then total pulse broadening from the

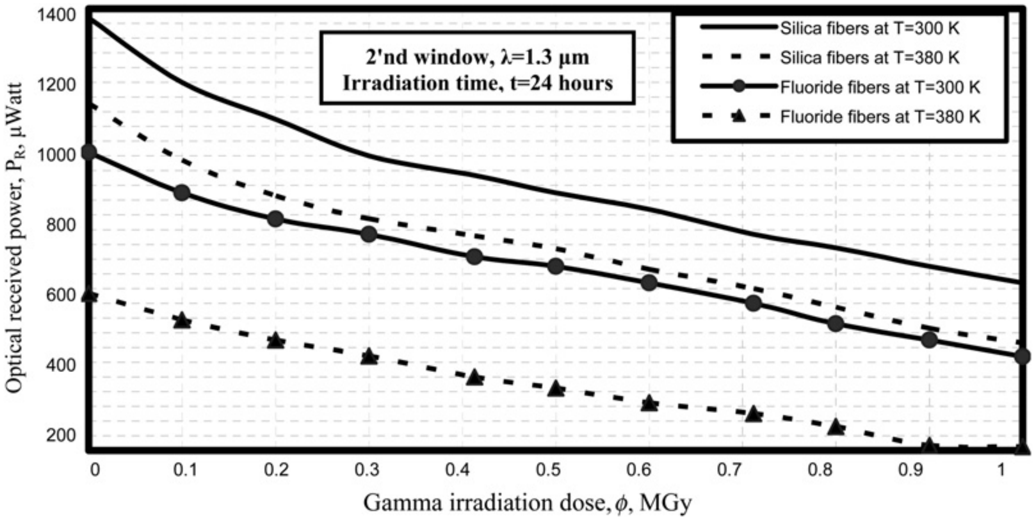

**Fig. 10** *Optical received power in relation to different gamma irradiation doses and ambient temperature at the assumed set of operating parameters*

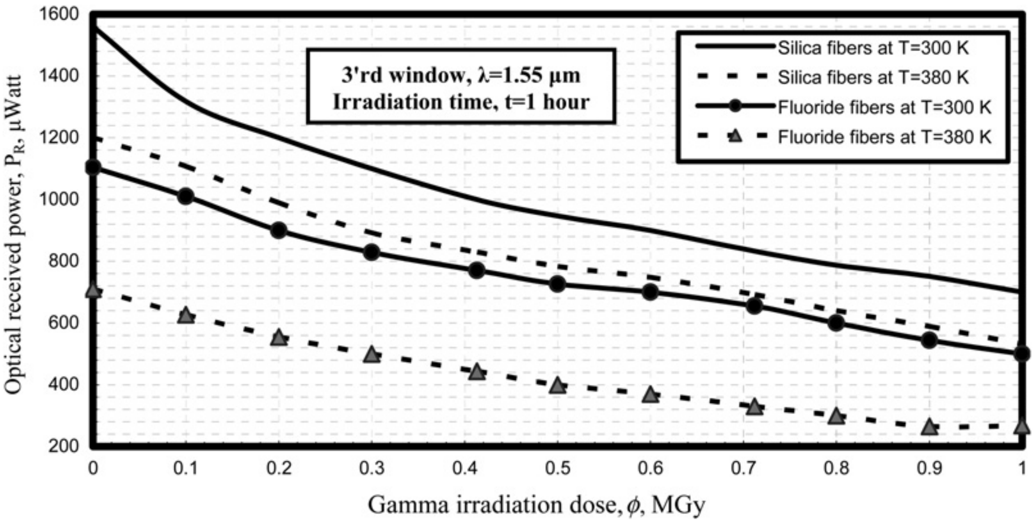

**Fig. 11** *Optical received power in relation to different gamma irradiation doses and ambient temperature at the assumed set of operating parameters*

previous equation can be expressed as the following formula

$$\tau_0 = \sqrt{\frac{\lambda^3 D_t(\lambda, T, \phi) A_{\text{eff}}}{12.7 P(I, T, \phi) n_{\text{nl}} c}}, \text{ ns} \tag{16}$$

Then the soliton transmission bit rate for different fibre cable systems is given by

$$B_{rs} = \frac{0.1}{\tau_0}, \text{ Gbit/s} \tag{17}$$

The basic formula for a typical optical fibre cable is an exponential decaying function as function of the fibre length $L$ and initial transmitted power under thermal irradiation fields as the following expression [20, 21]

$$P_R = P(I, T, \phi) e^{-\sigma L} \tag{18}$$

where $P_R$ is the received power after travelling in fibre length L through the lossy medium and $\sigma$ is the radiation induced loss, $\sigma$, of several potential fibre optic material which was shown to obey an equation of the form [22]

$$\sigma = h_1(\phi) e^{h_2(\phi)t/\lambda} + \frac{h_3(\phi)}{\lambda^4} + h_4(\phi) e^{-h_5(\phi)t/\lambda} \tag{19}$$

where $h_1$ and $h_2$ are material constants representing the UV absorption edge under irradiation effects, $h_3$ represents the Rayleigh scattering coefficient under irradiation effect, $h_4$ and $h_5$ are material constants representing the infrared absorption edge under irradiation effects and $t$ is the irradiation time. These coefficients are given in Table 1 for both fibres under consideration.

## 3 Simulation results and performance analysis

The model has been deeply investigated for transmission performance of optical transmission communication links in thermal gamma irradiated hard environments under the set of wide range of operating parameters listed below.

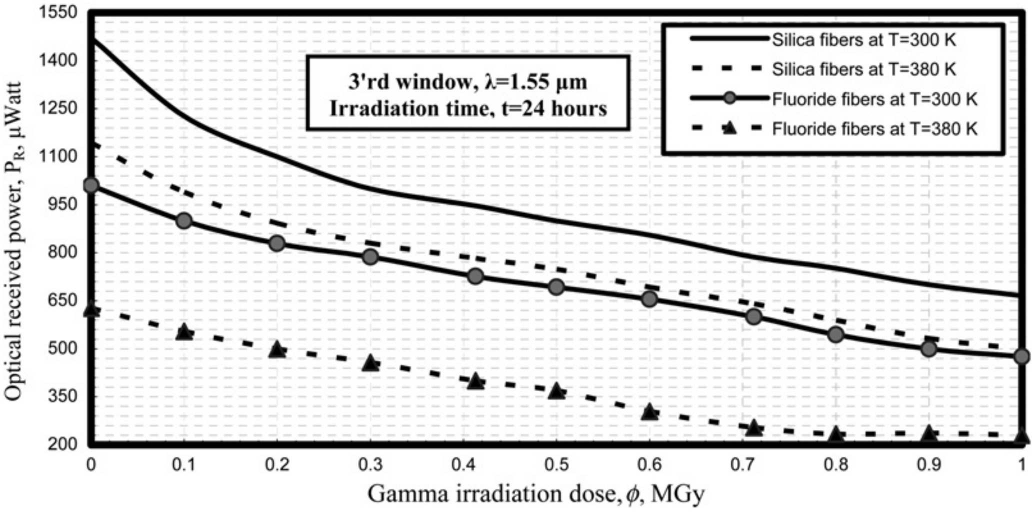

**Fig. 12** *Optical received power in relation to different gamma irradiation doses and ambient temperature at the assumed set of operating parameters*

Based on the model equations analysis, assumed set of operating parameters as listed in Table 2 and based on the series of Figs. 1–12, the following facts are ensured:

1. Figs. 1 and 2 have ensured that both ambient temperature and gamma irradiation doses increase and operating optical signal wavelength decreases, resulting in decrease of transmitted signal bandwidth through fibre cable system. We have concluded that at the third window of system operation ($\lambda = 1.55\ \mu m$), the fibre cable system has presented the highest transmitted signal bandwidth and less harmful radiation effects on fibre cable system operation for different fibres under study.
2. Figs. 3 and 4 have indicated that both ambient temperature and gamma irradiation doses increase and operating optical signal wavelength decreases; therefore there is a decrease in soliton transmission bit rate through fibre cable system. We have also found that at the third window of system operation ($\lambda = 1.55\ \mu m$), the fibre cable system has presented the highest soliton transmission bit rate and less harmful radiation effects on fibre cable system capacity for different fibres under consideration.
3. Figs. 5–8 have demonstrated that ambient temperature, optical signal wavelength, gamma irradiation doses and irradiation time increase, resulting in increase of radiation induced loss for different fibres under study. We have indicated that the silica glass fibres have presented lower radiation induced loss compared with fluoride glass fibres under the same operating conditions.
4. Figs. 9–12 have ensured that ambient temperature, gamma irradiation doses, operating optical signal wavelength and irradiation time increase, leading to decrease of optical received power in fibre cable system. We have indicated that at the third window of system operation ($\lambda = 1.55\ \mu m$), the fibre cable system has presented the highest optical received power and less harmful radiation effects on fibre cable system operation for different fibres under study. Moreover, we have found that silica glass fibres have presented higher optical received power compared with fluoride fibres under the same operating conditions.

## 4 Conclusions

To summarise, we have investigated the optical fibre cable transmission communication system under thermal and gamma irradiation doses environment. It is theoretically found that the decreased ambient temperature, the decreased gamma irradiation doses environment and the increased operating optical signal wavelength (the best third window of optical fibre communication system operation efficiency and transmission capacity at which $\lambda = 1.55\ \mu m$), result in the increase of both transmitted signal bandwidth and transmission bit rate by soliton technique for both fibre mediums under consideration. It is observed that silica glass fibres have presented both higher transmitted signal bandwidth and transmission bit rate compared with fluoride glass fibres at the same operating conditions. It is also theoretically indicated that decreased irradiation time and gamma irradiation doses, lead to decreased radiation induced loss and consequently to increased optical received power into fibre cable system for different fibres under study. Moreover, it is observed that silica fibres have presented lower radiation loss and higher optical received power compared with fluoride fibres under the same operating conditions. Therefore it is evident that silica glass fibres have presented higher transmission capacity, optical received power and lower transmission characteristics (loss and dispersion) compared with fluoride glass fibres under the same irradiation time and gamma irradiation doses.

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