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A radiation–temperature coupling model of the optical fiber attenuation spectrum in the Ge/P co-doped fiber

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A radiation–temperature coupling model of optical fiber attenuation spectrum has been developed. The spectrum in Ge/P co-doped fiber ranging from 800 nm–1600 nm at different temperatures and doses was measured and decomposed according to the configurational coordinate model based on which the power-law model was employed to predict the intensity of the color center absorption band at different doses. And the fiber loss in space was predicted by the model. This work will benefit the application of fibers in a complicated radiation environment.

Keywords: radiation, temperature, color centers, optical fiber

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1. Introduction

Optical fibers are increasingly used in various radiation environments like space systems, nuclear power plants, and military facilities because of their characteristics of small volume, lightweight, flexible structure, electromagnetic immunity, and electric insulation.[1,3] However, optical fiber sensors usually work under the combined influence of radiation and temperature fields. The presence of highly energetic radiation significantly increases fiber attenuation leading to the so-called radiation-induced attenuation (RIA) effect. This RIA phenomenon will of course affect the functionality of all fiber-based devices, such as fiber optic gyroscope (FOG) and optical fiber communication systems.[4,5] The RIA in optical fibers has been extensively studied.[6–11] During the past decades and a number of papers have treated the modeling of RIA with the irradiation dose at a single wavelength during irradiation and recovery after irradiation. The power-law model, the stretched saturating exponential model, and the saturating exponentials model have been proposed by different authors.[12–14] These models can be used to predict the RIA with the irradiation dose, thus benefiting the application of optical fiber sensors in radiations. The temperature dependence of the color center absorption is proposed as an important factor influencing the RIA behavior of post-irradiation fibers besides the thermally driven color center generation, conversion, and annealing process.[15] In our previous work,[16,17] a model for the temperature sensitivity of the RIA was investigated and it was found that there was an approximate linear relationship between the parameters of the color center absorption band and temperature. Nevertheless, no studies to date have considered the influence of radiation and temperature on RIA at the same time. Therefore, to evaluate the applicability of the fiber optical system in a radiation environment, the effect of radiation–temperature coupling on the RIA should be investigated.

In this paper, a novel model for radiation–temperature coupling of optical fiber attenuation spectrum was developed in Ge/P co-doped fiber after being sufficiently annealed based on a model of the temperature sensitivity of the RIA. The fiber attenuation spectrum was measured and decomposed into the absorption bands of color centers. Considering the radiation–temperature coupling, we quantified the parameters of the color center absorption band. Then the relationship between the parameters and radiation condition, namely, irradiation dose and temperature, was investigated. Furthermore, the model was verified by simulating experiments at the telecommunication wavelength. The model for radiation–temperature coupling of the optical fiber attenuation spectrum can be applied to assess the performance of optical fiber systems applied in radiation–temperature coupling environments.

2. Experimental procedure and experimental results

For this study, Ge/P co-doped fibers were realized: F1, F2, and F3. Its working temperature is $-60^{\circ} \sim 85^{\circ}$. Ge/P elements are usually used for changing the refraction index, and they are widely used in communication fibers, sensing fibers, as well as fiber Bragg gratings.[18] We conducted the irradiation experiments using a ^{60}Co source at room temperature.

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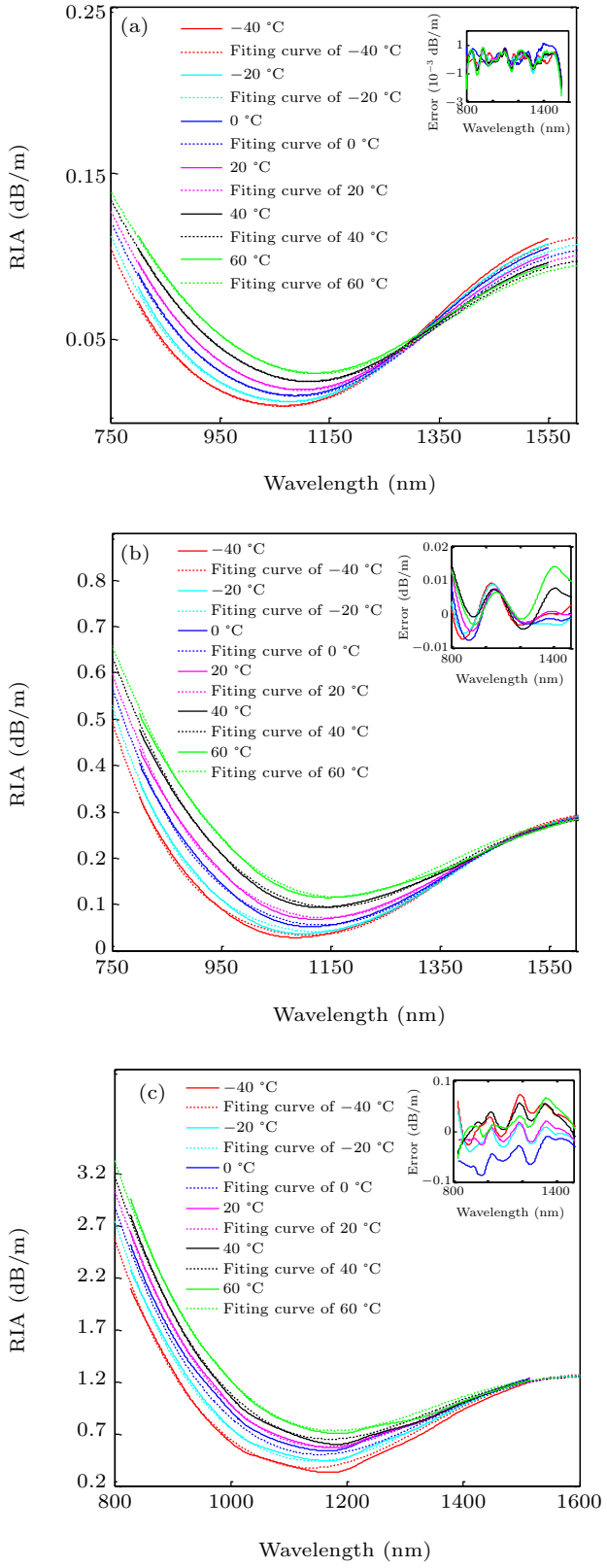


Fig. 1. Experimental data (solid lines) and fitting curves (dashed lines) of RIA spectra. The inset shows the errors: (a) 100 Gy; (b) 1000 Gy; (c) 10000 Gy.

As the penetration depth of the ^{60}Co source is much higher than most other photons and particles in space, it is reasonable to use the ^{60}Co source for the test. Each fiber was irradiated at a total dose of 100, 1000, and 1000 Gy, respectively, which is beneficial for reconstructing the RIA trend. Full spectral recordings were obtained by an optical spectrum analyzer (OSA) both before and after the gamma exposure, covering the wavelength ranging from 800 nm–1600 nm. The fibers have been placed in an 80° temperature-controlled chamber to accelerate the color center annealing process after the radiation until most of the unstable color centers had been annealed or transformed to other ones.[19] The temperature measurements were performed at −40 °C, −20 °C, 0 °C, 20 °C, 40 °C, and 60 °C in a session. Forty-five min were spent at each temperature to ensure that the fiber temperature stabilizes at the appointed temperature. Figure 1 shows the normalized radiation-induced attenuation spectrum smoothed by 300-pts SG of the experimental data of the tested fibers.

3. Modeling of the optical fiber attenuation spectrum

The optical fiber attenuation spectrum is the sum of the color center absorption bands related to underlying radiation-induced defects, and the color center absorption bands can be tackled by Gaussian resolution.[20] With this method, the measured optical fiber attenuation spectra were decomposed into individual absorption bands. To analyze the spectral dependence of the color centers with temperature, the configurational coordinate model was employed.[21] In Ref. [17], it was found that there was a linear relationship between the parameters of color center absorption band and temperature. The fitting formula of the Gaussian band can be expressed as

$$\mathrm{RIA}(E,T) = \sum a_{\mathrm{n}}(T) \exp\left[-\left(\frac{E - E_{\mathrm{n}}(T)}{\omega_{\mathrm{n}}(T)}\right)^2\right], \quad (1)$$

$$E = \frac{hc}{\lambda}, \quad (2)$$

where E_{n} and ω_{n} are the peak position and full-width at half maximum, respectively, they are only influenced by the color centers types and temperature. E represents the photon energy, and a_{n} is the intensity of the color center absorption band, which can be affected by the radiation dose and temperature. It is found that the optical fiber attenuation spectrum ranging from 800 nm–1600 nm in Ge/P co-doped fibers could be decomposed into three kinds of color center absorption bands, namely, P1, Ge-NBOHC, and Ge(X). The parameters of the color centers are shown in Table 1.[22]

Table 1. Values of color center parameters.

Color center (CC)	E_{n} (eV)	ω_{n} (eV)
P1	0.765	0.224
Ge-NBOHC	1.97	0.3–0.6
Ge(X)	2.61	0.82

According to the configurational coordinate model, $E_{\rm n}$ and $a_{\rm n}$ will decrease, and $\omega_{\rm n}$ will increase as the temperature increases. Based on the temperature sensitivity model of RIA, the radiation–temperature coupling effect is studied in this paper. The irradiation dose is the physical quantity measuring the absorbed radiation energy of the optical fiber, which will have a significant impact on the formation and degradation of color centers. And the irradiation dose rate determines the energy radiating into the fiber unit time and mainly affects the attenuation characteristics during irradiation. Irradiated and high temperature annealed fibers were investigated, and thus the effect of the dose rate was ignored.

We focus our discussion on two main points. Firstly, we attempted to decompose the fiber optical attenuation spectrum with the help of a set of Gaussian bands corresponding to the absorption bands of the defects identified. Secondly, we investigated the model for radiation–temperature coupling of the optical fiber attenuation spectrum based on quantitative analysis of the parameters of the color center absorption. To achieve the best fits of the experimental curves, we adjusted the characteristics $a_{\rm n}$, $E_{\rm n}$, and ω_n as shown in Table 1. The intensity of the color center absorption depended on the irradiation dose and the temperature affects the optical fiber attenuation spectrum. We fitted the experimental curves with fixed positions $E_{\rm n}$ and widths $\omega_{\rm n}$ in the photo-energy domain at the same temperature. The formula for the temperature sensitivity of the RIA in the Ge/P co-doped fiber is shown in Ref. [17].

3.1. Spectrum decomposition

The parameters have subtle variations in the fitting process while trying to adapt the fitting curves to the smoothed optical fiber attenuation spectrum as perfectly as possible. The fitting curves of each kind of color center absorption bands and their integrated fitting curves are depicted in Fig. 2.

Then the parameters of three kinds of color center absorption curves along with the irradiation dose and temperature were quantitatively analyzed. The scatter diagrams were plotted and the fitted values are listed in Table 2. The relationship between a_n and dose at the same temperature as shown in Fig. 3, which accorded with an RIA model in Ref. [12]:

$$\mathrm{RIA} = C \cdot D^f, \tag{3}$$

where C and f are experimental constants, D is the irradiation dose. The change in f along with T can be ignored.

To investigate the relationship of $a_{\rm n}$ with T, the coefficient in the power-law function $C(T)$ was fitted and the fitting curves are shown in Fig. 4. The fitting function coefficients of $a_{\rm n}(D,T)$ are listed in Table 3.

The intensity of the color center absorption with radiation–temperature coupling fitting equations and the model for the temperature sensitivity of the RIA were combined, so the model for the radiation-temperature coupling of the optical fiber attenuation spectrum in Ge/P co-doped fiber can be expressed as

$$\begin{aligned}\mathrm{RIA}(E,D,T) = {} & a_{\rm P1}(D,T)\exp\left[-\left(\frac{E-E_{\rm P1}(T)}{\omega_{\rm P1}(T)}\right)^2\right] \\ & + a_{\rm Ge(X)}(D,T)\exp\left[-\left(\frac{E-E_{\rm Ge(X)}(T)}{\omega_{\rm Ge(X)}(T)}\right)^2\right] \\ & + a_{\text{Ge-NBOHC}}(D,T)\exp\left[-\left(\frac{E-E_{\text{Ge-NBOHC}}(T)}{\omega_{\text{Ge-NBOHC}}(T)}\right)^2\right].\end{aligned} \tag{4}$$

This formula is given as a function of wavelength, total radiation dose and temperature quantitatively. Within the scope of the applicable conditions, the fiber RIA sensitivity is

$$\delta_{\rm F} = \frac{|\mathrm{RIA}(E,D_{\max},T_{\max}) - \mathrm{RIA}(E,D_{\min},T_{\min})|}{(D_{\max}-D_{\min})\times(T_{\max}-T_{\min})}. \tag{5}$$

So, the radiation–temperature coupling sensitivities are 2.848×10^{-6} dB/(mGy·°C), 8.07×10^{-7} dB/(mGy·°C), and 1.127×10^{-6} dB/(mGy·°C) at 850 nm, 1310 nm, and 1550 nm, respectively. It can be seen that at 1310-nm radiation–temperature coupling, the sensitivity is lower than those at the other two wavelengths; therefore, 1310 nm is more suitable for application in a complex radiation environment.

Table 2. $a_{\rm n}$ values of color center absorption fitting curves.

T (°C)	Color center								
	$a_{\rm P1}$			$a_{\text{Ge-NBOHC}}$			$a_{\rm Ge(X)}$		
	D Dose (Gy)								
	100	1000	10000	100	1000	10000	100	1000	10000
−40	0.1124	0.346	1.242	0.1747	0.8849	4.84884	4.48×10^{-2}	0.39	2.1278
−20	0.1081	0.341	1.228	0.1727	0.8829	4.80792	4.38×10^{-2}	0.372	2.0989
0	0.1044	0.337	1.208	0.1707	0.8814	4.767	4.28×10^{-2}	0.354	2.07
20	0.1009	0.3336	1.188	0.1687	0.8799	4.72608	4.18×10^{-2}	0.336	2.0411
40	0.0968	0.3295	1.170	0.1667	0.8789	4.68516	4.08×10^{-2}	0.318	2.0122
60	0.093	0.326	1.150	0.1647	0.8778	4.64424	3.99×10^{-2}	0.3	1.9833

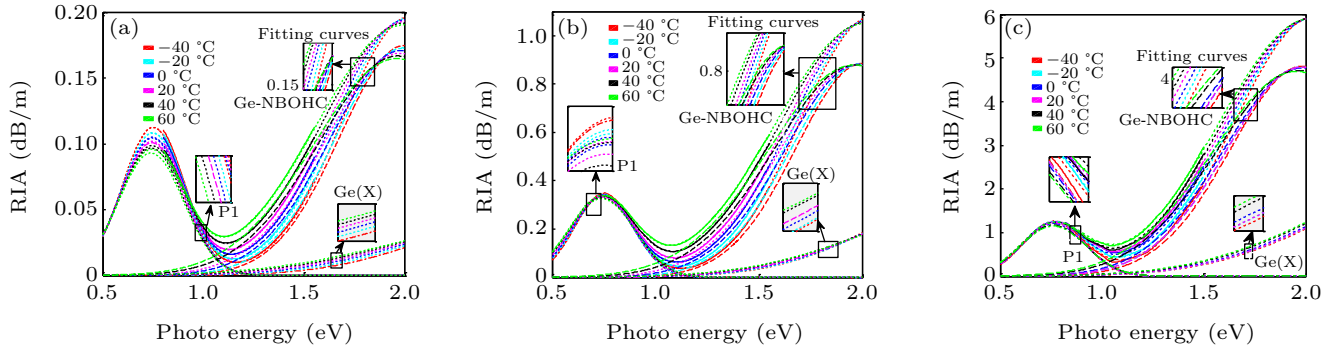


Fig. 2. Absorption bands (dotted lines) of P1, Ge-NBOHC, and Ge(X) at six temperatures and their integrated fitting curves. The inset shows the partial enlargement of the curves: (a) 100 Gy; (b) 1000 Gy; (c) 10000 Gy.

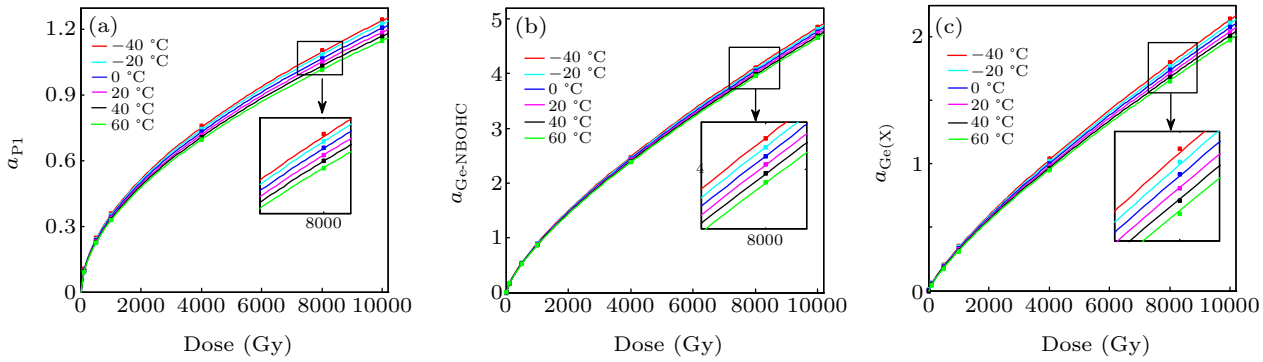


Fig. 3. Fitting curves of parameters $a(D)$ of P1, Ge-NBOHC, and Ge(X) CC at six temperatures and six doses (a) $a_{P1}(D)$, (b) $a_{Ge\text{-}NBOHC}(D)$, (c) $a_{Ge(X)}(D)$. The inset shows a partial enlargement of the curves.

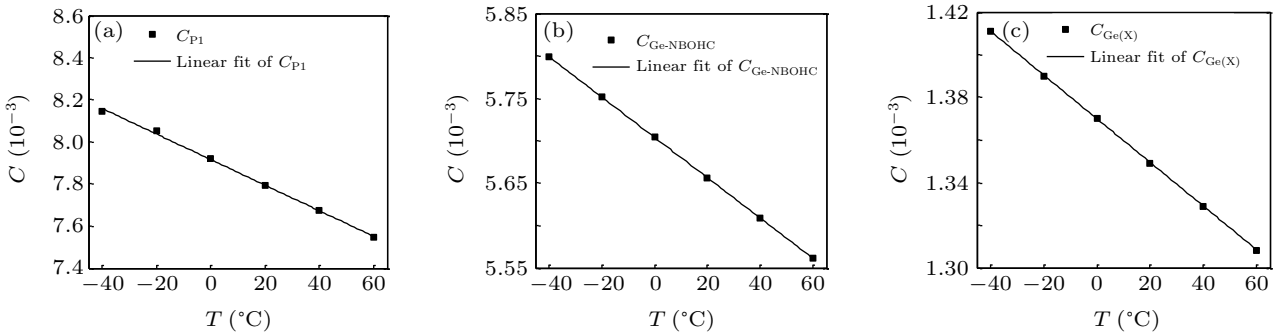


Fig. 4. Linear fitted curves of C_{P1}, $C_{Ge\text{-}NBOHC}$, and $C_{Ge(X)}$.

Table 3. Coefficients of the fitting functions of a_n.

Fitting function: $a_n(D,T) = (p_1 \cdot T + p_2) \cdot D^f$			
Parameters	p_1 (10^{-6})	p_2	f
a_{P1}	−6.073	0.007916	∼0.5457
$a_{Ge\text{-}NBOHC}$	−2.381	0.005704	∼0.7305
$a_{Ge(X)}$	−1.027	0.00137	∼0.7950

3.2. Verification and discussion

Additional tests have to be done to prove the validity of the model for radiation–temperature coupling of the optical fiber attenuation spectrum. Complementary experiments of doses at 500, 300, and 8000 Gy and temperatures ranging from −50 °C to 70 °C measurements have been conducted. The RIA of the fiber was obtained at telecommunication wavelengths of 850, 1310, and 1550 nm, by the experiment and simulation. The interval of temperature is 10 °C. The simulation results and experimental data are shown in Fig. 5.

The experimental results are relatively consistent with the simulation results because the mean square error (MSE) between the simulation and experiment is as small as 5.59×10^{-3} or less. Therefore, the optical fiber attenuation spectrum fitting is proved to be correct. For a 20-year geostationary orbit mission, a basic shielding equivalent to 1-mm thick Al sphere leads to a total of 140 Gy at a temperature range of −40 °C to 60 °C. The RIA in the Ge/P fiber was calculated by using the model as shown in Fig. 5. The annual variations of the RIA from −40 °C to 60 °C are 0.0020, 0.0039, 0.0057, and 0.0073 dB·m^{-1} annually. Therefore, the radiation environment of the applicability of the fiber optical system was predicted and some measures could be taken to increase the fiber lifetime and reliability.

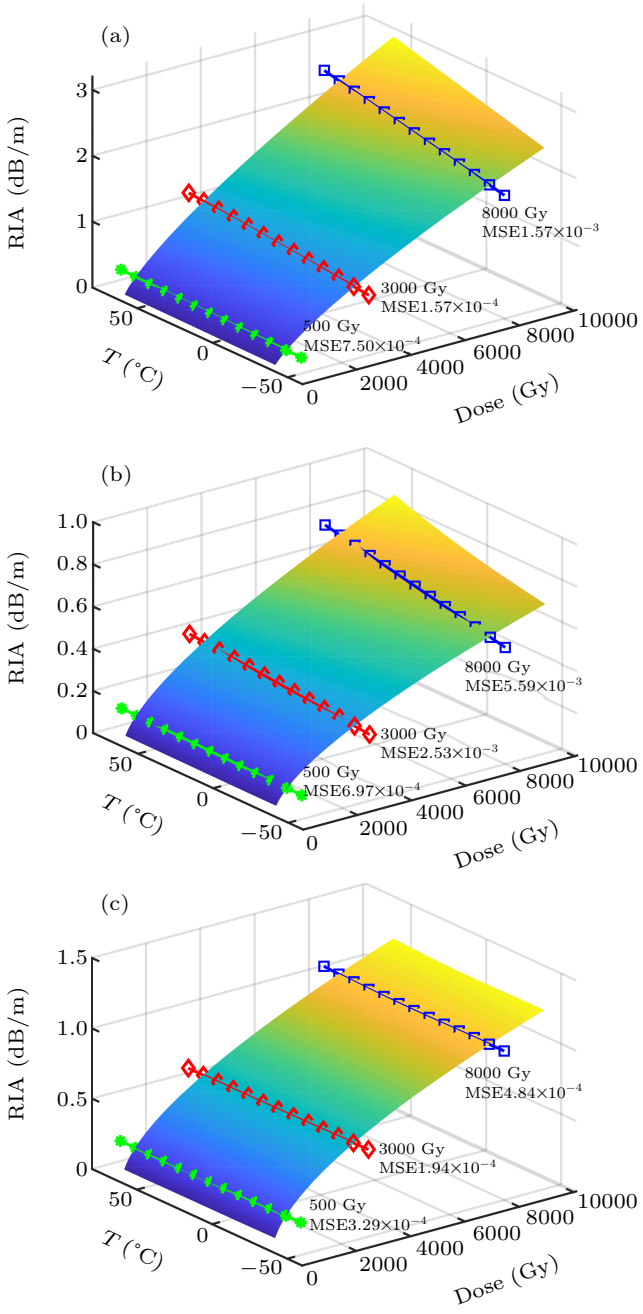


Fig. 5. Experimental data and simulation results at three wavelengths: (a) 850 nm, (b) 1310 nm, (c) 1550 nm.

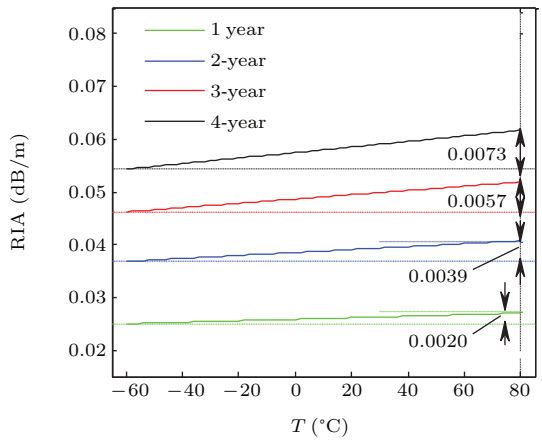


Fig. 6. RIA calculated by the model.

4. Conclusion

Based on the model for the temperature sensitivity of the RIA, a novel radiation–temperature coupling model of the optical fiber attenuation spectrum was developed. We conducted a radiation experiment on Ge/P co-doped fibers at total doses of 100, 1000, and 10000 Gy and temperature tests for the three irradiated fibers after sufficient annealing. The fiber transmission spectrum was measured and decomposed into three absorption bands of P1, Ge-NBOHC, and Ge(X) color centers. Moreover, the parameters of the color center absorption were quantified and the fitting functions were obtained. It was found that the intensity of color center absorption and irradiation dose conform to a power-law relationship at the same temperature. Furthermore, the parameters of C in the power-law function showed a linear temperature dependence. Finally, the model was validated at 850 nm, 1310 nm, and 1550 nm. It can be concluded that the radiation–temperature coupling sensitivity at 1310 nm is 8.07×10^{-7} dB/(mGy·°C), which is lower than those at the other two wavelengths. Therefore, 1310 nm is more suitable for the application of Ge/P co-doped fibers in a radiation environment. Above all, the radiation–temperature coupling model method can be used for predicting the optical fiber performance in the combined radiation and temperature field. This study has some theoretical significance for improving environment adaption performance.

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