Irradiation effect on strain sensitivity coefficient of strain sensing fiber Bragg gratings*

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The effect of irradiation on the strain sensitivity coefficient of strain sensing fiber Bragg gratings (FBGs) has been investigated through experiments. FBGs were fabricated in single mode fibers with 3 mol% Ge-concentration in the core and with a H_2-loading treatment. In experiments, the FBGs were subjected to γ-radiation exposures using a Co^{60} source at a dose-rate of 25 Gy/min up to a total dose of 10.5 kGy. The GeO defect in fiber absorbs photons to form a GeE' defect; the interaction with H_2 is a probable reason for the γ-radiation sensitivity of gratings written in hydrogen loaded fibres. The effect mechanism of radiation on the strain sensitivity coefficient is similar to that of radiation on the temperature sensitivity coefficient. Radiation affects the effective index n_{eff}, which results in the change of the thermo-optic coefficient and the strain-optic coefficient. Irradiation can change the strain sensitivity coefficient of FBGs by 1.48%–2.71%, as well as changing the Bragg wavelength shift (BWS) by 22 pm–25 pm under a total dose of 10.5 kGy. Our research demonstrates that the effect of irradiation on the strain sensitivity coefficient of FBG is small and that strain sensing FBGs can work well in the radiation environment.

Keywords: fiber Bragg grating, irradiation effect, strain sensitivity coefficient

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1. Introduction

Fiber Bragg gratings (FBGs) are increasingly used in the strain monitoring of space systems and nuclear power plants because of their characteristics of low mass, high precision and the immunity from electromagnetic interference.[1,2] In order to be used in radiation environments, FBGs must perform with high stable properties over the whole mission time. However, radiation is a factor that can compromise this stability. Motivated by the improving radiation tolerance of FBGs, the effect of radiation on FBGs has been studied for more than a decade.[1–7]

Early studies on the effect of radiation have demonstrated that the temperature sensitivity was not affected by radiation within 3% accuracy and that the amplitude and width of the Bragg resonance were unchanged under γ-radiation.[4] Lower values of 20 pm–50 pm of the Bragg wavelength shift (BWS) in the red direction have been reported in subsequent publications.[3,4,9] However, there have been few reports on the irradiation effect on the strain sensitivity coefficient of FBGs. In this paper, the irradiation effect on the strain sensitivity coefficient is studied in theory and experiment.

The use of a FBG as a strain sensor is based on the dependence of BWS on the strain change. The BWS λ_B is well approximated by a linear expression

$$\lambda_B(\varepsilon) = \lambda_B(\varepsilon_0) + K_\varepsilon(\varepsilon - \varepsilon_0), \tag{1}$$

where K_ε is the strain sensitivity coefficient, ε is the strain and ε_0 is a reference strain. Defects generated by ionizing radiation affect the effective refractive index, resulting in the change of the Bragg wavelength. The application of FBGs for strain sensing in radiation environments depends on the extent $\lambda_B(\varepsilon_0)$ and K_ε are sensitive to the radiation.

The strain sensitivity coefficients of FBGs are measured before the irradiation experiment as an initialization reference. After that, the FBGs will be irradiated with a Co^{60} source at a dose-rate of 25 Gy/min up to a total dose of 10.5 kGy. Then, another strain sensitivity coefficient testing of FBGs is implemented and the results are compared with that of the first testing before radiation. BWS and reflection spectra will be tested to verify the effect of irradiation on the FBGs.

2. Experimental setup

2.1. Design of strain sensing fiber Bragg grating

Four FBGs are fabricated for γ-radiation experiments. All the four FBGs are written in single mode optical fiber SMF 28C with 3 mol% GeO_2-concentration in the core. Their parameters are shown in Table 1.

Because of the low GeO_2-content of single mode optical fiber, it is almost impossible to write FBG into that fiber without hydrogen loading treatment. All the four FBGs are loaded with H_2 before grating inscription (about one week at 2 kMPa and 50 °C). An argon-ion laser (Braggstar-s, pulse energy 10 mJ/cm^2, 193 nm) is used for fabricating all the gratings. The stabilized pulse energy density is 7 mJ/cm^2. The

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acrylate coating is mechanically stripped before grating inscription and all the gratings are recoated after fabrication. After the recoating, these gratings are annealed for 12 h at 120 °C to accelerate the out-diffusion of H_2.

The length of gratings is 10 mm, the reflectivity is $> 85\%$ and the full-width at half-maximum (FWHM) is ~ 0.25 nm. The Bragg wavelength of gratings ranges from 1549.954 nm to 1558.940 nm. For exactly sensing structural parameters and enhancing the strain sensitivity of FBG, a strain sensitivity-enhancing packing is designed.

2.2. FBG strain coefficient testing system

A manual translation stage (TSM50D-1S by Zolix instrument Inc.) is used for testing the strain coefficient of FBG; the resolution of the translation stage is 0.01 mm. A horizontal datum plane and an immovable block are designed to compose the strain coefficient testing system, which is shown in Fig. 1.

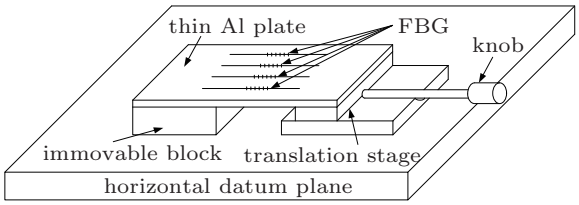


Fig. 1. Strain coefficient testing system.

The immovable block and the translation stage are fixed on the horizontal datum plane with a 30-mm distance. Two sides of a thin Al plate are fixed on the immovable block and the vernier of the translation stage, respectively. When the vernier of the translation stage slips, the middle area of the thin Al plate is subjected to strain. The FBG sensors are stuck to the middle area of the thin Al plate. Bragg peaks are measured in reflection with a FBG interrogation system sm125 from Micro Optics Int. with wavelengths ranging from 1510 nm to 1590 nm, a wavelength resolution of 1 pm and repeatability 1 pm.

In order to be sure of the accuracy of the experimental process, the testing system is laid on a marble table. The temperature is kept unchanged (room temperature) during the experiment. The experimental setup is shown in Fig. 2.

The whole experiment is composed of three steps: strain coefficient testing before radiation, the radiation experiment and strain coefficient testing after radiation. Firstly, the Bragg reflection spectrum is tested with sm125 for 1 min; the testing Bragg peaks as the initial reference data. Then, the knob of the translation stage is circumgyrated clockwise, the vernier slips and pulls the thin Al plate. When the vernier slips 0.2 mm, the Bragg reflection spectrum is tested for 1 min. There are six testing points: 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, 1 mm, and 1.2 mm, respectively. After that, the knob of the translation stage is circumgyrated counter-clockwise and the pulling strain in the thin Al plate is released slowly.

When the thin Al plate returns to the initial length, the knob of the translation stage keeps on being circumgyrated counter-clockwise, the vernier slips and extrudes the thin Al plate. The Bragg reflection spectrum is tested at the same testing points. After dealing with the experimental data, the strain sensitivity coefficients are calculated by using the least squares method.

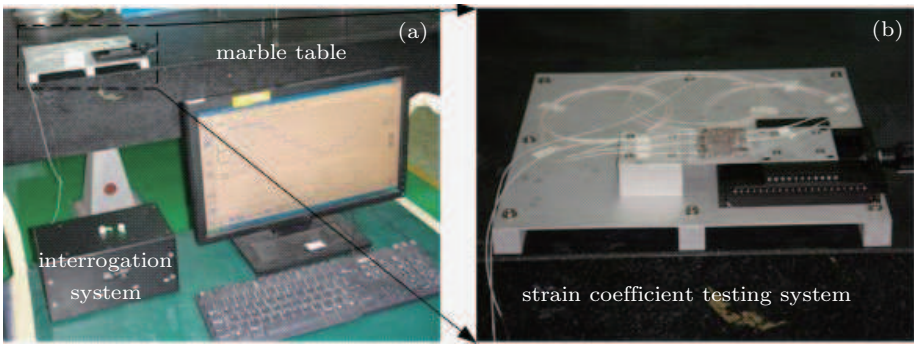


Fig. 2. (color online) (a) Photo of strain sensitivity coefficient testing experimental setup. (b) Strain coefficient testing system.

2.3. Radiation experimental condition

After fitting the strain sensitivity coefficient, the FBGs will be irradiated with a Co^{60} source at a dose-rate of 25 Gy/min up to a total dose of 10.5 kGy. A ferrous sulfate dosimeter was used to measure the dose-rate before the experiment. The FBGs are kept unstrained during the irradiation to avoid complications related with the radiation and strain cross sensitivity. The irradiation experimental setup is shown in Fig. 3.

During the irradiation experiment, FBG4 is placed behind the two 8-cm-thick lead bricks to avoid irradiation. As a reference FBG, the experimental data of FBG4 are used in contrast to the results of other FBGs.

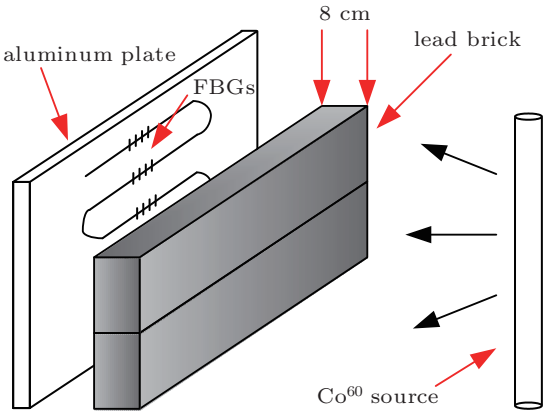


Fig. 3. (color online) Irradiation experimental setup.

The experiment measurement procedure is shown in Table 2. The strain coefficient testing is carried out before and after the irradiation to study the radiation effect on the strain sensitivity coefficient. The strain sensitivity coefficient is measured immediately after γ-radiation exposure to compare with the result before the radiation.

Two groups of FBG are used to compare the effect of the radiation dose rate on the sensitivity coefficient of FBG. FBG1, and FBG2 are in group 1 and FBG3 and FBG4 are in group 2. The FBGs in group 1 are irradiated with a Co^{60} source at a dose-rate of 0.1 Gy/s up to a total dose of 50 kGy; the FBGs in group 2 are irradiated with a Co^{60} source at a dose-rate of 0.09 Gy/s up to a total dose of 50 kGy. The strain sensitivity coefficient is measured immediately after radiation exposure to compare the effect of the radiation dose rate on the sensitivity coefficient of FBG.

Table 1. Parameters of fiber Bragg gratings used in the experiment.

Label	Fiber	Core dopant/mol%	Wavelength/nm	H_2-loading	Length/mm	Reflectivity/%	FWHM/nm
FBG1	SMF28C	GeO_2 (3)	1551.242	Yes	10	90	0.25
FBG2	SMF28C	GeO_2 (3)	1549.954	Yes	10	86	0.24
FBG3	SMF28C	GeO_2 (3)	1558.940	Yes	10	88	0.25
FBG4	SMF28C	GeO_2 (3)	1555.367	Yes	10	89	0.25

Table 2. Experimental measurement procedure.

Number	Measurement procedure	Measurement condition
1	strain sensitivity coefficient measurement	strain testing from 0 $\mu\varepsilon$ to 70 $\mu\varepsilon$
2	irradiation experiment	γ-irradiation at a dose-rate of 25 Gy/min up to a total dose of 10.5 kGy at $\sim$ 26 °C
3	strain sensitivity coefficient measurement	strain testing from 0 $\mu\varepsilon$ to 70 $\mu\varepsilon$

3. Results

3.1. Variation of reflection spectra during irradiation

Figure 4 shows the Bragg reflection spectra of FBG1 under irradiation. The baseline denotes the reflection spectra before radiation. The dashed line represents the reflection spectra after a radiation dose of 10.5 kGy. The FWHM of the reflection spectra is nearly unchanged during the radiation exposures. Table 3 shows the variation of reflection power during irradiation. The reflection power changes of FBG1–FBG3 are 0.06 dBm, 0.07 dBm, and 0.06 dBm, respectively. FBG4 is not subjected to irradiation and the change of the reflection power is 0.01 dBm. All the reflection power changes of the FBGs are smaller than 0.1 dBm.

3.2. BWS during irradiation

The shift of the Bragg wavelength during irradiation is listed in Table 4. The BWS of FBG1, FBG2, and FBG3

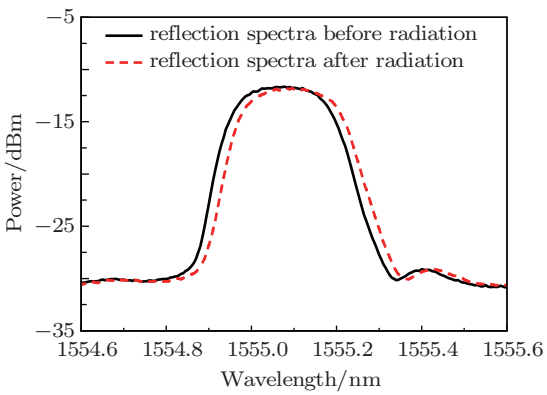


Fig. 4. (color online) Variation of reflection spectra (FBG1).

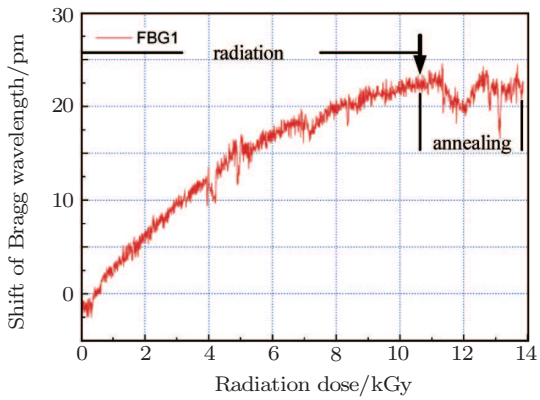


Fig. 5. (color online) BWS of FBG1.

are 24 pm, 22 pm, and 25 pm, respectively. The BWS of FBG1 is shown in Fig. 5. As the reference FBG, the BWS of FBG4 is 4 pm, nearly unchanged.

After the irradiation, FBG1, FBG2, and FBG3 show similar behaviors, the Bragg wavelengths shift toward the red direction, which agrees with the result reported in Refs. [11]–[13].

3.3. Strain sensitivity coefficient variation during irradiation

The strain sensitivity coefficient variations during irradiation are shown in Table 5. The strain sensitivity coefficient K_ε is fitted according to Eq. (1) using the least squares method.

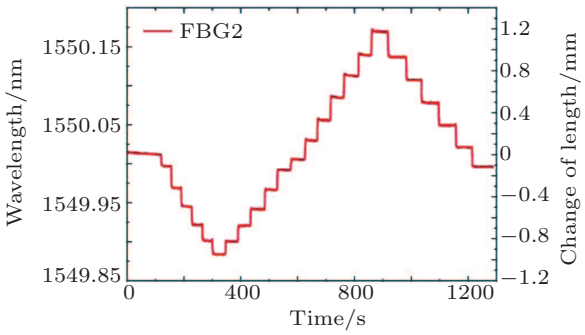


Fig. 6. (color online) BWS during strain sensitivity coefficient testing.

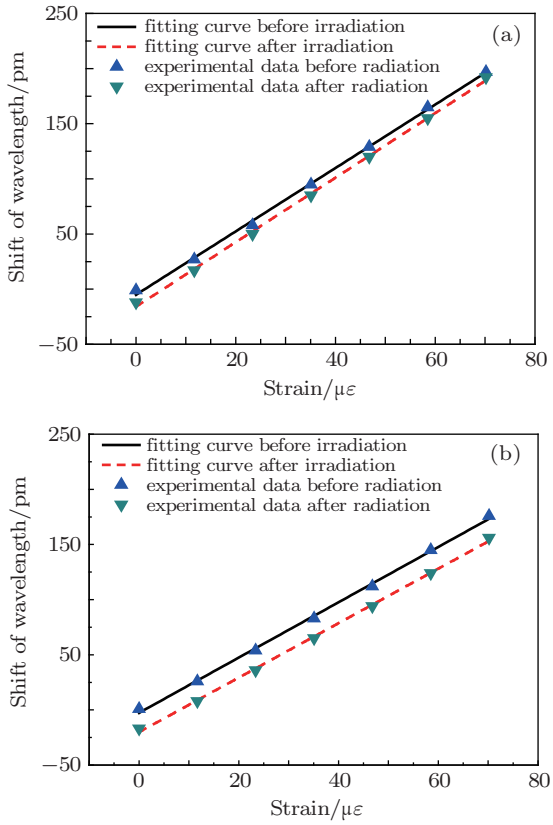


Fig. 7. (color online) Strain sensitivity coefficient contrast between pre-irradiation and post-irradiation. (a) FBG1; (b) FBG2.

The strain sensitivity coefficient variations of FBG1, FBG2, and FBG3 are 1.81%, 1.48%, and 2.71%, respectively. The strain sensitivity coefficient change of FBG4 is 0.13%, within the measurement uncertainty. All the variations of FBGs are below 3%. The BWS during the strain sensitivity coefficient testing is shown in Fig. 6. Strain sensitivity coefficient contrasts between the pre-irradiation and the post-irradiation are shown in Figs. 7 and 8.

The influence of the radiation dose on the strain sensitivity coefficient is shown in Table 6. The total radiation dose of group 1 is the same as that of group 2, but the corresponding radiation dose rates are different. The BWS of FBG1 is 39 pm and the BWS of FBG2 is 40 pm, slightly higher than those of FBG3 (36 pm) and FBG4 (37 pm). However, the corresponding strain sensitivity coefficients of FBGs are nearly the same.

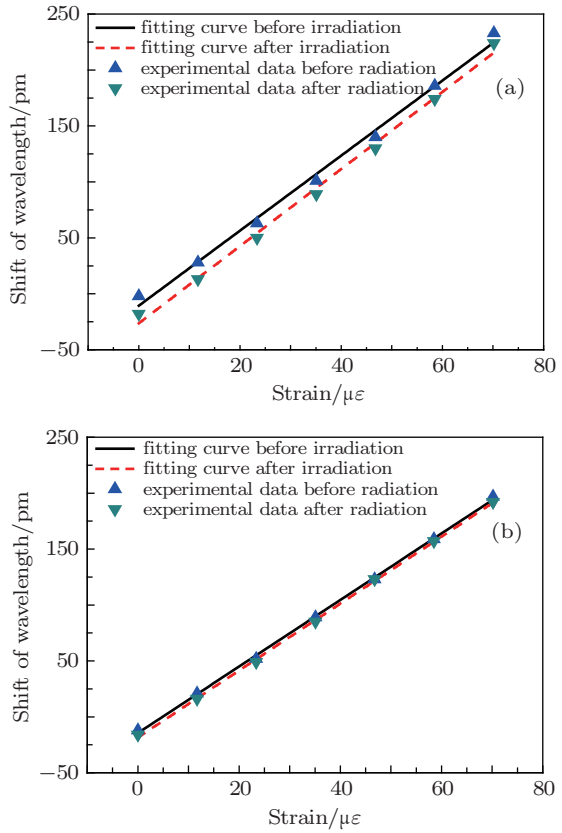


Fig. 8. (color online) Strain sensitivity coefficient contrast between pre-irradiation and post-irradiation. (a) FBG3; (b) FBG4.

Table 3. Variation of reflection power.

Label	Reflection power before radiation/dBm	Reflection power after radiation/dBm	Variation/dBm
FBG1	–11.77	–11.83	–0.06
FBG2	–11.34	–11.41	–0.07
FBG3	–11.20	–11.26	–0.06
FBG4	–11.56	–11.57	–0.01

Table 4. Shift of Bragg wavelength.

Label	Bragg wavelength before radiation/nm	Bragg wavelength after irradiation/nm	Shift of Bragg wavelength/pm
FBG1	1551.242	1551.273	24
FBG2	1549.955	1549.987	22
FBG3	1558.940	1558.974	25
FBG4	1555.367	1555.371	4

Table 5. Variation of strain sensitivity coefficient.

Label	Strain sensitivity K_ε before radiation (pm/με)	Strain sensitivity K_ε after radiation (pm/με)	Variation
FBG1	2.873	2.925	1.81%
FBG2	2.507	2.544	1.48%
FBG3	3.353	3.444	2.71%
FBG4	3.017	3.021	0.13%

Table 6. Influence of radiation dose rate on the strain sensitivity of FBG.

Group	Label	Radiation dose rate/(Gy/s)	Radiation time/h	Total radiation dose/kGy	Max peak shift/pm	Strain sensitivity variation/%
1	FBG1	0.1	139	50	39	2.76%
	FBG2	0.1	139	50	40	2.35%
2	FBG3	0.09	156	50	36	2.69%
	FBG4	0.09	156	50	37	2.58%

4. Discussion

It is known that the photosensitivity of fiber is correlated to the defect centers of fiber. Like the photosensitivity of fiber, the radiation sensitivity of FBG is also correlative with the defect centers. A probable interaction involves two stages.[14] First, a photon with suitable energy excites a regular Ge–O bond, as shown in Fig. 9.

At room temperature, molecular hydrogen is known to react with non-bridging oxygen leading to the production of an OH-group and atomic hydrogen. Non-bridging oxygen is a center that is different from the excited Ge–O bond. However, it is reasonable to assume that the interaction with molecular hydrogen is similar in both cases, as shown in Fig. 10.

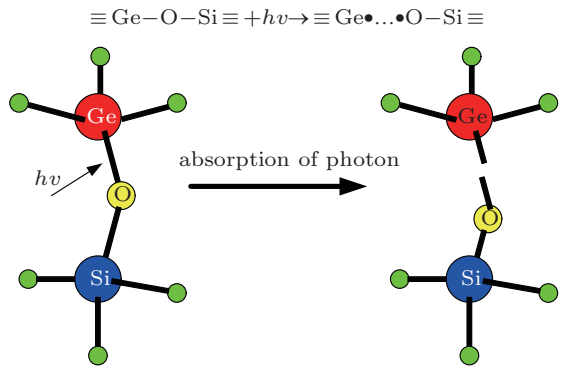


Fig. 9. (color online) GeO defect absorb a photon to form a GeE' defect.

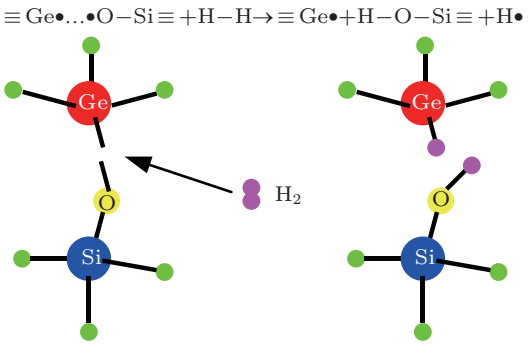


Fig. 10. (color online) The GeE' defect interaction with H_2.

The atomic hydrogen may react with ≡Ge• to form a Ge–H bond or may participate in the breaking of another regular Ge–O bond. Radiolytic rupture of the OH-bonds is a probable reason for the high γ-radiation sensitivity of gratings written in hydrogen loaded fibres, as observed in our experiment.

Considering the effect of radiation, temperature and strain on FBGs simultaneously, the shift of the Bragg wavelength as a function of radiation, temperature and strain is given by

$$\lambda_B(d,T,\varepsilon) = 2n_{\text{eff}}(d,T,\varepsilon)\Lambda(d,T,\varepsilon), \tag{2}$$

where d is the total radiation dose, T is the temperature and ε is the strain. Performing a Taylor series expansion to formula (2), ignoring the fact that the temperature and the high-order terms dependent on strain and only terming up to the second order in the radiation induced wavelength shift are preserved, one can obtain

$$\begin{aligned}\lambda_B(d,T,\varepsilon) = \lambda_B(d_0,T_0,\varepsilon_0) + \Bigg[&2\Lambda\frac{\partial n_{\text{eff}}}{\partial d}\Delta d + \Lambda\frac{\partial^2 n_{\text{eff}}}{\partial d^2}(\Delta d)^2 \\ &+2\left(\Lambda\frac{\partial n_{\text{eff}}}{\partial T}+n_{\text{eff}}\frac{\partial\Lambda}{\partial T}\right)\Delta T \\ &+2\left(\Lambda\frac{\partial n_{\text{eff}}}{\partial \varepsilon}+n_{\text{eff}}\frac{\partial\Lambda}{\partial \varepsilon}\right)\Delta\varepsilon\Bigg]_{d=d_0,T=T_0,\varepsilon=\varepsilon_0},\end{aligned} \tag{3}$$

where $\Delta\lambda_B = \lambda_B(d,T,\varepsilon) - \lambda_B(d_0,T_0,\varepsilon_0)$ is the total BWS of FBG. Formula (3) could be transformed to

$$\begin{aligned}&\Delta\lambda_B(d,T,\varepsilon) \\ &= \Bigg[2\Lambda\frac{\partial n_{\text{eff}}}{\partial d}\Delta d + \Lambda\frac{\partial^2 n_{\text{eff}}}{\partial d^2}(\Delta d)^2 \\ &\quad+2\left(\Lambda\frac{\partial n_{\text{eff}}}{\partial T}+n_{\text{eff}}\frac{\partial\Lambda}{\partial T}\right)\Delta T \\ &\quad+2\left(\Lambda\frac{\partial n_{\text{eff}}}{\partial \varepsilon}+n_{\text{eff}}\frac{\partial\Lambda}{\partial \varepsilon}\right)\Delta\varepsilon\Bigg]_{d=d_0,T=T_0,\varepsilon=\varepsilon_0}.\end{aligned} \tag{4}$$

The first two terms of formula (4) are the radiation induced wavelength shift, the third term is the Bragg wavelength shift induced by the temperature variation and the fourth term is the Bragg wavelength shift induced by the strain.

According to our previous radiation experiment results,[12] temperature sensitivity coefficients are affected by radiation within 5% up to a total dose of 50 kGy, which agrees with the report in Ref. [4]. This is similar to the results of the strain sensitivity coefficient being affected by radiation, which is within 3% up to a total dose of 10.5 kGy.

According to the derivation of formula (4), it can be found

$$K_T = 2\left[\Lambda\frac{\partial n_{\text{eff}}}{\partial T} + n_{\text{eff}}\frac{\partial \Lambda}{\partial T}\right], \tag{5}$$

$$K_\varepsilon = 2\left[\Lambda\frac{\partial n_{\text{eff}}}{\partial \varepsilon} + n_{\text{eff}}\frac{\partial \Lambda}{\partial \varepsilon}\right], \tag{6}$$

where K_T is the temperature sensitivity coefficient, K_ε is the strain sensitivity coefficient, T is the temperature, ε is the strain, $(\partial n_{\text{eff}}/\partial T)$ is the temperature induced refractive index change, $(\partial n_{\text{eff}}/\partial \varepsilon)$ is the strain induced refractive index change and $(\partial \Lambda/\partial \varepsilon)$ is the elasticity coefficient. Radiation can affect the refractive index n_{eff}, which could explain the change of K_T and K_ε during the irradiation experiment.

5. Conclusion

The effect of irradiation on the strain sensitivity coefficient of FBG has been investigated. some conclusions are summarized based on the experimental results and discussion. The strain sensitivity coefficient variation is less than 3 % during the radiation. The reflection power of FBGs decreases below 0.1 dBm and the FWHM is nearly unchanged during the radiation. Irradiation treatment does not affect the reflection spectra of FBGs significantly. The Bragg wavelength of FBGs with H_2-loading treatment shifts toward the red direction, 22 pm–25 pm up to a total dose of 10.5 kGy. The GeO defect absorbs photons to form the GeE' defect and the interaction with H_2 is a probable reason for the γ-radiation sensitivity of gratings written in hydrogen loaded fibres. The mechanism of the effect of radiation on the strain sensitivity coefficient is similar to the effect of radiation on the temperature sensitivity coefficient. Radiation affects the refractive index n_{eff}, which results in the change of the thermo-optic coefficient and the strain-optic coefficient.

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