Experimental investigation of pre-irradiation effect on radiation sensitivity of temperature sensing fiber Bragg gratings*

Jin Jing(金 靖)†, Lin Song(林 松), and Song Ning-Fang(宋凝芳)

School of Instrument Science and Optic-electronics Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, *China*

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The effect of pre-irradiation on radiation sensitivity of fiber Bragg gratings (FBGs) is verified experimentally. FBGs are fabricated in photosensitive optical fibers and single mode fibers with Ge-concentration in a range from 3 mol% to 23.37 mol% in the core. In experiments, the FBGs are subjected to twice γ-radiation exposures to a Co^{60} source at a dose-rate of 0.1 Gy/s up to a total dose of 50 kGy. Pre-irradiation treatment can reduce the temperature sensitivity variation of FBGs by 18.12%–35.91%, as well as Bragg wavelength shift (BWS) by 8%–27.08 %. Our research demonstrates that pre-irradiation treatment is a feasible method to improve the radiation tolerance of FBGs.

Keywords: fiber Bragg grating, pre-irradiation, radiation sensitivity

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1. Introduction

Fiber Bragg gratings (FBGs) are increasingly used in temperature monitoring of space systems and nuclear power plants because of their characteristics of low mass, high accuracy and immunity from electromagnetic interference.[1,2] In order to be used in radiation environments, FBGs must possess high stable properties over the whole mission time. However, radiation is a factor which can reduce this stability. Motivated by the improving radiation tolerance of FBGs, people have studied the effect of radiation on FBGs for more than a decade.[1−7]

The use of an FBG as a temperature sensor is based on the dependence of Bragg wavelength shift (BWS) on temperature change. The BWS (λ_B) is well approximated by a linear expression

$$\lambda_B(T) = \lambda_B(T_0) + K(T - T_0), \quad (1)$$

where K is the temperature sensitivity, T is the temperature, and T_0 is a reference temperature. Defects generated by ionizing radiation affect the effective refractive index, and thus result in the change of Bragg wavelength. The application of FBGs to temperature sensing in radiation environments depends on to what extent $\lambda_B(T_0)$ and K are sensitive to radiation.[3−8]

Early studies on the effect of radiation have demonstrated that temperature sensitivity was not affected by radiation within 3% accuracy, and the amplitude and the width of Bragg resonance were unchanged under γ-radiation.[4] Lower values of the BWS in red direction (20 pm–50 pm) were reported in subsequent publications.[3,4,9] Radiation of a fiber doped with GeO_2 creates the same type of paramagnetic defects related to the photosensitivity effect as 248-nm UV-light does. Therefore, the red direction of the BWS under radiation is consistent with the shift during fabrication.[8,10] Fiber properties, post-fabrication treatment and inscription parameters are important factors that determine the radiation sensitivity.[8,10−15] For example, the radiation sensitivity of FBGs strongly depends on the chemical composition of the fiber and the photosensitization technique used for writing FBGs.[5,6]

BWS shows a saturating behaviour during γ-irradiation.[5,8,11,13] In this case, grating pre-irradiation should be a possible way to increase the radiation hardness. According to Ref. [5], pre-irradiation treatment can reduce the BWS of photosensitive Ge-doped fiber from approximately 20 pm to 10 pm. However, in Refs. [3] and [8], the possibil-

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†Corresponding author. E-mail: jinjing@buaa.edu.cn

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ity to improve the radiation stability via grating pre-exposure to γ- or UV-radiation was not confirmed. The negative result is attributed to the use of pre-irradiation in combination with hydrogen loading. In this paper, we will investigate the improvement of FBG radiation tolerance by pre-irradiation treatment. To achieve this goal, two γ-radiation experiments will be implemented. The first radiation experiment will be used as pre-irradiation treatment. And the results will be compared with those of the second radiation. BWS, temperature sensitivity, and reflection spectra will be tested to verify the effect of pre-irradiation treatment on the radiation sensitivity of FBGs.

2. Experimental setup

Five FBGs are fabricated for γ-radiation experiments. FBG1 is written in a single mode optical fiber SMF 28C; FBG2 and FBG3 are written in photosensitive optical fibers PSF-GeB-125; FBG4 and FBG5 are written in coupling single mode optical fibers CS 1060. Their parameters are shown in Table 1. Because of low Ge-content of single mode optical fiber, it is almost impossible to write FBG into that fiber without hydrogen loading treatment. FBG1, FBG3, FBG4, and FBG5 are loaded with H_2 before grating inscription (about one week at 2 kMPa and 50 °C). FBG2 without hydrogen loading treatment is used for comparison with FBG3. An argon-ion laser (Blackstar-s, pulse energy 10 mJ/cm^2, 193 nm) is used for fabricating all the gratings. The 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 out-diffusion of H_2. The lengths of gratings are 11 mm–12 mm, reflectivity is $> 85\%$ and full-width at half-maximum (FWHM) is ~ 0.25 nm. The Bragg wavelengths of gratings range from 1545 nm to 1555 nm.

The experiment system, which is set-up for characterizing the FBGs during irradiation, is shown in Fig. 1. The FBGs will be 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 are mounted on a 5-mm thick aluminum board. In order to compensate the effect of temperature fluctuations during irradiation, three Pt1000 temperature sensors each with a measurement accuracy of 0.1 °C are placed on the same aluminum board near the FBGs. Lead shields are used to protect the temperature sensors from radiation. The FBGs are kept unstrained during the irradiation to avoid complications related to the temperature-strain cross sensitivity. Bragg peaks are measured in reflection with an FBG interrogation system sm125 from Micro Optics Int. with working wavelengths ranging from 1510 nm to 1590 nm, a wavelength resolution of 1 pm, and a repeatability of 1 pm.

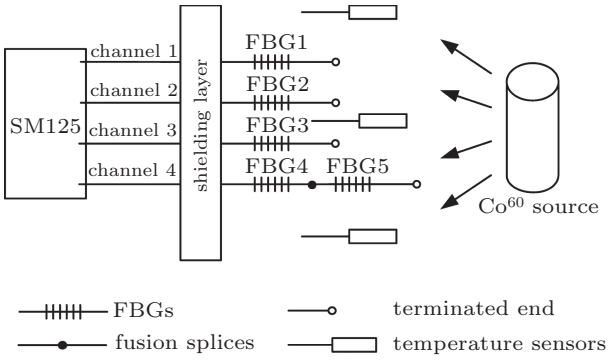


Fig. 1. Experimental set-up.

The experimental measurement procedure is shown in Table 2. To find the effect of pre-irradiation treatment on radiation sensitivity of FBGs, the gratings are subjected to double-exposures in radiation using a Co^{60} source at dose-rate of 0.1 Gy/s up to a total dose of 50 kGy (single exposure). The variation of temperature during γ-radiation exposure is smaller than 1 °C. Between two radiation exposures, there are 80 days at ~ 25 °C for post-irradiation relaxation. To obtain the change of temperature sensitivity, the gratings are put in a temperature-controlled chamber to carry a thermal cycling heating up to 50 °C and then cooling down to 0 °C slowly. The thermal cycling is carried out before and after pre-irradiation to find the radiation effect on temperature sensitivity. The temperature sensitivity is measured immediately after γ-radiation exposure to compare with the result before the radiation.

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
1	SMF28C	GeO_2 (3)	1550	yes	12	90.603	0.25
2	PSF-GeB-125	GeO_2 (23.37)	1555	no	11	85.106	0.23
3	PSF-GeB-125	GeO_2 (23.37)	1555	yes	11	85.803	0.23
4	CS 1060	GeO_2 (12.1)	1545	yes	12	88.857	0.25
5	CS 1060	GeO_2 (6)	1550	yes	12	88.305	0.25

Table 2. Experimental measurement procedure.

Number	Measurement procedure	Measurement condition
1	temperature sensitivity measurement	temperature circulation between 0 °C to 50 °C
2	pre-irradiation	$\gamma-$irradiation at a dose-rate of 0.1 Gy/s up to a total dose of 50 kGy at $\sim$ 24 °C
3	temperature sensitivity measurement	temperature circulation between 0 °C to 50 °C
4	post-irradiation relaxation	during 80 days at 25±3 °C
5	temperature sensitivity measurement	temperature circulation between 0 °C to 50 °C
6	second irradiation	$\gamma-$irradiation at a dose-rate of 0.1 Gy/s up to a total dose of 50 kGy at $\sim$ 26 °C
7	temperature sensitivity measurement	temperature circulation from 0 °C to 50 °C

3. Results and discussion

3.1. Temperature sensitivity variation during irradiation

The temperature sensitivity variations during pre-irradiation and second irradiation are shown in Table 3. The temperature sensitivity K is fitted to Eq. (1) using the least squares method. The temperature sensitivity variation of FBG1 is smaller than 6%; variations of FBG2 and FBG3 are below 3%. The temperature sensitivity variations during the second irradiation are 18.12%–35.91% lower than those during pre-irradiation, which means that pre-irradiation can reduce temperature sensitivity variation during later irradiation.

Table 3. Variation in temperature sensitivity.

FBG	Pre-irradiation			Second irradiation			Decreasing of temperature sensitivity variation
	temperature sensitivity K before radiation (nm/°C)	variation	temperature sensitivity K after radiation (nm/°C)	temperature sensitivity K before radiation (nm/°C)	variation	temperature sensitivity K after radiation (nm/°C)	
1	0.01312	0.01237	–5.72%	0.01227	0.01171	–4.56%	20.28%
2	0.00999	0.00977	–2.20%	0.00978	0.00961	–1.74%	20.91%
3	0.00977	0.01004	2.76%	0.00993	0.01015	2.26%	18.12%
4	0.01126	0.01164	3.37%	0.01159	0.01184	2.16%	35.91%
5	0.01155	0.01196	3.55%	0.01192	0.01224	2.68%	24.51%

3.2. Variation of reflection spectra during irradiation

Figure 2 shows the Bragg reflection spectra of FBG1 under irradiation. Figure 2(a) shows the spectrum variation under pre-irradiation and figure 2(b) exhibits the spectrum variation under the second irradiation. The baseline denotes the reflection spectra at the beginning of radiation. The dashed line represents the reflection spectra at a radiation dose of 28 kGy. The FWHMs of reflection spectra remain nearly unchanged during the twice radiation exposures. Table 4 shows the variation of reflection power during irradiation. The reflection power changes of the gratings are lower than 0.20 dB.

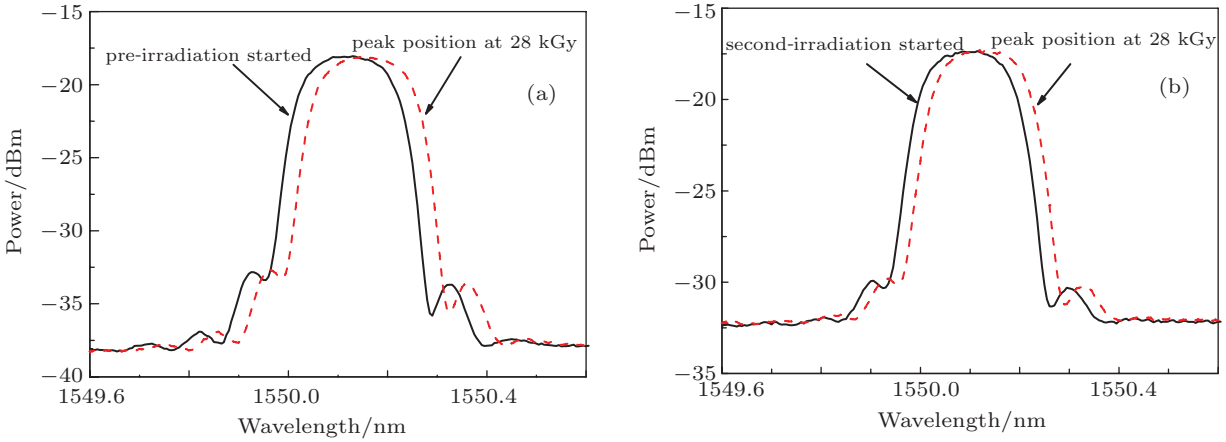


Fig. 2. (colour online) Reflection spectra of FBG1, showing spectrum variations under pre-irradiation (a) and under the second irradiation (b).

Table 4. Variations in reflection power.

FBG	Pre-irradiation			Second irradiation		
	reflection power before radiation /dBm	reflection power after radiation /dBm	variation/dBm	reflection power before radiation /dBm	reflection power after radiation /dBm	variation/dBm
1	–17.29	–17.35	–0.06	–18.07	–18.14	–0.07
2	–18.04	–18.11	–0.07	–17.09	–17.18	–0.09
3	–15.97	–16.15	–0.18	–16.30	–16.44	–0.14
4	–15.37	–15.48	–0.11	–15.06	–15.15	–0.09
5	–17.61	–17.70	–0.09	–16.03	–16.11	–0.08

3.3. Bragg wavelength shift during irradiation

The temperature varies from 23.9 °C to 24.5 °C during the pre-irradiation, and it varies from 25.8 °C to 26.5 °C during the second irradiation. We compensate the temperature effects during the irradiation by subtracting the computed temperature-induced BWS from the raw Bragg wavelength drift to obtain the compensated radiation-induced BWS.

Figure 3 shows the BWS of FBG1 during the experiment. The arrows indicate the start and the end of irradiation. During the pre-irradiation, there is a decrease of Bragg wavelength at the beginning of irradiation. About 5 h later, the Bragg wavelength shifts towards red direction and is saturated at a total dose of 36 kGy. The BWS of FBG1 is 46 pm. After the pre-irradiation, there exists a post-radiation recovery time lasting 80 days at ∼ 25 °C. During the second irradiation, the Bragg wavelength increases up to 35 pm and then decreases rapidly. About 60 h later, the Bragg wavelength increases again but slowly.

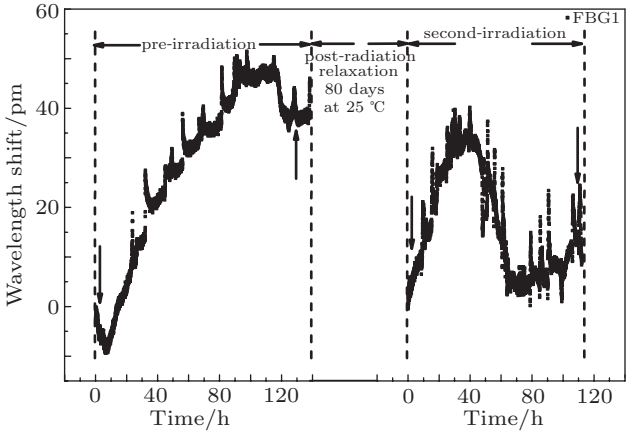


Fig. 3. Bragg wavelength shifts of FBG1 during the experiment.

Figure 4 shows that the BWS of FBG3 is higher than that of FBG2. FBG2 and FBG3 are both written in photosensitive optical fiber PSF-GeB-125 but FBG2 is without the hydrogen loading treatment. Under these experimental conditions, a conclusion we can draw is that hydrogen loading treatment can increase the radiation sensitivity of FBG. In Fig. 5, the BWS of FBG4 is higher than that of FBG5. FBG4 and

FBG5 are both written in coupling single mode optical fibers CS 1060 but the Ge-content of FBG4 is higher. The experimental result shows that the FBG with more Ge-content has a higher radiation sensitivity. The variations of BWS during irradiation are summarized in Table 5. The FBG1 written in SMF28C has the highest BWS of 46 pm. The FBG2 written in PSF-GeB-125 has the lowest BWS of 18 pm. According to Tables 3 and 5, the effect of pre-irradiation on radiation sensitivity of FBG3 is relatively small.

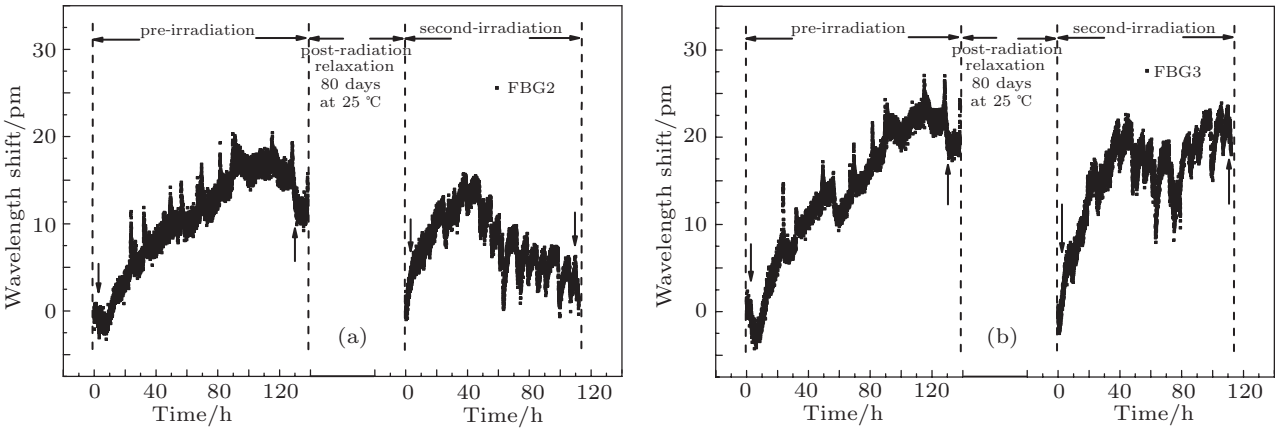


Fig. 4. Bragg wavelength shifts of FBG2 (a) and FBG3 (b) during the experiment.

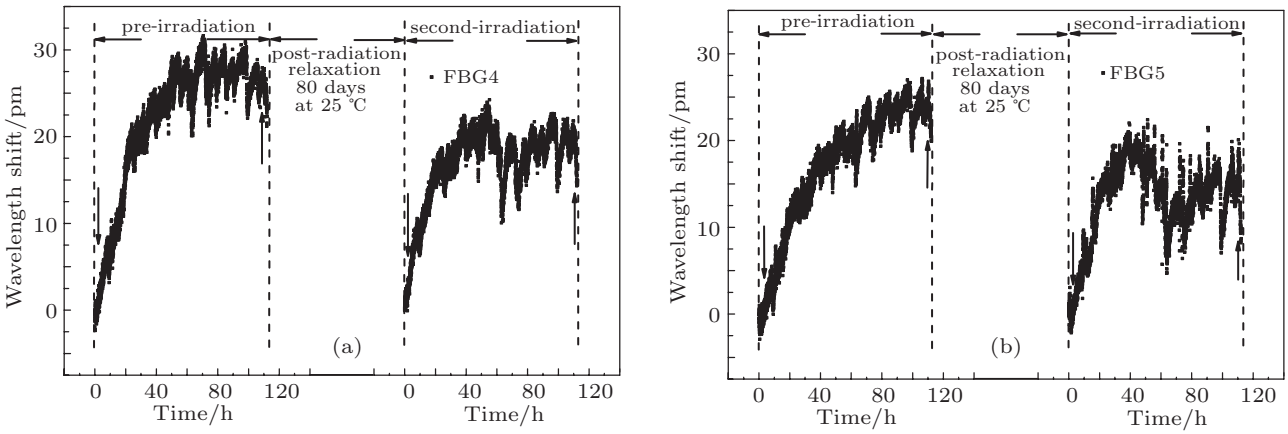


Fig. 5. Bragg wavelength shifts of FBG4 (a) and FBG5 (b) during the experiment.

Table 5. Variations in Bragg wavelength shift, dose rate: 0.1 Gy/s, total dose: 50 kGy.

FBG	Bragg wavelength shift during pre-irradiation/nm	Bragg wavelength shift during second irradiation/nm	Variation in Bragg wavelength shift
1	0.046	0.035	–27.08%
2	0.018	0.015	–16.67%
3	0.025	0.023	–8%
4	0.030	0.023	–23.33%
5	0.025	0.020	–20%

It is known that the photosensitivity of fiber is correlated with the defect centre of fiber. Like the photosensitivity of fiber, the radiation sensitivity of FBG is also correlative with the defect centre.[16] A probable interaction involves two stages.[17] First, a photon with a suitable energy excites a regular Ge–O bond $\equiv$ Ge–O–Si $\equiv$ $+h\nu \rightarrow$ Ge $\bullet \cdots \bullet$ O–Si $\equiv$. At room temperature molecular hydrogen is known to

react with non-bridging oxygen, leading to the productions of an OH-group and an atomic hydrogen. A non-bridging oxygen is a centre that is different from the excited Ge–O bond. However, it is not unreasonable to assume that interactions with a molecular hydrogen in both cases are similar, i.e., $\equiv$ Ge$\bullet\cdots\bullet$O–Si $\equiv$ +H–H $\rightarrow$ $\equiv$ Ge $\bullet$+H–O–Si $\equiv$ +H$\bullet$. The atomic hydrogen may react with $\equiv$ Ge$\bullet$ to form a Ge–H bond or may participate in the breaking of another regular Ge–O bond. Radiolytic rupture of the OH-bond is a probable reason for the high γ-radiation sensitivity of gratings written in hydrogen loaded fibres, as observed in our experiment.

The BWS during the first 80 h (28.8 kGy) of γ-radiation can be explained as the conversion of pre-cursors into colour defects when the fiber is exposed to gamma rays. A total dose of 36-kGy γ-radiation is adequate to convert pre-cursors into these defect centres, meanwhile the BWS is saturated. In addition, the concentration of these defect centres is constant along the grating. Therefore, the radiation results only in the BWS, but does not change the reflectivity.[9] Under this assumption, the radiation tolerance can be improved by reducing the concentration of such active defect centres. This can be achieved by pre-irradiating the fiber or the grating. The validity of pre-irradiation treatment can be confirmed from two aspects: one is that the pre-irradiation treatment should convert pre-cursors into the majority of the defect centres and make the BWS saturated; the other is that the BWS should show low level recovery during the post-irradiation relaxation lasting sufficient time.

All the five FBGs show similar behaviours during the radiation experiments. During the pre-irradiation, their Bragg wavelengths shift toward red direction, and indicate that the BWS is saturated at a dose of 28.8 kGy–39.6 kGy successively. After the pre-irradiation, there are 80 days for relaxation. During the second irradiation, the BWSs are lower than those during pre-irradiation. The above research demonstrates that the pre-irradiation treatment can reduce the radiation sensitivity of FBGs significantly. Moreover, the Bragg wavelengths shift toward blue direction after a dose of 14.4 kGy–18 kGy, and the Bragg wavelengths shift toward red direction after a dose of 21.6 kGy–28 kGy. The curves of BWSs during the second irradiation show non-monotonic character. We do not have enough evidence to explain this phenomenon yet.

4. Conclusion

We investigated the effect of pre-irradiation treatment on radiation sensitivity of FBG, and confirm that the pre-irradiation treatment is feasible to improve the radiation tolerance of FBG. Conclusions can be drawn based on the experimental results and discussion. Temperature sensitivity variation is less than 6% during radiation. The reflection power of FBGs decreases below 0.2 dBm, and the FWHM is nearly unchanged during the radiation. Pre-irradiation treatment can reduce the temperature sensitivity variation of FBGs effectively by 18.12%–35.91% at a 50-kGy radiation dose. Pre-irradiation treatment does not affect the reflection spectra of FBGs significantly. Pre-irradiation treatment can reduce the variation of radiation-induced BWS by 8%–27.08% at a dose of 50 kGy. After the pre-irradiation, the curves of BWS during the second irradiation show a non-monotonic character. The experimental results of FBG2 and FBG3 indicate that using the photosensitive optical fiber and the hydrogen loading treatment can play a negative role in improving the radiation hardening capability by pre-irradiation.

References

[1] Udd E, Schulz W L, Seim J M, Trego A, Haugse E and Johnson P E 2000 *Proc. SPIE* **3994** 96

[2] Ferdinand P, Magne S, Marty V and Rougeault S 1994 *Proc. SPIE* **2425** 11

[3] Gusarov A I, Fernandez A F, Berghmans F, Valiliev S, Medvedkov O, Decreton M, Deparis O, Megret P and Blondel M 2000 *Proc. SPIE* **4134** 86

[4] Gusarov A I, Berghmans F, Deparis O, Fernandez A F, Defosse Y, Megret P, Decreton M and Blondel M 1999 *IEEE Photon. Technol. Lett.* **11** 1159

[5] Gusarov A I, Starodubov D S, Berghmans F, Deparis O and Defosse Y 1999 *Proc. SPIE* **3872** 43

[6] Fernandez A F, Brichard B, Borgermans P, Berghmans F, Decreton M, Megret P, Blondel M and Delchambre A 2002 *Proceedings of IEEE Conference on Optical Fiber Sensors* Portland, USA, May 2002, p. 63

[7] Fernandez A F, Gusarov A I, Brichard B, Bodart S, Lammens K, Berghmans F, Decreton M, Megret P, Blondel M and Delchambre A 2002 *Opt. Eng.* **41** 1246

[8] Gusarov A I, Vasiliev S, Medvedkov O, Mckenzie I and Berghmans F 2008 *IEEE Trans. Nucl. Sci.* **55** 2205

[9] Gusarov A I, Berghmans F, Fernandez A F, Deparis O, Defosse Y, Starodubov D, Decreton M, Megret P and Blondel M 2000 *IEEE Trans. Nucl. Sci.* **47** 688

[10] Gusarov A I, Brichard B and Nikogosya D N 2010 *IEEE Trans. Nucl. Sci.* **57** 2024

[11] Maier R R J, MacPherson W N, Barton J S, Jones J D C, McCulloch S, Fernandez A F, Zhang L and Chen X F 2005 *Proc. SPIE* **5855** 511

[12] Henschel H, Hoeffgen S K, Krebber K and Kuhnhenn J 2008 *IEEE Trans. Nucl. Sci.* **55** 2235

[13] Vasiliev S A, Dianov E M, Golant K M, Medvedkov O I, Tomashuk A L, Karpov V I, Grekov M V, Kurkov A S, Leconte B and Niay P 1998 *IEEE Trans. Nucl. Sci.* **45** 1580

[14] Lin S, Song N F, Jin J, Wang X Q and Yang G L 2011 *IEEE Trans. Nucl. Sci.* **58** 2111

[15] Wang K R, Cheng J L, Sang X Z and Chen G 2011 *Chin. Phys.* B **20** 034210

[16] Tsai T E, Williams G M and Friebele E J 1997 *Opt. Lett.* **22** 224

[17] Grubsky V, Starodubov D S and Feinberg J 1999 *Opt. Lett.* **24** 729