

High Total Dose Radiation Effects on Temperature Sensing Fiber Bragg Gratings

A. I. Gusarov, F. Berghmans, O. Deparis, *Member, IEEE*, A. Fernandez Fernandez, Y. Defosse, P. Mégret, *Member, IEEE*, M. Décreton, and M. Blondel

Abstract—Fiber Bragg gratings (FBG's) written in a 10 mol.% Ge-doped core silica fiber using a phase mask were exposed to γ -radiation. The transmission and reflection spectra were recorded during irradiation up to doses in excess of 1 MGy. There was no detectable change of the Bragg peak amplitude and the grating temperature sensitivity. The radiation-induced shift of the Bragg wavelength saturated at a dose of 0.1 MGy at a level less than 25 pm, which could still be decreased by optimization of the grating parameters. Our results confirm that FBG's are good candidates for sensing applications in radiation environments.

Index Terms—Fiber Bragg grating, gamma radiation, optical fiber sensor, radiation effects.

I. INTRODUCTION

MODERN PHOTONIC sensing technology is seriously considered for application in nuclear environments [1]. Nuclear infrastructure can benefit from the numerous advantages of optical fiber sensors. Their immunity to electromagnetic interference, intrinsic safety, mechanical simplicity and small size as well as possibly high sensitivity and multiplexing capabilities make those devices a real alternative for standard nuclear instrumentation. However, the presence of radiation fields can significantly affect the performance of photonic devices and fiber sensors in particular [2].

The effect of radiation on an optical fiber is well-known to be an increase of the transmission loss [3]. The advantage of a fiber Bragg grating (FBG) based sensor is that information on the measured parameter (temperature or strain) is wavelength-encoded and is therefore insensitive to radiation-induced losses. FBG temperature sensors use the dependence of the Bragg wavelength λ_B on the temperature T . For a restricted temperature interval from 0 °C to 100 °C, this

dependence is well approximated by a linear expression:

$$\lambda_B(T) = \lambda_B(T_0) + \alpha_0(T - T_0)$$

where α_0 is the FBG temperature sensitivity at $T = T_0$ with a typical value of about 10 pm/°C at 1550 nm. The possible application of FBG's for temperature sensing in a radiation environment thus depends on to what extent $\lambda_B(T_0)$ and α_0 are influenced by radiation.

To the best of our knowledge, there are only a few publications on this subject [4]–[6]. For a Ge-doped silica fiber, the shift of λ_B can be as high as 0.1 nm toward the blue at reported doses of 12 kGy [5] and 412 kGy [4] (1 Gy corresponds to 1 J absorbed by 1 kg of material). A nonmonotonous shift of the Bragg wavelength under γ -radiation up to a dose of 71 kGy was reported in [6]. The value of α_0 may also be changed under radiation. Those results question the use of FBG's for sensing applications in radiation environments. A 0.1-nm drift of the Bragg peak, which corresponds to a 10 °C error on the temperature estimation is unacceptable for most applications.

The purpose of our work was to investigate more accurately the evolution of the FBG spectra during γ -irradiation at MGy dose levels and to study the sensitivity of FBG parameters to γ -radiation. The MGy level is considered as relevant for nuclear applications. Such studies could also improve the understanding of fiber grating formation mechanisms.

II. EXPERIMENTAL PROCEDURE

Seven FBG's (G1–G7) with λ_B around 1546 nm and reflectivities (R) from 21% (1.05 dB) to 82% (7.40 dB) were written in 10 mol.% Ge-doped silica fiber (Accutether AT120) using a phase mask. The length of the gratings was 1.7 or 0.65 cm. The fluence of the excimer laser beam (248 nm) varied from 450 to 520 mJ/cm² per pulse. The writing time was between 10 min. and 1 h with the pulse repetition rate of 30 Hz, corresponding to the total fluence from 9 to 56 kJ/cm². The amplitude and the Bragg wavelength were changed monotonously during inscription, yielding Type I gratings. After the writing, the gratings were annealed at 80 °C during 24 h.

The FBG transmission and reflection were recorded at a controlled temperature during γ -irradiation, using an optical spectrum analyzer (a sampling interval of 2.5 pm and a resolution of 50 pm). An LED with about 50 μ W of output optical power was used as a light source. The signal to noise ratio (SNR) was better than 20 dB. For each FBG, λ_B was

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A. I. Gusarov is with Faculté Polytechnique de Mons, B-7000 Mons, Belgium. He is also with SCK-CEN, Belgian Nuclear Research Centre, B-2400 Mol, Belgium.

F. Berghmans is with SCK-CEN, Belgian Nuclear Research Centre, B-2400 Mol, Belgium. He is also with the Vrije Universiteit Brussel, Laboratory for Photonics, B-1050 Brussels, Belgium.

O. Deparis, Y. Defosse, P. Mégret, and M. Blondel are with Faculté Polytechnique de Mons, B-7000 Mons, Belgium.

A. F. Fernandez is with SCK-CEN Belgian Nuclear Research Centre, B-2400 Mol, Belgium. He is also with Université Libre de Bruxelles, B-1050 Brussels, Belgium.

M. Décreton is with SCK-CEN, Belgian Nuclear Research Centre, B-2400 Mol, Belgium.

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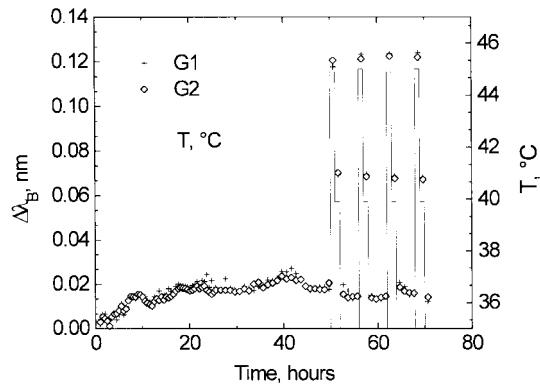


Fig. 1. Shift of λ_B under γ -radiation for G1 ($R = 1.83$ dB) and G2 (3.12 dB). T is the oven temperature. The peaks in λ_B observed after 48 h are due to the oven temperature modulation.

determined by fitting a part of its transmission spectrum (65 pm) near the minimum with a Gaussian function. The effect of ambient temperature variations on the spectrum analyzer readings was taken into account. We obtained a long-term stability of ± 5 pm.

In [6], radiation-induced transmission losses in the Ge-doped fiber made it impossible to measure the FBG characteristics for radiation levels above 70 kGy and the authors expressed a doubt that sensors based on a Ge-doped fiber can be used in radiation environments. We implemented an idea first proposed in [5] and spliced short pieces of the “radiation sensitive” Ge-doped fiber, in which the FBG’s were written, to a Ge-doped fiber with a very low P impurity content (Siecor SMF 1528), which possesses a high radiation hardness [3], [5]. That allowed us to run the experiment for doses above the MGy level without noticeable SNR degradation.

The seven FBG’s and a reference fiber with a piece of photosensitive fiber but without FBG were inserted in a dedicated oven, similar to that described in [2]. For the irradiation, the container with the FBG’s was installed into an immersed ^{60}Co γ -irradiation facility. The dose rate was 3 kGy/h [7]. The measurements were performed *in situ* during 15 days, up to an accumulated dose in excess of 1 MGy. During the first two days, the temperature of the FBG’s was kept at 35.0 ± 0.1 °C. This temperature is high enough to avoid the effect of γ -heating. After two days, a periodic temperature modulation was applied. One period of the temperature modulation consisted of three steps. After a measurement set, the temperature was increased up to 45 °C and kept fixed until the end of the next measurement set. Then the temperature was decreased down to 40 °C and, further down to 35 °C.

III. RESULTS AND DISCUSSION

Fig. 1 compares the radiation response of G1 and G2 with the oven temperature. The other FBG’s demonstrated a similar behavior. The change of the Bragg wavelength is shown with respect to its value before irradiation. A shift of λ_B toward the red is observed at the start. It saturates after the first day of irradiation at a level of 20 pm and a dose of 100 kGy. Subsequently, λ_B remains unchanged within the accuracy of our measurements (± 5 pm). It should be noted that the change

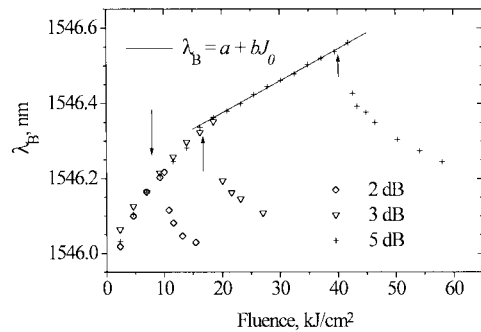


Fig. 2. Evolution of the Bragg wavelength during fabrication. The arrows indicate the stop of the UV-irradiation. The values associated to the symbols in the figure mean the final reflectivities of each grating. The solid line represents a linear fit of a part of the data for UV-fluences between 20 and 40 $\text{kJ}\cdot\text{cm}^{-2}$.

of 20 pm is significantly smaller than the values reported earlier [4]–[6]. The periodic peaks are due to the temperature modulation.

This temperature modulation allowed to compute the temperature sensitivity coefficient of the gratings. The values averaged on all data and on all FBG’s are: $\alpha_0 = 10.85 \pm 0.19$ pm/°C before irradiation; $\alpha_0 = 10.76 \pm 0.24$ pm/°C during the irradiation test, and $\alpha_0 = 10.88 \pm 0.20$ pm/°C after irradiation. We conclude that, within the accuracy of our measurements, α_0 is not affected by γ -radiation. The radiation did not influence significantly the shape of the Bragg resonance: the 3-dB width of the Bragg resonance and the reflectivity were constant within a $\pm 2.5\%$ limit during the radiation test.

It was shown experimentally that γ -irradiation (^{60}Co source) of a silica glass doped with 11 mol.% of GeO_2 creates the same type of paramagnetic defects related to the photosensitivity effect as 248 nm UV-light does [8]. This agrees with our observation that the Bragg wavelength shift is toward the red for both UV- and γ -irradiation. According to our data, γ -radiation affects only λ_B , but not the reflectivity, i.e., the spatial distribution of γ -radiation induced refractive index changes is uniform and γ -irradiation works analogous to a fringe-less UV-irradiation. Therefore, it would be possible to expect that the effect of γ -radiation can be in some way scaled to that of UV-light. However, the FBG’s behave differently under UV-light and γ -radiation.

The evolution of the Bragg wavelength during inscription is shown in Fig. 2. The UV-fluence per pulse was $430 \text{ mJ}\cdot\text{cm}^{-2}$. The peak experienced a significant shift after the stop of writing. The direction of the shift is in agreement with the assumption that the temperature of the fiber decreases. A high temperature rise during writing is natural because the fiber was “sandwiched” between the supporting quartz plate and the phase mask. This shift could also be explained by defect relaxation, which, however, would contradict with an almost constant grating amplitude after the writing. The solid line in Fig. 2 is a linear fit $\lambda_B = a + bJ_0$ of a part of the data corresponding to the stable temperature regime, with J_0 being the UV-light fluence, $a = 1546.204$ nm and $b = 8.52$ pm/($\text{kJ}\cdot\text{cm}^{-2}$).

For the photosensitive fiber used in our study, the natural absorption coefficient is $a_{248} \approx 220 \text{ cm}^{-1}$ and the average

UV-energy deposition in the core corresponds to a dose $D = J_0 a_{248} / \rho$, where ρ is the core density. For example, a dose of 10^6 Gy corresponds to a fluence of 10 J/cm^2 . If the sensitivity to γ -radiation would be the same as that for UV-light, then the shift of the Bragg wavelength in our experiments should be far below 1 pm even for the maximal accumulated dose of γ -radiation. However, the sensitivity to γ -radiation at the initial stage of irradiation is about three orders of magnitude higher than that for UV-light. The Bragg wavelength shift is about 10 pm for a 50-kGy dose of γ -radiation and about 4 pm for a 50 MGy dose of UV. Under γ -radiation, the shift of λ_B saturates at a dose of 100 kGy, whereas no saturation is observed for UV-fluences corresponding to a GGy dose.

To explain the behavior of the FBG's, we assume that although UV- and γ -radiation create the same defects, some precursors can interact with γ -radiation but not with UV-light. The concentration of "UV-insensitive" precursors N_0 should be rather low to explain the quick saturation. A 20-pm λ_B shift corresponds to a refractive index change of $\Delta n \approx 2 \times 10^{-5}$. GeE'-centers are often considered as defects associated with formation of the FBG's in Ge-doped fibers. According to [9], $\Delta n \approx 6 \times 10^{-23} N_0$, where N_0 is the concentration of GeE'. The change of 2×10^{-5} corresponds to $N_0 \approx 3.3 \times 10^{17} \text{ cm}^{-3}$. Additional experiments to verify this assumption are on-going.

The magnitude and the direction of radiation induced shift λ_B are different for our FBG's and for the FBG's studied in [4]–[6]. It was also reported in [4] that in a 28 mol.% Ge-doped fiber a change of α_0 under radiation was observed. We believe that these differences can be attributed to differences in the FBG's under study, although the irradiation conditions in our experiment and in [4]–[6] were also different. The sensitivity of FBG's to radiation can probably be further decreased by an optimal choice of the photosensitive fiber, FBG parameters, and writing/annealing conditions. For example, we plan to investigate the effect of hydrogen loading, used to increase the photosensitivity, on the sensitivity of FBG's to γ -radiation.

IV. CONCLUSION

For the first time, parameters of FBG's exposed to γ -radiation were measured *in situ*, up to very high doses (>1 MGy). For the FBG's used in our study the experimental results allow to draw several conclusions.

The temperature sensitivity coefficient α_0 is not affected by radiation within a 3% accuracy.

The amplitude and the width of the Bragg resonance are unchanged under the γ -radiation.

The change of the Bragg wavelength as a result of irradiation is not higher than 25 pm and saturates at doses of 0.1 MGy.

Consequently, FBG-based temperature sensors are probably capable to maintain the required performance even in a MGy dose level radiation environment. Parameters of the FBG's should be optimized to decrease the sensitivity to radiation.

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