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► To cite this version:

Thomas Blanchet, Romain Cotillard, Adriana Morana, Rudy Desmarchelier, Emmanuel Marin, et al.. Effect of radiation and temperature on high temperature resistant fiber Bragg gratings. Optical Sensing and Detection VII, Apr 2022, Strasbourg, France. pp.54, 10.1117/12.2621473 . hal-04675573

HAL Id: hal-04675573

<https://hal.science/hal-04675573v1>

Submitted on 23 Aug 2024

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Effect of Radiation and Temperature on High Temperature Resistant Fiber Bragg Gratings

T. Blanchet^{*a}, R. Cotillard^a, A. Morana^b, R. Desmarchelier^a, E. Marin^b, Y. Ouerdane^b, A. Boukenter^b, D. Fourmentel^c, S. Bréaud^c, A. Gusarov^d, C. Destouches^c, S. Girard^b and G. Laffont^a

^aUniversité Paris-Saclay, CEA, List, F-91120, Palaiseau, France

^bHubert Curien Laboratory, Univ. Lyon, UJM, Saint-Etienne, CNRS, IOGS, F-42000 Saint-Etienne, France

^cCEA, DEN, DER, Instrumentation, Sensors and Dosimetry Laboratory, Cadarache, F-13108 St-Paul-lez-Durance, France

^dSCK CEN – Belgian Nuclear Research Center, Boeretang, 200 2400 Mol, Belgium

ABSTRACT

Fiber Bragg gratings can be used to monitor temperature or strain in harsh environments. We investigate the effect of X-rays on type III gratings – also called void gratings – which are known for their capacity to withstand high temperatures. The tested gratings are inscribed in a SMF28 germanosilicate optical fiber using the point-by-point method and a frequency-doubled Yb femtosecond laser emitting at 515 nm. The tested FBGs are separated in two groups depending on their reflectivity levels (Low/High). Half of each group is pre-annealed at a temperature of 750°C during 30 min. We have irradiated all the gratings up to 100 kGy(SiO₂) at a dose-rate of 10 Gy/s at two different irradiation temperatures: 25°C and 150°C. For all the irradiations, the grating radiation response is identical independently of the chosen writing and pre-annealing conditions. When the irradiation is performed at 25°C, a Bragg wavelength shift of 10 pm is observed for all the gratings, which represents an error of less than 1°C at the total dose of 100 kGy while at 150°C the Bragg peak shift only of less than 4 pm corresponding to an error of 0.3°C.

Keywords: Fiber Bragg Grating, FBG, Optical Fiber, Radiation, High Temperature

1. INTRODUCTION

Fiber Bragg Gratings (FBGs) are studied for more than two decades in nuclear industry for the monitoring of nuclear facilities and Nuclear Power Plants (NPPs), especially for temperature monitoring^{1 2 3}. FBGs-based sensors present a low intrusiveness, a temperature resolution better than 0.1°C and an acquisition rate of 35 kHz⁴ fixed by the interrogation device. FBGs can be written directly into the fiber core using either interferometric methods or direct writing techniques with lasers⁵. Both methods generate a periodic modulation of the fiber refractive index which gives rise to a reflected narrow band of wavelengths centered around the Bragg wavelength (λ_B) defined as⁶:

$$\lambda_B = 2 \frac{n_{eff} \Lambda}{m} \quad (1)$$

with n_{eff} the effective refractive index, Λ the modulation period and m the diffraction order. When the FBG is heated, the Bragg Wavelength Shifts (BWS) to the upper wavelengths – also called red-shift. Then it is possible to calibrate the sensor with the following equation if no external stress is applied onto the grating²:

$$\Delta\lambda_B = C_T \Delta T \quad (2)$$

where $\Delta\lambda_B$ is the Bragg wavelength variation according to the temperature variation (ΔT) and C_T is the thermal sensitivity coefficient which is around 10 pm/°C for a Bragg wavelength of 1550 nm for a silica-based optical fiber². This equation is only valid for temperature range of typically 100°C.

Several FBG types can be produced and are classified according to Canning's classification⁷. Type I gratings are inscribed in photo-sensitive fiber, sometime hydrogenated before the inscription. This grating type erases at temperature above 400°C, due to the recombination of the defect centers created during the grating inscription⁵. Moreover, if a thermal annealing at high temperature (> 650°C) is performed on the hydrogenated type I grating, the FBG first erases and then reappears few seconds or minutes later. This new grating, called regenerated grating⁵ – type R – can withstand temperatures at least as high as its regeneration temperature⁸. Type II gratings mostly inscribed with femtosecond laser in any fiber type are generated by the creation of nanostructure (nanogratings) inside the FBG fringes⁹. This type of FBG can withstand temperature as high as 1000°C. Type III or void gratings are not present in Canning's classification⁵. This grating is inscribed using a femtosecond laser and for instance a point-by-point method and each dot consist of a micro-void bubble¹⁰ surrounded by a densified shell¹¹. This grating type can operate up to 1000°C¹¹.

Under irradiation, the defects generation can lead to a Bragg wavelength shift that induces a temperature error if the grating is used as a temperature sensor. The radiation vulnerability of the grating depends on the grating type^{12 13 14}, where type I gratings are the most sensitive, on the fiber composition^{15 16 17}, on the irradiation temperature^{3 13 16}, on the radiation type¹⁸, However, for type II gratings, an annealing at 750°C during 15 min is enough to obtain radiation hardened sensors up to 3 MGy(SiO₂) around RT, leading to a temperature error under radiation of less than 1°C¹⁶. The same type of gratings irradiated under the same conditions but at a temperature of 230°C presents an error of less than 2°C¹⁶.

Moreover, type R gratings regenerated at 650°C during 1 h present a temperature error of less than 1°C¹³ when they are irradiated under X-rays at a total dose of 100 kGy and an irradiation temperature of 250°C, while the error is less than 4°C for the same irradiation conditions at Room Temperature¹³. Type III gratings – also called void gratings – have been less studied under radiation with only one publication from Morana *et al.*¹⁴. Results showed a temperature error of 1.5°C at RT⁴ for a total dose of 1 MGy and an error of more than 4°C at an irradiation temperature of 200°C at the same dose without any stabilization even during the recovery (i.e. after the end of the irradiation).

Moreover, under irradiation the fiber attenuation can increase¹⁹ due to the defects creation associated with absorption bands. However, in our experimental conditions the irradiated fiber length is of a few centimeters, so the Radiation Induced Attenuation (RIA) will be almost negligible. Radiation Induced Emission (RIE) and Radiation Induced Compaction (RIC) will be negligible since RIE occurs in the UV and visible parts of the electromagnetic spectrum¹⁹ – in this study the FBGs are inscribed near 1550 nm – and no compaction has been observed under X-rays²⁰.

In this publication, we have irradiated type III gratings inscribed with the point-by-point technique using a femtosecond laser. We compare the behavior under radiation for such gratings written with two different pulse energies and with or without a pre-annealing at 750°C during 30 min. The irradiation was performed at a dose-rate of 10 Gy/s up to 100 kGy at RT or at a temperature of 250°C.

2. EXPERIMENTAL SETUP

The type III FBGs were inscribed at the CEA List LCFO facility on uncoated segment of SMF-28 fiber from Corning using a femtosecond laser emitting at 515 nm. The fiber core refractive index periodic modulation was performed using the point-by-point technique which consists of focalizing the laser beam inside the fiber core, which creates a micro-void surrounded by a densified shell¹¹, then the fiber is moved to the next writing position to create another micro-void where the displacement corresponds to the grating period. For each sample, five 2nd order FBGs were inscribed between 1510 nm to 1550 nm separated by 10 nm. Each 5 mm long grating was inscribed close to the previous one, leading to a total length of 25 mm for the array. The gratings were inscribed at two different pulse energies leading to one group (Low Energy – L-E) with a reflectivity lower than 5 dB (R ~ 70%) and the other group (High Energy – H-E) with a reflectivity greater than 10 dB (R ~ 90%).

During all the experiments, the grating spectra were recorded using the Tunics/CT-400 from Yenista – now EXFO – which consists of an external cavity tunable laser²¹ and a spectrometer with a maximal resolution of 1 pm²². Afterwards, each spectrum was analyzed to determine the Bragg wavelength by using a 3rd order polynomial equation²³, the grating amplitude and the Full Width at Half Maximum (FWHM). For each grating line, the average Bragg wavelength of the five gratings inscribed was recorded and we estimate the error to be less than ± 3 pm on the Bragg wavelength.

For each grating group (L-E and H-E), half of the gratings were annealed at a temperature of 750°C during 30 min with a slope of 40°C/min and the grating were hanged stress free in the oven and the fiber was cut about 15 mm after the last FBGs end.

The gratings were irradiated using the Moperix X-rays chamber²⁴ at the LabHC where the X-rays were generated by deaccelerating electrons on a tungsten target (Bremsstrahlung effect). The X-ray mean energy is about 40 keV and the dose-rate was set at 10 Gy/s. The gratings were placed on a V-groove machined in an aluminum pad and they were attached stress free with aluminum bridles as previously described in publication¹³. The whole setup was set on a heating plate for the irradiation at 150°C. At least one thermocouple was used to record the aluminum pad temperature and to correct the Bragg wavelength from the temperature fluctuations according to equation (2). We estimate temperature fluctuations to be about 0.5°C when the irradiation occurs at 150°C.

During the oven cooldown or the high temperature pre-irradiation or post-irradiation cooldown, the grating spectrum was recorded in order to calculate the thermal sensitivity coefficient for all the grating groups – using equation (2) – at two temperature ranges: from 20°C to 60°C and from 130°C to 150°C. The thermal coefficients are presented in table I where the thermal sensitivity coefficient stands for the average of the five Bragg wavelengths corresponding of the five gratings inscribed per fiber. As it can be observed all of the thermal coefficients are similar since we evaluate the coefficient uncertainties at 0.2 pm/°C.

Table 1. Thermal sensitivity coefficients for all the grating types by using the average of five gratings inscribed between 1510 nm and 1550 nm separated by 10 nm

		L-E		H-E	
		No annealing	Annealed 750°C – 30 min	No annealing	Annealed 750°C – 30 min
C_T (pm/°C)	$T = [20^\circ\text{C} - 60^\circ\text{C}]$	11.2	11.4	11.2	11.4
	$T = [130^\circ\text{C} - 150^\circ\text{C}]$	13.7	13.8	13.7	13.7

3. RESULTS

All the gratings were irradiated up to 100 kGy in the Moperix chamber at a dose-rate of 10 Gy/s. In figure 1.a. the irradiation was performed at RT and the shown Bragg wavelengths were corrected from the temperature fluctuations. For the four configurations – low/ high reflectivity – and with or without annealing, the RI-BWS at the end of the irradiation is 10 pm, which represents an error of less than 1°C if the grating is used as a temperature sensor. Moreover, we can decompose the irradiation run in two phases. For doses lower than 12 kGy – 20 min – a BWS of almost 12 pm is observed (1.2°C). For doses between 12 kGy and 100 kGy the Bragg wavelengths shift toward the lower wavelengths – also called blue shift – by 3 pm. After the irradiation, the Bragg peaks shift by less than 2 pm i.e. no recovery effect is observed.

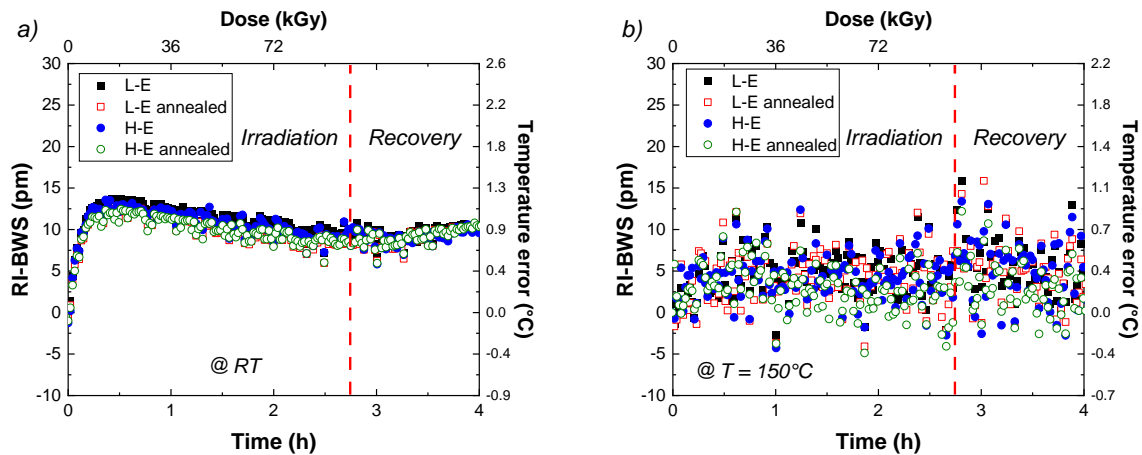


Figure 1. Mean Bragg wavelengths shift of 5 gratings for the four lines during an irradiation at a dose rate of 10 Gy/s up to 100 kGy at room temperature (a) and at 150°C (b). The Y-right axis represents the temperature error if the grating is used as a temperature sensor.

In figure 1.b., the gratings were subjected to the same irradiation conditions as in figure 1.a. but with an irradiation temperature of 150°C. As observed, the gratings behavior is the same for all the configurations. The BWS for all the lines is about 4 pm (0.3°C), but with an uncertainty of ± 7 pm due to the temperature fluctuations during the experiments. After the irradiation at 150°C, the Bragg peaks did not shift for almost 2 h. During all the experiments, no amplitude nor FWHM modifications were observed.

4. DISCUSSION

For the two performed irradiations, all the grating responses are similar whatever the inscription conditions or the thermal pre-annealing. Since micro-void bubbles are created inside the fiber core, only the non-inscribed parts are transformed by the radiation, with the hypothesis that the shell did not change under radiation. In addition, the shell influence on the grating response will be limited since the shell size is only few tenths of nanometers compared to the non-inscribed parts which sizes are of hundredths of nanometers. So the energy per pulse modification between the low- and high-energy gratings increases only the bubble size and perhaps the shell size but did not modify significantly the fiber structure. The thermal pre-annealing treatment is not efficient enough to change the bubble size nor the fiber structure, which explains the non-influence of the thermal pre-annealing on the BWS during the irradiation as well as the similarity in the thermal sensitivity coefficient for all the gratings presented in table I.

During the irradiation the X-rays change the refractive index of the fiber material and not the void-bubble. We can hypothesize that FBG inscribed in radiation-resistant fiber with a low RIA as Pure Silica Core (PSC) fiber can generate radiation-resistant grating. However, in the article of Morana *et al.*¹⁴ the gratings inscribed in both PSC or Ge-doped fibers present a thermal instability after the irradiation.

As for comparison, Morana *et al.*¹⁴ shows a BWS of 15 pm of voids FBGs written in a Ge-doped fiber and irradiated at 40 Gy/s up to 1 MGy. However, they observed a fast BWS at the beginning of the irradiation and a stabilization afterward. This Bragg peak shift is similar to the results in figure 1.a. but in our case, no stabilization occurs after the initial shift. In addition, during the recovery a BWS of 5 pm is shown in the results of Morana *et al.* while no recovery is observed in our experiments. During the irradiation at 200°C, Morana *et al.* observed a BWS of less than 10 pm at 100 kGy. However, their Bragg peak continues to shift even after the irradiation end, which has been explained by the fact that the gratings are not stable during the thermal treatment performed after the irradiation.

However, in figure 1.b. we did not observe any modification of the Bragg peak behavior at 150°C after the irradiation. This difference of behavior can be due to a threshold effect that occurs between 150°C and 250°C, but we do not have any explanation of this threshold effect. Additional irradiation runs must be performed at higher temperatures in order to complete the results and to conclude about this possible threshold effect.

5. CONCLUSION

Type III fiber Bragg gratings written in a SMF-28 fiber were irradiated at a dose-rate of 10 Gy/s up to a total dose of 100 kGy at both room temperature and 250°C. In order to evaluate the effect of the pulse energy used to inscribe the void bubble as well as an eventual effect of a thermal pre-annealing on the grating response under X-rays, four groups of gratings were compared. During the irradiation at RT and at 150°C the grating response is the same leading to an equivalent temperature error of 1.5°C at RT and less than 0.4°C at an irradiation temperature of 150°C. No recovery was observed in the two experiments. From our results, we conclude that our grating response depends only of the fiber composition. However, in order to get a better understanding of the type III FBG behavior under radiation, especially for irradiation temperature above 150°C, more experiments have to be performed. These preliminary results are an attempt to get insight into type III FBG behavior at high irradiation temperature in order to establish a basis to interpret forthcoming results which will come from an in-core test at the SCK-CEN BR2 reactor co-organized between CEA and SCK-CEN.

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