Behavior of Fibre Bragg Gratings Under High Total Dose Gamma Radiation

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Abstract

We report on the effect of MGy dose level γ-irradiation on the parameters of fibre Bragg gratings intended for sensing applications. The γ-radiation sensitivities of gratings written with near-UV 330 nm light in hydrogen loaded Ge-doped fibres and of a grating written in a N-doped fibre were found to be higher than that of gratings written in a 10 mol.% Ge-doped fibre without hydrogen loading. In the former cases, changes in the amplitude and the width of the Bragg peak were observed during γ-irradiation while no change was observed in the latter case. For the grating written in the N-doped fibre, the radiation-induced shift of the Bragg peak did not saturate while for gratings written in hydrogen-loaded Ge-doped fibres it saturated to a higher level than for gratings written in unloaded Ge-doped fibre.

I. INTRODUCTION

Fibre Bragg gratings (FBGs) have numerous existing and emerging applications in optical communication and sensing. It is well known that FBGs can be used for strain, temperature, and multi-point structural integrity monitoring. Such applications are of increasing importance for nuclear infrastructure. The unique properties of optical fibre sensors, and FBGs in particular, make such devices a real alternative to existing nuclear instrumentation. Their resistance to intense radiation fields, however, still needs to be assessed. It was recently demonstrated that commercial optical fibre sensors have to be redesigned to withstand radiation environments [1]. In this paper we report on the effect of γ-radiation on the characteristics of FBGs written in several different fibres. We propose a possible explanation for the observed radiation response of the FBGs.

The application of FBGs for sensing is based on the dependence of the Bragg wavelength on strain and/or temperature. Typical values for the sensitivity are 10 pm per 1°C and 1 pm per $\mu\varepsilon$. Radiation influences the refractive index of glass and, therefore, the position of the reflection (Bragg) peak. Previous experimental results showed that in a fibre with Ge-doped core, the Bragg peak shift can be about 0.1 nm *towards the blue* after γ-irradiation up to a dose of 12 kGy [2], [3]. Such a shift corresponds to a fictive temperature change of about 10°C. Recently, we reported results of a γ-irradiation of FBGs written in a 10 mol.% Ge-doped fibre [4], [5]. The Bragg peak was found to be shifted *towards the red* under γ-radiation. The shift saturated at a level of about 20 pm after a dose of 100 kGy and subsequently remained unchanged during irradiation up to a dose in excess of 1 MGy. The amplitude of the reflection spectrum (i.e., the reflectivity) was unchanged within the accuracy of our measurement. In the present paper, we report results of a γ-irradiation of FBGs written in hydrogen loaded Ge-doped fibres with the use of a novel writing technique [6], [7], and of a FBG written in a N-doped fibre [8]. From the point of view of sensing applications, the most important parameter is the shift of the Bragg peak. This problem was addressed in detail in [5], [9]. However, information about the Bragg peak position is not sufficient to fully understand the behaviour of FBGs under radiation. Therefore, we discuss here the behaviour of two other important parameters: the amplitude and the width (at -3 dB) of the reflection spectrum of FBGs.

II. EXPERIMENT

The experimental set-up was described in details in [4], [5], [9]. It allowed characterising the gratings both in transmission and reflection. A few tens of μW of optical power from a standard LED were launched into the fibre. The transmission and reflection spectra were recorded in situ during γ-irradiation, using an optical spectrum analyser (OSA) with a sampling interval of 4 pm and a resolution of 50 pm. It is known that the OSA read-out is influenced by ambient temperature variation. Therefore, we calibrated the temperature sensitivity of the OSA using a highly stable laser source and we used these data to correct the results of the measurement for the ambient temperature variation. We also monitored the LED output through a reference arm in order to correct for both spectral and output power fluctuations of the light source. For each grating, the reflectivity (R) was obtained from the transmission spectrum and the Bragg wavelength (λ_B) was determined by fitting with a Gaussian function a part of the reflection spectrum (100 pm) near the maximum. Given a signal to noise ratio better than 20 dB, the long-term stability of the set-up was ±5 pm for the Bragg peak measurement and ±0.05 dB for the reflectivity measurement, respectively.

Our FBGs were written in four different types of fibre. Gratings S1, S2 and K1, K2 with the Bragg wavelength near 1546 nm were written in two telecommunication Ge-doped silica fibres with low phosphorous content, manufactured by Siecor (SMF1528) and Alcatel Cable (Kabelrheydt E9.3/F3.5) respectively. These fibres were loaded with hydrogen at room temperature (2.5 mol.%) to enhance the photosensitivity. The

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gratings were fabricated using a phase mask (pitch of 1065 nm) and a writing technique based on the use of near-UV 330 nm light from an Ar laser [6], [7]. After writing, the gratings were annealed at 80°C during 24 h to remove the residual hydrogen. Annealing resulted in approximately 20% decrease of the grating strength. Monotonic changes in the grating strength and the Bragg wavelength during inscription indicated that the gratings originated from the Type I photosensitivity [10]. Grating N1 was written at the University des Sciences et Technologies de Lille (USTL) in a N-doped fibre by means of a phase mask and an ArF excimer (193 nm) laser. The fibre was fabricated at the Fiber Optic Research Center (Moscow) using SPCVD process [8]. The Bragg peak for this grating was located near 1511 nm. For comparison, we give results for a grating G1 written in a photosensitive 10 mol.% Ge-doped silica fibre using a phase mask and an excimer laser operating at 248 nm. The results of a γ-irradiation of FBGs written in this fibre for a dose level of 1 MGy were published elsewhere [4], [5], [9]. To write G1 and N1, no hydrogen loading was required.

The irradiation was continued during 22 days up to an accumulated dose in excess of 1.5 MGy in an immersed ^{60}Co γ-irradiation facility at SCK·CEN, delivering a dose rate of 3 kGy/h [11]. The temperature of the gratings was controlled with the accuracy of ±0.1 °C using a dedicated oven described in [5], [9]. The gratings were unstrained during the experiment.

III. RESULTS

Figure 1 shows the shift of the Bragg peak during γ-irradiation for gratings K1, S1, N1 and G1. The curves for S2 and K2 are very similar to the curve for S1 and are therefore not shown. Before the irradiation, we performed a 22-hours stability test (the initial part of curves in Figures 1-4).

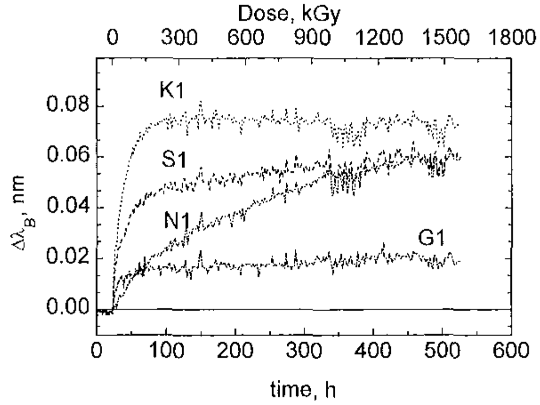

Figure 1: Shift of the Bragg peak during γ-irradiation.

For the gratings written in Ge-doped fibres the shift of the Bragg peak saturates after three days of irradiation. The saturated shift is however higher for hydrogen-loaded fibres (K1, S1) than for the unloaded fibre (G1). By contrast, the shift of the Bragg peak for the grating written in the nitrogen-doped fibre (N1) shows no saturation even at the maximal accumulated dose.

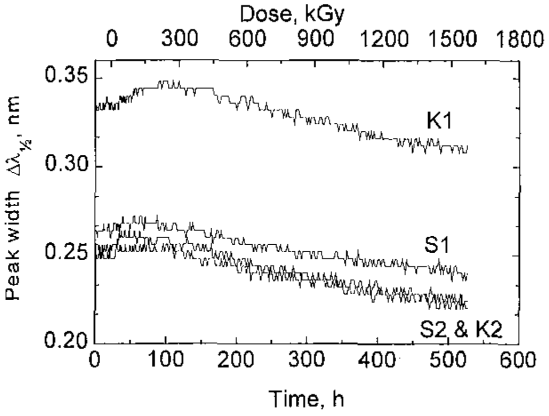

Figure 2: Evolution of the 3-dB width of the Bragg peak during γ-irradiation. Gratings N1 and G1 showed no detectable change in the width.

The variations of the amplitude (R) and the width ($\Delta\lambda_{½}$) of the reflection spectrum are shown in Figure 2 and Figure 3, respectively. For the FBGs written in the hydrogen-loaded fibres (S1, S2, K1, K2), both the amplitude and the width of the reflection spectrum show a non-monotonic behaviour with dose, whereas for G1 the variations are below the measurement accuracy, in agreement with the previous observations [5], [9]. Grating N1 shows a change in the amplitude but no change in the width of the Bragg peak.

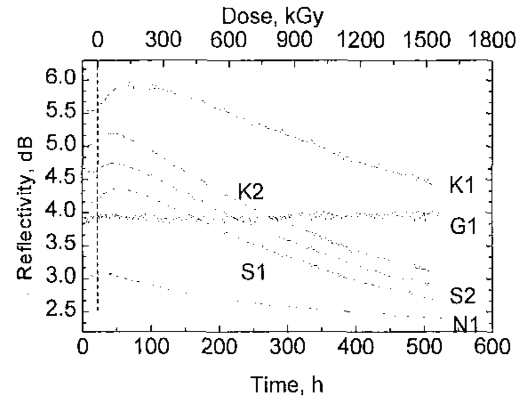

Figure 3: Evolution of the amplitude of the Bragg peak during γ-irradiation.

IV. DISCUSSION

It is known that the post-writing UV exposure of a part of a grating may be implemented to fabricate apodised and/or chirped gratings [12], [13]. It was reported recently that, using

CW UV-light fringeless exposure of a weak grating written in a Ge-doped H_2 loaded telecommunication fibre, it is possible to increase the refractive index modulation, that is to increase (and not erase) the grating strength [14].

Figure 3 shows that γ-irradiation can lead to an analogous effect for fibre Bragg gratings with initial reflectivity higher than 50%. For all gratings except G1, an increase of grating reflectivity is observed at the beginning of γ-irradiation. In [14], the increase of the grating strength was explained by the shape of the curve relating the amplitude of the refractive index modulation to the exposure time during grating inscription. This curve followed a S shape with respect to the exposure time [14]. As a result, during fringe-less UV post-exposure, the refractive index changed faster at the maxima of the UV fringe pattern than at the minima. A similar effect takes place in the case of γ-radiation : the sections of the fibre core that received different UV-fluences during grating inscription possess different sensitivities to γ-radiation. However, this effect of γ-radiation is observed here for gratings having a reflectivity higher than 50%. For such relatively strong gratings, the growth of the reflectivity under UV-light exposure does not follow a S-shape function but a simple saturating function.

From the reflectivity kinetics and the shift of the Bragg wavelength that were measured during γ-irradiation, we have computed the values of the effective refractive index at the maxima and at the minima of the UV-fringe pattern, the grating strength being determined by the difference between these values. We assumed that the modulation of the effective refractive index was sinusoidal. Figure 4 shows the result of the computation for gratings K2 and S2 with initial strengths of 4.3 dB and 5.5 dB, respectively. At the beginning of γ-irradiation the refractive index at the maxima of the UV-fringe pattern grows faster than that at the minima, resulting in an increase of the grating strength. After an irradiation time of about 100 h (300 kGy), the refractive index at the maxima starts to decrease slowly, while the refractive index at the minima continues to grow, giving rise to a decrease of the grating strength. It should also be noted that the behaviour of gratings written in hydrogen loaded fibres differs from that of gratings written in highly Ge-doped photosensitive fibres without hydrogen loading. Figures 1 and 3 show that in unloaded fibres only the mean value of the refractive index modulation (the Bragg wavelength) is changing, whereas the amplitude of the refractive index modulation (reflectivity) remains the same.

The formation of gratings in H_2-loaded fibres is due to photochemical reactions involving hydrogen. It is known that the growth of a grating in such fibres is correlated with the growth of GeE' centres [15]. Therefore, a probable interaction involves two stages [16]. First, a photon of suitable energy excites of a regular Ge-O bond:

$$\equiv\text{Ge-O-Si}\equiv + h\nu \rightarrow \equiv\text{Ge}\bullet \ldots \bullet\text{O-Si}\equiv.$$

At room temperature molecular hydrogen is known to react with non-bridging oxygen leading to the production 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 interaction with a molecular hydrogen is similar in both cases:

$$\equiv\text{Ge}\bullet \ldots \bullet\text{O-Si}\equiv + \text{H-H} \rightarrow \equiv\text{Ge}\bullet + \text{H-O-Si}\equiv + \text{H}\bullet$$

The atomic hydrogen may react with $\equiv\text{Ge}\bullet$ to form a Ge-H bond or may participate in breaking of another regular Ge-O bond. Radiolytic rupture of the OH-bonds is a probable reason of the high γ-radiation sensitivity of gratings written in hydrogen loaded fibres, as observed in our experiment.

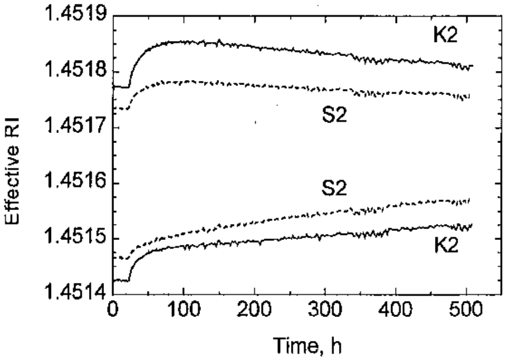

Figure 4: Computed values of the effective refractive index at the maxima (upper curves) and at the minima (lower curves) of the UV fringe pattern, for gratings S2 (dashed lines) and K2 (solid lines).

Little is known about the photosensitivity mechanism in the oxynitride optical fibre. CVD-processes result in material with a strong absorption in the 1.3-1.6 μm region, related to OH, NH and SiH groups. Reduced-pressure glow-discharge SPCVD fabrication process with silicon tetrachloride as the raw material allows to decrease drastically the concentration of hydrogen in silicon oxynitride [8]. However, an absorption in excess of 100 dB/km at 1.505 μm (the first overtone of the NH-group) and 1.43 μm (OH-group) indicates that hydrogen is present and its concentration is significantly higher than that in a germano-silica fibre (< 1 dB/km). The presence of bonded hydrogen in silicon oxynitride fibre was explained by a high humidity of reagents and the hydrogen diffusion from the jacketing tubes [8]. We may expect, therefore, that the photosensitivity mechanism of the N-doped fibre is similar to that of the H_2-loaded Ge-doped fibres. If that is the case, the γ-radiation sensitivity of gratings written in the N-doped fibre should be attributed to the radiolytic rupture of both OH- and NH-bonds.

The photosensitivity mechanism in the Ge-doped photosensitive fibres without hydrogen is related to structural transformation of germanium oxygen deficient centres [10], 16]. Indeed, it was experimentally demonstrated that γ -radiation creates the same paramagnetic defects in the Ge-doped fibre as UV-light does during FBG inscription [17]. The activation efficiency of structural transformations should not be significantly different for both UV-light and γ-radiation. In a 10 mol.% Ge-doped fibre the magnitude of the Bragg peak shift *towards the red* during FBG inscription is about 10 pm for a fluence of the order of kJ cm^{-2} [18]. Such a fluence level corresponds to a dose of 10^8 Gy. Should γ- and UV-radiation be completely equivalent, one would expect a shift far below 1 pm even for a MGy γ-dose.

To explain the shift of the Bragg peak during the first 30-35 hours (100 kGy) of γ-irradiation, we can assume that there are centres that do not interact with UV-light but only with γ-radiation. The concentration of these centres is constant along the grating. Therefore, γ-radiation results only in the shift of the Bragg peak, but do not change the reflectivity. A γ-radiation dose of 100 kGy is enough to convert all these centres. A further increase of the dose results in a change of the refractive index to the same extent as during the grating inscription. It follows from this assumption that the sensitivity to γ-radiation can be decreased by decreasing the concentration of such active centres. This can be done by pre-irradiating the fibre or the grating. The result should be independent on what is done first : pre-irradiation or grating inscription.

V. CONCLUSIONS

Under high total dose γ-radiation, the behaviour of FBGs written in hydrogen-loaded Ge-doped fibres and in a N-doped fibre were found to be different from that of FBGs written in a 10 mol.% Ge-doped fibre without hydrogen loading. The radiation-induced shift of the Bragg peak saturated at a higher level for FBGs written in hydrogen-loaded Ge-doped fibre than for FBGs written in unloaded Ge-doped fibre. By contrast, the Bragg peak shift showed no saturation for the FBG written in N-doped fibre even at the maximal accumulated dose. The amplitude and the width of the Bragg peak changed during irradiation for gratings written in hydrogen-loaded Ge-doped fibres and in N-doped fibre, while it did not change for gratings written in unloaded Ge-doped fibre. Changes of the grating strength during γ-irradiation are attributed to different kinetics in radiation-induced changes of refractive index at minima and maxima of UV fringe pattern. The higher γ-radiation sensitivity of gratings written in the hydrogen loaded fibres is thought to be due to radiolytic ruptures of OH-bonds.

VI. ACKNOWLEDGEMENT

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