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# X-ray and High Temperature Responses of Regenerated Fiber Bragg Gratings

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## ABSTRACT

Fiber Bragg Gratings (FBGs) can be used as non-intrusive and multiplexed temperature or strain sensors with an acquisition rate larger than 1 kHz and a resolution better than 0.1°C and 0.1  $\mu\text{e}$ . Regenerated Gratings (RFBGs) can withstand high temperature. Also, radiations induce an additional error of less than 4°C for a total dose of 100 kGy(SiO<sub>2</sub>) at Room Temperature (RT) and less than 1°C at 250°C for the same total dose. We have inscribed at the CEA List LCFO or at the Laboratory H. Curien, FBGs in three different fibers: two different Ge-doped fibers and one B/Ge co-doped fiber. The gratings were regenerated at respectively 650°C, 900°C and 750°C and then irradiated at Room Temperature (RT) and at 250°C with a dose rate of 10 Gy/s.

The gratings inscribed in the Ge-doped fibers, independently of the Ge content or the inscription and regeneration conditions present similar behavior, with a Bragg Wavelength Shift (BWS) of less than 10 pm (equivalent to  $\sim 1^\circ\text{C}$ ) at a total dose of 100 kGy and for a temperature of 250°C while the grating inscribed in the B/Ge co-doped fiber presents a BWS of more than 60 pm.

**PACS Keywords:** Fiber Bragg Grating, Regeneration, High Temperature, Radiations

## 1 INTRODUCTION

Since few decades Optical Fibers (OFs) are studied for applications as temperature or strain [2] sensors. These sensors have all the advantages of OFs as for example a small size and an immunity to almost all the electromagnetic perturbations. Amongst all of these sensors, Fiber Bragg Gratings (FBGs) are one of the fastest ( $> 10$  kHz) [3] since the only limitation comes from the acquisition system and not from the sensor itself.

A FBG is a wavelength filter where for an input spectrum all of the light pass through the grating except a narrow band which is reflected. The central wavelength of this band is the so-called Bragg wavelength and it depends on the effective refractive index of the fundamental mode and on the modulation period [4]. Moreover, the Bragg wavelength is temperature dependent and for range of 100°C can be

approximated by a linear equation where the slope is the temperature sensitivity of the FBG [4].

The Regenerated gratings (RFBGs) are known to be stable at temperature up to their regeneration conditions [5], and they can also operate continuously at a temperature of about 890°C during 9000 hours [6] while preserving the multiplexing capabilities of standard Type I FBGs [7].

Under X-rays, the fiber attenuation can increase which in turn decreases the Signal to Noise ratio. This phenomenon is called Radiation Induced Attenuation (RIA) [8]. For the gratings the RIA will decrease the Bragg peak amplitude. However, the irradiation also generates defects that leads to a refractive index change according to the equations of Lorentz-Lorenz and Kramers-Krönig [8]. The modification of the mean refractive index will lead to an evolution or drift of the Bragg wavelength: this behavior is called Radiation Induced Bragg Wavelength shift (RI-BWS) [8].

## 2 EXPERIMENTAL SETUP

The detailed laser writing parameters and the subsequent thermal regeneration conditions for each of the tested RFBGs can be found in references [1], [9] and are summarized in the table hereafter.

Fiber		FBG # 1 Ge (1)	FBG # 2 Ge (2)	FBG # 3 B/Ge
Dopant	Ge	unknown	$\sim 5$ wt%	$\sim 10$ wt%
	B	0 wt%	0 wt%	5 wt%
Hydrogenation		2 weeks 200 bars	6.5 days 130 bars	
Inscription	Laser	KrF ns-pulsed @ 248 nm Talbot Interferometer	Argon cw @244 nm	
	Method		Lloyd Mirror	
Regeneration	Temperature	650°C	900°C	750°C
	Duration	2 h	1 h	1 h

Table 1: Laser writing parameters and thermal regeneration conditions of the RFBGs.

The irradiation tests have been performed in the Moperix or the LabHX X-ray chambers with a maximal energy of 100 keV at a dose-rate of 10 Gy(SiO<sub>2</sub>)/s up to a total dose of 100 kGy at Room Temperature (RT) or at 250°C. The grating are placed stress free on an aluminum plate which is in contact with the heating plate at 250°C as described in [1]. At least two gratings are used during the experiments to assess our measurement repeatability and the results show the Bragg wavelength means. Two thermocouples monitor the temperature during all the irradiations.

During the experiments all the spectra are recorded with the Tunics/CT-400 Component Tester with a spectral resolution of 1 pm or the NI-PMA-1115 with a spectral resolution of 4 pm. During the result analysis the Bragg wavelength are corrected from the temperature fluctuations.

### 3 RESULTS

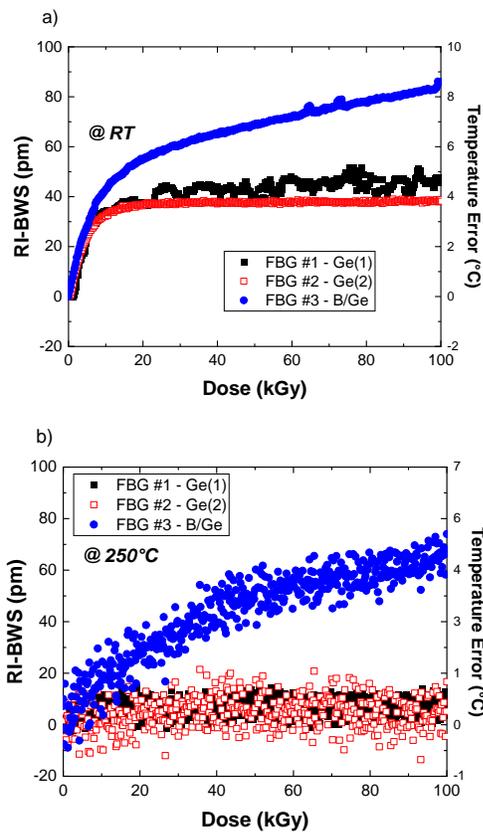


Figure 1: Irradiation at a dose-rate of 10 Gy/s up to 100 kGy at RT (a) and 250°C (b) of three RFBGs inscribed in a Ge-doped fiber and regenerated at 650°C (black square) or in another Ge-doped fiber and regenerated at 900°C (Red empty square) or in a B/Ge co-doped fiber regenerated at 750°C. The Y-right axis represents the temperature error if the grating is used as a temperature sensor

The RFBGs as described in Table 1 have been irradiated at a dose-rate of 10 Gy/s up to an accumulated dose of

100 kGy at RT (figure 1.a) while another set of gratings is irradiated at a temperature of 250°C (figure 1.b).

At a total dose of 100 kGy at RT the RI-BWS of RFBG #3 written in the B/Ge co-doped fiber is greater than 80 pm which is more than a type I Bragg peak shift (> 40 pm) observed in the same fiber at the same dose [10]. Even under high temperature, the RFBG (#3) presents a BWS of more than 60 pm at 100 kGy.

The other RFBGs whose seed gratings have been inscribed in the two different Ge doped fibers have a similar behavior. The RI-BWS of the two gratings at 100 kGy is around 40 pm at RT and around 0 pm at 250°C. At high temperature under radiation, we suppose an equilibrium between the defect generation due to X-ray irradiation and the recombination due to the high temperature to which the gratings are exposed. For the B/Ge co-doped fiber this equilibrium is not reached.

### 4 CONCLUSION

The Regenerated FBGs are promising candidates for the temperature monitoring under radiation and especially at high temperature since their temperature error is negligible for the Ge-doped fibers at 100 kGy/250°C independently of their dopant concentration or their regeneration conditions.

For the conference we will show the regeneration processes as well as a study on the dose-rates.

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