

Impact of Ionizing Radiations on Fiber Bragg Gratings for Space Systems

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ABSTRACT

With the development of terrestrial telecommunication systems based on photonics, the number of photonic devices potentially usable for space applications strongly increases. Amongst those Fiber Bragg Gratings (FBG) are narrow spectral filters, made of a sub-wavelength grating, inscribed in the core of an optical fiber, designed to reflect a mode at a specific wavelength (called the Bragg wavelength). FBG are mainly used for spectral filtering in photonic systems (LIDAR, Fiber gyroscopes, Optical feeder-links, Quantum Key Distribution), but they are also interesting for optical fiber sensing and interrogation units.

The space radiative environment is known to significantly affect the transmission of optical fibers through RIA (Radiation Induced Attenuation). The latter is likely to be influenced by key manufacturing processes and design [1]. As FBGs are optical fiber based, radiations impact their optical responses in two ways: a reduction of the peak reflection (reduction of the SNR) and, in most of the cases, a shift of the Bragg wavelength (Radiation Induced Bragg wavelength shift or RI-BWS) [2]. The radiation sensitivity of a FBG strongly depends on its inscription conditions and on the irradiation conditions. Depending of the system that integrates the FBG, the induced wavelength shift can be far greater than the system tolerances, leading to strong degradations of its performances. Even with potentially predictable schemes based on manufacturing data, it is very difficult to evaluate the potential sensitivity of a FBG without testing it.

In this study, several FBGs of different profiles and different inscription conditions, have been irradiated in order to highlight the main contributors that lead to a change in the FBG radiation sensitivity. Based on the results, we will emphasize major trends on FBG sensitivity highlighting the risks and suitability of each technology for the different applications.

Keywords: Fiber Bragg Grating, ionizing radiation, radiation-induced Bragg wavelength shift, optical fiber sensing

1. INTRODUCTION

Fiber Bragg Gratings (FBGs) are key building blocks of modern space photonic systems. They are used for spectral filtering in photonic subsystems such as LIDAR instruments, fiber-optic gyroscopes, optical feeder links and quantum key distribution terminals, and they are widely deployed as point sensors in optical fiber sensing networks for structural health and thermal monitoring.

When exposed to the ionizing radiation encountered in the space environment, FBGs are affected in two main ways: a Radiation-Induced Bragg Wavelength Shift (RI-BWS), and a reduction of the peak reflection caused by the Radiation-Induced Attenuation (RIA) of the host fiber. Both effects can degrade the performance of spectral filters and introduce a measurement error in fiber sensing applications. The radiation hardness of a given FBG is not simply related to that of the base fiber: it also depends on the inscription conditions, the loading gas used to enhance the photosensitivity of the fiber, and any post-treatment applied after inscription.

This paper presents an experimental campaign aimed at quantifying the impact of ionizing radiation on Type I FBGs manufactured with different fibers, loading gases and post-treatments, in order to support the selection and hardening of FBG-based components for space missions.

2. FIBER BRAGG GRATINGS FOR SPACE SYSTEMS

2.1 Principle of operation

A FBG is an interference pattern photo-inscribed in the core of an optical fiber by locally and periodically modulating its refractive index. When a broadband source is launched into the fiber, the grating reflects a narrow spectral band centered on the Bragg wavelength and transmits the rest of the spectrum (Figure 1). The Bragg wavelength is set by the grating period Λ and depends on the length L of the photo-inscribed region and on the effective refractive index of the propagating mode. Any process that changes the refractive index of the core — including ionizing radiation — therefore shifts the Bragg wavelength and can modify the amplitude of the reflected peak.

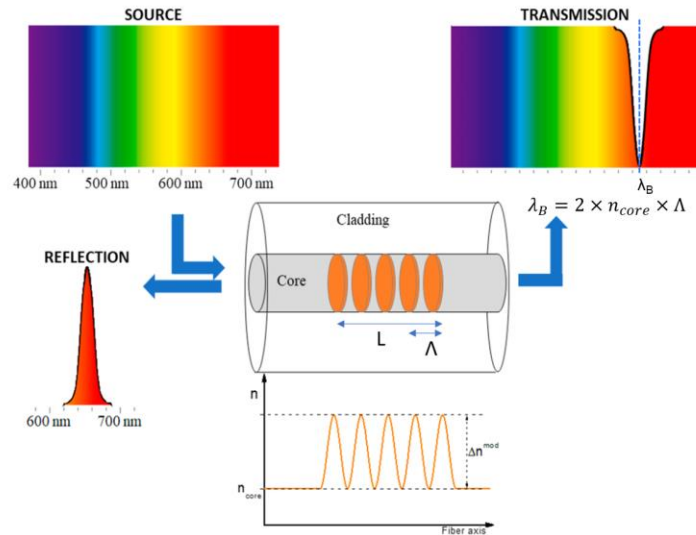


Figure 1. Principle of a Fiber Bragg Grating ^[1]

2.2 Manufacturing process

This study focuses on Type I FBGs inscribed by UV laser-pulsed writing; the process used for about 99% of commercial gratings. The main drawback is a temperature limitation 500°C, in comparison to other FBG types, but sufficient for space application. The manufacturing sequence, illustrated in Figure 2, consists of selecting the optical fiber, removing the acrylate cladding, loading the fiber with hydrogen (H₂) or deuterium (D₂) to enhance its photosensitivity, writing the grating with a UV pulsed laser, applying an optional post-treatment (thermal annealing, which will stabilize the grating, or CO₂-laser irradiation, which will decrease the effective refractive index), and re-cladding the fiber with an acrylate coating.

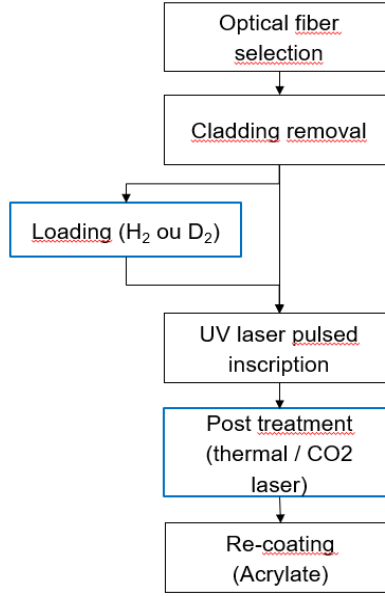


Figure 2. FBG manufacturing process flow

3. EXPERIMENTAL DETAILS

3.1 Samples

Eight FBG samples were selected from Exail to separate the influence of the loading gas, the post-treatment and the fiber type on the radiation response, as summarized in Table 1. Six gratings were written on SMF28e+ fiber at 1.55 μm , loaded with either D2 or H2 and thermally annealed (8 h at 120°C), with or without an additional CO₂-laser post-treatment. Two further gratings were written at 471 nm on 405-HP and unloaded PM460-HP fibers to assess the influence of the fiber type.

Table 1. FBG samples selected from Exail for this study.

Sample	Fiber	Loading	Post-treatment (thermal)	Post-treatment (CO ₂)
162962	SMF28e+ 1.55 μm	D2 (deuterium)	8 h @ 120°C	None
162963	SMF28e+ 1.55 μm	D2 (deuterium)	8 h @ 120°C	Yes
162964	SMF28e+ 1.55 μm	H2 (dihydrogen)	8 h @ 120°C	None
162965	SMF28e+ 1.55 μm	H2 (dihydrogen)	8 h @ 120°C	Yes
162478	SMF28e+ 1.55 μm	H2 (dihydrogen)	8 h @ 120°C	None
162479	SMF28e+ 1.55 μm	H2 (dihydrogen)	8 h @ 120°C	None
163414	405-HP 471 nm	Unloaded	9 h @ 120°C	—
163415	PM460-HP 471 nm	Unloaded	—	—

3.2 Irradiation set-up and conditions

Irradiation was performed at the Laboratoire Hubert Curien with the X-ray irradiator IDEFIX, with in-situ optical characterization for all samples except for the FBG written on UV fibers (163414, 163415). As illustrated in Figure 3, each FBG under test was interrogated with a low-power broadband source (about 30 μW per grating) through a 1×4 coupler

and a circulator, and the reflected spectrum was recorded on an optical spectrum analyzer with a 1 pm resolution; the sample holder temperature was actively controlled to separate thermal effects from radiation-induced effects. All samples were irradiated to 10 kGy at a dose rate of 0.3 Gy/s, except sample 162479, which was irradiated to 1 kGy at a lower dose rate of 0.03 Gy/s. A monitored recovery phase of several hours at ambient temperature followed each irradiation run.

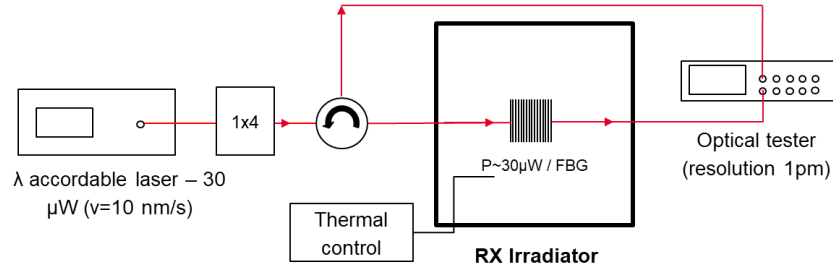


Figure 3. Irradiation test set-up: broadband source, 1×4 coupler, circulator, FBG under test with active thermal control, and optical spectrum analyzer.

4. RESULTS AND DISCUSSION

4.1 Impact of the manufacturing process at 10 kGy

Figure 4 compares the RI-BWS measured at 10 kGy for SMF28e+ gratings loaded with H₂ or D₂, with or without CO₂ post-treatment. The RI-BWS ranges between about 10 pm and 40 pm at end of irradiation for this set of samples, i.e. the manufacturing process alone can change the radiation response by up to a factor of about 3. D₂-loaded gratings are systematically less sensitive to ionizing radiation than their H₂-loaded counterparts. Two hypotheses are considered to explain this difference: the loading pressure used during manufacturing, about twice as high for H₂ as for D₂, and/or an intrinsic difference in the way the two loading gases interact with the glass under irradiation. CO₂-laser post-treatment is also found to increase the radiation sensitivity of the grating, even though it improves the nominal (pre-irradiation) performance of the FBG.

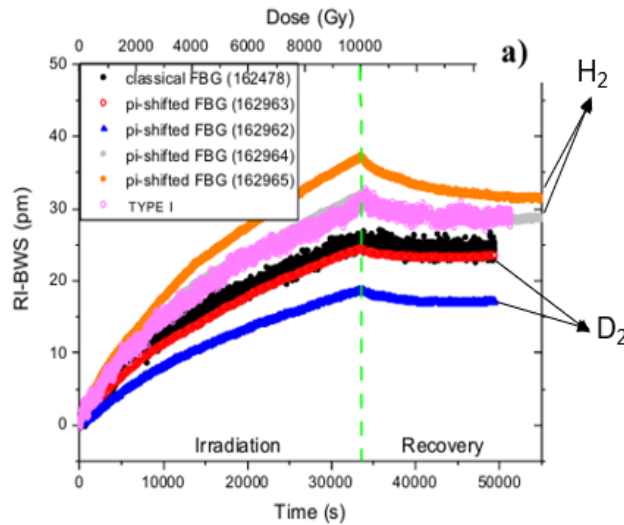


Figure 4. Impact of the manufacturing process on the RI-BWS at 10 kGy (0.3 Gy/s) for SMF28e+-based gratings: D₂ loading (blue, red), H₂ loading (orange, grey).

Over this same set of samples, the impact of the manufacturing process on the peak amplitude (Figure 5) remains small compared to the effect on RI-BWS, confirming that for standard telecom-grade fiber the dominant radiation effect on these gratings is the wavelength shift rather than a loss of reflectivity due to RIA.

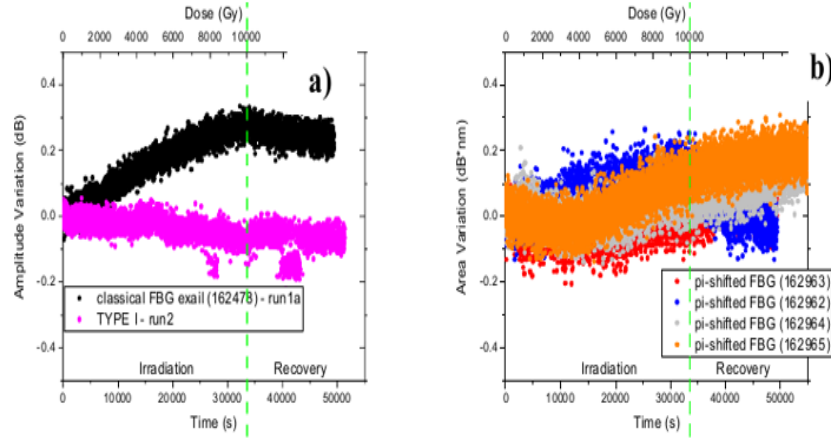


Figure 5. Impact of the manufacturing process on the amplitude variation on (a) FBG 162478 and (b) 162962, 162963, 162964, 162965 at 10 kGy

4.2 Impact of the fiber type at 10 kGy

The influence of the fiber type was assessed by comparing gratings written on 405-HP, UV single mode fiber and on PM460-HP, UV Polarization maintaining fiber (Figure 6). On PM460-HP, a RI-BWS of about 40 pm is observed on both polarization axes, together with a significant impact on the peak amplitude (about 0.5 dB). On 405-HP, the RI-BWS is limited to about 12 pm with only a minor impact on the amplitude. These results confirm that the fiber selection has a comparable influence to the manufacturing process on the radiation response of the FBG, and should therefore be considered jointly when selecting a component for a given space application.

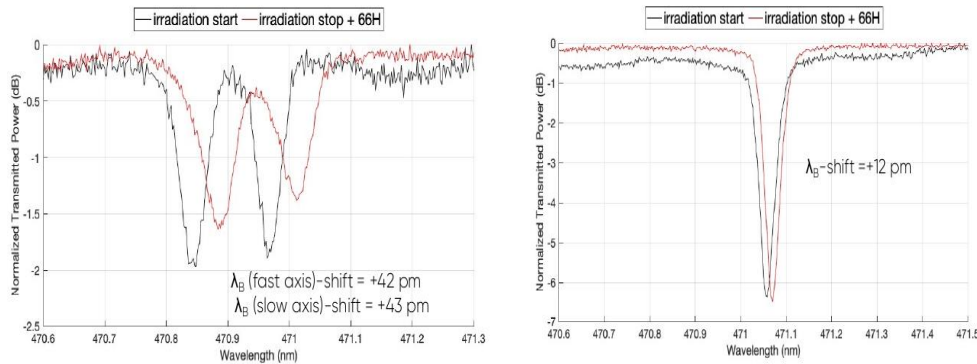


Figure 6. Radiation-induced spectral shift for (left) PM460-HP fiber and (right) 405-HP fiber, both at 10 kGy.

4.3 Impact of the deposited dose and dose rate

Sample 162479 was irradiated to a lower deposited dose and at a lower dose rate (1 kGy, 0.03 Gy/s) than the rest of the batch (10 kGy, 0.3 Gy/s) to probe the sensitivity of the FBG response to these two parameters. As shown in Figure 7, no significant degradation of either the RI-BWS or the amplitude was observed within the precision of the set-up under these low-dose, low-dose-rate conditions, in contrast with the clear response measured at 10 kGy and 0.3 Gy/s. Dose rate and

deposited dose therefore appear to have an impact on the RI-BWS of a similar order of magnitude to the fiber selection and the manufacturing process, all three parameters being able to produce RI-BWS values up to about 40 pm.

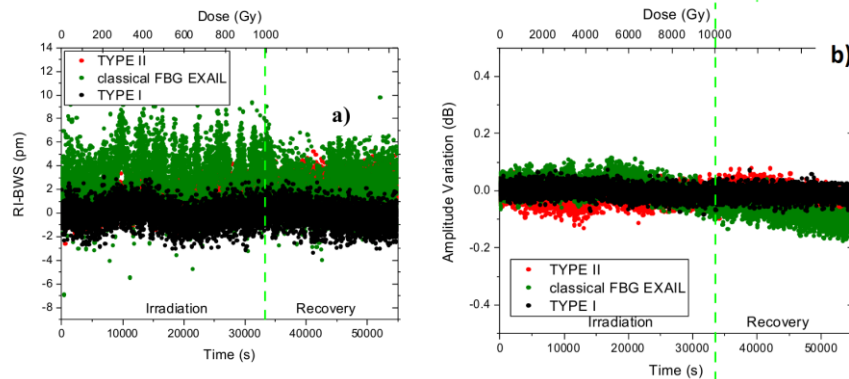


Figure 7. Impact of the deposited dose and dose rate: at 1 kGy and 0.03 Gy/s (sample 162479), RI-BWS (a), amplitude (b).

5. CONCLUSIONS

This study confirms that ionizing radiation has a major effect on the Bragg wavelength of Type I FBGs, with RI-BWS values ranging between about 10 pm and 40 pm at 10 kGy depending on the loading gas, the post-treatment and the fiber type. This level of shift has a low impact on FBGs used for spectral filtering applications, but a higher impact on fiber sensing networks, where it translates into a temperature measurement error of about 1°C to 4°C (sensitivity of 1°C/10pm) that needs to be accounted for in the overall performance budget of the sensing system. Three parameters — the dose rate and deposited dose, the fiber selection, and the manufacturing process steps (loading gas and post-treatment) — were found to have a comparable impact on the RI-BWS, each able to produce shifts of up to about 40 pm. These results provide practical guidelines for the selection and hardening of FBG-based components intended for spectral filtering and fiber sensing applications in the space radiation environment.

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