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Comparative study of long period and fiber Bragg gratings under gamma irradiation

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ABSTRACT

We evaluated comparatively the radiation sensitivity of two long period gratings (LPGs) manufactured in a SMF28^{TM} optical fiber through the melting-drawing method based on CO_2 laser assisted by a micro-flame, of a commercial fiber Bragg grating (FBG), and of a commercially available Draw Tower Grating (DTG), all exposed to gamma radiation. The tests were run on-line using the optical frequency domain reflectometry (OFDR) technique, in order to provide unequal sensitivity, the gratings being wavelength multiplexed. The dose rate dependence of the LPGs response was evaluated for dose rates of 0.37 kGy/h and 0.24 kGy/h, up to the total dose of (33.9 ± 0.8) kGy and (21.5 ± 0.5) kGy. The FBG and DTG proved to be radiation hardened having a radiation sensitivity of 12 pm/kGy, while the LPGs radiation sensitivity was as high as 1.2 nm/kGy under the same irradiation conditions. A recovery of the radiation induced wavelength shift for LPGs was noticed at room temperature, at a rate of 2.2 pm/h, over a 211 h period. The effect of LPG wavelength change after exposure to gamma-ray can be exploited in the development of radiation dosimeters, up to the dose of 10 kGy, when saturation appears. The temperature sensitivity of the LPG2 changed from 48 pm/°C before the irradiation, to 50 pm/°C after the irradiation for a total dose of 21 kGy.

1. Introduction

We evaluated the durability of several optical fiber sensors for operation under harsh environment within the framework of "Cigéo" project, the French deep geological repository for long-lived high and intermediate level nuclear waste, and the Romanian project "Sensor Systems for Secure Operation of Critical Installations".

In the Cigéo future outstanding repository structure, monitoring is required for a century. It will contribute to assess the reversible management (imposed by law) and the safety analysis during operation as well as after closure. Parameters to monitor are temperature, strain, water content, radiation.

Over the last ten years, optical fiber Bragg gratings (FBGs) were extensively investigated under irradiation, with a focus on: (i) the influence of the optical fiber type (photosensitive optical fibers with different dopants or hydrogen-loaded), (ii) the technologies used to produce the grating (Type I, Type II, Type IIA FBGs) [1]. Usually, FBGs showed a remarkable radiation resistance, [2], as small wavelength shifts were recorded, in the order of 10–30 pm. [1]. In one case, a vulnerability to ionizing radiation was proved, recommending these FBGs for radiation dosimetry [3].

However, there are only few reports concerning the behavior of long period optical fiber gratings (LPGs) under gamma ray irradiation. Off-line tests run on LPGs inscribed with a CO laser in N-doped optical fibers or written by UV radiation in Ge doped optical fibers indicated no significant changes up to the accumulated dose of about 100 kGy [4]. By interferometric investigations important changes in the refractive index of the optical fiber core were monitored. A slight modification of the transmission characteristic of the gratings was observed in the case of LPGs produced by the electric arc discharge technique in pure-silica-core fibers with F-doped silica cladding, irradiated by gamma source (dose rate of 1 kGy/h, total dose of 560 kGy, at 37 °C) [5]. The gratings were monitored on-line with an optical spectrum analyzer (OSA). The irradiation induced effects were almost recovered at room temperature in one month.

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The temperature sensitivity of the gratings was not affected by the irradiation.

Some other studies dealing with specially designed LPGs report their sensitivity to gamma radiation. One example refers to chiral type LPGs from five different suppliers, irradiated by gamma-ray up to 100 kGy [6]. The central wavelength shift was about 10 nm, 1000 times bigger than in the case of FBGs, suggesting a possible use as radiation detectors down to a detecting limit of 10 Gy, for a dose rate of 0.1 Gy/s up to a dose of 20 kGy.

A more recent approach involved turn-around-point (TAP) LPGs produced in B/Ge co-doped fiber using the CO_2 writing techniques [7]. The gratings were irradiated by gamma source with a dose rate of about 1.3 kGy/h. Off-line measurements of the transmission spectrum were performed after 1/2–3 h after irradiation. The wavelength dip shift for 6.5 kGy was 35 nm and more than 80 nm at 65 kGy. It is estimated that such LPGs can be used for dose measurements down to the Gy range.

In a previous paper [8], we evaluated a LPG manufactured into a F-doped radiation hardened optical fiber produced by a melting-drawing method based on CO_2 laser radiation assisted by a micro-flame, as it was exposed to gamma radiation. The grating was tested on-line with a LUNA OBR 4600 optical frequency domain reflectometry (OFDR). For the dose rate of 0.2 kGy/h, and total dose of 45 kGy, the measured wavelength shifted 700 pm toward shorter wavelengths. The radiation sensitivity was about 16 pm/kGy. We estimated the increase of refractive index in the order of 10^{-6}, at the end of the irradiation. In the laboratory, the recovery process was almost completed in 120 h, at a rate of 6.7 pm/h. Based on these results, we decided to design a radiation sensors of LPG type, by selecting the appropriate optical fiber type and the manufacturing parameters. In the mean time, we were interested to test under the same irradiation conditions LPGs and FBGs/ DTGs, to evaluate the capability of FBGs or DTGs to act as temperature reference to LPGs during the radiation exposure, by proving that these sensors (FBG and DTG) are quite immune to gamma irradiation over the same total doses, for the same dose rate.

2. Materials and Experiment

The present paper reports on-line investigations of: (i) two LPGs manufactured by the melting-drawing method based on CO_2 laser assisted by a micro-flame in a SMF-28^{TM} optical fiber; (ii) one commercially available fiber Bragg grating FBG; and (iii) one commercially available Draw Tower Grating (DTG). In this experiment the two similar LPGs were exposed to two different dose rates.

The novelty of our approach constitutes in the way the mode propagation of the guided modes of such optical fiber gratings is exploited in order to control the radiation field in the optical fiber device, having as result the increase of LPG sensor sensitivity to gamma irradiation.

The operating principle of optical fiber long period gratings (LPGs) relies on a periodic phase/amplitude perturbation along the fiber, allowing the coupling between the forward propagating guided modes to the forward propagating cladding modes. As a consequence, appears an induced modifications in the radiation field. In the case of the tapered LPGs we produced, the effective index perturbation is mainly induced by the periodic change in the fiber diameter along the component. Fig. 1 illustrates a simulation result for a SMF28^{TM} optical fiber showing the dependence of the effective indices of LP modes on the radius of the optical fiber.

Similarly to our previous paper [8], the two LPGs (LPG1 and LPG2), produced by iXFiber SAS, are characterized by periodic 5% variations of the diameter of the optical fiber, with revolution symmetry. The LPGs engraving setup is illustrated in Fig. 2. The obtained LPGs are re-coated with acrylate and inserted into a special case of glass and ceramic, transparent to gamma radiation. The LPG1 (respectively LPG2) is 22 mm long (respectively 25 mm), with a grating pitch of 730 μm (respectively 720 μm). The wavelength dip occurs at 1555 nm (respectively 1538 nm), at 21 °C. The advantage of our writing set-up in comparison with other CO_2-based methods is that the fiber is drawn point-by-point according to curves governed by predetermined laws of variation. (It means its is manufactured in one run, not by iteration or several round-trips). Furthermore the grating is generated uniformly by this method, with symmetry of revolution sufficient to have a filtering function independent of the polarization of light.

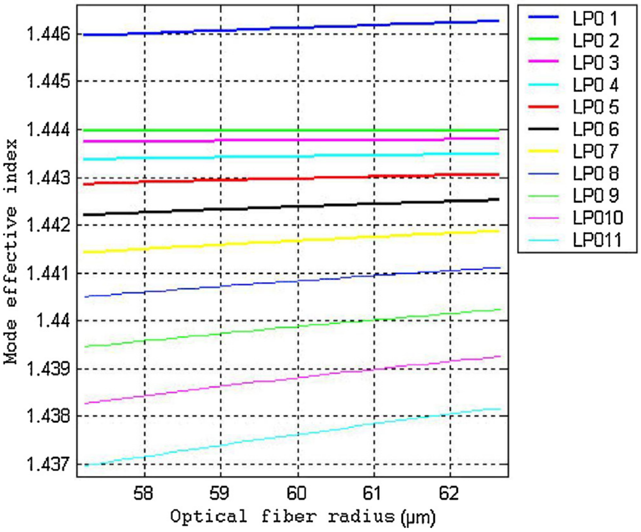

Fig. 1. The change of the effective index of LP modes as function of a LPG radius written in a commercial SMF28^{TM} optical fiber.

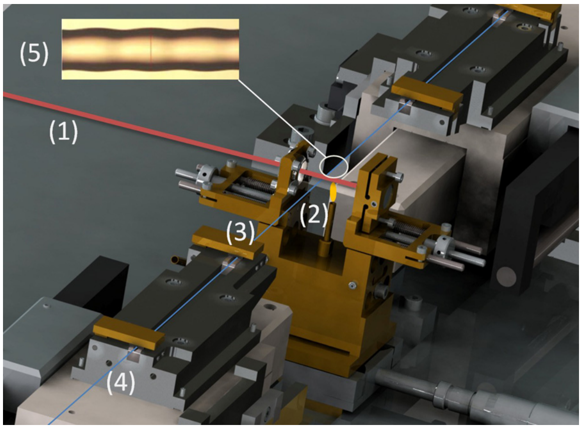

Fig. 2. Setup of the original LPG inscription bench: (1) CO_2 laser beam, (2) micro-flame, (3) optical fiber, (4) air-bearing stage, (5) fused LPG.

The FBG is produced by Technica SA, written in SMF-28^{TM} optical fiber ($\lambda = 1546$ nm; grating length of 12 mm; reflectivity >80 %; bandwidth (BW) @3 dB < 0.3 nm; side lobe suppress ratio (SLSR) > 15 dB; Acrylate recoating). The DTG sensor was purchased from FBGS International ($\lambda = 1560$ nm; reflectivity > 15%; full width at half maximum — FWHM of 100 pm; SLSR > 10°dB; attenuation of 8.6 dB/km@1550 nm; Acrylate coating).

From the above description the main advantage of the tapered LPGs is evident: they are intrinsically more resistant to erasure than the fiber Bragg gratings (FBGs) when they are exposed to harsh environments, as the manufacturing process does not require the photosensitivity of the fiber in order to write such a type of grating. On the other hand, the resonant wavelength of the LPG ($\lambda_{LPG}{}^{(n)}$) is