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Long Period Gratings in unconventional fibers for possible use as radiation dosimeter in high-dose applications

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ABSTRACT

In this work, we conducted experimental and theoretical investigations on gamma radiation sensitivity of Long Period Gratings (LPGs), fabricated by electric arc discharge technique in two different single mode optical fibers, designed to be radiation resistant, with the aim to understand their behavior under irradiation and their radiation hardness as a function of core/cladding dopants. The first fiber is sold by the manufacturer to be used in harsh environments and has doped core and pure-silica cladding, while the second one is radiation-hardened with pure-silica core and F-doped silica cladding. Gamma irradiation was performed at a ^{60}Co source with a 0.2 kGy/h dose rate, until a total absorbed dose close to 30 kGy was reached. During the experiments, the LPGs spectral changes were recorded in real-time, moreover pre- and post- irradiation investigations were done to establish the impact of gamma radiation over fiber refractive index modification and LPGs temperature sensitivity. The LPG in pure-silica core fiber proved its radiation hardness exhibiting changes in resonant wavelength position lower than 0.2 nm, on the contrary the LPG written in doped-core fiber showed high sensitivity to radiation with a wavelength shift of 5.7 nm at the end of the irradiation. The outcomes of this experimentation, along with our previous results on gamma irradiated LPGs, are useful for the design of an all LPG-based temperature compensated radiation dosimeter.

1. Introduction

Over the years, great efforts have been made in order to enhance the sensitivity of in-fiber sensors to external parameters like temperature, strain, humidity, pressure and so on, with the aim to diversify their field of application [1,2]. More recently, their use in radioactive environments has attracted a growing interest for research, industrial and medical purposes [3,4]. In fact, optical fiber sensors operating in ionizing radiation fields have been studied in several papers, with respect to the radiation effects on their properties [4,5], as well as for radiation dosimetry [6]. A critical aspect is the assessment of their resistance under different radiation conditions, ranging from low radiation levels of medical applications to high-energy applications. For these reasons, the investigations focused on the exposure of optical fibers and sensors to gamma-ray [7–9]. The main effect studied in literature, concerning optical fibers in radiation environments, is the radiation-induced absorption (RIA). It has been proven that this parameter depends in a consistent way on the chemical composition of the fiber core and cladding regions, as well as on the manufacturing process. In fact, while in-fiber dopants like Ge, B, P, and Al increase the sensitivity to radiations, pure silica fibers were found to be more resistant to radiation induced attenuation [4,10].

Many works have been done, in order to study the effects of radiation on in-fiber gratings. Most of the studies targeted Fiber Bragg Gratings (FBGs), fabricated in different optical fibers (photosensitive, H-loaded, or rad-hard), and exposed to different kinds of radiations [4,11–14]. Nowadays, only few papers present the effects of gamma-radiation on Long Period Grating (LPG) sensors [15–19], whereas their behavior under mixed neutron-gamma radiation was investigated for the first time only recently [20]. LPGs consist of a periodic perturbation of the refractive index and/or geometry of the silica waveguide with relatively large period Λ in range 100 μm–1

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mm, whose fabrication is possible with different techniques, such as the use of: UV radiation [21], infrared femtosecond lasers [22], CO_2 lasers [23], and electric arc discharge (EAD) [24,25]. Previous studies highlighted that the radiation effects on fiber gratings are dependent on the radiation-induced changes of the effective refractive indices, of the core mode (for FBGs) and core-cladding modes (for LPGs). Finally, it is worth to highlight that, even if there exists a relationship described by the Kramers–Kronig relation, often no direct correlation between the RIA and the refractive index change was found [4,10].

Our recent work showed the different behavior of LPGs fabricated by electric arc discharge in various optical fibers, when subjected to gamma ray [26]. In particular, the attention was focused on real time measurement of the changes produced by radiation over two Ge-doped core fibers based on the standard Corning SMF28, provided by Oz Optics and Thorlabs, and one radiation resistant R1310-HTA fiber from Nufern. Experimental and numerical analyses were performed to establish the radiation induced effects on LPGs sensitivity with temperature and refractive index changes, after a total absorbed dose of 35 kGy reached with a dose rate of 0.2 kGy/h. Different results were obtained concerning the changes of LPGs resonant wavelengths as function of exposure time and in-fiber dopants. The most radiation sensitive LPG was the Nufern-LPG with a wavelength shift of 6.7 nm; comparatively, for the other sensors the change was around 3.8 nm after a 35 kGy gamma radiation dose. We also reported that saturation behavior was observed for doses higher than 15 kGy. Despite the fact that R1310-HTA has a lower RIA with respect to SMF28, the resonant wavelength shift made the Nufern-LPG the most radiation sensitive with potential for dosimetry application. In fact, for doses up to 0.5 kGy the sensitivity of the sensor was as high as 1.2 nm/kGy.

In this paper, we complete our previous research by investigating the effects of gamma radiation over two new LPG sensors, produced for the first time by EAD technique in unconventional optical fibers. For a comparative study, the experiment runs nearly in the same conditions as those previously described [26]. The first fiber is declared by the manufacturer as suitable for harsh environments, exhibiting a doped-core and pure-silica cladding. The second fiber exhibits a pure-silica core an F-doped cladding and thus is sold as radiation hardened by the same manufacturer. For confidentiality reasons, we will be referring to them as Fiber-A and Fiber-B, respectively. According to our knowledge, there are no reports on gamma irradiation of LPGs produced in such types of optical fibers. Both sensors were subjected to gamma radiation, with dose rate of 0.2 kGy/h up to a total dose of 26.6 kGy and 29.6 kGy, respectively. Moreover, they were investigated both (i) in real-time during the irradiation, and (ii) off-line prior and post irradiation, in terms of temperature sensitivity and changes in the refractive index of the optical fiber. The major aim of our present work is to fill the gap concerning radiation effects on LPGs, by diversifying the fibers used to produce the LPG, targeting: (i) their use either as temperature sensors in radiation environments, if they are able to survive to gamma-rays exposure, or (ii) their application in radiation dosimetry, if they exhibit significant degradation after gamma exposure. In this way, we are developing a database concerning the behavior of LPGs under gamma irradiation.

2. Materials and methods

2.1. LPG sensors fabrication

The fibers selected for this study, Fiber-A and Fiber-B, which are purchased from the same manufacturer, are declared to be single mode fibers for wavelengths higher than 1250 nm, exhibit a cladding diameter of 125 μm, have a numerical aperture of 0.12 and are polyimide coated. For Fiber-A, the attenuation at 1550 nm is lower than 0.6 dB/km, while it is <0.8 dB/km for Fiber-B. In the case of Fiber-A the core component is doped silica, while the cladding is made of pure-silica. Whereas in Fiber-B the core is made of pure-silica, and the cladding is doped with Fluorine. Finally, they are recommended to be suitable for harsh environments (Fiber-A) and as radiation hardened (Fiber-B), respectively, by their manufacturer.

Both Fiber-A LPG and Fiber-B LPG were fabricated by EAD technique. During the procedure, part of the uncoated optical fiber was positioned between two electrodes of a fusion splicer machine (model Sumitomo), in this way the arc discharge may be applied to the fiber to create the perturbation of refractive index and fiber geometry. By using a translation stage, one end of the fiber is moved while the other one is kept under constant tension, as the arc discharges is applied. The procedure is repeated several times until the desired spectral features of the grating are reached. The details of LPG fabrication using EAD technique are described in our previous papers, regarding their fabrication in standard and unconventional fibers [27–31].

Concerning the EAD parameters, Fiber-A LPG has a period $\Lambda = 625\ \mu m$ and was fabricated by using arc power of 1 step (proprietary unit of Sumitomo) for 430 ms. Fiber-B LPG was produced with a period $\Lambda = 665\ \mu m$ by using same arc power and a duration of 410 ms. Both gratings are shorter than 25 mm.

The transmission spectra of Fiber-A LPG and Fiber-B LPG are illustrated in Fig. 1(a) and (b), respectively. They were acquired by using OSA model Yokogawa AQ6370B (resolution set to 0.1 nm), the illumination being provided by a broadband source involving several SLEDs in the spectral range 1100–1700 nm. During our analysis, for Fiber-A we focused the attention on the band located at 1568 nm (due to coupling with LP_{04}) while for Fiber-B we considered the band located near 1560 nm (corresponding to LP_{03}). In the same Figure, numerical spectra are also reported with dotted lines, as obtained by using the coupled-mode theory (CMT) model [32,33]. Good agreement between the simulation and the measured data can be observed.

2.2. Irradiation and measurement setup

The irradiation experiments took place in two sessions. Fiber-A LPG was irradiated up to a total dose of 26.6 kGy, while Fiber-B LPG accumulated a dose of 29.6 kGy. It is important to highlight that dose rate was the same in both cases and equal to 0.2 kGy/h.

The irradiations were performed at the industrial irradiator part of "IRASM" Facility in Romania, at room temperature, using the same setup of [26]. The ^{60}Co gamma source manufactured by the Institute of Isotopes Co. Ltd in Budapest, is a class IV source, and it is stored in a pool. The dosimetry was assured by the accredited facility of "Horia Hulubei" Institute, Romania, having traceability to the National Physics Laboratory (UK) via Risoe High Dose Reference Laboratory (Denmark). The absorbed dose was evaluated using an ethanol-chlorobenzene (ECB) dosimetry system based on oscillometric readout method [34], employing an oscillometric reader Radelkisz OK-303 (Institute of Isotopes – Hungary). All doses are expressed as absorbed dose in water. The uncertainty of the ECB dosimetry system [35] has four major sources:

- the calibration of the reference dosimeters: the uncertainty of their irradiation in a standardized radiation field – 1.7%;
- the intrinsic variation in the dosimeter response: variations of the dosimetric signal of three dosimeters from the same batch which were irradiated at the same dose – 1.3%;
- the variation of the read-out equipment: variations in the dosimeter reading – 2.5%; - the calibration curve fitting (a 3rd degree