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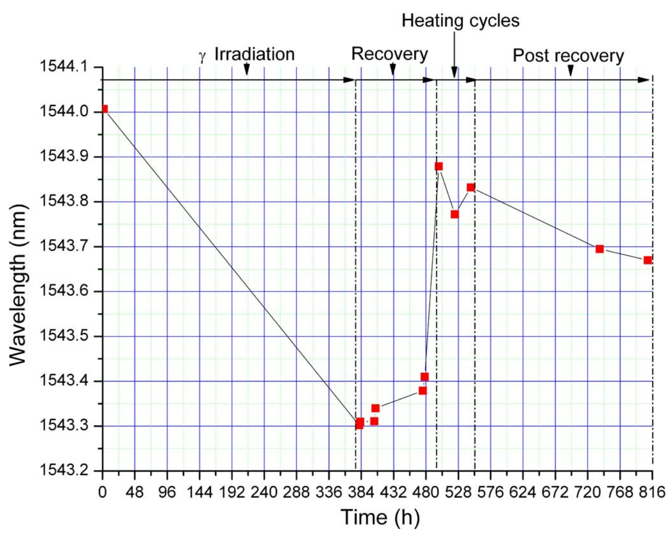

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Online Tests of an Optical Fiber Long-Period Grating Subjected to Gamma Irradiation

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Abstract: This paper reports the outcomes of the tests that we conducted as online measurements for the evaluation of one optical fiber long-period grating produced by a fusion technique in a single-mode radiation-hardened optical fiber, and subjected to gamma irradiation. During the irradiation, the grating temperature was monitored. Before the irradiation, the temperature sensitivity of the grating was 27.7 pm/°C, while the value of this parameter postirradiation was found to be 29.3 pm/°C. The spectral characteristics of the grating were measured (i) in the laboratory with an ANDO AQ6317C optical spectrum analyzer and (ii) online, ***for the first time***, with a LUNA OBR 4600 backscatter reflectometer, operating in the frequency acquisition mode. Such online measurement enables the study of recovery effects during the irradiation. The wavelength dip of the grating shifted under gamma irradiation, with 16 pm/kGy for the maximum total dose of 45 kGy. At room temperature, the recovery of the irradiation-induced shift of the wavelength dip was almost complete in about 120 h, at a rate of 6.7 pm/h. Postirradiation heating of the sensor produced the reversing of the recovery effect. The investigation indicated that, up to 45 kGy, the grating is more sensitive to radiation than other optical fiber sensors.

Index Terms: Fiber gratings, optical properties of photonic materials, waveguide devices.

1. Introduction

Long period fiber gratings (LPGs) constitute an extension of the classical Fiber Bragg Gratings (FBGs) as the changes in the refractive index occur in this case either in the fiber optic core, its cladding or in both locations [1], [2]. As compared to FBGs, LPGs have a length of the order of centimeters against few mm in the case of FBGs, and a larger pitch of the modulation profile, in the order of hundreds of μm as compared to FBGs which exhibit a period < 750 nm [3], [4]. Various techniques were used to fabricate LPGs: CO_2 lasers [2], [4], [5]; UV radiation [6]–[8]; visible

[3] or UV fs laser radiation [3], [9], [10]; IR fs laser radiation [11]; electric arc discharge [8], [12], [13]; LPGs were inscribed in pure-silica-core fibers/ F-doped silica cladding [13]; SMF-28 Ge-doped SiO_2 [2]–[4], [7], [9], [11], [14]; B co-doped fiber [8]; N-doped silica fibers [14]; micro-structured PMMA optical fiber [6]; special optical fibers for radiation environments [15]; FORC or Fujikura telecommunication optical fiber [3]; pure fused silica photonic crystal fiber [10]; H2-loaded SMF-28 [10]; Al^{3+}-doped and Er^{3+}/Al^{3+}-codoped fibers [12]; solid-core PCFs or air-core PBFs [5]. The writing methods were either a step-by-step process [1], [2], [4], [6], [9]–[11] or amplitude mask [1], [7]. An alternative constitutes the chiral long-period gratings (CLPGs) when optical fibers are uniformly twisted to produce single or double helices [15]. LPGs cover a large spectrum of applications: vibration sensing [16]; strain measurement [1], [5], [7]; temperature monitoring [1], [4], [5]; bend, pressure or torsion measurements [1], [5]; humidity sensing [17]; pressure monitoring [18]; refractive index sensing [1], [19]. Other types of applications referred to optical communications passive components (optical filters, gain flatteners for optical amplifiers, fiber coupling; dispersion compensation) [20].

FBGs were extensively investigated under irradiation in order to assess their survivability in nuclear environments as sensing devices. The results were mixed, depending on the type of the optical fiber (e.g., photosensitive optical fibers with various dopants or hydrogen-loaded), the technology used to produce the grating (Type I, Type II, Type IIA FBGs) [21] or the characteristics of the irradiation field (gamma-ray [21], neutron [22], proton beams [23]). When such gratings are irradiated under high total irradiation doses they show a remarkable radiation resistance [24] or demonstrate some vulnerability to ionizing radiation [25], recommending them for radiation dosimetry.

As it concerns LPGs only few papers addressed their behavior under irradiation, all reports being related to gamma-ray exposure. Almost 25 years ago, off-line test were run on N-doped optical fiber where LPGs were inscribed with a CO laser and grating written by UV radiation in a Ge-doped optical fiber [14]. No significant changes were noticed, up to accumulated dose of about 100 kGy, neither in the Ge-doped, nor in N-doped gratings. Interferometric investigations indicated no important changes in the refractive index of the optical fiber core.

One of the first reported on-line measurements refer to LPGs produced by the electric arc-discharge technique, in pure-silica-core fibers with F-doped silica cladding from Oxford Electronics and Acreo, and irradiated by a ^{60}Co gamma source, with a dose rate of 1 kGy/h. The total dose received by the samples was 560 kGy. During the irradiation the irradiation ring temperature was kept constant $(37.4 \pm 0.1\ ^{\circ}C)$ [13]. The gratings characteristics were monitored with an OSA. Some slight modification of the transmission characteristic of the some gratings was observed, but this effect is almost recovered as samples were stored at room temperature for one month. The study indicated also that the temperature sensitivity of the gratings is not affected by the irradiation.

LPGs were prepared in standard telecommunication grade fiber (Corning SMF28) by CO_2 laser radiation engraving, considering their higher temperature sensitivity, as compared to FBGs, and tests were done under gamma irradiation [4]. No effect of gamma irradiation on the sensitivity of the sensor was noticed, for doses up to 5 kGy.

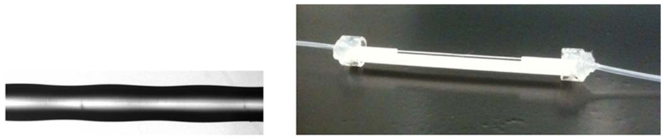
Comparing with the above mentioned results proving the radiation hardening of the LPGs under moderate to high total doses, some other studies dealing with specially designed LPGs reports their sensitivity to gamma radiation, with the direct outcome of using them for gamma dosimetry. One such example refers to chiral type LPGs irradiated by gamma-ray up to 100 kGy [26]. The basic SM optical fibers employed for the fabrication of chiral LPGs were from ALCATEL, Corning, FiberLogic, FORC, Fujikura, and Nufern. The grating period varied from 590 μm to 2050 μm, the diameter from 67 to 114 mm, while the grating length was from 10 to 26 mm. The measurements were done in reflection with an interrogator. During the irradiation the temperature in the irradiation zone was monitored by Pt 100 sensors. After the irradiation the central wavelength shift was 100 to 1000 times bigger (about 10 nm) than in the case of FBGs, suggesting a possible use of such grating 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 of turn around point (TAP) LPGs produced in B/Ge co-doped fiber using the CO_2 writing techniques, for possible application in gamma radiation dosimetry [27]. The gratings' length was about 20 mm, and they were irradiated at gamma source with a dose rate of about 1.3 Gy/h. Off-line measurements of the transmission spectrum were performed after 1/2 to 3 h from the irradiation moment in the spectral interval 1300 to 1600 nm. The operation was run in several steps, the total dose reached being 65 kGy. The wavelength deep shift for 6.5 kGy was $\pm$35 nm and more than $\pm$80 nm was obtained for the highest dose (65 kGy). It is estimated that such LPGs can be used for dose measurements down to the Gy range.

LPGs have several advantaged against FBGs: They are more robust, more sensitive and, the most important characteristic, they are easy to produce. More precisely, they can be inscribed whatever the optical fiber type: they can be realized in poorly UV-sensitive optical fibers such as radiation-hard fibers with pure silica core and F-doped cladding. As a result, it is a promising technology to perform temperature measurements into nuclear structures, such as the envisioned French deep geological repository for long-lived high level and intermediate level wastes (the Cigéo project). In this future outstanding structure, monitoring is planned for a century. It will be implemented in a nuclear environment, in the underground structures, included in some waste package storage cells. It will contribute to assess the reversible management (imposed by law) and the safety analysis in operation and after facility closure. Target temperature accuracy is 1 °C, which are fully compatible with the performances of most optical fiber sensor measuring systems, unless they derive under harsh environments. To obtain durable and long-term measurement, intensity-based sensors are rejected. On the opposite, wavelength-encoded principles, such as Bragg gratings and Brillouin scattering, are promoted. Thanks to remote sensing, the optical fiber is the only element of the sensing system subject to hostile conditions. To handle the radioactive environment and the performance requirement, Andra evaluated various optical fibers types including telecom fibers (i.e., Corning SMF28). The LPG used in this study was developed in F-doped fiber from iXFiber. Previous investigations proved high tolerance of this optical fiber at 10 MGy [28]. This is why we evaluated through on-line measurements the performances of this fiber temperature sensor under gamma radiation. The grating was subjected to gamma irradiation. In a first attempt, we irradiated the LPG at a constant dose rate of (4.0 $\pm$ 0.4) Gy/h up to a total dose of (311.0 $\pm$ 30.5) Gy. As no significant results were noticed we resume the irradiation at the dose rate of (0.2 $\pm$ 0.01) kGy/h. In this second investigation, the highest dose achieved in this study was (45 $\pm$ 0.8) kGy.

2. Materials and Experiment

LPG was produced by a melting-drawing method based on CO_2 laser assisted by a micro-flame. This technique was selected because it can be implemented into any kind of optical fibers, whatever the dopant natures, whatever the UV sensitivity. It is thus suitable with radiation-hard fibers with no Ge dopants. The optical fiber is drawn point-by-point according to curve governed by predetermined laws of variation. The LPG is characterized by periodic variations of the diameter of the optical fiber and symmetry of revolution. The 19 mm long grating having a period of 740 μm and a variations in the diameter of about 10% enables the coupling between the fundamental mode and the first radially-symmetric cladding-mode LP02. Change in the effective index is mainly due to the variation in the core diameter. The grating was developed by iXFiber SAS in a fluorine (F)-doped 8.5 μm core diameter SM optical fiber. The fluorine concentration is about 0.2 wt.% in the core and 1.8 wt.% in the cladding. This fiber class was chosen as we previously demonstrated that such an F-doped optical fiber presents interesting radiation hardness at high doses in terms of radiation induced absorption (RIA) [28]. Finally, the fiber was re-coated with acrylate and the grating was inserted into a special case of glass and ceramic, transparent for radiation (Fig. 1). Thus the grating is only exposed to temperature and radiation variations (isolated from strain).



(a) (b)

Fig. 1. (a) Fused optical fiber with a geometrical pitch and (b) the packaged component.

The LPG resonant wavelength (λ) is defined by

$$\lambda = \Lambda(neff_{01} - neff_{02}) \tag{1}$$

where Λ represents the grating period, $neff_{01}$ is the effective index of the LP01 mode and $neff_{02}$ is the one of the LP02 mode.

The coupling coefficient (Ω) depends on the modulation amplitude and $\acute{\eta}(V)$ the mode covering factor between the fundamental mode and LP02:

$$\Omega = \frac{\pi \Delta n}{\lambda} \eta(V). \tag{2}$$

At resonance wavelength the fundamental mode power can be express as

$$P = \cos^2(\Omega L). \tag{3}$$

The testing protocol included following steps:

a. calibration of the LPG in a temperature controlled oven to evaluate the temperature sensitivity prior to irradiation;
b. on-line measurements of the grating characteristics (attenuation and wavelength depth versus total irradiation dose) at fixed dose rate;
c. post irradiation estimation of the thermal annealing at room temperature;
d. post irradiation measurements on temperature sensitivity.

Steps a, c, and d of the investigations were run by the team at the National Institute for Laser, Plasma and Radiation Physics, Măgurele, in the laboratory of Laser Metrology, while the irradiations were done at the IRASM irradiator of the “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Măgurele. The Irradiator (http://www.nipne.ro/facilities/facilities/irasm.php) includes a SVST Co-60/B type gamma source (Institute of Isotopes Co. Ltd. Budapest), class IV (source storage in a pool, automatic transport system)and has the declared characteristics; source type—CoS-43 HH (pencil shape), identical model with C 188; source rack—rectangular, split in 4 modules; rack numbers: 3; pencil number in a module: 33; total pencil number: 396; source hoist mechanism—pneumatic; source comes back—gravitational; pool—stainless steel, 6 m high; biological shield (both water and concrete)—calculated for 2 MCi. For dose measurements, an Alanine-EPR dosimetry system was used by placing the dose monitor close to the LPG subjected to irradiation.

For the Laboratory measurements two setups were used, one based on an optical spectrum analyzer (OSA) and the other one employing a optical frequency domain reflectometer (OFDR). The first approach is presented in Fig. 2. The LPG is inserted between an ANDO AQ6317C OSA and a broad band very stable light source (ANDO AQ-4303B) or the OSA built-in LED. For the second setup the Luna Technologies 4600 optical backscatter reflectometer was used. The LPG was connected to the instrument by interposing a circulator. The on-line measurements of the LPG's characteristics were performed with the OFDR. In Fig. 3 is illustrated the measuring setup used in connection with LPG calibration against temperature, for the estimation of its temperature sensitivity, done with the Luna instrument.

The setup used for the on-line irradiation tests is shown in Fig. 4. The LPG was enclosed into a thermally insulating box formed by two polystyrene separated by a mineral wool layer

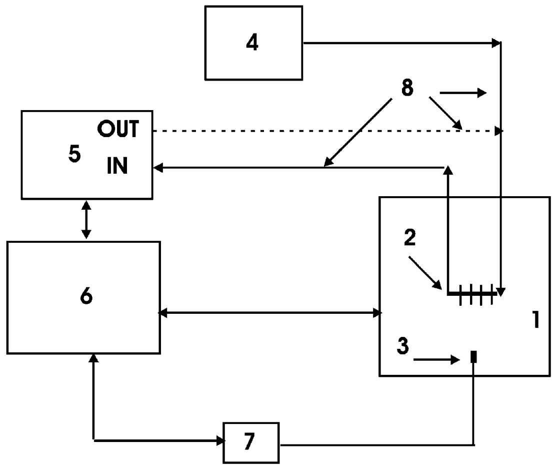


Fig. 2. The setup for the measurement of the LPG using the OSA: 1—temperature controlled oven; 2—LPG; 3—thermocouple; 4—wide band white light source; 5—ANDO OSA; 6—laptop; 7—thermocouple-based temperature data logger; 8—connecting optical fibers.

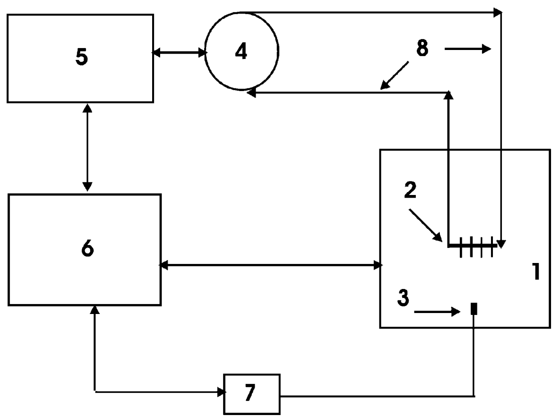


Fig. 3. The setup for the measurement of the LPG using the OFDR: 1—temperature controlled oven; 2—LPG; 3—thermocouple; 4—optical fiber circulator; 5—OFDR; 6—laptop; 7—thermocouple-based temperature data logger; 8—connecting optical fibers.

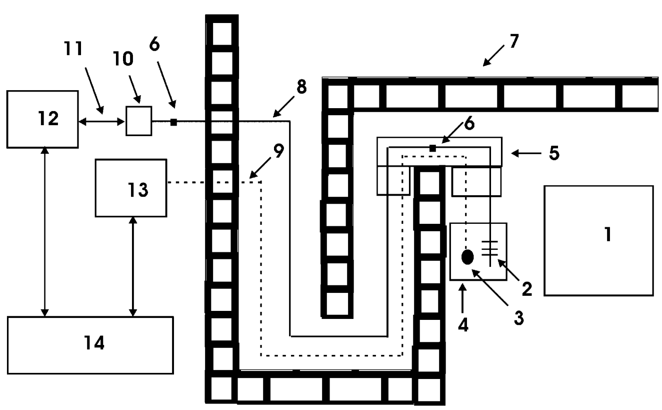


Fig. 4. The localization of the LPG to be irradiated in the irradiation facility and the measuring setup: 1 – ^{60}Co gamma source; 2—LPG to be irradiated; 3—thermocouple; 4—thermally insulated box; 5—lead shield; 6—optical fiber connector; 7—irradiation facility shield; 8—connecting optical fibers; 9—thermocouples connecting wires; 10—circulator; 11—connecting optical fiber; 12—OFDR; 13—NI temperature data logger; 14—laptop.

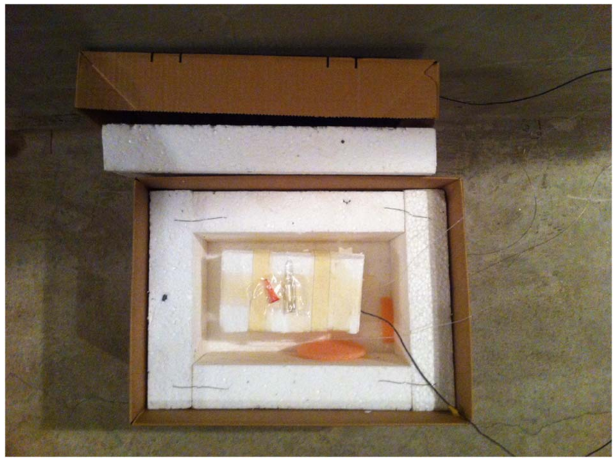


Fig. 5. The insulating box carrying the LPG during gamma irradiation.

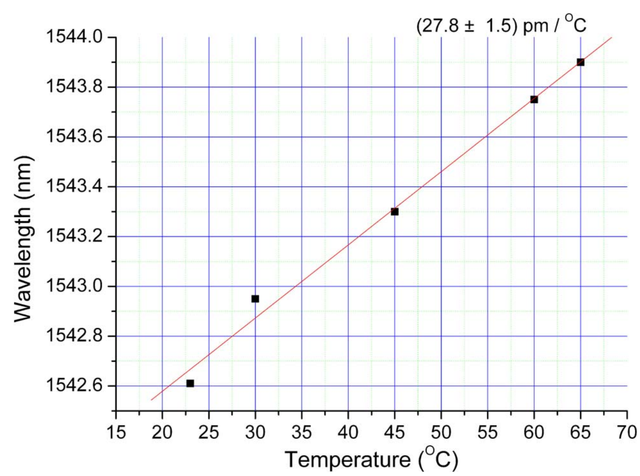


Fig. 6. The calibration of the LPG in relation to the temperature change before the irradiation.

(see Fig. 5). In any case, during the irradiation process both the temperature in the irradiation chamber and that inside the box containing the LPG were monitored by two thermocouples. Temperature is acquired continuously, while LPG data are read three times/day, excepting weekend when no access to the irradiation facility is permitted.

Data for the thermocouples were collected with the NI-cRIO-9211 temperature data logger by USB connection, at 10 min intervals. These data were further used for temperature corrections applied to the spectra acquired from the LPG. In the mean time, the temperature motoring was used to assess the duration of the irradiation pauses done for technical reasons.

In previous reports, the spectral characteristics of LPGs are assessed ether with an OSA [7], [9], [13], [27] or with an interrogator [26]. For our first tests were run with the setup depicted in Fig. 2. The light source was either a very stable broad spectrum incandescent lamp or the OSA own LED. We tested the LPG by heating and cooling cycles in order to evaluate the reproducibility of our setup and to compute the sensitivity of the grating (Fig. 6). The heating was done in a temperature controlled oven, from room temperature to 65 °C, with 0.1 °C uncertainty. The upper limit was imposed by the grating coating, i.e., acrylate. After each heating operation the sample was cooled by natural convection to room temperature. During the entire operation the temperature in the oven, near the LPG location, was monitored by the thermocouple and the NI data logger. The temperature sensitivity of the grating derived from our measurements was

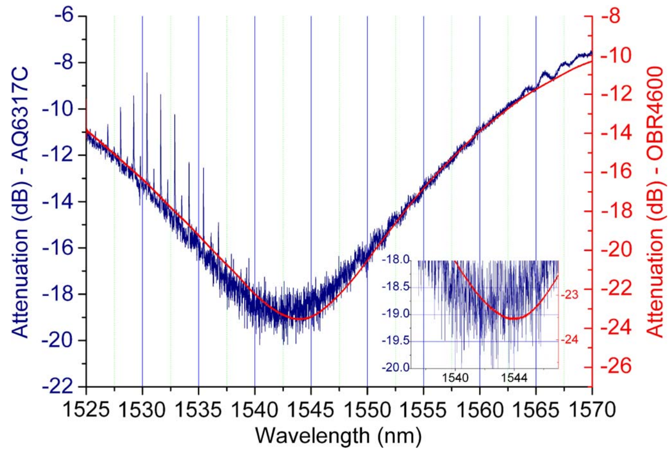


Fig. 7. The spectral response of the LPG as detected by AQ6317C OSA and OBR 4600 OFDR.

before irradiation 27.7 pm/°C, which is a value comparable to those reported in literature [1]. A sample of the spectral behavior of the LPG is given in Fig. 7, as it was measured with the OSA and the OFDR.

In order to improve the repeatability of the measurements, the spectral resolution and the S/N at detection, we try *for the first time* according to our knowledge, to run the spectral measurements on the LPG using an Optical Frequency Domain Reflectometer (the LUNA 4600 unit). In this setup the LPG was connected between two arms of an optical fiber circulator the other connection being coupled to the OFDR (Fig. 3). The instrument was operated in the frequency mode. As compared to the data acquired with the OSA, in this case, a better resolution and S/N can be achieved which make the localization of the wavelength dip much more precise. The wavelength accuracy of the OSA for the spectral range of interest is $+/-0.02$ nm, while the OFDR has a specified accuracy of $+/-1.5$ pm. The accuracy of the signal detection is $+/-0.3$ dB for the OSA, and $+/-0.1$ dB for the OFDR. The OFDR accuracy is guaranteed by its built-in HCN-13-M-25 absorption cell, traceable to NIST.

To secure the spectral measurements of the LPG independent of the temperature variation an insulating box was used and the temperature was monitored during the irradiation process, both inside and outside the box. The thermal insulation was previously tested in the Laboratory by measuring the inside temperature under forced heating and cooling. For a variation by 3 °C of the external temperature the temperature inside the box changes by 0.7 °C.

3. Results

Because no modifications were observed during the first irradiation session at a dose rate of (4.0 ± 0.4) Gy/h, we move the LPG closer to the gamma source, for an equivalent of (0.2 ± 0.01) kGy/h dose rate. The small variation of the central wavelength for the low dose rate is illustrated in Fig. 8. For the higher dose rate, the results are presented in Fig. 9 for the wavelength change as well as the spectra attenuation, for a total dose of (45 ± 0.8) kGy. As an example, arrows (1) and (2) indicate the start, respectively, the stop, of the irradiation during irradiator technological breaks. In Fig. 9 the acquired data are corrected against the temperature change inside the box, even for small variation, by using the temperature sensitivity coefficient derived from laboratory measurements. This graph demonstrates a strong correlation between measured intensity attenuation along the sample and wavelength shift under gamma exposure. For the investigated total dose and dose rate, gamma rays induce both propagation losses and refractive index variation.

On-line measurements enabled us to evaluate the importance of recovery processes. During the irradiation the irradiator was stopped several times either for technical interventions (sessions of ordinary irradiation performed) or during the weekend break (irradiation is not run on

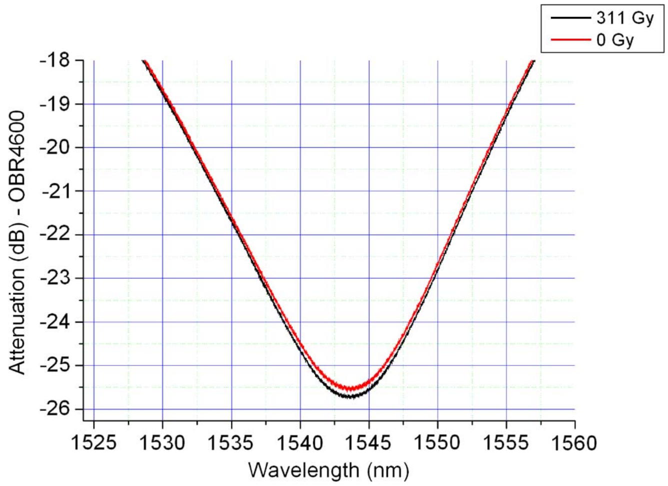


Fig. 8. The change of the LPG wavelength dip at low gamma ray dose rate.

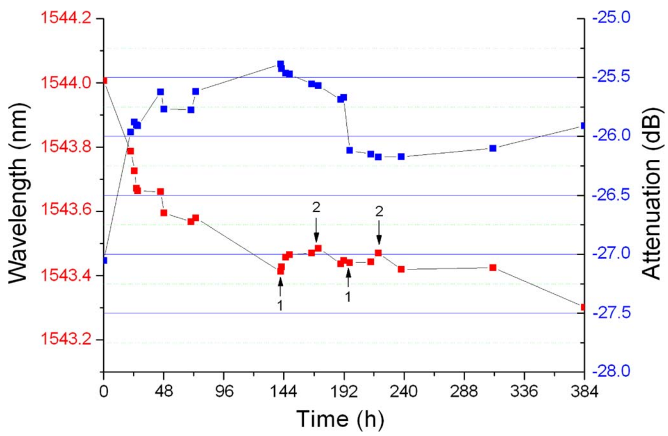


Fig. 9. The change of the wavelength (red) and of the attenuation (blue) at high dose rate gamma exposure. 1—the stop of the irradiation process; 2—the restart of the irradiation process.

Sundays). These irradiation breaks are localized (time and duration) from the temporal variation of the temperature in the technical corridor. Such pauses are also accounted for the calculation of the total irradiation dose. These events are visible on the curves in Fig. 9. They contribute in some extent to the recovery effect or flatness of the curve present in the measured results. From 144 h to 288 h several stops and starts of the irradiation process occurred and the variations in Fig. 9 are the results of the balance between the recovery effects at room temperature and further exposure to gamma-ray. For the entire irradiation (up to 45 kGy total dose) the measured wavelength shift towards shorter wavelengths was 700 pm. The tests indicated an overall radiation sensitivity of the wavelength of about 16 pm/kGy. In the first part of the irradiation process this sensitivity was about 44 pm/kGy, while in the final stage of the irradiation the sensitivity was about 9 pm/kGy, as it was also affected by some irradiation pauses.

Since these gratings are wavelength encoded, independent from intensity, wavelength shift with irradiation can be related to refractive index change. The observed decrease of the resonant wavelength upon the irradiation corresponds to a change in the effective refractive indices $(\mathrm{neff}_{01} - \mathrm{neff}_{02})$ of about 10^{-6} for the LGP pitch of 740 μm, which, if we consider the core of the fiber to be stable, implies an increase in the order of 10^{-6} for the LP02 refractive index.

During the irradiation a degradation of the LPG optical fiber jacket was noticed (see Fig. 10). No degradation of the LPG package was noticed for the total dose used. The influence of

Fig. 10. The degradation of the LPG connecting fiber jacket.

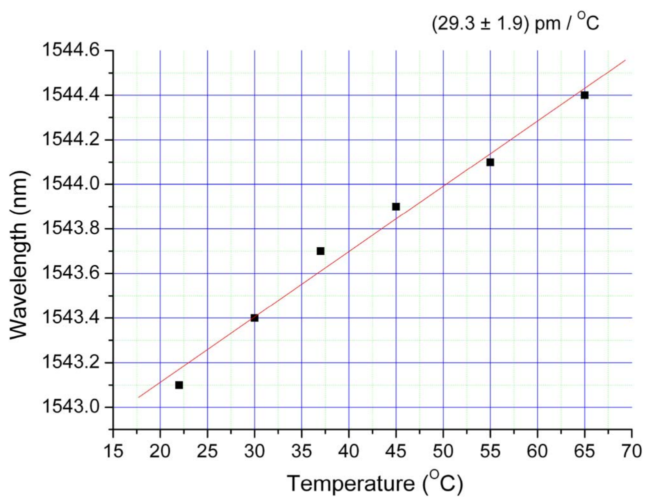


Fig. 11. The change of the LPG wavelength dip with temperature after the irradiation.

external stress on the LPG was assured by the integrity of this gals/ceramic case and by keeping fixed the entire insulating box.

The evaluation of the temperature sensitivity of the grating after gamma irradiation was derived from the graph in Fig. 11.

Post irradiation, we investigated if some recovery occurred at room temperature. We kept the sensor at constant temperature for 120 h and measured the wavelength dip shift (Fig. 12). A recovery effect was noticed, marked in Fig. 12 by "Recovery." The recovery rate was of 6.7 pm/h. This could only be observed thanks to on-line measurements. After 120 hours we started the evaluation of the LPG temperature sensitivity, by cycles of heating to 65 °C and natural cooling to room temperature. From that point on a decrease of the grating wavelength was observed. In Fig. 12 all the values for the wavelength were temperature corrected (i.e. they are represented at the temperature of 22.6 °C).

4. Discussions and Conclusion

A LPG inscribed by fusion technique in a fluorine (F)-doped 8.5 μm core diameter optical fiber was tested at two dose rates for gamma irradiation, through on-line measurements of the spectral characteristics. *For the first time a LPG was monitored with an OFDR.*

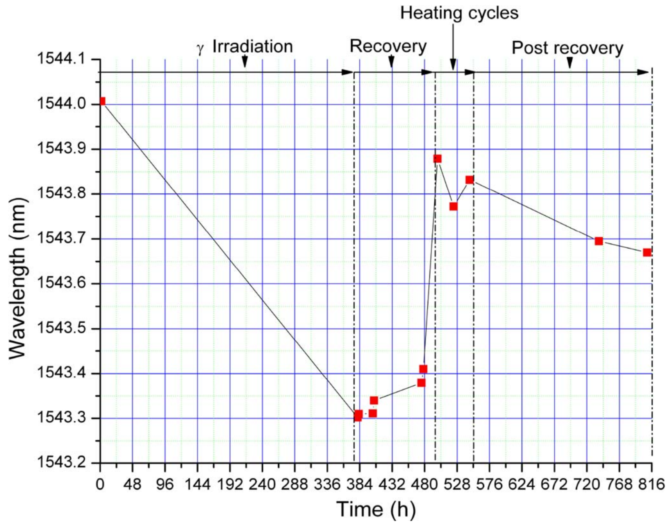


Fig. 12. The post irradiation variation of the wavelength dip shift.

Before the irradiation the temperature sensitivity of the grating was 27.7 pm/°C while the post irradiation value was 29.3 pm/°C, which indicate a moderate radiation dependence of the grating temperature sensitivity for quite high total doses. For low dose rates (4 Gy/h) no significant changes were noticed. At higher dose rates (0.2 kGy/h) the resonant wavelength shift was 700 pm/45 kGy. These results place the investigated LPG between FBGs and chiral type LPGs, as it concerns the radiation sensitivity. In the dose range from 0 to 45 kGy we can consider that such a LPG is more sensitive than other sensors (i.e., Brillouin ones) having a radiation sensitivity of 16 pm/kGy. The recovery of the wavelength change was in the range of 600 pm during 120 h, at room temperature.

We shall focus in the near future on the comparative investigation of LPGs produced in standard SMF28 and radiation hardened optical fibers. By considering the experience acquired during this investigation, an intermediary dose rate will be selected and more readings will be done up to doses of 4–6 kGy in order to better catch the linearly dependence of the wavelength dip shift with the dose. In the mean time, tests have to be carried out to investigate the possibility of multiple re-use of LPGs as radiation sensors. Further investigations (irradiation–pause cycles) can bring more information on the recovery process and its reproducibility. The use of multiple LPGs for distributed monitoring of temperature can be accomplished by coupling at the OFDR output the FOS-036 Fiber Optic Switch offered by the instrument manufacturer.

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