

EXPERIMENTAL CHARACTERIZATION OF THE OPTICAL FIBER SENSORS

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In this work an extensive set of experimental investigations has been performed in order to characterize the optical fiber sensors, based on various types of gratings. The investigation refers to the behavior of different optical fiber sensors response to temperature changes and gamma radiation exposure. All experiments were conducted using multiple sensor types, one of them being used as a reference. Each time, before their use, the optical fibers were carefully cleaned and calibrated against temperature change by using a heating chamber. The samples were subjected to several heating cycles in the range of 20-60 °C.

Keywords: fiber Bragg gratings, gamma radiation, temperature sensors, optical fibers

1. Introduction

The optical fibers can be used as fiber optical sensors for temperature and pressure measurement by modifying the structure of the fiber in such way that the parameter we want to measure will modulate the intensity, phase, polarization, wavelengths or time needed for the light to pass. The technologies based on optical fiber sensors are widely used in applications from bio-medicine and chemistry to Structural Health Monitoring (SHM) for buildings, vehicles, planes, bridges, trains or wind turbines.

Since their introduction, fiber gratings were found their way into widespread application in both, telecommunication and the sensor field. They have been embedded into telecommunication applications for wavelength division multiplexing, allowing an extremely high density of communication channels and terabyte levels of communication over a single fiber. At the same time, researchers in the fiber sensors field were quick to adopt fiber gratings into their systems for usage as strain and temperature sensors. They share common advantages with many fiber optic sensors, relative to electrical sensor technology,

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including high levels of immunity to electromagnetic interference, discreet size, high-temperature operation, and a high degree of resistance at the environmental severity conditions. Fiber gratings also have the advantages of being compatible with multiplexing and distributed sensing capabilities of present interrogating equipments, being in this respect of orders of magnitude superior to electrical sensors [1]. Due to their properties such as: low mass, low dimensions as well as their immunity to electromagnetic interference, the Fiber Bragg Gratings (FBGs) are incorporated in various applications: in space born systems, satellite to earth station telecommunication system.

A FBG is a perturbation in the refractive index along the length of the optical fiber, which is manufactured by exposure of the core fiber to an interference pattern. They are widely used [2, and references herein] in many optical systems as band filters, dispersion compensators, in- fibre sensors or fibre grating lasers and amplifiers.

This modulation is along the fiber axis, creating periodic structures of refractive index change, δn . A lot of techniques to increase fiber photosensitivity have been reported. The theory behind is that periodically modified refractive index modifies the phase or the intensity of a wave reflected on, or transmitted through, it. The condition to be reflected is that its wavelength equals Bragg resonance wavelength, λ_{Bragg} , in the other cases being transmitted. If the grating period, Λ , and the refractive index change, δn , are constant over whole length of grating, then the fiber is uniform:

$$\lambda_{\text{Bragg}} = 2n_{\text{eff}} \Lambda \quad (1)$$

Two important characteristics define Bragg sensors applications domain: *their sensitivity* to temperature and pressure/mechanical stress, both being affected by the type of the optical fiber, and *their performance* under external changes. Some previous investigations [3-5] highlighted some optical fiber gratings sensitivity under radiation exposure.

The variation of the refractive index or of the grating pitch with subsequent change in the Bragg wavelength occurs when physical influences (like strain or temperature) appears on the optical fibre. Due to their characteristics fiber optic sensors are good candidates for temperature / strain measurement in a various number of industries from transportation, energy, medical to telecom or civil and geotechnical applications. Being immune to electromagnetic fields, having light weight and good sensitivity, fiber sensors have the possibility of being multiplexed and have the advantage to transmit online information from hazardous environments where classical solutions are not an option.

When FBGs are used as radiation sensors the most obvious and best-known effect is an increase of fibre attenuation. Also the spectral shift of the central wavelength can be used to calculate the corresponding refractive index changes.

In the present work we investigate the changes in sensitivity and reproducibility of the Long Period Grating (LPG) and FBGs sensors signal after their exposure to gamma radiation. Measurements have been performed on-line, monitoring the maximum value of gratings' wavelength shift during the irradiation procedure. The radiation exposure has been performed in several steps. The response of the irradiated fiber sensors have been recorded, and analysed, in order to decide if they might be used as radiation sensors, accounting for their wavelength shift, the signal to noise ratio and the full transmission spectrum. Finally, the data collected over a series of experiments are to be compared with those recorded before gamma irradiation, in order to test the fiber sensors history, i.e. they will recover after exposure to gamma radiation, or the effect is permanent.

The paper is structured as follows. Section 2 gives details on the experimental setups and results. The present work entails two distinct activities: *Experiments* consisting in a) sensor calibration under temperature stress, and b) sensor submission to gamma radiation. These procedures cover: manipulate the fiber, decide on the experimental set-up, make the necessary online connections with the hardware and special equipment used for measurements, check the fiber with an electronic microscope before manipulating to avoid macroscopic defects that could affect the experiment, cleaning connectors according to the standard recommended usage. The second part of our study represents *the interpretation* of resulting Bragg Peak Shift and overall recorded spectrum. The experiments were conducted in order to complement with additional information of the existing reported investigation [6, 7] on the specific properties of optical fibers. We have evaluated the change in the temperature sensitivity as well as the reproducibility of temperature measurements using the Bragg sensors. The sensors were subjected to a controlled temperature stress, from room temperature up to 85 °C, while the cooling process was reached under natural convection. Section 3 presents our concluding remarks and further directions of research.

2. Experimental method and results

In order to investigate the permanent, or temporal, effects that could appear during the irradiation phase, we have used, during the calibration procedure, in parallel with the sensor subjected to be irradiated, other sensor used

as reference. Irradiation with different dose rates was made at a ^{60}Co γ -source by varying the distance between the source and the optical fibers.

The experimental spectra have been analyzed with respect to the changes in the full width at half maximum (FWHM), in the distance from the nearest lateral lobe, the signal to noise (S/N) ratio, and the amplitude of main lobe.

The optical fiber sensors spectra have been characterized on-line, in transmission or reflection, during irradiation or heating. The spectra were recorded using the SM125 Optical Sensing Interrogator from Micron Optics, that operates very stably (based on Fabry-Perrot interferometer) and an optical backscatter reflectometer model OBR4600 fabricated by Luna Inc., achieving very high wavelength resolution.

Before and after the irradiation, the characteristics of both, the test sensor and the reference sensor, were simultaneously recorded in the laboratory. The calibration procedure of the optical fiber sensors aims to: *a*) study their parameters at constant temperature; the Bragg sensors parameters are stored in databases which contain also, the recorded Bragg peak shift, the fiber attenuation and/or the full transmitted spectrum. The entire recording procedure is done at every second or at user' selected intervals. The measurements have been performed in the presence of a thermocouple in order to compare, in real time, the temperature values as given by sensor and thermocouple itself; *b*) study the parameters during the heating - cooling cycles. The purpose of this type of evaluation is to check the *fidelity* of Bragg sensors as temperature sensors, i.e. to investigate the stress impact on the sensor sensitivity. These measurements have also been done in the presence of a thermocouple of high sensitivity (under 0.1 $^{\circ}\text{C}$). For a Bragg sensor to be temperature sensor, its overall wavelength characteristics should be proportional to the temperature characteristics indicated by thermocouple.

In order to evaluate correctly sensor response to temperature, mechanical stress, or nuclear radiation dose, several experimental setups have been used, involving Micron Optics optical interrogator, a optical spectrum analyzer ANDO AQ6317C and LUNA Optical Backscatter Reflectometer OBR4600. Depending on the used instrument operating principle, the sensors response was investigated in reflection and transmission. In Fig.1 we show, as an example, the transmission and attenuation spectrum as output of different interrogating methods. In this case the sensors under test are Draw Tower Gratings Fiber (DTG) sensors.

Experimental characterization of the optical fiber sensors

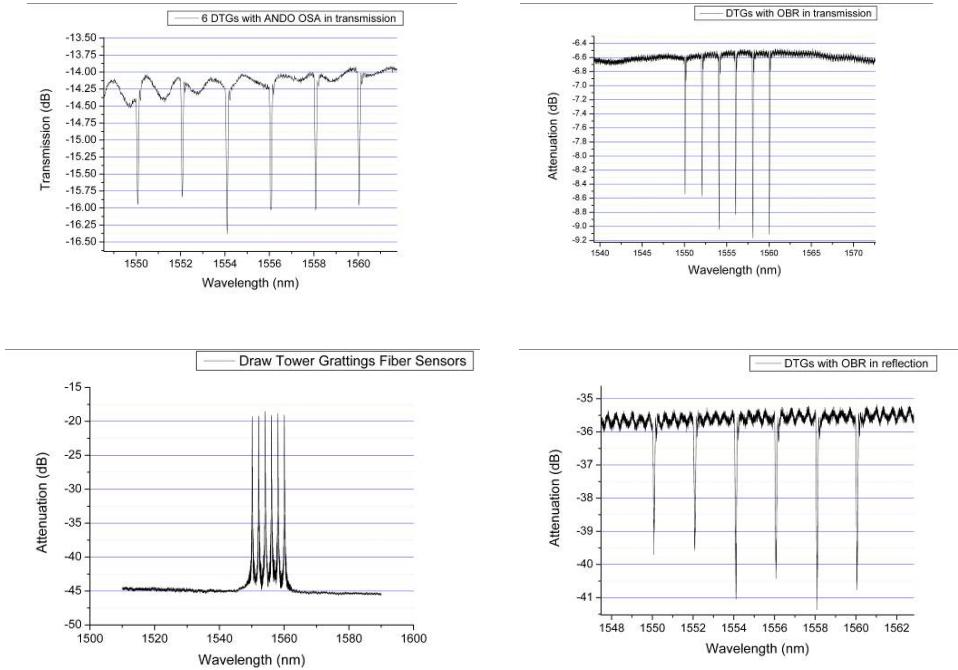


Fig.1 Setup consisting of six sensors written during the drawing process of the fiber interrogated with a) ANDO AQ6317C OSA in transmission mode b) LUNA OBR4600 c) Micron Optics SM125 in reflection mode d) LUNA OBR4600 in reflection mode

The sensors sensitivity with temperature is one of the factors that are taken into consideration when studying the permanent or temporal radiation effects over the fibers or sensors itself. It has been shown that the radiation induced effects can bring changes in sensors central wavelengths shift with temperature. Calibration of sensors under tests is made both before and after subjecting them to radiation experiment, such tests being presented in fig.2.

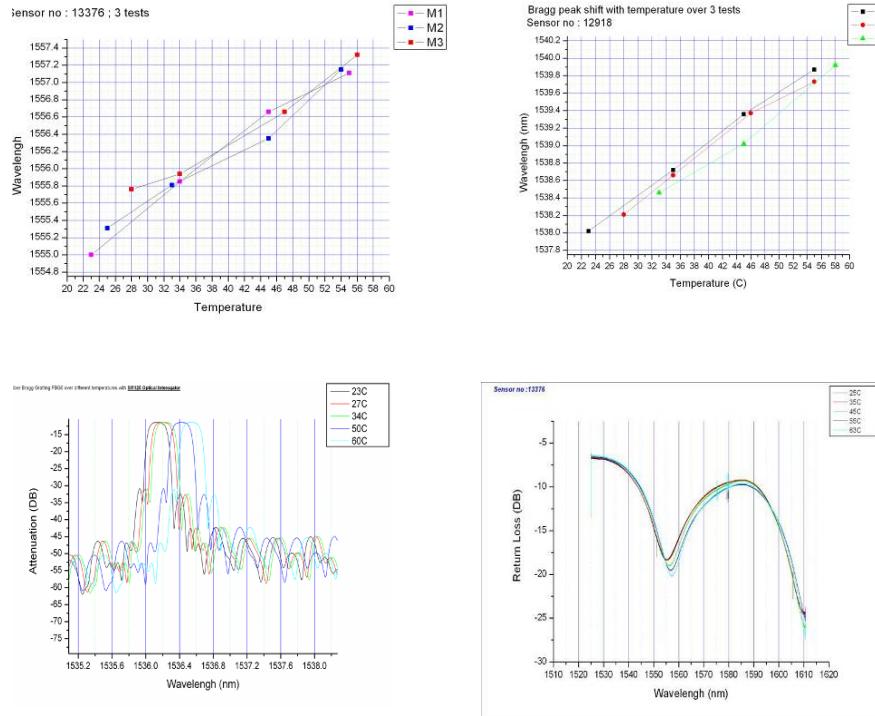


Fig 2. Calibration tests of long period gratings and fiber Bragg gratings with two different equipments. a) SM125 optical spectrum interrogator and b) LUNA OBR4600

By comparing the interrogation techniques we eliminate any possible errors induced by the equipments or optical connections between them and the devices under test. In the above results it has been shown that the gratings center wavelengths shift is about 0.029 nm per 1 °C, results calculated first with the interrogator then confirmed with the OBR. Differences between optical interrogating techniques show different advantages depending on the application. As the OBR shows an improved spectral resolution as compared to the SM125, but the time needed for scanning the setup is considerable greater, which can create an issue for some experiments conducted on-line. The time needed for the sensor to respond is of great importance in describing the phenomena. Also one of the great advantages of the SM125 is proven to be the automatic peak detection of the central wavelengths of the gratings. The OBR can give us enhanced spectral resolution but the recorded data is discreet. One might prefer the techniques involving a fast optical interrogator as the first effects of the irradiation experiments can be noticed in a matter of seconds.

Also there is to be found a great difference in spectral resolution obtained by comparing the ANDO AQ6317C spectrum analyzer and the OBR4600 as shown in Fig 3. The difference here is that with the help of the OSA we can analyze a wider spectral range giving us the opportunity to focus on the lateral lobes.

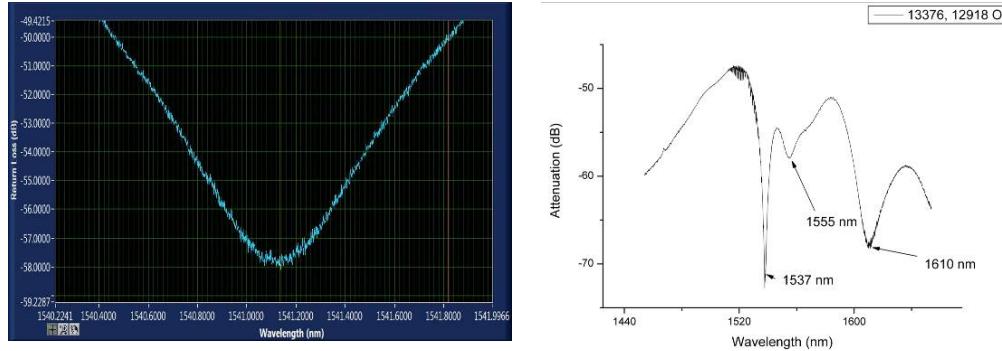


Fig 3. Setup tested with LUNA OBR 4600 and ANDO AQ6317C. As the different spectral resolution is well visible, the wider range of the OSA proves useful in the study of side-lobes

Furthermore, using different interrogation techniques helped us to study and to prove the use of a fiber optical sensing setup consisting of two long period gratings (LPG), a reference FBG sensor, and a reference draw tower grating (DTG). This setup was subjected to gamma irradiation up to 43 kGy, and up to 34 kGy total dose. The sensors have been analysed with an SM125 Micron Optics interrogator and with OBR4600 LUNA. These experiments were run during more than 500 hours of irradiation, with a few months between the two stages in order to evaluate sensors recovery.

After comparing techniques, all the results have showed and have validated the fact that the LPG sensor is extremely sensitive to gamma-ray irradiation, and that this sensor is a good candidate for dose-meter system component up to the total doses of 7 kGy. The experiment with the OBR showed detailed information regarding the transmission spectra while the optical interrogator SM125 measurements proved that sensors have quick response but also quick recovery when irradiation was stopped.

We present in Fig. 4 results from two stages of gamma irradiation. The first refers to two long period grating sensors, one FBG sensor and one DTG sensor. In the second (right side of the figure) we show the results obtained for same LPG sensor over the second irradiation experiment when the SM 125 was used instead of LUNA OBR over the recovery period of time.

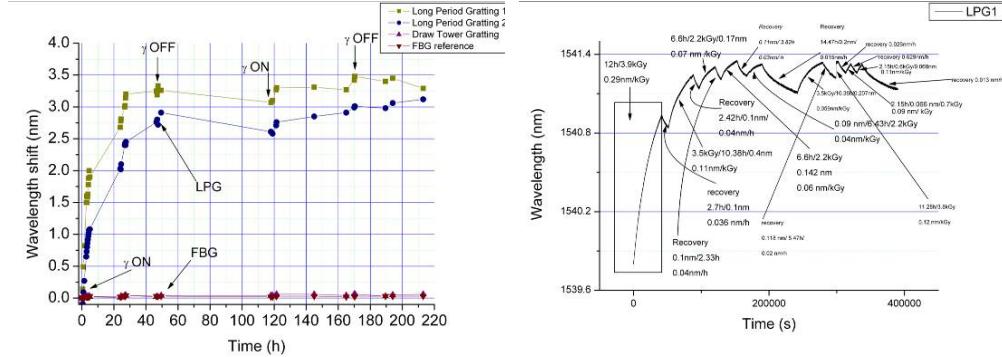


Fig. 4. The two stages of gamma irradiation of the setup : a) (left) two LPGs , one FBG and DTG irradiated up to 43 kGy and interrogated with OBR LUNA b) (right) The same LPG responded while being irradiated up to 35 kGy clearly showing recovery elements due to the time resolution of the SM125 Optical Interrogator.

Comparing the two measurement techniques it has been noticed that while FBG and DTG sensors are good candidates for temperature reference as the irradiation does not affect them, the LPG proves a very high sensitivity to gamma-ray within a range of 3.5 nm central wavelengths shift. It has been proven that a saturation level occurs and it can be concluded that the sensors sensitivity with radiation is depending on that value given by saturation as shown in fig 5.

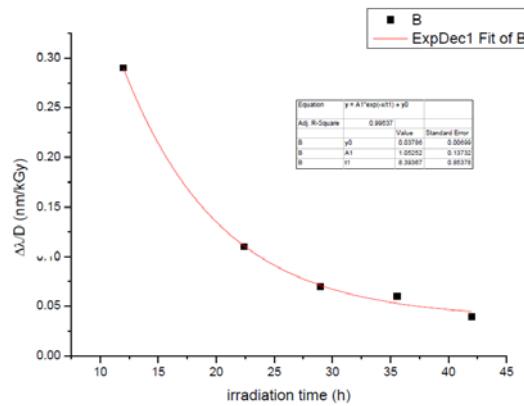


Fig 5. LPGs sensitivity to radiation dose as function of saturation level as a property of the LPG

3. Conclusions

The present work enhances the possibility of using different setups for monitoring optical fiber sensors depending of application. It was considered, as an example, the on-line irradiation with gamma-ray of a setup consisting of different types of optical sensors and interrogated as a daisy-chain. From our knowledge it is the first time when a setup consisting of different type of sensors is studied repeatedly up to total dose of more than 70 kGy in two different irradiation stages, first up to 43 kGy then up to 35 kGy. Given the several methods used for investigation we validated the sensitivity of the LPG sensor. The FBG reference sensor was used to compensate with temperature. Differences between the setups consist in temporal and spectral resolution but also in the case of ANDO AQ6317C optical spectrum analyzer in the wavelength range that can be covered by the equipment. While the LPG can be used for measuring on-line the dose, its sensitivity depends on the saturation level given by the relative central wavelength shift, and also on the total dose absorbed.

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R E F E R E N C E S

- [1] Fiber Optic Sensors – An introduction for engineers and scientists, Eric Udd, 2011, John Wiley & Sons.
- [2] *K.O. Hill, G. Meltz.*, Fiber Bragg grating technology fundamentals and overview, *J. Lightwave Techn.*, **15**, 1263 – 1276 (1997).
- [3] *A. Gusarov, S.K. Hoeffgen*, Radiation effects on fiber gratings, *IEEE Trans. Nucl. Sci.*, **Vol. 60**, 2037 – 2053 (2013).
- [4] *S.A. Vasiliev, E.M. Dianov, K.M. Golant, O.I. Medvedkov, A.L. Tomashuk, V.I. Karpov, M.V. Grekov, A.S. Kurkov, B. Leconte and P. Niay*, Performance of Bragg and long period gratings written in N- and Ge-doped silica fibers under γ -radiation, *IEEE Trans. Nucl. Sci.* **45**, 1580 – 1583 (1998).
- [5] *H. Henschel, S.K. Hoeffgen, J. Kuhnhenn, U. Weinand*, High radiation sensitivity of chiral long period gratings, *IEEE Trans. Nucl. Sci.*, **Vol 57**, 2915 – 2922 (2010).

- [6] *D. Sporea, A. Stancalie, D. Negut, G. Pilorget, S. Delepine-Lesoille, L. Lablonde*, On-line tests of an optical fiber long-period grating subjected to gamma irradiation, IEEE Photonics J. **Vol. 6** 1943-0655, doi: 10.1109/JPHOT.2014.2337877(2014).
- [7] *D. Sporea, A. Stancalie, D. Negut, G. Pilorget, S. Delepine-Lesoille, L. Lablonde*, Comparative study of long period and fiber Bragg gratings under gamma irradiation, Sensors and Actuators A, <http://dx.doi.org/doi:10.1016/j.sna.2015.07.007>(2015).