Preliminary investigation of radiation dose sensors based on aluminum-doped silicate optical fibers

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***Abstract*—The paper reports on the first demonstration of in-situ, real-time dosimetry realized with an enhanced back-scattering optical fiber and a high-resolution optical back-scattering reflectometry measurement. This work is devised to overcome the current problems in monitoring radiotherapy treatments, in particular the difficult evaluation of not only the actual x-ray dose that is accumulated on the target volume, but also the distribution profile of the ionizing radiation beam. The experiments have been conducted by evaluating the radiation-induced spectral shift of the Rayleigh back-scattering along the fiber under test during x-ray exposure, in a radiation chamber. The sensing region is a section of aluminum-doped silicate fiber, that overcomes the poor sensitivity to radiation of standard, germanium-doped, silicate fibers for telecom applications. The preliminary results show that it is possible to remotely track the x-ray dose at high dose rates (700 Gy/min) and at rates closer to therapeutic values (22 Gy/min). A linear relationship between accumulated dose and spectral shift has been found. This research aims at developing a dose sensor with the most demanding features of small form factor, spatial profiling and remote interrogation.**

***Index Terms*—Optical fiber sensors, Radiation monitoring, Radiation dosage, Ionizing radiation sensors**

I. Introduction

Ionizing radiations find many medical applications, going from diagnostic, such as in Computed Tomography (CT), to therapeutics, such as in tumor radiotherapy. These two fields are characterized by quite different dose levels, practically at the opposite of the scale: extremely low doses for imaging to investigate tissues without producing damages and relatively high doses for radiotherapy to kill cancer cells or slows their growth by damaging their DNA. In both cases, however, modern medical protocols require accurate monitoring of the dose at which the patient is exposed. While this can be straightforward to understand for the high-doses used in therapeutic applications, it has to be considered that also the low doses used in imaging equipment can be harmful if, for some reason, the instrument is not working properly. For instance, the literature reports cases of patients who have filed lawsuits for having suffered burns from extreme over-exposures during CT exams, due to improper settings on CT scanners.

Ionizing radiations can be measured using a number of instruments, the most common being personal dosimeters in the form of film badges worn on clothing, which measure the cumulative radiation dose a person receives while exposed to radiation sources. More quantitative evaluations can be made with hand-held detectors, such as Geiger-Müller counters and ionization chambers, which are used to measure the exposure rate from a source (for example, emissions from radioactive wastes). In medical applications, however, it is interesting not only to measure the total dose at which the patient is exposed, but also the spatial distribution of the radiation in the target volume. Unfortunately, the latter measurement is difficult to implement in real time before and during the treatment. Indeed, the previously mentioned radiation monitoring instruments cannot be used because they measure the amount of radiation on a quite large area and thus are not easy to be multiplexed to recover the radiation distribution, not to mention the poor resolution achievable in that case. The most common technique to evaluate the intensity distribution is to use GafChromic (GaF) films. These films contain a special dye that polymerizes upon exposure to radiation, with a subsequent increase in its absorption at optical frequencies; that is, the optical density (OD) of the film increases with the dose [1], turning it more opaque (Fig. 1).

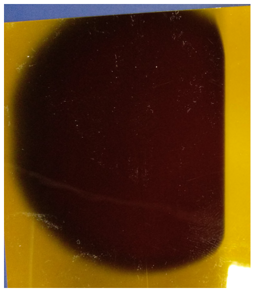

Fig. 1. GaF film exposed at 700 Gy/min. The spot size is about 2 cm.

Another alternative proposed in the literature exploits gel-based nano-sensors in which exposure to ionizing radiation results in the conversion of gold ions to nanoparticles, with subsequent visual change in color due to their plasmonic properties [2]. Both approaches, however, cannot be used for real-time continuous measurements [3].

Optical fibers can constitute an attractive alternative technology for the realization of a new class of ionizing radiation sensors thanks to a number of unique features, among which: i) they are minimally invasive; ii) can be remotely interrogated; iii) do not involve electrical currents (a plus feature in medical applications as it intrinsically avoids electrocution). Standard optical fibers for telecom applications are made by ultra-pure silica, with some dopants added to slightly increase the refractive index in the core region (usually, Germanium or Phosphorus), and exhibit little sensitivity to ionizing radiations; however, it is know from literature that this low sensitivity can be enhanced by co-doping with Aluminum.

The sensitivity of fibers to radiation typically manifests in the form of Radiation Induced Attenuation (RIA), for which the propagation loss of an irradiated fiber is higher than that of the pristine fiber. This is a local effect, so the loss increase against the fiber length is proportional to the cumulative radiation along the fiber. In other words, this effect can be exploited to evaluate the radiation intensity profile by measuring the loss spatial distribution along the fiber, a kind of measurement that in telecom applications is performed with an Optical Time Domain Reflectometer (OTDR). In OTDR a light pulse of known width is transmitted through the fiber and the reflected power and the time of flight are measured to determine the magnitude and location of the perturbations along the fiber. An application of OTDR for long-range gamma-ray detection has been presented in [4]. Furthermore, the OTDR technique has been used to qualify the RIA of different optical fibers, by exposing samples of lengths about $10\,\mathrm{m}$ [5]. However, besides for having a dead zone (i.e., an initial length in which the interrogator is blind) in the order of meters, OTDRs are non suitable for radiotherapy dosimetry applications for the poor resolution, in terms of both loss and position, especially considering that for this application the radiation intensity (and thus the loss variation) is expected to be small and the dose profile should ideally be measured with sub-cm resolution. Therefore, another radiation-dependent feature must be investigated; in particular, the Rayleigh back-scattering can be measured with high accuracy by Optical Frequency Domain Reflectometry (OFDR). OFDR instruments relies on a swept wavelength laser coupled into an interferometer. One leg of the interferometer is a reference path of fixed length, while the other leg is the optical fiber under test. The backscattered light is combined with light from the reference arm generating an interference signal that contains information related to the precise location and magnitude of reflective events along the fiber length. OFDR is able to measure the precise location of very small reflective events with no dead zone.

In this work, an enhanced backscattering Aluminum-doped optical fiber was exposed to x-rays while its Rayleigh scattering was recorded using an OFDR. Then the Rayleigh scattering signature was processed in real time to calculate a spectral shift parameter that could be correlated to the dose, through a linear relationship. The radiation induced attenuation was also measured to prove its weak effect and the need of advanced measurement techniques for the evaluation of the radiation profile. The novelty of this research relies both in exploiting a radiation-sensitive custom-made optical fiber and in investigating the spectral shift of the Rayleigh backscattering rather than measuring the RIA, by exploiting a high resolution OFDR interrogation. This work is expected to pave the way to the development of novel distributed dosimeters based on optical fibers.

II. Measurement Setup

The experimental setup is shown in Fig. 2. The interrogation unit is an Optical Backscatter Reflectometer (OBR) Luna OBR4600 [6]. The OBR is a swept-laser interferometer that implements an optical frequency-domain reflectometry principle. The system is capable of sensing Rayleigh scattering signatures along the fiber under test, with a nominal spatial resolution of $\sim 9.6\,\mu\mathrm{m}$, operating on a $88\,\mathrm{nm}$ wavelength grid centered around the infrared C-band ($1550\,\mathrm{nm}$) [7], [8]. The fiber to be tested as a dosimeter is positioned in a shielded radiation chamber, under a x-ray beam, and connected to the OBR through a lead-in fiber of length about $4.5\,\mathrm{m}$. The x-ray generator (INEL model XRG3D) is based on a tube containing a Cu target with an accelerating voltage of $30\,\mathrm{kV}$. The cone-like x-ray emission, produced in air and at room temperature, is controlled by adjusting the supplied electrical current and the distance between the generator and the fiber under test. The beam was calibrated, in terms of dose rate, by means of a flat ionization chamber (PTW model 23342) and a high precision/high resolution electrometer (PTW model UNIdos E). Two different irradiation conditions were considered: i) a very high dose by positioning the fiber $2.6\,\mathrm{cm}$ from the source window, leading to a dose rate of $710\,\mathrm{Gy/min}$; ii) a medium-high dose obtained by moving the fiber down to $29.5\,\mathrm{cm}$ from the source window, corresponding to a lower dose rate of about $22\,\mathrm{Gy/min}$.

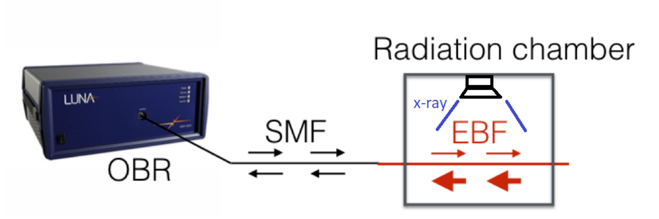

Fig. 2. Schematic representation of the measurement setup.OBR=Optical Backscattering Reflectometer. SMF=Single Mode Fiber. EBF=Enhanced Back-scattering Fiber. The arrows represent the optical signals propagating through the fibers.

The lead-in fiber is a standard Single-Mode Fiber (SMF), while the sensing section is an alumino-silicate fiber that exhibits enhanced back-scattering (EBF). Its fabrication process is detailed in several publications, such as in Ref. [9], [10]; it consists of a preform fabrication by a standard Modified Chemical Vapor Deposition (MCVD) technique followed by fiber drawing. The preform used is a silicate one containing approximately 2 wt % of Aluminum. The preform is pulled into a drawing tower to produce an optical fiber with core/cladding diameter of $10/125\,\mu\mathrm{m}$, respectively. SMF and EBF fibers are spliced with a standard fusion splicer, as they have matching core/cladding sizes and similar effective refractive index.

III. Experimental Results

The effects of exposure to x-rays was evaluated in terms of the spectral shift versus longitudinal position along the EBR fiber. In order to qualitatively understand the rationale of spectral shift, one can consider the exposed fiber as a cascade of densely spaced weak fiber Bragg gratings (FBGs) [11]. These back-scatter a portion of the signal provided by the swept laser of the OBR, thus producing a reference signature of that fiber (the Rayleigh-scattering signature). Any change of refractive index or pitch of each grating will produce a spectral shift of its Bragg reflection peak and the collection of these shifts represents the spectral shift curve with respect to the fiber signature. The procedure to measure the spectral shift along the fiber is then performed in a two-steps process: the reference signature is acquired in steady conditions and then Rayleigh back-scattering spectra are subsequently recorded and cross correlated to the reference to retrieve the spectral shift (these operations are performed by the OBR instrument). The fiber under exposure was fastened and kept at constant temperature, so that the spectral shift could only be ascribed to the effect of radiation. The OBR was computer-controlled through a custom developed program that recorded the spectral shift every $30\,\mathrm{s}$, providing real-time monitoring. The spatial resolution was set to $5\,\mathrm{mm}$.

As a preliminary test, a high dose rate of $700\,\mathrm{Gy/min}$ was used; the resulting spectral shift is reported in Fig. 3. The graph demonstrates that the considered fiber is sensitive to high doses because there is clearly a strong modification of the spectral shift exactly where the x-ray exposure occurred. Moreover, the full width half minimum (FWHM) of the dip is about $2\,\mathrm{cm}$, in good agreement with a comparative measure performed by GaF films.

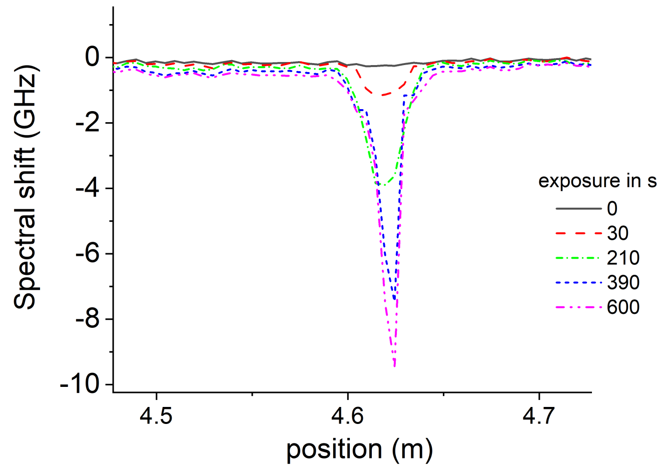

Fig. 3. Spectral shift versus position along the fiber for different times of exposure at $700\,\mathrm{Gy/min}$. The spatial resolution of the data is $5\,\mathrm{mm}$.

A negative spectral shift is induced, producing a dip that deepens as the energy is deposited on the fiber. Once the x-ray beam is turned off, a partial recovery of the spectral shift is observed, indicating a possible reversible process. The dynamics of the dip at the position $4.62\,\mathrm{m}$, observable in Fig. 4, is well approximated by a linear dependence on the dose.

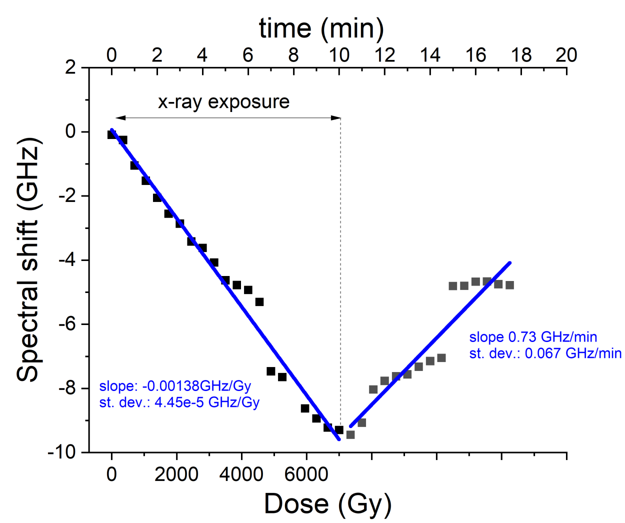

Fig. 4. Spectral shift versus exposure time and corresponding dose.

In order to make a quantitative comparison of the sensitivity of the EBR fiber with a standard SMF, the same experiment at the high dose rate of $700\,\mathrm{Gy/min}$ was repeated exposing an SMF pigtail (G652 compatible fiber). The SMF exhibited, as expected, a much smaller, yet still detectable, spectral shift (Fig. 5) located at the exposed section.

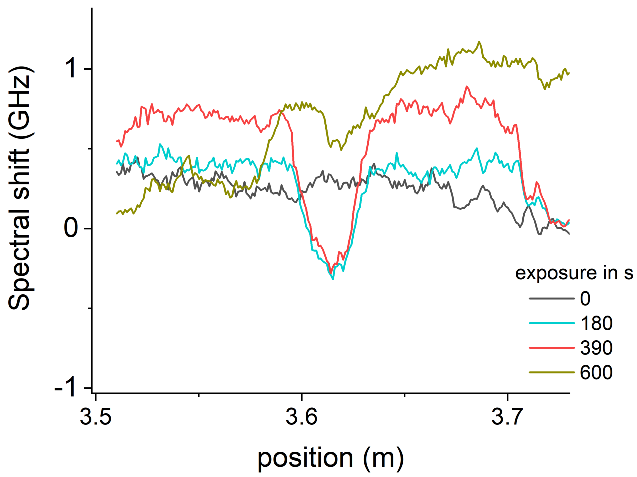

Fig. 5. Spectral shift versus position for a standard SMF (G652 compliant fiber) exposed at 700 Gy/min.

The final spectral shift for a cumulative dose of 5200 Gy was about 0.3 GHz and did not show any further change with time. Fig. 6 reports the spectral shift evolution versus time and corresponding dose. The graph axes are set on the same scales as Fig. 4 to make a straightforward comparison and highlight the different sensitivities of EBR and SMF fibers.

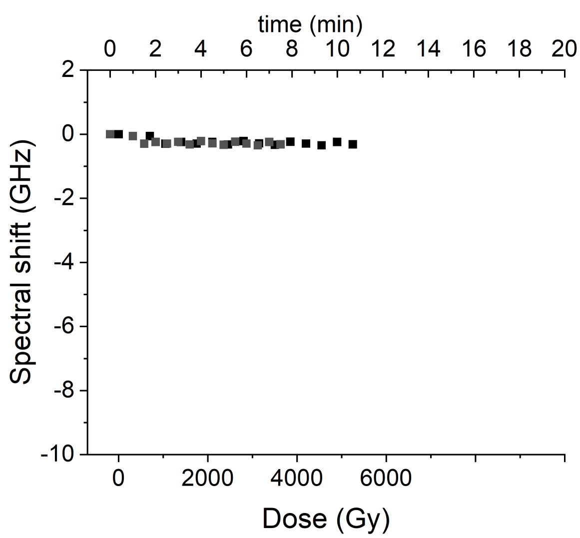

Fig. 6. Evolution of the spectral shift for a standard SMF28 exposed at 700 Gy/min.

The Al-doped fiber was also tested at a nearly therapeutic dose of 22 Gy/min (Fig. 7), exhibiting a similar trend for the accumulated dose as for the high-dose exposure (Fig. 8). In both high- and low-dose experiments, the linear dependence between spectral shift and dose exhibits a slope in the order of magnitude of 0.001-0.002 GHz/Gy.

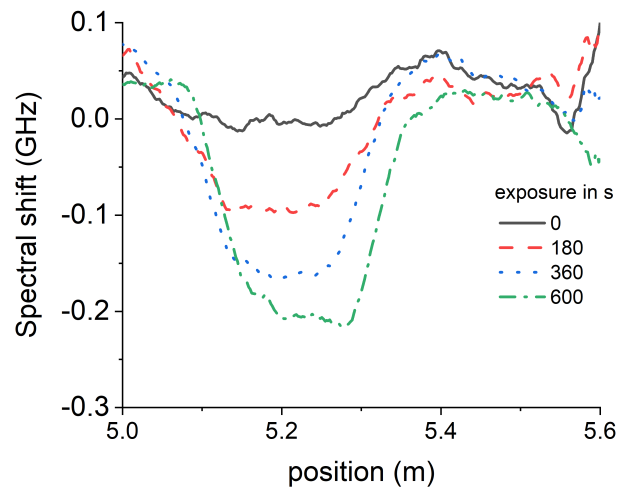

Fig. 7. Spectral shift versus position along the fiber for different times of exposure at 22 Gy/min.

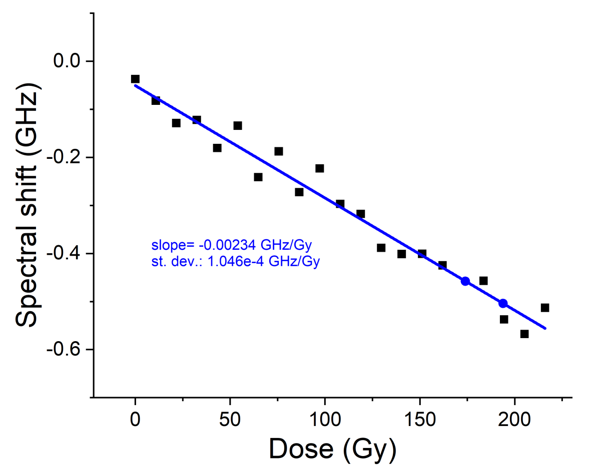

Fig. 8. Spectral shift versus accumulated dose at 22 Gy/min.

It must be pointed out that the fairly poor reproducibility of the slope coefficient can be ascribed to two reasons: 1) the recordings at 22 Gy/min were performed with slightly different settings of the OBR to enhance the sensitivity and 2) still the data from the experiment at 22 Gy/min were at the limit of sensitivity of the instrument and had to be smoothed by adjacent averaging for representation in Fig. 7 and Fig. 8). Therefore the actual relationship between spectral shift and dose for the considered fiber will have to be further investigated by repeated measurements.

However, the previous graphs demonstrate, as a proof-of-concept, that the alumino-silicate fibers can be used as a distributed dosimeter by measuring the radiation-induced spectral shift with an OBR. Although the idea of using an EBF and an OBR for distributed sensing in therapeutic applications has previously been conceived [12], this represents the first example of real-time in-situ monitoring of radiation with an EBF and OBR technique. These experiments also highlight that the spectral shift is a relevant parameter to track the dose evolution in time. On the other hand, fairly simple measurement of radiation-induced attenuation (RIA), which could be performed with a cost-effective optical time domain reflectometer (OTDR), seems not to be effective.

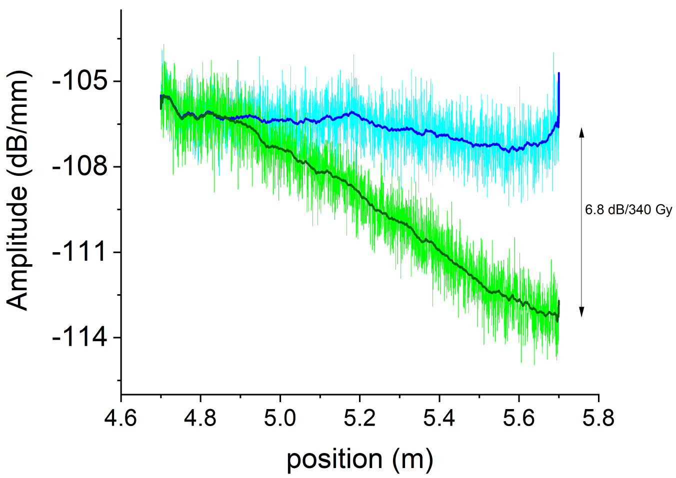

Fig. 9. Rayleigh back-scattering signatures of a 1 m-long coiled fiber, as pristine (cyan curve) and after exposure at 22 Gy/min. A RIA of 6.8 dB can be observed.

Indeed, during the previous experiments, the RIA was also measured by the OBR, but negligible values were recorded. In order to verify whether a weak RIA occurred, a 1 m-long coiled fiber was exposed at 22 Gy/min for at 10 min. Fig. 9 reports the outcome of this test and shows a RIA of 6.8 dB, meaning about 0.07 dB/cm. Such a low value is close to the resolution limit of an OTDR (0.01 dB). Together with its limited spatial resolution (about 1 cm), OTDR seems therefore not as suitable as OBR for optical fiber dosimetry.

IV. Conclusions

A preliminary demonstration of the setup for a novel concept of real-time distributed dosimetry has been presented. The system exploits an enhanced back-scattering optical fiber as the sensing element, interrogated with an optical backscatter reflectometer that can measure the local spectral shift of the Rayleigh scattering along the fiber. The measurements demonstrate that is possible to measure down to 22 Gy/min with a resolution of 5 mm. The spatial resolution can be set to lower values and preliminary experiments (not reported here) have demonstrated that lower doses can be detected by playing with the acquisition parameters of the optical backscatter reflectometer. Further developments of this research will include a comprehensive investigation of the optical backscatter reflectometer settings for optimized measurements, the testing of new optical fibers with possible further enhanced sensitivity, and a thorough investigation of the physical effects of radiation on the optical fiber. As a perspective, the system will be finally tested in a real framework of radiotherapy treatment.

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