Radiation Dosimetry with Fiber Optic Sensors (RaDFOS)

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ABSTRACT

The RaDFOS project envisions a radically new extrinsic optical fiber nano-dosimeter that will meet the needs for present and future energy machines, and will overcome the limitations suffered by the majority of dosimetry approach available on the market. The development of a new nano-dosimeter, able to measure radiation with unprecedented levels foreseen by the next generation of particle accelerators and fusion reactors, is of vital importance in the safety and protection of these energy machines. We designed, manufactured and successfully tested the first prototypes of optical fiber nano-dosimeters based on Lab On Fiber concept.

Keywords: dosimetry; fiber optic sensor; lab on fiber; nanolayer; ionizing radiation.

1. INTRODUCTION

The main goal of RaDFOS project is to secure the possibility to monitor doses beyond the limits of present modern dosimeters, above the MGy level, that is to say in the high (H) and ultra high (UH) dose scenarios. The realization of this goal represents an answer to the need of dosimeters tailored for H and UH dose applications, like future high energy particle accelerators in high energy physics (HEP) and nuclear fusion reactors [1].

The RaDFOS dosimeter is based on the Lab On Fiber (LOF) technology, whose key idea is to transform a "simple" optical fiber (OF) tip into a miniaturized and multifunctional sensor through the integration of functionalized materials and components defined at micro or nanoscale. Indeed, the LOF represents an attractive platform for remote sensing applications, thanks to its inherently light coupled micro-sized active area, joined with the faculty of integrating complex micro and nanometric structures made of dielectric and metallic materials supporting resonant light trapping effects. The principle of operation of this kind of devices is based on the sensitivity of such resonant phenomena to the optical and geometrical variations induced from the surrounding. Moreover, the LOF miniaturized dimensions could overcome many limits in term of occupancy and environment compatibility for the use of present commercial dosimeters in HEP. Finally, for its innovation potential, it opens to patent opportunities for commercial exploitations in the industrial domains where H and UH dose scenario play a key role, like present nuclear fission reactors and future nuclear fusion reactors.

In RaDFOS, we succeed in the validation of the dosimeter prototypes with X-ray, for total ionizing dose monitoring up to 4.6 MGy. We understand that there was room to push forward the dynamic range and we started the design of an improved version of the sensors, to overcome the 10 MGy threshold. Furthermore, we started to explore options to go for a broader market, meaning for potential impact for the society, by enhancing the sensitivity of the RaDFOS dosimeter to lower dose levels.

2. STATE OF THE ART

Radiation dosimetry, *i.e.* the measurement of absorbed dose delivered by ionizing radiation, is fundamental to ensure tight control on radiation processes and the safety of personnel in a wide range of areas, from industrial processes to medical applications. As such, it is the focus of much recent research to develop novel dosimeters and to improve dosimetry systems, be it increasing the sensitivity, providing real-time measurements or significantly reducing the costs. The inherent properties of OF lend themselves to be used with great success in monitoring ionizing radiation. OF provide the means whereby real-time, in situ, remote monitoring of radiation doses can be realized. Being immune to electromagnetic and chemical interferences OF sensors can be employed in harsh environments, such as in high-radiation-level areas in the vicinity of a nuclear reactors or gamma sterilization facilities. In addition, their very limited massive occupancy allows their positioning in regions so far prohibited to conventional dosimeters.

Fig. 1 shows the integration ranges of several types of dosimeters that are today commonly used. Special focus is made on the MGy range expected for the future high energy particle accelerators and nuclear fusion reactors, where none of these technologies are capable of properly function, because of saturation problems and/or extensive and irreversible radiation damage. These noticeable limitations have triggered an extensive research for new technologies, and while for the ultra-high fluence monitoring devices based on metallic thin-films are currently under research at CERN and are showing promising results, no solutions have yet been proposed as H and UH dose monitoring technology.

We reported [4] the first proof-of-principle of an alternative technology for the H and UH dose monitoring based on the LOF technology and, the ATTRACT funding gave us the possibility to push forward our research in this field.

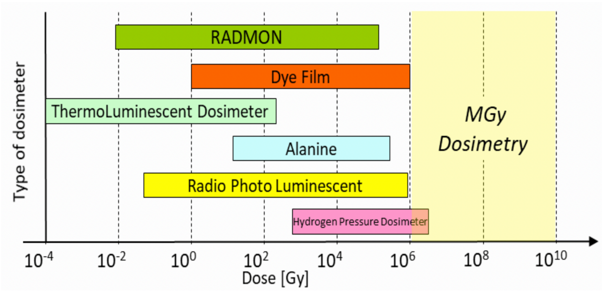

Fig. 1. Different active and passive technologies for TID dosimetry available on the market are shown with respect to their monitoring range.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The development of a new dosimeter able to measure radiation up to the unprecedent levels foreseen by the next generation of particle accelerators and fusion reactors is of vital importance in the safety and protection of these new energy machines. Dosimetry prompts the timely replacement of parts, prevents disasters and keeps the instrumentation on its mettle.

The Europe is the home place of the largest particle accelerator, the LHC (Large Hadron Collider), and the HEP community is currently discussing the next generation HEP accelerator where collisions will occur at higher energy with respect to present LHC. The drawback of this increase in energy is that the accelerator parts, together with the experiments that are mounted at the collision points, will accumulate a level of radiation damages never experienced before. As a consequence, the performance of all parts will degrade limiting the capability for doing physics. In many cases, the accumulated radioactivity will be so high that rules for material handling and disposal are imposed. A dosimetry system capable to measure that activity has the added benefit of assisting compliance with those stringent rules.

Still in Europe, there is a firm development program for the nuclear fusion facility ITER (International Thermonuclear Experimental Reactor). A large research effort has begun with the object of showing that fusion will be an economically viable source of carbon-neutral energy. As with accelerators, the drive to increase overall reactor power usually drives up the damaging effects of the radiation. If for ITER, the radiation damage is only moderate, the severity of the damage and the dose measurement problems in its successor, DEMO (DEMOnstrating fusion power reactor), will be startlingly worse and will be orders of magnitude greater than those we know in fission reactors. The radiation damage for commercial fusion reactors would be even higher. In these hostile environments the dosimeter systems currently used would be exhausted long before the machinery itself wore out, and new device are needed.

The RaDFOS project introduce a new extrinsic OF dosimeter that will meet the abovementioned needs for present and future HEP infrastructures and fusion reactors, and will overcome the limitations suffered by the majority of dosimetry approach available on the market.

4. PROJECT RESULTS

The research carried-out in present RaDFOS project focused on the realization of a metallo-dielectric resonator on the optical fiber tip (OFT) sensitive to H and UH radiation dose. In particular, this LOF structure can be regarded as the superimposition of two metallic gratings separated by a dielectric layer (Fig. 2).

By illuminating the metal-dielectric structure, localized surface plasmon resonances may be excited by the phase-matching conditions between the scattered components and the modes supported by the hybrid structure. The spectral response arising from these resonant phenomena is sensitive to variations of both optical properties and size of the platform components. These include real and imaginary parts of the refractive index (RI) of adopted materials, as well as lattice period, holes radius, metal and dielectric thickness.

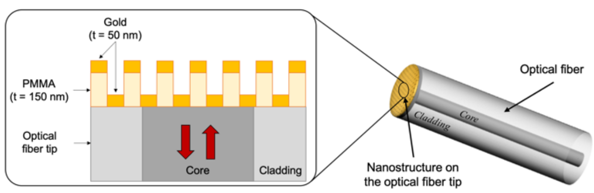

Fig. 2. Cross section of the LOF metallo-dielectric nanostructure realized on the OF tip.

The dielectric layer, in particular, is one of the constituent elements able to play a fundamental role in the design and tailoring of the spectral features of a LOF device for dosimetry application. Among dielectrics, polymers are recognized as highly sensitive to radiations. Within this class of materials, the attention has been focused on the PMMA. The LOF nanostructure is realized in three main steps, as summarized in Fig. 3, consisting of:

- polymeric overlay deposition onto the OFT;
- OFT exposure to electron beam and polymer development;
- gold superstrate deposition.

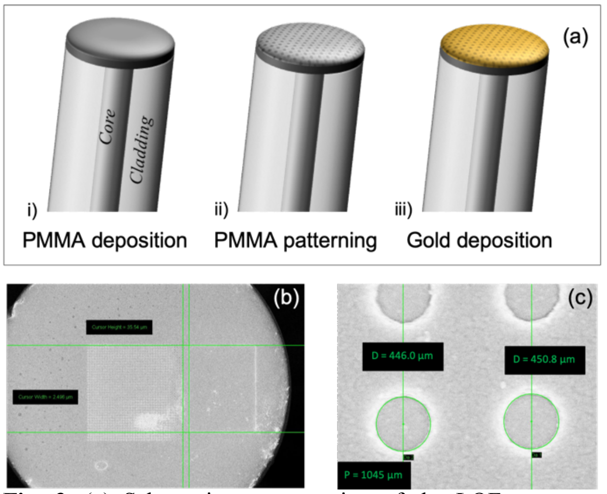

Fig. 3. (a) Schematic representation of the LOF prototype manufacturing: i) polymeric overlay deposition, ii) OFT exposure to electron beam and polymer development, iii) gold superstrate deposition. (b) SEM image showing the top view of the metallo-dielectric nanostructure realized on the OFT. (c) SEM image showing the diameter of the holes in the polymeric layer and the period of the grating.

A customized spin coater, whose rotating plate has been properly drilled to host the OF, has been used to guarantee an uniform deposition of a PMMA layer on the OFT. The optimized combination of spin-coater plate acceleration (2000 rpm) and rotation time (1 minute) allowed to obtain onto the tip of a standard single mode OF an uniform PMMA layer for a region wider than the fiber core diameter (~ 50 µm) with a thickness of about 150 nm. The periodic pattern has been realized via Electron Beam Lithography (EBL) process. The design, consisting of a periodic holes array with period of 1050 nm and radius of 240 nm has been realized in the PMMA layer with the following exposure parameters: electron acceleration voltage of 20 kV, dose of 100 µC/cm2 and electron beam aperture of 7.5 µm. In addition, in the same exposure step, a rectangular window with dimensions of 27 µm x 40 µm has been opened into the PMMA layer in the proximity of the holes array in order to allow both the resist and the gold thickness measurement, before and after irradiation. After the PMMA exposure, the desired pattern has been obtained by developing the polymeric layer. Lastly, the patterned polymeric layer has been covered with a 50 nm thick gold superstrate by means of a DC magnetron sputtering. The OFT was kept perpendicular to the gold target with properly designed holder, which also ensures a good gold film uniformity.

Before performing the exposure to ionizing radiation, the LOF prototypes were subjected to a morphological characterization based on the Atomic Force Microscopy (AFM) in order to measure the thickness of both the PMMA and gold layers. After the irradiation, the AFM measurement was repeated to appreciate the geometrical changes occurred in the nanostructure due to the irradiation. In particular, the LOF device showed a relative decrease of the PMMA thickness of about 50% in respect to the evaluation before the irradiation, while no significant changes were detected for the gold thickness. Such a result confirms the previous literature which tributes to PMMA the capability to compact when exposed to ionizing radiations [4]. Moreover, during the irradiation, the spectrum reflected by the LOF resonator was monitored by means of an optoelectronic interrogator in order to detect the spectral changes due to the effect of the absorbed dose on the morphological features of the nanostructure.
As an example, some spectra acquired during the exposure of a LOF device to X-rays, at the CERN ObeliX facility, up to a dose of 4.6 MGy with a dose rate of 88 kGy/h are shown in Fig. 4a. The major effect is the blue-shift of the resonant wavelength, which reaches a value higher than 4 nm in correspondence of the maximum absorbed dose of 4.6 MGy, as reported in Fig. 4b. This behaviour is consistent with the reduction of the PMMA thickness measured through AFM technique.

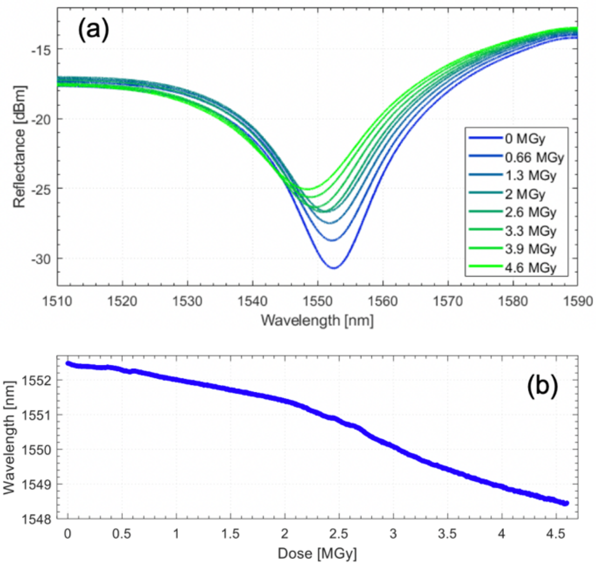

Fig. 4. (a) Reflected spectrum at different doses acquired during the exposure to X-rays at a dose rate of 88 kGy/h. (b) LOF resonant wavelength as a function of the dose.

5. FUTURE PROJECT VISION

In Phase 1, we succeeded in the validation of the RaDFOS dosimeter prototype with X-ray. The analysis of the experimental results deepened our knowledge of the LOF response to ionizing radiation and paved the way to the design of improved version of the LOF dosimeter in view of the Phase 2.

5.1. Technology Scaling

The results achieved in present ATTRACT Phase 1 moved our LOF dosimeter prototype, as described in [4], from a basic technology research status, namely a Technology Readiness Level (TRL) between 1 and 2 to almost a TRL 3 as the result of the experimental proof of concept achieved so far. Additionally, we set the basis for a validation of the RaDFOS prototype in a relevant environment. Indeed, as agreed with the management of the CMS experiment, we will install some RaDFOS dosimeters in the CMS experimental cavern, to monitor the radiation during the LHC Run3. This will pave the way for an additional step in the TRL of our technology.

In view of the ATTRACT Phase 2, scale up to TRL 5-7 is certainly achievable fulfilling the consolidation of sensor manufacturing process. We will focus on the reproducibility and parallelization of the fabrication, in order to have a standardized and reliable product. Moreover, in the Phase 2, a work package will be dedicated to the development on a custom readout optoelectronic system. This additional effort will free the RaDFOS dosimeter from the conventional readout instrumentation, resulting in the realization of a RaDFOS standalone dosimetry measurement system.

5.2. Project Synergies and Outreach

In present ATTRACT Phase 1 we established a fruitful collaboration with the NanoRadMet project [5], sharing expertise on irradiations and nanolayers fabrication. Since the goals of NanoRadMet and RaDFOS, are complementary, in Phase 2 we plan to reinforce the collaboration.

To scale up the RaDFOS prototype to TRL 5-7, in Phase 2 we may need to include in the consortium a Nano-tech facility to standardize the fabrication process of the RaDFOS final prototype in view of a mass production. Also, we would include an Optoelectronic company to have additional expertise in the optimization, prototyping and manufacturing of the custom readout system.

We planned to attend conferences in 2020 to disseminate the results achieved in Phase 1, but those were postponed to 2021. To share the RaDFOS results with the scientific community, we are preparing two manuscripts to be submitted by the end of 2020 to open source scientific journal. We are currently preparing an informative article to be published on an Italian newspaper in order to spread the RaDFOS innovation to the general public. This dissemination strategy will be reinforced in Phase 2, where we also plan to make use of social networks.

5.3. Technology application and demonstration cases

The RaDFOS dosimeter, being tested to operate in harsh environment where the ionizing dose exceeds the MGy level, will be an answer to the need for new dosimetry principles and devices for future and present energy machines, like particle accelerators, fission and fusion reactors.

Furthermore, being designed as an optical fiber extrinsic nano-sensor, the RaDFOS dosimeter inherits all the appealing features of optical fiber sensors, such as the miniaturization, the possibility to have a long-distance monitoring, the immunity to electromagnetic interference, just to cite the more appealing with respect to the, above mentioned, application fields.

Another relevant application for the society will be achieved with the enhancement of RaDFOS dosimeter sensitivity to lower dose level. In this scenario, the RaDFOS dosimeter has the potential to be used for real time, non-invasive, in-vivo dosimetry in the medical fields, where the ionizing radiation is used to treat the patient.

All the industrial processes involving the ionizing radiation, as for example the sterilization, could profit of the features offered by the RaDFOS dosimetry approach.

Finally, being based on nanolayers, the deep understanding of the response of the RaDFOS structure to ionizing radiation will represent a benchmark for the analysis of the radiation effects at the nanoscale level.

5.4. Technology commercialization

Given the positive results achieved so far, we recently started a preliminary exploitation of the nuclear market, with support of CERN KT Office.

We will apply for ATTRACT Phase 2 to secure the further studies needed to make the RaDFOS dosimeter eligible as a market product given the promising results of present Phase 1 and the exciting possibility to further develop our technology as broader platform into lower dose range. This opens up a much broader market and hence more potential business partners and investment sources to address.

5.5. Envisioned risks

The risks envisaged for the ATTRACT Phase 2, in view of the industrial scaling of the RaDFOS dosimeter, may be mainly related to the lack of proper industrial partner for the fabrication of the LOF nanostructure. In order to mitigate this potential risk and to favour the knowledge transfer, we may reinforce the collaboration with Research Institutes stipulating an agreement for the time sharing of the fabrication facilities. The foundation of a dedicated spin-off could be a valuable solution.

5.6. Liaison with Student Teams and Socio-Economic Study

In Phase 1 we were not in the condition to profit of the MSc student teams to investigate the societal impact of the RaDFOS prototype. We will take all the needed actions to liaise with the student teams to deeply investigate the potential societal challenge related to the RaDFOS technology.

In view of expert-driven socio-economic study of the ATTRACT initiative and ecosystem, we are ready to contribute sharing all the needed information related to our technology.

6. ACKNOWLEDGEMENT

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