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Multidisciplinary evaluation of X-ray optical fiber sensors

Dan Sporea[a,*], Laura Mihai[a], Ion Tiseanu[a], Ion Vâţă[b], Denis McCarthy[c], Sinead O'Keeffe[c], Elfed Lewis[c]

[a] National Institute for Laser, Plasma and Radiation Physics, 409 Atomistilor St., Magurele RO-077125, Romania
[b] "Horia Hulubei" National Institute of Physics and Nuclear Engineering, 30 Reactorului St., Magurele RO-077125, Romania
[c] Optical Fibre Sensors Research Centre, University of Limerick, Limerick, Ireland

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ABSTRACT

We report the complex evaluation of an extrinsic optical fiber sensor for X-ray detection, consisting of different phosphor materials (ZnS:Ag, Gd_2O_2S:Pr, Gd_2O_2S:Eu, Gd_2O_2S:Tb) optically coupled to the end of a plastic optical fiber. X-ray fluorescence and radioluminescence measurements were used for the evaluation of sensors responsivity. The sensitivity and linearity of sensors response as a function of the X-ray source voltage and current were assessed. The dependence of the sensor responsivity on the irradiation dose rate was measured. X-ray radiography and tomography were employed to investigate the homogeneity of the active material distribution inside the detecting tip. The most sensitive sensor proved to be that based on Gd_2O_2S:Tb, fixed with the EpoFix glue and manufactured using a plastic cylinder to shape the sensor tip.

1. Introduction

Optical fiber based sensors constitute an exciting alternative to classical optical and/or electric sensors as they provide several exceptional advantages: small dimensions; low mass and footprint; multiplexing capabilities (time, wavelength); immunity to various hazards (fire, explosions) and electromagnetic interferences; extended communication bandwidth; possibility to handle multi-parameter distributed configurations with remote control.

Of a special interest is the use of intrinsic or extrinsic optical fiber sensors under irradiation conditions, as their performances in such environments have to be evaluated in relation: to their radiation reliability (how well they keep their basic characteristics unaltered by the radiation–matter interaction) or to the way they can act as radiation detectors/monitors [1]. As radiation detectors or monitors, optical fiber sensors found their use in niche application such as particle accelerators, synchrotron installations, free electron lasers, for scientific or industrial purposes (dose rate, total dose, beam losses, beam profiling, reconstruction of charge particle tracks) [2–7]; neutron, gamma-ray, beta ray distributed dosimetry [8,9]; water and soil contamination monitoring [10]. In the medical field, optical fiber sensors were applied in the dosimetry of ionizing radiation [11–16]; dosimetry in computed tomography [17]; sterilization of instrumentation [18].

Extrinsic optical fiber sensors for radiation dosimetry are classified in three categories: sensors employing the optical stimulated luminescence [11], those of thermoluminescence type [19], and sensors based on scintillating materials (organic or inorganic) [9,12,14,20]. In these sensors the optical fiber is used mainly to guide the radiation induced optical signal from the exposure location to the detecting system. Thermoluminescent sensors and those developed around the optical stimulated luminescence are able to measure the total dose, being of integrating type. Optical fiber sensors based on scintillating materials are dose rate measuring device. So, scintillating type sensors have to be read in real time. Scintillating optical fibers use a tip made of a scintillating material which is optically coupled to the end of an optical fiber. As the scintillator is exposed to ionizing radiation, an optical signal is generated and is guided by the optical fiber toward a detecting device placed far away from the irradiation zone.

This paper describes briefly the design of a novel extrinsic optical fiber detector for radiation monitoring and presents a detailed characterization of such a sensor as it is exposed to X-ray radiation. The sensor is intended to be used as a low energy X-ray detector for monitoring radiation levels in radiotherapy environments, industrial X-ray applications and for personnel dosimetry [21].

* Corresponding author. Tel.: +40 745759545.
E-mail addresses: dan.sporea@inflpr.ro, sporea@nipne.ro (D. Sporea).

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2. Extrinsic sensor design and manufacturing

The proposed optical fiber sensor manufacturing process is described elsewhere [22]. The sensor consists of a PMMA type FDPF 4001 EH optical fiber, having a fiber core diameter of 1000 μm and a polyethylene jacket encapsulating the fiber core of 1.2 mm in diameter. The fiber core jacket was striped at both ends over a length of between 5 and 15 mm. At one end an SMA 950 connector was mounted, while at the other end the sensor tip is located. Two methods of coating the fiber were used for this work. Both methods use the same technique of creating a mold around the fiber core using an injection method. The first method of coating used for the sensors was a method where the exposed optical fiber core was introduced coaxially inside a solid plastic cylinder having the inner diameter of 3 mm (sensors 1–7 in Table 1). The second method uses a thin rubber cylinder with a 2 mm inner diameter as the mold and employs the mold injection method to create the sensor (sensor 8 in Table 1). Different types of phosphors were employed to develop the sensors and for the phosphor having an emission spectrum better matched with the optical transmission of the PMMA fiber a set of sensors was prepared. Sensors 1–4 were creating using the ViaFix epoxy system while sensors 5–8 the EpoFix epoxy system was employed. Two different types of epoxy were tested as several conditions have to be verified: the viscosity of the glue and its relation to its capability to embed phosphor particles in it; the possibility to obtain a higher homogeneity of the phosphor–glue mixture; the curing time of the mixture and its potential to be easily manipulated into specific shape; the mixture transmission for the X-ray and the radioluminescent signal. Their behavior under special conditions (exposure to X-ray and optical signal transmission) for which they were not tested cannot be predicted from their data sheets.

The phosphor materials used in manufacturing of the sensor are commercially available products, and are listed in Table 1 along with their characteristics. Sensors 55–59 are identical, as it concerns the luminescent material. Sensors 55, 56 and 59 are 10 mm length, while sensor 57 has a length of 5 mm. The diameter of the sensing tip is 3 mm for sensors 55–57, while the diameter of sensor 59 is only 2 mm.

3. Measurements set-ups

The manufacturing process of the X-ray detector requires the optimization of both its design and the technology used to obtain better responsivity for low energy X-ray detection.

The research focused on: the homogeneity of the active material in the sensing tip, the symmetry of its distribution, and sensors responsivity and linearity as a function of the excitation X-ray source operating parameters. For this purpose, a thorough investigation was performed through:

- X-ray radiography of the sensor tip.
- X-ray tomography of the sensing tip.
- X-ray fluorescence.
- X-ray generated radioluminescence.

3.1. X-ray imaging

Because different technologies were used to develop the sensors (see Table 1 for each sensors components and preparation method), X-ray imaging techniques were used to evaluate the homogeneity of the scintillating material in the sensors tip. The preliminary tests consist of X-ray radiographies for sensors from Table 1. In the second stage, a complete X-ray tomography was done for all sensors. The two studies were run on the nanoCT X-ray

Table 1
The phosphor materials used for the sensors and their characteristics [22,23].

Sensor number	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8
Phosphor	GL47/N-C1	UKL59N-R1	UKL63 F-R1	UKL65/FR1	Sample 55 UKL65/FR1	Sample 56 UKL65/FR1	Sample 57 UKL65/FR1	Sample 59 UKL65/FR1
Epoxy	ViaFix	ViaFix	ViaFix	ViaFix	EpoFix	EpoFix	EpoFix	EpoFix
Mold type	Plastic cylinder	Plastic cylinder	Plastic cylinder	Plastic cylinder	Plastic cylinder	Plastic cylinder	Plastic cylinder	Rubber cylinder
Symbol	ZnS:Ag	Gd_2O_2S:Pr	Gd_2O_2S:Eu	Gd_2O_2S:Tb	Gd_2O_2S:Tb	Gd_2O_2S:Tb	Gd_2O_2S:Tb	Gd_2O_2S:Tb
Peak λ	450 nm	513 nm	626 nm	544 nm	544 nm	544 nm	544 nm	544 nm
Mean particle size	4.0 μm	8.0 μm	4.0 μm	3.5 μm	3.5 μm	3.5 μm	3.5 μm	3.5 μm