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Dynamic gamma-ray monitoring at radioprotection levels with extrinsic polymer optical fiber sensors

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ABSTRACT

The dynamic performance of extrinsic gamma-ray sensors at radioprotection levels is studied. The sensors have been fabricated with chemically etched polymer optical fibers covered with an inorganic scintillator powder (Terbium doped Gadolinium Oxysulfide). This scintillator shows a maximum emission peak at 543 nm, therefore only the signal amplitude at this wavelength has been measured with a commercial grade CCD spectrometer. The transducers have been done at the end of both short (1 m) and large fiber patchcords (27 m). Short patchcords are further mechanically spliced to a fiber link 25 m length through an industrial grade connector-less mating sleeve, and therefore can be easily replaced if needed.

All tests were run under gamma irradiation from a ^{137}Cs source, the reference isotope for environmental protection. The measured response of the devices is very repeatable and stable, with a percentage standard deviation below 2% when the air kerma rate is above 1 Gy/h. This deviation increases for lower rates. A Limit of Detection of 0.2 Gy/h, with an integration time at the detection stage of 10 s, has been achieved for transducers done in the 1 m length patchcords spliced to the 25 m length fiber link. This integration time can be further reduced when no splice is included between transducer and detection unit. The behavior of the devices is linear with the delivered air kerma rate, and can provide reliable measurements under repeated radiation exposures. This behavior makes the sensors useful to quickly detect the presence of hazardous radioactive materials in accidental leakage scenarios.

1. Introduction

The detection and measurement of ionizing radiation has been recently the focus of intense research [1], searching for solutions in areas such as nuclear science [2,3], metallurgy [4], healthcare [5,6], food industry [7] and environment protection [8].

In nuclear facilities, nuclear fuel is composed of a variety of radioactive isotopes. The most important is the contribution of ^{137}Cs to the gamma activity [9,10]. This isotope is also the reference for environmental protection. Thus, any quick response to an incident involving a hazardous nuclear material must be supported by a reliable detection of its presence in a constrained area [11]. Furthermore, the demands for real-time monitoring of a relatively large area leads to the use of optical fiber devices.

When dealing with optical fiber sensors applied to this range of gamma-ray detection, two options have been reported in literature. Both arrangements are based on polymethylmethacrylate (PMMA) fibers (POF). POF fibers share the common advantages of standard silica optical fibers such as lightweight, small size, multiplexing capabilities and feasibility of being deployed over large areas in a harsh environment. But they add some other features, such as large core diameter, easy handling and higher interconnection tolerances, which are clearly advantageous for working in harsh environments since a minor contamination of the fiber end does not result in the complete failure of the sensor [9].

The first choice to get gamma-ray dosimetry, is an intrinsic sensor in which the Radiation Induced Attenuation (RIA) measurement is done. This method requires a relative long fiber, the tested irradiation kerma rate is really high, up to 700 Gy/h, and the whole arrangement includes both light source and high sensitivity spectrometer as detector [9]. Furthermore, the fiber is not fully recoverable after irradiating [10], and its replacement could be hard in harsh environments. Another choice, suitable for low-dose applications has also been reported. In this case, an extrinsic device made by attaching an inorganic scintillator at the end of a polymer fiber tip has been successfully demonstrated for kerma rates up to 2 Gy/h [12]. The scintillator fluoresces with the incident gamma-ray, and the released visible light is gathered by the optical fiber and guided till its distal end, where the signal is recorded with a

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Table 1
Summary of fabricated transducers features.

Sample	Transducer length (mm)	Fiber tip diameter (μm)	Total fiber length (m)
S1	19	850	1
S2	19	830	1
S3	20	800	27

commercial grade spectrometer. This later system takes advantage of the large cross-section of the POF fibers to perform fluorescence measurements, in which the signal obtained from the scintillator under irradiation is usually very weak, especially when the kerma rate is low. However, no data about the dynamic performance of these sensors, including uncertainties, repeatability and Limit of Detection (LoD) are provided in [12].

In this work, we present the dynamic performance of these devices, based in the already demonstrated improvement of the chemically etched fiber tip, covered with a Terbuim doped Gadolinium Oxisulfide (Gd_2O_2S:Tb) powder [12]. The sensing head has been done in either the distal end of a continuous long patchcord, or a short length patchcord that can be mechanically spliced to the main fiber linking the irradiated area with the detection room. This arrangement allows the simple replacement of the sensing head if needed. Several tests have been performed to get both the repeatability and uncertainties in gamma-ray measurements, the dynamic behavior of the sensors, the limit of detection as a function of the integration time at the optoelectronics unit, and the effect of the mechanical splice in the measurements.

2. Transducers fabrication and experimental setup

The fabrication procedure has been already depicted elsewhere [12–14]. A POF fiber tip 1 mm diameter and 2 cm length, is chemically etched with pure acetone followed by an air-drying. The final fiber tip has a homogeneous profile around 850 μm diameter and 2 cm length. Therefore, the cladding and part of the fiber core are removed in the chemical process, allowing to get access directly to the fiber core. Once the fiber tip has been etched, it is inserted into a Teflon capsule 5 mm inner diameter and 25 mm length filled with 1 g approximately of the scintillating powder, Terbium doped Gadolinium Oxysulfide with a main grain size of 2.5 μm in our case (Phosphor Technology UKL65/UF-R1) [15], which has been proved as the most efficient for gamma-ray detection [16]. Thus, a scintillating cylindrical shell of about 2 mm thick covers the etched fiber, which gathers the fluorescence signal when irradiated. Finally, the capsule is black shielded to prevent any influence of ambient light. Three samples have been prepared following the depicted procedure. Two of them have been done at the end of a 1 m patchcord, while the third one has been done at the distal end of a 27 m length fiber. The features of the prepared samples are summarized in Table 1, where the fiber tip diameter and fiber length is specified.

All samples have been transversally irradiated under the same conditions at the LMRI-CIEMAT (Spain) reference lab for radioprotection levels with a ^{137}Cs calibrated source (<100 TBq nominal activity, peak energy 662 keV). This source continuously covers a spectral range from about 50 keV to beyond 800 keV [17]. The air kerma rates have been selected through a change in the source-sensing head distance. Therefore, the transducer is fixed to a mobile stand inside the irradiation bunker room. The detection optoelectronics unit is a commercial grade CCD spectrometer (StellarNet BlueWave) located at the control room, to which the fiber is attached through an SMA connector. A complete view of the measurement setup is shown in Fig. 1. Samples S1 and S2 are mechanically spliced through a connector-less mating sleeve to a 25 m length POF whose distal end is attached to the CCD spectrometer at the control room. For minimizing the optical losses at the splice, both the fiber link and the transducer patchcord ends have been carefully polished and an index matching gel has been used. In the case of sample S3, the fiber is directly attached to the detector.

3. Experimental results

Each sensing head has been irradiated following the procedure depicted above. The emission spectrum is shown in Fig. 2 for all tested samples. This spectrum has been taken with an integration time of 20 s with a transducer fabricated at the end of a 10 m length POF under an air kerma rate of 2 Gy/h. It is straightforward to identify three local maxima, at 543 nm, 586 nm and 620 nm respectively, which are characteristics of the used phosphor.

The performance of all fluorescence intensity peaks is equivalent when changing the gamma irradiation kerma rate, as previously shown by the authors [12], although the main peak at 543 nm wavelength renders the maximum sensitivity and dynamic range. Therefore, dynamic measurements have been done only by measuring the time-variation of the fluorescence intensity at the wavelength of 543 nm. With this choice, the linearity of the response and the detection limit, the repeatability and stability of the measurement, and the behavior against repeated exposures have been tested.

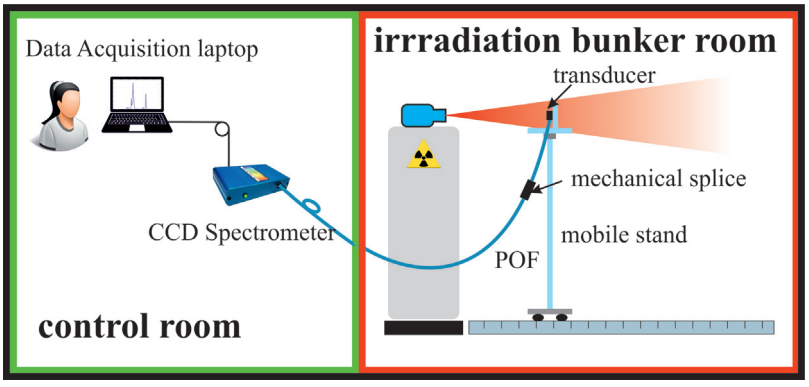

Fig. 1. Scheme of the arrangement use for irradiating the fabricated devices. The transducers are placed normal to the beam propagation of the gamma radiation, and the distal end of the fiber, located at the control room, is attached to a commercial CCD spectrophotometer and a laptop.