1. Introduction

Optical fibers and optical fiber sensors were investigated quite extensively in relation to the possible use in radiation monitoring and dosimetry. Various optical fiber intrinsic and extrinsic dosimeters based on radiation induced attenuation, radiation induced radio-luminescence, thermo-luminescence, Cerenkov radiation, or optically stimulated luminescence were proposed [1]. One novel extrinsic optical fiber dosimeter, approach pioneered by a team at University of Limerick, was built by encapsulating the end of a PMMA optical fiber, to which the outer jacket was removed, into a tip of scintillating material. This end of the optical fiber constitutes the detector head and is exposed to X-ray radiation (Fig. 1a). The other end of the optical fiber is coupled either to the QE65000 Ocean Optics spectrometer or to the Hamamatsu C10507–11–100U Multi-Pixel Photon Counter. When exposed to ionizing radiation the sensor tip emits a visible radiation because of the fluorescence effect. Part of the optical radiation, having a wavelength dependent on the type of phosphor used to prepare the tip, is coupled to the core of the plastic optical fiber and guided towards the detecting unit (mini spectrometer/ MPPC) [2].

In some cases the emitted optical spectrum has several emission bands (Fig. 2). Such a sensor is of interest to be used for in-situ, in vivo radiation dosimetry during patient radiologic treatment. The major advantage of this type of radiation sensor is its low cost.

Fig. 1. The picture of the tip for two of the sensors (a); Cu wires were wrapped on the tips to identify different zones when X-ray fluorescence is used. The tomographic view of one sensor tip (b).

The challenge of our investigation was to evaluate the response of these sensors (for different phosphor materials and technologies used) under X-ray exposure and to characterize them. The investigations were complex involving X-ray

Title: Evaluation of an extrinsic X-ray optical fiber sensor

Key words: extrinsic optical fiber sensor, X-ray detector, X-ray radioluminescence

Technique: Visible emission spectroscopy

Application: characterization of X-ray detector operating parameters
radioluminescence, X-ray fluorescence and X-ray tomography. In this Application Note we shall refer only to those tests where the Ocean Optics QE65000 acted as a detecting system.

![Spectra detected by QE65000](image)

Fig. 2. The spectra detected by QE65000 when different scintillating materials were used to fabricate the sensors tips, as the detector was exposed to X-rays generated for the source voltage of 45 kV and the driving current of 850 μA.

2. Experiment and results

Depending on the technology employed in the preparation and fixing of scintillating tip X-ray tomography highlighted some non-uniformities concerning the distribution of the phosphor in the glue material (Fig. 1b) [3]. The first step of our research tried to associate these non-uniformities with the localization of the phosphor grains in the tip volume. For this purpose, the tip of each sensor was scanned along its axis and the X-ray induced radioluminescence was recorded. The X-ray excitation was done with a 2 mm spot produced by a miniature AMPTEK Inc. X-ray tube system, operating with an Ag target, while the X-ray fluorescence was detected by a AMPTEK Inc. Silicon Drift Detector [4]. The radioluminescence signal produced during the X-ray exposure, coupled in the plastic optical fiber was recorded by the QE65000 spectrometer. Cu wires were placed along the sensor tip to identify different zones during X-ray fluorescence investigations. For our investigations the amplitude of the peak emitted by the optical signal was monitored as the X-ray beam scanned the sensor tip. In order to have a 3D measurement after a full scan of the tip this was rotated by 90° for another longitudinal scan. In this way we mapped the generation and coupling of the optical radiation in the optical fiber (Fig. 3).
Fig. 3. The 3 D map of the optical radiation coupled to the plastic fiber core [4].

By using the same scanning and detection technique we evaluated the effect of two reflecting materials on the coupling efficiency of the radioluminescent signal towards the spectrometer (Fig. 4).
Fig. 4. The effect of the external reflector on the efficiency of generated optical signal coupling to the optical fiber core: (a) sensor without a reflector; (b) the same sensor with an Al foil reflector [4].

The detection of the radioluminescence signal was also used to estimate the dosimeter response as function of the X-ray source high voltage or current. In this situation, the optical signal recorded by the spectrometer was correlated with the operating parameters of the X-ray emitter (Fig. 5). The sensitivity and the linearity of the sensor response were evaluated.

![Graph](image1)

**a**

![Graph](image2)

**b**

**Fig. 5.** The responsivity of sensors at $\lambda = 542$ nm, as function of the X-ray source driving current, for the driving voltage $V = 40$ kVp (a); the responsivity of sensors at $\lambda = 542$ nm, as function of the X-ray source driving voltage, for the driving current $I = 80$ $\mu$A (b). 1–4 designate sensors based on different technologies or scintillating materials.

3. Conclusions
The visible emission spectroscopy proved to be a valuable tool in the evaluation of several characteristics of a new type of extrinsic optical fiber dosimeter: the dependence of sensor response on the driving condition of the X-ray source; the effect of different reflector materials applied to the sensor tip; the coupling efficiency of the radioluminescence signal to the core of the connecting plastic optical fiber. These results make possible the optimization of the sensor design and its calibration for specific operating conditions.

By combining spectral measurements with X-ray fluorescence investigations, the contribution of different scintillating materials to the generated optical signal can be estimated.

The extreme sensitivity of the QE65000 spectrometer made possible the detection of very weak signals associated with the radioluminescence emission.

Acknowledgments

This work was financially supported by the contract “Sensor Systems for Secure Operation of Critical Installations”, Grant 8/2012 of the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI). The contribution of authors from University of Limerick was part of the bilateral cooperation between Romania and Ireland in the frame of the European Union COST Action TD1001 “Novel and Reliable Optical Fibre Sensor Systems for Future Security and Safety Applications (OFSeSa)”. The Irish authors acknowledge the support of the European Commission under the 7th Framework Programme through the “Marie Curie Re-integration” action of the “Peoples” Programme (PERG04–2008–239207).

References