

Radiation induced attenuation in perfluorinated polymer optical fibres for dosimetry applications

P. Stajanca*, K. Krebber

Bundesanstalt für Materialforschung und –prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany

*Corresponding author: pavol.stajanca@bam.de

Abstract: Real-time measurement of radiation-induced attenuation (RIA) in a commercial perfluorinated polymer optical fibre (PF-POF) is performed with regard to on-line radiation monitoring purposes. Spectral character and dose dependence of fibre's RIA is measured in 450-900 nm spectral region. Fibre exhibited high radiation sensitivity in the visible region with strong increase towards the UV wavelengths. Good linearity and high sensitivity reaching up to $130 \text{ dBm}^{-1}/\text{kGy}$ was demonstrated in the VIS region for a low-dose range. This of-the-shelf PF-POF could be therefore interesting for on-line remote dosimetry applications.

1. Introduction

Considerable efforts have been devoted to the development of optical fibre-based dosimeters (OFDs) over the last decades [1, 2]. Compared to other available dosimetry techniques, OFDs offer numerous advantages including possibility of remote and real time monitoring, electromagnetic immunity or small footprint. Various effects taking place in optical fibres upon irradiation can be used for dosimetry purposes; for example radiation-induced attenuation (RIA), radiation-induced luminescence, thermally- or optically-stimulated luminescence. Among these, RIA monitoring represents one of the most straightforward OFD techniques. Ionizing radiation degrades the fibre transmission and corresponding attenuation increase can be correlated to the total dose absorbed by the fibre. Most of the research activities have been focusing on more common glass optical fibres (GOF). However, recent advancements of polymer optical fibres (POF) have made them an attractive alternative for various applications [3, 4]. POFs are typically robust multi-mode (MM) fibres which are easy to handle and their interconnections are not as technically demanding as in case of glass fibres. In addition, POFs don't fail in brittle manner and are generally more acceptable for in-vivo medical applications. Utilization of polymethyl methacrylate (PMMA) POF as a low-cost, real-time OFD has been suggested and demonstrated in the past [5]. Our recent study suggested that radiation sensitivity of perfluorinated (PF) POFs might be considerably higher than in case of PMMA [6]. Perfluorinated fibres based on Cytop polymer offer low-loss operation in a broad spectral region unmatched by any other POF [7]. Therefore, here we investigate RIA sensitivity of PF-POF in a more precise on-line irradiation experiment and explore possibilities of utilizing the fibre as for real-time radiation monitoring.

2. Methodology

A commercially available MM PF-POF GigaPOF-50SR from Chromis Fiberoptics was investigated in this work. The fibre has $50 \mu\text{m}$ graded-index (GI) Cytop core with $490 \mu\text{m}$ polycarbonate over-cladding and is prepared by co-extrusion process [8, 9]. In on-line spectral RIA measurement, 2.3 m long piece of the fibre was homogeneously irradiated with ^{60}Co irradiator at a dose rate of 267 Gy/h . Experimental configuration of fibre irradiation is schematically illustrated in Figure 1.

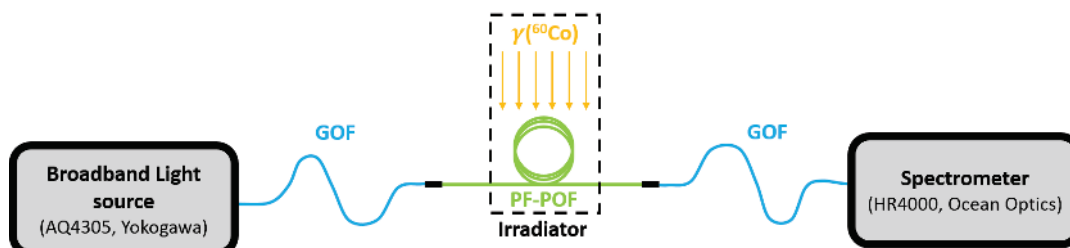


Figure 1. Schematic illustration of experimental configuration utilized for on-line measurement of spectral RIA in the investigated PF-POF.

Broadband light from fibre coupled Halogen lamp (AQ4305, Yokogawa) was send into the irradiated fibre sample with the help of auxiliary GOF. Transmission spectrum from irradiated fibre was monitored with a CCD-based spectrometer (HR4000, Ocean Optics) working in the VIS-NIR spectral range. Auxiliary interconnecting GOFs as well as connectors were shielded by lead bricks. The RIA (in dB/m) evolution with total dose $D(t)$ was evaluated from spectral transmission data as

$$RIA(\lambda, D) = -\frac{10}{L_0} \log \left(\frac{I(\lambda, D)}{I(\lambda, 0)} \right). \quad (1)$$

Here, $I(\lambda, D)$ is the measured transmitted spectral intensity at dose D and L_0 is the length of irradiated fibre (2.3 m). The dose D was calculated according to utilized dose rate and irradiation times.

3 Results and discussion

Radiation degrades the material of optical fibre which manifest itself as an intensity decrease of light transmitted through the fibre. Figure 2a illustrates a drop of transmitted spectral intensity of the investigated fibre upon irradiation. High radiation sensitivity of the fibre in the visible region is evident, when wavelengths below 700 nm are completely depleted already for doses at 500 Gy level. Here we would like to note that monitoring range of interrogating system is limited by depletion of the transmitted signal below detection level of utilized spectrometer. Dose level at which this limit is reach depends on the fibre radiation sensitivity, length of irradiated section and the spectral intensity distribution before irradiation. The actual sensitivity range of the fibre may greatly overcome this practical monitoring range imposed by the experimental apparatus. At the same time, performance of RIA-based OFD can be widely tailored by changing the interrogation wavelength or length of irradiated fibre.

To visualize the spectral dependence of the induced attenuation, Figure 2b depict the dose evolution of fibre's spectral RIA in a low-dose region (< 100 Gy) calculated from transmission data according to eq. (1). Increase of fibre's RIA sensitivity from NIR towards UV wavelengths is apparent. In the VIS region, RIA exhibits a local minima around 540 nm and local maxima at 650 nm. The figure illustrates that a wide range of sensitivities and sensing ranges can be achieved with this type of the fibre.

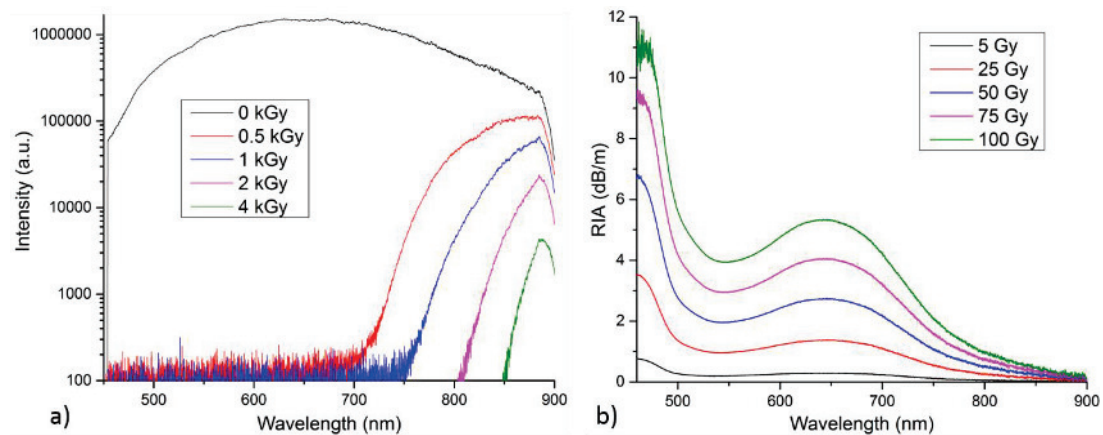


Figure 2. Evolution of fibre's transmission spectrum (a) and spectral RIA (b) with increasing radiation dose.

Due to spectral dependence of RIA, wide range of radiation sensitivities can be achieved through selection of suitable monitoring wavelength. In practice, sensitivity of OFD can be further increased by irradiating longer fibre section, boosting the RIA impact on the system transmission. At the same time, RIA monitoring range is dependent on the fibre radiation sensitivity, length of irradiated section and the spectral intensity distribution before the irradiation. Based on these parameters, upper limit of monitoring range is defined as a point when the measured spectral intensity drops below the spectrometer noise level. RIA-based fibre dosimeters thus offer large space for tailoring of OFD sensing parameters.

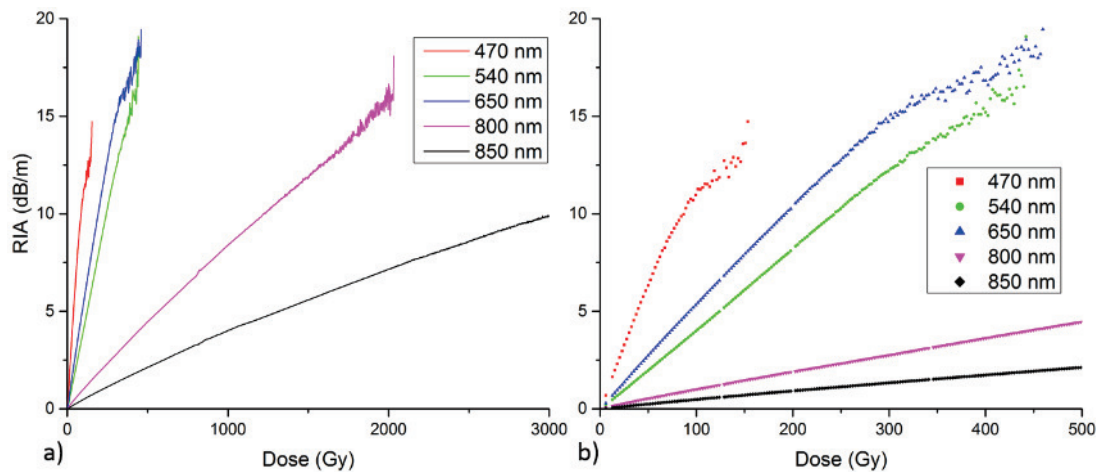


Figure 3. RIA as a function of radiation dose at five selected wavelengths up to total dose of 3 kGy (a) and detail on low-dose region up to 500 Gy (b).

Figure 3 shows the evolution of fibre’s RIA with total radiation dose at five selected wavelengths from the monitored spectral range. Only the data in system monitoring range at respective wavelengths is presented. Fibre RIA sensitivity can be determined from an apparent slope of presented RIA versus dose dependence curves. Red curve of 470 nm wavelength represents highly sensitive region at the blue edge of the monitored spectral interval. Wavelengths of 540 and 650 nm correspond to local spectral RIA minima and maxima in the VIS range, respectively. Near-infrared wavelengths of 800 nm and 850 nm illustrated the rapid sensitivity drop towards the longer wavelengths. Fibre RIA response has slightly sub-linear character that becomes apparent when monitored over kGy dose range (Figure 3a). However, for limited dose range intervals, good linearity between measured RIA and applied dose can be found (Figure 3b). Monitoring of fibre’s RIA within these intervals can be exploited for on-line radiation dosimetry.

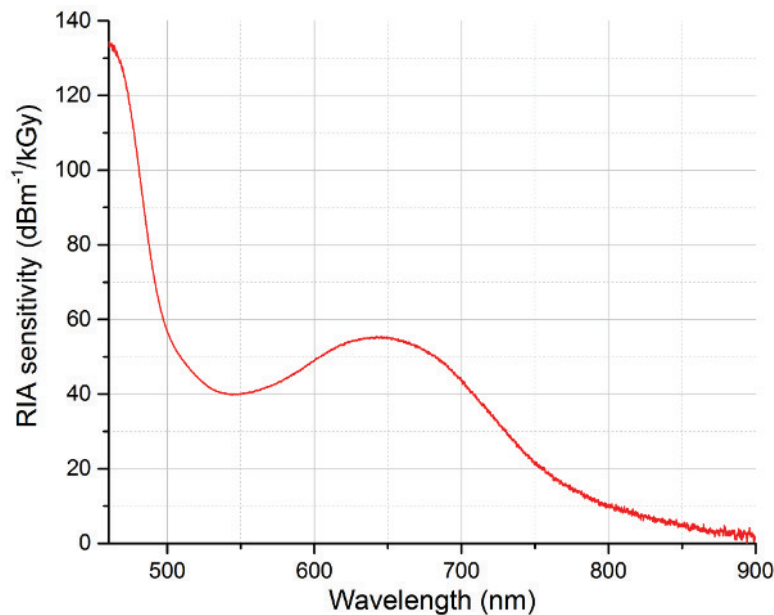


Figure 4. Spectral character of radiation sensitivity of GigaPOF-50SR PF-POF calculated as a linear fit of fibre’s RIA versus dose dependence in the low-dose range (0-60 Gy).

Figure 4 presents the spectral dependence of fibre's RIA sensitivity evaluated from linear regression of RIA response curves at individual wavelengths in the low-dose region of 0-60 Gy, where good linearity is achieved at all monitored wavelengths. The evaluated dose range is more than sufficient for personal dosimetry or radiotherapy monitoring applications, where imparted doses are at the level of single Gy and lower. Broad range of sensitivities spanning from 40 dBm⁻¹/kGy to over 130 dBm⁻¹/kGy can be achieved in the visible range. Spectral character of the RIA sensitivity curve on the blue edge of our monitoring spectral region suggests that even larger sensitivities can be achieved at shorter wavelengths. On the other hand, operation at less sensitive NIR wavelengths can be used for applications involving larger radiation doses. Recorded sensitivity values are more than two orders of magnitude higher than those measured for PMMA POFs [5]. Even though higher sensitivities has been achieved with specialty custom-made P-doped silica fibres [10, 11], PF-POF offers considerably higher sensitivity than the most of the studied silica-based fibres [12]. Therefore, performance of the investigated fibre is highly promising, especially considering that it is readily available of-the-shelf POF.

4. Conclusion

Sensitivity of a low-loss commercial PF-POF (GigaPOF-50SR, Chromis Fiberoptics) to gamma radiation was measured and exploited for on-line dosimetry purposes. Due to strong spectral dependence of fibre's RIA, wide range of OFD sensitivities can be achieved by the choice of suitable interrogation wavelength. For a limited dose range, fibre's RIA response exhibits good linearity with increasing dose and can be therefore used for dosimetry purposes. In the low-dose range up to 60 Gy, RIA sensitivities spanning from 40 dBm⁻¹/kGy to over 130 dBm⁻¹/kGy were measured in the VIS range (450-700 nm). Lower sensitivities down to single dBm⁻¹/kGy can be reached further in the NIR region. Demonstrated sensitivities significantly exceeds performance of PMMA POFs [5] and most of the silica-based fibres [12]. As an of-the-shelf polymer fibre, investigated PF-POF holds a considerable potential for on-line radiation monitoring applications.

5. Acknowledgements

Research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007 2013/ under REA grant agreement n° 608382. Authors would like to thank Dr. A. Denker of Helmholtz-Zentrum Berlin for facilitating the fibre irradiation.

6. References

- [1] A. L. Huston, B. L. Justus, P. L. Falkstein *et al.*, "Remote optical fiber dosimetry," *Nuclear Instruments and Methods in Physics B*, 184, 55-67 (2001).
- [2] S. O'Keefe, C. Fitzpatrick, E. Lewis *et al.*, "A review of optical fibre radiation dosimeters," *Sensor Review*, 28(2), 136-142 (2008).
- [3] O. Ziemann, J. Krauser, P. E. Zamzow *et al.*, [POF Handbook: Optical Short Range Transmission Systems] Springer, Berlin(2008).
- [4] K. Peters, "Polymer optical fiber sensors - a review," *Smart Mater. Struct.*, 20(1), 013002 (2011).
- [5] S. O'Keefe, and E. Lewis, "Polymer optical fibre for in situ monitoring of gamma radiation processes," *International Journal on Smart Sensing and Intelligent Systems*, 2(3), 490-502 (2009).
- [6] P. Stajanca, L. Mihai, D. Sporea *et al.*, "Effects of gamma radiation on perfluorinated polymer optical fibers," *Opt. Mater.*, 58, 226-233 (2016).
- [7] H. P. A. van den Boom, W. Li, P. K. van Bennekom *et al.*, "High-Capacity Transmission over Polymer Optical Fibre," *IEEE J. Sel. Top. Quantum Electron.*, 7, 461-470 (2001).
- [8] W. White, "New Perspectives on the Advantages of GI-POF," *Proceedings of POF 2005*, (2005).
- [9] C. Lethien, C. Loyez, J.-P. Vilcot *et al.*, "Exploit the Bandwidth Capacities of the Perfluorinated Graded Index Polymer Optical Fiber for Multi-Services Distribution," *Polymers*, 3, 1006-1028 (2011).
- [10] S. Girard, Y. Querdane, C. Marcandella *et al.*, "Feasibility of radiation dosimetry with phosphorus-doped optical fibers in the ultraviolet and visible domain," *J. Non-Cryst. Solids*, 357, 1871-1874 (2011).
- [11] M. C. Paul, D. Bohra, A. Dhar *et al.*, "Radiation response behavior of high phosphorous doped step-index multimode optical fibers under low dose gamma irradiation," *J. Non-Cryst. Solids*, 255, 1496-1507 (2009).
- [12] S. Girard, J. Kuhnenn, A. Gusarov *et al.*, "Radiation Effects on Silica-Based Optical Fibers: Recent Advances and Future Challenges," *IEEE. Trans. Nucl. Sci.*, 60(3), 2015-2036 (2013).