

Impacts of gamma irradiation on Cytop plastic optical fibres

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Abstract: Impact of gamma radiation on transmission of a commercial Cytop polymer optical fibre (Lucina, Asahi Glass Company) is investigated. Spectral dependence of radiation-induced attenuation in the investigated fibre is measured in the VIS-NIR spectral region. Besides attenuation increase, radiation is found to increase fibre susceptibility to water as well. While pristine Cytop fibre is rather humidity insensitive, strong humidity-related absorption in the NIR region is observed after fibre irradiation. Selective irradiation of separate fibre sections is proposed as a way of fibre humidity sensitization and quasi-distributed water detection is demonstrated using optical time domain reflectometry at 1310 nm.

1. Introduction

Optical fibres offer several advantages for operation in harsh environments both for data transmission and sensing applications. These include electromagnetic immunity, low-weight, small dimensions, low loss and high bandwidth. However, before any fibre-based system can be employed in radiation environment, impact of the high-energy radiation on the fibre and system performance need to be evaluated. Effects of gamma radiation on silica-based fibres have been subject of numerous studies for more than three decades [1]. In contrast, investigations on plastic optical fibres (POFs) are rather scarce. Nevertheless, considerable attention has been devoted to development of POFs which proved their potential for short-range data transmission [2] and numerous sensing applications [3]. Among variety of available POFs, graded-index (GI) Cytop-based fibres are one of the most promising candidates exhibiting low attenuation and dispersion [4]. In general, two different types of multi-mode (MM) Cytop fibres are commercially available; co-extruded POFs manufactured by Chromis Fiberoptics, and fibres drawn from a preform produced by Asahi Glass Company. Compared to co-extruded type, Cytop fibres drawn from a preform are known to have higher degree of purity. Thanks to that, they typically exhibit lower attenuation and smoother back-reflection traces [4]. In previous works, we have studied effects of gamma radiation on performance of co-extruded Cytop POFs [5, 6]. However, radiation effects on fibre transmission properties can be strongly dependent not only on fibre material but also manufacturing procedure [1]. Therefore, here we investigate impacts of gamma irradiation on a commercial Cytop POF drawn from a preform. Radiation damages molecular structure of the fibre, which leads to attenuation increase. Fibre's radiation-induced attenuation in the VIS-NIR spectral region is measured and discussed. Moreover, we show that in addition to attenuation increase, irradiation makes fibre more susceptible to moisture. We show that fibre irradiation can be used to sensitize the fibre for humidity monitoring applications.

2. Radiation-induced attenuation

2.1 Fibre irradiation

Commercial Cytop-based MM POF Lucina from Asahi Glass Company was used in this study. The fibre has 120 µm graded-index Cytop core with 500 µm over-cladding and is drawn from a preform. Radiation-induced attenuation (RIA) of the fibre was measured on-line in 400-1000 nm region. A 2.3 m long piece of the fibre was homogeneously irradiated with ⁶⁰Co irradiator up to maximal dose of 36.7 kGy at a dose rate of 267 Gy/h. Halogen lamp (AQ4305, Yokogawa) was used as a broadband light source, while CCD-based spectrometer (HR4000, Ocean Optics) was used to monitor fibre transmission during the irradiation. All auxiliary interconnecting fibres and connectors were shielded from radiation by lead bricks. Fibre's RIA was evaluated from spectral transmission data as

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

where $I(\lambda, t)$ is the recorded transmitted spectral intensity at time t from the start of irradiation and L_0 is the length of irradiated fibre section (2.3 m). Time dependence of RIA evolution was later transform to dependence on radiation dose D accounting for utilized dose rate and irradiation time.

On-line investigation of RIA deeper in the NIR region (> 1000 nm) was not possible with the employed setup. After the irradiation session was finished, spectral attenuation of the irradiated fibre was measured by the cutback method in the NIR spectral region (1000-1700 nm). Halogen lamp light source (AQ4305, Yokogawa) and an interferometric optical spectrum analyser (Q8347, Advantest) were used for off-line spectral attenuation measurements. RIA of the fibre was then evaluated relative to the spectral attenuation of pristine Lucina fibre that was measured by the same method.

2.2 Results and discussion

Figure 1 depicts the spectral dependence of fibre's RIA measured on-line for 400-1000 nm spectral region (a) and off-line for 1000-1700 nm region (b). Measured RIA of the investigated fibre has similar spectral character as in case of co-extruded Cytop POF [6]. Fibre transmission is very radiation sensitive for the visible wavelengths (Figure 1a), where RIA reaches fairly large values of several dB/m already for dose levels under 100 Gy. Magnitude of induced attenuation shows strong spectral dependence and generally increases towards UV wavelengths with a local minima and maxima in the VIS region at around 540 nm and 650 nm, respectively. RIA drops rapidly from the visible region towards the IR wavelengths. Results in the NIR (Figure 1b) indicate much lower magnitude of RIA in this spectral region, considering rather high irradiation dose of 36.7 kGy. RIA spectral profile has a minimum at around 1250 nm, from where RIA starts to grow again towards longer wavelengths. Strong attenuation feature with three distinct peaks is present in the RIA profile around 1400 nm.

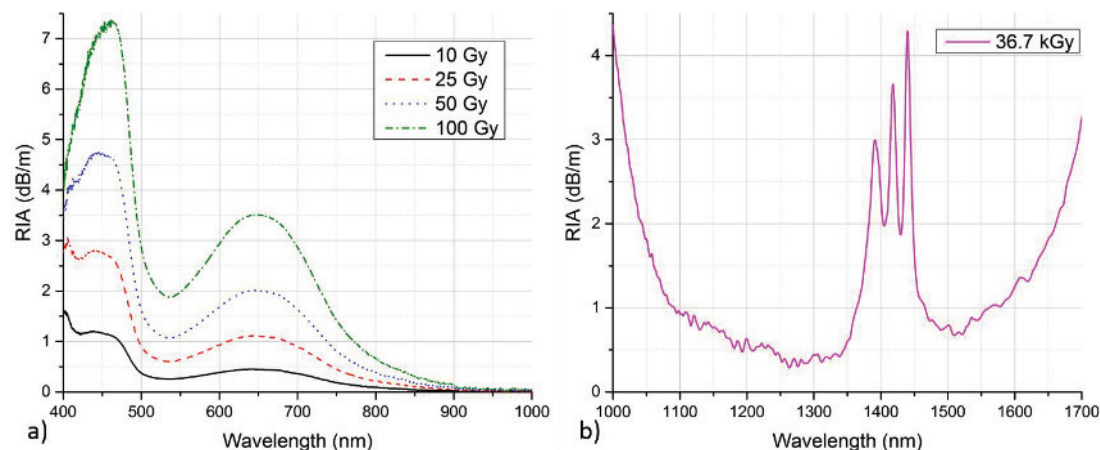


Figure 1. Spectral dependence of fibre's RIA in 400-1000 nm region (a) measured on-line and in 1000-1700 nm region (b) calculated from off-line measurement.

In the case of glass optical fibres, RIA typically comes from an absorption on colour centres generated in the fibre material during irradiation [1]. Presence of paramagnetic centres upon gamma irradiation has been demonstrated previously also for perfluorinated POFs [7]. In addition to colour centre formation, irradiation of polymer materials may lead to more profound alteration of material molecular structure. In particular, formation of systems with increased conjugation is typically associated with attenuation increase and discoloration in polymers. More than one mechanism are involved in RIA increase for POFs in the visible range. With regard to strong RIA feature around 1400 nm, OH group is known to have vibrational absorption overtone in this spectral region [8] and corresponding moisture-related absorption peak has been observed in various optical fibres. Growth of this attenuation feature upon irradiation of Cytop POF indicates increased amount of water absorbed into the fibre. Fibre transmission properties will be therefore more sensitive to environmental conditions around the fibre, namely relative humidity (RH) of the fibre's surroundings.

3 Humidity-induced attenuation

Even though increased humidity susceptibility of the fibre may be undesirable for most of the practical applications, it can be exploited for fibre optic humidity sensing. While pristine Cytop POF is relatively humidity insensitive, attenuation of irradiated fibre at suitable wavelength can exhibit rather large dependence on RH level. Monitoring of fibre attenuation can be then used for humidity sensing. In this section we show, that irradiation can be used to locally sensitize the fibre for RH monitoring applications.

3.1 Methodology

To demonstrate possibility of selective fibre sensitization to humidity, two different segments of 30 m Lucina fibre were irradiated simultaneously to 36.7 kGy while the rest of the fibre was shielded. The same irradiation facility and dose rate as in previous section was used. Approximate position and length of the first irradiated section was 10 m from the beginning of the fibre and 1 m, respectively. The second irradiation section started roughly at 21 m and was approximately 1.6 m long. After irradiation, the fibre was coiled and placed in a cylindrical container. The container with the fibre was kept inside a climate chamber (VCL 4006, Vötsch Industrietechnik) except of connectorised input end of the fibre which was left outside of the chamber. Optical time domain reflectometer (ν -OTDR, Luciol Instruments) operating at 1310 nm was used to monitor fibre attenuation profile. Distributed attenuation measurement enables verification of localized fibre sensitization only in the irradiated regions. RIA as well as humidity-induced attenuation (HIA) in the irradiated fibre are strongly wavelength dependent. Strong inherent attenuation in the fibre would limit the length of the fibre that can be monitored with OTDR technique. On the other hand, monitoring at wavelength where there is no HIA would lead to no RH sensitivity. Selected wavelength of 1310 nm is a compromise between the two criteria. It lies, both, close to the RIA minimum around 1250 nm and on the rising edge of a 1400 nm moisture-related absorption peak. The fibre in the climate chamber was firstly kept at 20 °C and 10 % RH for 24 hours to allow for desorption of excessive water from the fibre. After this time, the container with fibre was filled with water and left in the climate chamber at 20 °C for another 28 hours. Fibre's OTDR trace was measured continuously during this period with 2 minute averaging.

3.2 Results and discussion

Figure 2a compares OTDR traces of the investigated fibre in the climate chamber before (10 % RH) and 28 hours after immersion in water (100 % RH). Two irradiated sections are indicated by red bars on graph X axis.

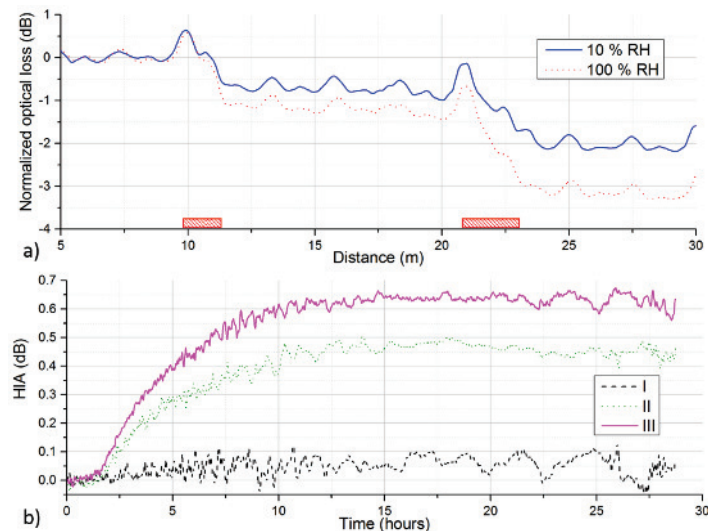


Figure 2. a) Comparison of 1310 nm OTDR traces of 30 m Lucina fibre with two irradiated sections at 10 % and 100 % relative humidity (RH). Position and length of irradiated sections are roughly indicated by red striped bars at the X axis.

b) Relative temporal evolution of HIA in: I – the non-irradiated fibre section (12-20 m); II - the first irradiated fibre section (10-12 m); III - the second irradiated fibre section (21-23 m)

It is obvious that irradiated sections exhibit larger loss than the rest of the fibre. However, induced RIA is small enough so it does not limit OTDR's sensing range in this case. Upon change in RH level, attenuation in the irradiated section rises while the rest of the fibre remains unaffected. This demonstrates that the irradiated sections have been selectively humidity sensitized while the rest of the fibre remains rather humidity insensitive. To evaluate magnitude and temporal response of the humidity-induced attenuation in the irradiated sections, evolution of mean loss values from OTDR traces between different fibre regions are calculated (Figure 2b). Attenuation in the first irradiated section is calculated as difference of mean OTDR loss level of region before the irradiated section (5-9 m) to section after the irradiated section (12-20 m). Relative increase of this difference after fibre immersion in water then expresses HIA evolution in the first irradiated section (Figure 2b – curve II). Analogically, HIA in the second irradiated section (Figure 2b – curve III) is evaluated from the data from 12-20 m versus 24-29 m regions of the fibre. For comparison, also HIA evolution between 12-15 m and 17-20 m regions in the non-irradiated section of the fibre (Figure 2b – curve I) was evaluated.

While there is virtually no HIA increase in the non-irradiated section of the fibre after fibre immersion into water, growth of HIA in the two irradiated sections is obvious. Water absorption into the fibre core is a rather slow, diffusion-based process. Therefore, response time of the fibre is rather long and steady conditions are reached after roughly 15 hours. Magnitude of HIA reaches approximately 0.45 dB and 0.65 dB in the first and second irradiated section, respectively. The difference in HIA levels between the two sections reflect the different lengths of the sections. Higher HIA in the second section, that is roughly 1.6 times longer than the first one, is expected. Presented results demonstrated that irradiation of PF-POF can be used to locally sensitize the fibre for humidity monitoring applications.

4. Conclusion

In the presented work, RIA of a commercial low-loss Cytop POF (Lucina, Asahi Glass Company) was measured in the VIS-NIR spectral region. Fibre exhibits rather high radiation sensitivity in the VIS region with RIA increasing strongly towards the UV wavelengths. On the other hand, sensitivity drops rapidly in the NIR region and has minimum around 1250 nm. Strong moisture-related absorption around 1400 nm was found for the irradiated fibre, showing that irradiation increases fibre's affinity for water. Potential of fibre irradiation as a mean of fibre sensitization for humidity monitoring applications was proposed. Local sensitization and quasi-distributed water detection was demonstrated with partly irradiated Cytop fibre utilizing OTDR measurement at 1310 nm.

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6. References

- [1] 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).
- [2] O. Ziemann, J. Krauser, P. E. Zamzow *et al.*, [POF Handbook: Optical Short Range Transmission Systems (2nd edition)] Springer, Berlin (2008).
- [3] K. Peters, "Polymer optical fiber sensors - a review," Smart Mater. Struct., 20(1), 013002 (2011).
- [4] 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).
- [5] P. Stajanca, D. Sporea, L. Mihai *et al.*, "Gamma Radiation Induced Effects in Perfluorinated Polymer Optical Fibers For Sensing Applications," in [POF Simulation beyond Data Transmission; Summary of the 3rd International POF Modelling Workshop 2015] Books on Demand, Norderstedt, 95-103 (2015).
- [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] A. Sporea, L. Mihai, D. Negut *et al.*, "On-line monitoring of gamma irradiated perfluorinated polymer optical fiber," Proc. of SPIE, 9886, 98861Q (2016).
- [8] J. J. Workman, and L. Weyer, [Practical Guide to Interpretive Near-Infrared Spectroscopy] CRC Press, Boca Raton, FL (2008).