MEASUREMENT OF ^{60}CO GAMMA RADIATION INDUCED ATTENUATION IN MULTIMODE STEP-INDEX POF AT 530 nm

by

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As optical fibres are used ever more extensively in space applications, nuclear industry, medicine and high-energy physics experiments, it has become essential to investigate the influence of ionizing radiation on their characteristics. In this work, the radiation-induced attenuation at 530 nm is investigated experimentally in step-index multimode polymethyl-methacrylate plastic optical fibres exposed to low dose-rate gamma radiation. Cumulative doses ranged from 50 Gy to 500 Gy. The radiation induced attenuation has been empirically found to obey the power law RIA = aD^b**, where** D **is the total radiation dose and** a **and** b **are the constants determined by fitting.**

Key words: plastic optical fibre, gamma radiation, radiation induced attenuation

INTRODUCTION

The importance of plastic optical fibres (POF) has grown tremendously over past decades. The POF are highly promising transmission media for short-range applications including local area network (LAN), multi-node bus networks, sensors, power delivery systems, and light guides (as in toys, entertainment and medical devices). The attractiveness of POF is chiefly due to their low cost, flexibility and ease of handling and interconnecting, while their relatively high attenuation limits the range of systems using them [1]. The main types of POF, their manufacturing and possible present and expected future applications have been reported [2, 3]. The status of POF development over the past half century, focusing primarily on the loss reduction and bandwidth enhancement has been presented by Koike [4, 5]. In many cases, plastic optical fibres may suffer from all kinds of irradiations. A draw-back of POF is that their attenuation is increased by effects of ionizing irradiation: the fibres do degrade irrecoverably with exposure [6-8]. This degradation is primarily by the main chain scissioning and cross-linking in the material of the fibre core, which give rise to material inhomogeneities and results in the radiation-induced optical attenuation. Such loss depends on the fibre type, fibre temperature, wavelength and intensity of the injected light, and irradiation conditions (especially dose rate and total dose). In spite of all fibres undergoing some degradation of optical transmission when exposed to radiation, fibre optic systems are nevertheless implemented in stressing radiation environments, particularly as optical fibre sensors. In radiation dosimetry, for example, optical fibres offer a unique capability for remote monitoring of radiation in difficult-to-access or hazardous locations because fibre sensors can be optically interrogated from a safe distance. Thus, the use of a polymethyl-methacrylate (PMMA) based plastic optical fibre has been reported as an intrinsic real-time gamma dosimeter [9]. Similarly, any fibre system applied in the orbiting space station would be exposed to γ-rays from space, and so would be those in manmade radioactive environments such as in nuclear power plants, nuclear waste repositories [10], and dosimetry [11]. The influence of irradiation should be considered for all these fibre systems. In recent years, changes in optical fibres irradiated by γ-rays have been actively investigated [12-14]. The fundamentals about the theory of radiation-induced absorption in optical fibres can be found in [15-17]. Much work has been reported by Ichikawa investigating the radiation degradation of PMMA [18].

In this work, the rise of attenuation in plastic optical fibre has been demonstrated in real-time during a

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low intensity irradiation by gamma rays. Green light emitted diode (LED) was used for light source to represent the frequency that is of interest for PMMA fibers. This effect was then investigated experimentally and quantified empirically. The fibre was exposed to the field of gamma radiation generated by a ^{60}Co head produced by Cisbio International (Cyrus model). The overall performance of the plastic optical fibre subjected to radiation is discussed.

RADIATION-INDUCED ATTENUATION IN STEP-INDEX POF EXPOSED TO GAMMA RADIATION

The irradiation degrades polymers by effects such as cross-linking, change of unsaturated link number, and production rate of fallen free radicals. All these changes can reflect the change of polymer material characteristics. In many polymers, both processes – main-chain scissioning (degradation) and cross-linking – take place in parallel. However, in certain cases, the scission dominates the cross-linking, and such polymers are known as degrading polymers. The PMMA is one such polymer. The irradiation cross-link in PMMA is the phenomena of the polymer molecule linking together through bounds, the result is the polymer molecular mass increases with absorbed irradiation dose. Irradiation degradation is the process of the polymer main link breaking off under high energy radiation, and the results is the molecular mass decreases with absorbed irradiation dose, so much as some polymer molecule degradation into monomer molecule. In both processes, after irradiation, the chemical structure of polymers changes, leading to radiation damage effects that cause the POF radiation induced attenuation to increase.

Using the Beer-Lambert law, it is possible to determine the radiation-induced attenuation (RIA) in the optical fibre. As optical attenuation is directly related to the fibre length, by monitoring the optical power in the fibre it is possible to determine the attenuation that was due to gamma radiation [9]

$$RIA \quad \frac{10}{L}\log\frac{P_{\mathrm{T}}(\lambda,t)}{P_{\mathrm{T}}^{0}(\lambda)} \quad [\mathrm{dB/km}] \qquad (1)$$

where L is the irradiated length of the test fibre, $P_{\mathrm{T}}(\lambda, t)$ – the measured optical power in the irradiated test fibre, and $P_{\mathrm{T}}^{0}(\lambda)$ – the optical power of the reference fibre which is not irradiated.

EXPERIMENTAL PROCEDURE

To conduct the radiation test, a PMMA-based plastic optical fibre was used as supplied by Mitsubishi Rayon Eska Optical Fibre Division with the core diameter of 0.98 mm and cladding diameter of 1 mm (core index 1.49, attenuation 0.2 dB/ml). The fibre was prepared with a length of 4 m and arranged into a spiral on an 80 mm diameter Perspex coil and placed into an irradiation container for exposure to gamma radiation. The an LED illuminated the fibre (IF-E93; λ = 530 mm). A low cost CMOS web camera displayed and recorded the beam profile on a notebook PC computer using LabVIEW$^{\mathrm{tm}}$ software [19]. The overall experimental set-up for *in situ* monitoring of the fibre attenuation during irradiation is shown in fig. 1. To account for the instability of the LED output, an optical beam splitter and a photo-detector IF-D93 (Darlington type) were used. The integrated design of the IF-D93 makes it a simple, cost-effective solution in a variety of applications. The optical response of the IF-D93 extends from 400 nm to 1100 nm, making it compatible with a wide range of visible and near-infrared LED and other optical sources. Light source and photo-detector is housed in a "connector-less" style plastic fibre-optic package, to which the POF can be easily connected.

The fibre was irradiated at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, in the irradiation chamber shown in fig. 2.

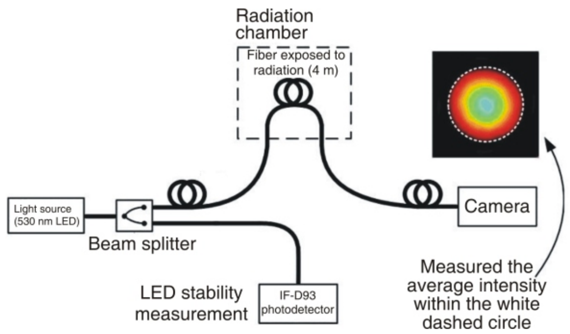

Figure 1. Experimental set-up

Figure 2. The ^{60}Co radiotherapy unit as source of gamma radiation for POF

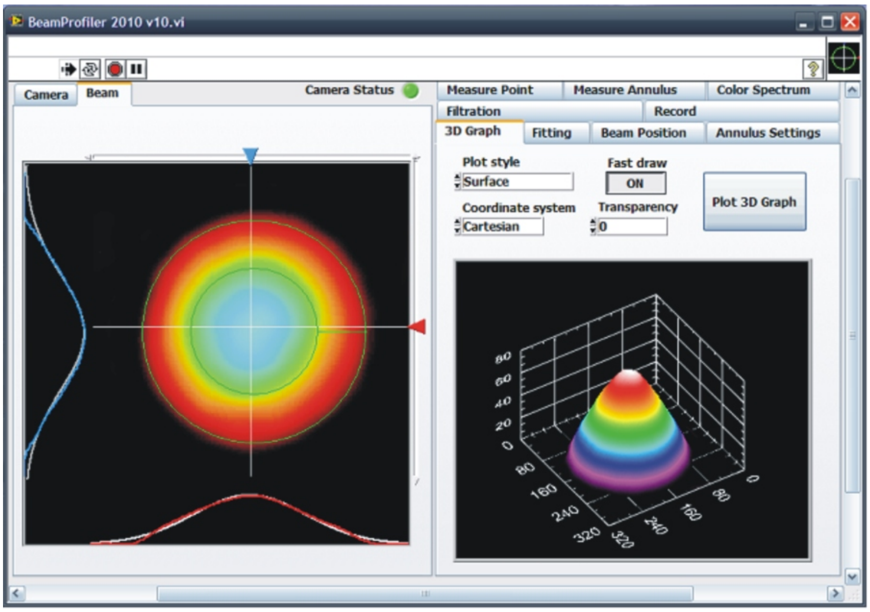

Figure 3. Front panel for optical beam profiling

RESULTS AND DISCUSSION

The fibre sample was irradiated by ten different radiation doses estimated to range from 50 Gy to 500 Gy. With polished fibre end-surfaces for reliable optical coupling, the power transmission test was conducted before and after irradiation using the set-up shown in fig. 1 that also provided visualization as indicated in fig. 3. The system performs real-time image-streaming and facilitates measurement, capture, display, and recording of parameters being measured. The experimental results are summarized in tab. 1.

As the function of the absorbed dose, fig. 4 shows normalized light output at the fibre end. This intensity was extracted from the measured optical beam profile as the average incident light output recorded by the camera. With the LED performance verified every 10 seconds drift-free fibre input was noted throughout the measurement with stable average value. The fibre output, on the other hand, was found to decrease with the radiation dose that the fibre received. The functional relationship between the normalized optical

Table 1. Normalized output and radiation-induced POF attenuation

Dose [Gy]	Normalized output	RIA [dB/m]
0	1	0
50	0.94340	0.063260
100	0.89598	0.119254
150	0.86806	0.153626
200	0.83876	0.190905
250	0.82525	0.208536
300	0.80967	0.229229
350	0.80230	0.239158
400	0.78960	0.256482
450	0.78287	0.265775
500	0.77639	0.274800

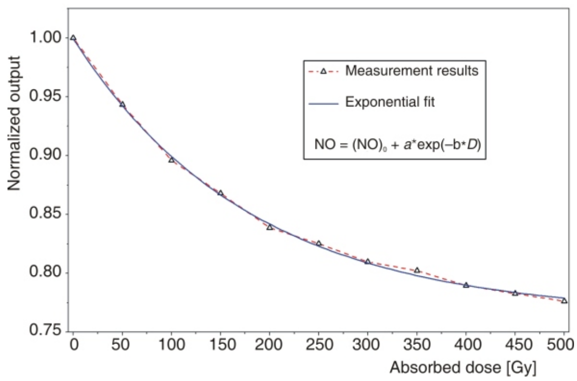

Figure 4. Normalized output power *vs.* absorbed dose

output and absorbed dose that best fits the curve of fig. 4 is

$$NO \quad (NO)_0 \quad ae^{\ bD} \qquad (2)$$

where *NO* and *D* are the normalized output and absorbed dose, respectively, with the other constants determined by curve fitting: $(NO)_0 = 0.8$ $a = 0.2$, and $b = 0.005$.

Normalized LED stability measured through the reference fibre that was not irradiated is shown in fig. 5.

For the measured data, Beer-Lambert law calculations (1) of the RIA as a function of the absorbed dose are shown in fig. 6. It follows that as the gamma radiation dose increases, so does the radiation induced absorption in plastic optical fibre. The increase in the induced fibre attenuation is directly related to the dose of incident radiation. The results in fig. 5 indicate that the radiation induced absorption RIA varies with the radiation dose *D* as $RIA = aD^b$, where *a* and *b* are constants determined by fitting of the experimental results ($a = 0.01$ and $b = 0.5$).

This is attributed to the radiation-induced main-chain scissioning and to cross-linking of the poly-

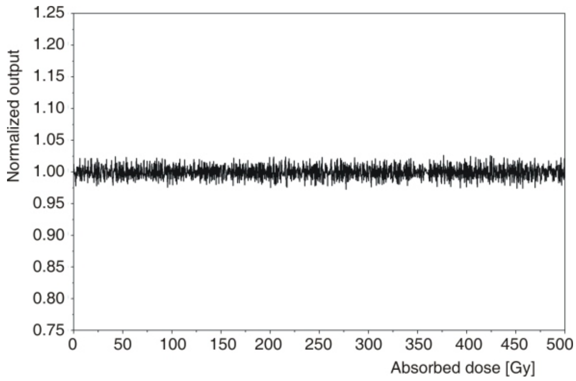

Figure 5. Normalized LED stability *vs*. absorbed dose

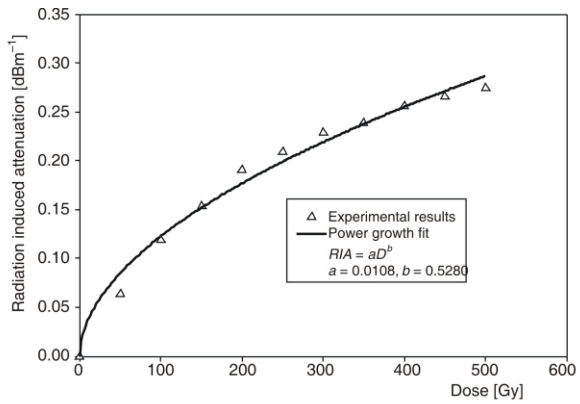

Figure 6. Real-time radiation induced attenuation at λ = 530 nm

mer molecules resulting in the molecular mass increase with absorbed dose. As PMMA is irradiated with ionizing radiation, such as gamma radiation, a free radical is generated on the ester side-chain-$COOCH_2$ (see fig. 7). This side chain radical may be generated in a number of ways [18]. This process leads to radiation induced attenuation, *i. e*. irradiation damage effects. The irradiation stability is dependent on the energy transmitted inside polymer and the molecule special effect.

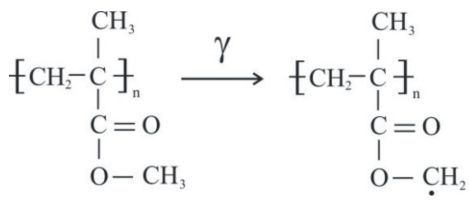

Figure 7. The PMMA polymer molecule that irradiated with ionizing radiation

CONCLUSIONS

The effect of a low-dose gamma-radiation on light transmission in step-index plastic optical fibres was investigated in this work. The results showed that the transmitted power is reduced by irradiation. This is because polymer molecule consists of millions of monomer nits and only a small chemical change caused by irradiation may change the physical performance. The irradiation cross-link is the phenomena of the polymer molecule linking together bonds; the results are polymer molecular mass increases with absorbed irradiation dose. This process leads to radiation induced attenuation, *i. e*. irradiation damage effects. The radiation induced attenuation deteriorates the performance of the plastic optical fibre causing the POF transmission loss to increase. The results indicate that the radiation induced absorption follows the power law $RIA = aD^b$. A good agreement of our experimental data and prediction of theory proposed by Duncan *et al,* [15] was obtained.

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AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by M. S. Kovačević, A. Djordjevich, and S. Savović. Literature research was carried out by M. P. Slankamenac and M. S. Kovačević. Experiments were carried out by J. S. Bajić, D. Z. Stupar, M. S. Kovačević, and M. Kovačević. Calculations were performed by S. Savović, A. Djordjevich and M. S. Kovačević. Figures were prepared by J. S. Bajić, D. Z. Stupar, and M. P. Slankamenac. All authors discussed the results and participated in the writing of the manuscript.

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МЕРЕЊЕ СЛАБЉЕЊА У МУЛТИМОДНОМ ОПТИЧКОМ ВЛАКНУ НА 530 nm УСЛЕД ОЗРАЧИВАЊА ГАМА ЗРАЦИМА ИЗ ^{60}CO

С обзиром на све чешће примену оптичких влакана у свемирским станицама, нуклеарној индустрији, медицини и експериментима у физици високих енергија, постало је веома важно испитати утицај јонизујућег зрачења на њихове карактеристике. У овом раду је експериментално испитивано слабљење у мултимодном пластичном оптичком влакну на 530 nm као последица озрачивања гама зрацима ниске дозе. Кумулативне дозе гама зрака биле су у опсегу од 50 Gy до 500 Gy. Емпиријски је утврђено да се слабљење изазвано гама зрацима ниске дозе – RIA мења као RIA = aD^b, где је D укупна доза озрачивања, а a и b су константе чије су вредности добијене фитовањем експерименталних података.

Кључне речи: пластично оптичко влакано, гама зрачење, слабљење изазвано гама зрачењем