Optical fibre sensor for the online monitoring of gamma radiation doses

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Abstract. The radiation-induced attenuation in poly-methylmethacrylate (PMMA) based plastic optical fibres is monitored online during exposure to gamma radiation, in an investigation into their use as an intrinsic real-time gamma radiation dosimeter. The PMMA fibre exhibited a linear radiation-induced attenuation response at various wavelengths for a dose range of 50Gy to 50kGy. The sensitivity, ranging from 0.4 dBm -1/kGy to 0.03 dBm -1/kGy, is wavelength dependent, with higher sensitivity at the lower wavelengths.

1. Introduction
In all radiation processes, dosimetry is involved as a necessary control to establish the processes and to provide the quantitative baseline against which the biological or chemical changes induced by the radiation can be measured. Gamma irradiation is widely used in the sterilisation of medical products. Currently there is no commercially available technology to provide remote real-time information of the gamma dose present in sterilisation facilities. One of the most widely used gamma dosimetry technique involves the use of dyed PMMA (poly methylmethacrylate) slides, which change colour on exposure to gamma irradiation. This radiation-induced attenuation is monitored using a spectrophotometer post-irradiation [1,2]. Different ranges can be monitored depending on the dye used, e.g., Harwell Red 4034 has a dose range of 5 kGy to 50 kGy, and Harwell [3] Gammachrome YR has a dose range of 100 Gy to 3 kGy. One of the main drawbacks of this system however, is the lack of real-time information. The PMMA slabs must be removed from the area of interest to be tested in a laboratory, and thus there is no information available on the dose until after irradiation is completed.

Optical fibres offer many advantages for monitoring gamma radiation doses, such as their immunity to electrical and electromagnetic interferences. The ability to remotely monitor radiation in real-time is also an advantage of optical fibres. The sensor can be placed several hundred metres from the control electronics, which means that they can be employed in harsh environments, such as in high-radiation-level areas in the vicinity of a nuclear reactor. Optical fibre sensors can also be multiplexed so that a single controller can monitor a number of sensors.

This project investigates the use of PMMA based plastic optical fibres for on-line dosimetry. Based on the same principle of radiation-induced attenuation as the commercial PMMA slabs use, by using...
PMMA optical fibres an in-situ system can be realised giving real-time information of the gamma dose received. However, unlike silica based optical fibre sensors, these PMMA optical fibres do not require any dopants for sufficient radiation sensitivity and so low cost, off-the-shelf PMMA fibres can be used. PMMA optical fibres offer a number of advantages to allow for a cost effective dosimetry system. Due to the large fibre cross-section of plastic optical fibres, connecting to the light source and detector is non-problematic. This means that no expensive precision components are required for centering the fibres. In addition, minor contamination, e.g. dust on the fibre end face, does not result in the complete failure of the sensor system due to its large core diameter. Consequently, fibres can be connected on site in industrial environments with relative ease and without affecting the system. PMMA is also easy to cut, grind and melt and so an uncomplicated process, requiring relatively little time, for processing the end faces is necessary to achieve a clean and smooth surface [4]. These fibres are extremely low in cost when compared with glass optical fibres. The properties of PMMA plastic optical fibres also results in relatively economical connectors for the system, which further contributes towards a low cost solution. By combining the traditional method of dosimetry using PMMA slabs, which is widely accepted for its reliability and stability, with optical fibre sensing methods, which will allow for on-line measurements, a reliable and cost effective real-time sensing method for routine gamma radiation dosimetry can be realised.

2. Gamma irradiation facility
The fibres were irradiated at the GEUSE II (Gamma Experiment Using Spent-fuel Elements) gamma irradiation, at the Belgian Nuclear Research Centre, SCK-CEN. GEUSE II is an underwater facility consisting of an irradiation container surrounded by 18 standard fuel assemblies, as shown in figure 1. Although the nuclear fuel is composed of many radioactive isotopes, the most important contribution to the gamma activity comes from $^{137}$Cs, and thus GEUSE II gives a $^{137}$Cs spectrum-like irradiation. The irradiation container is equipped with heaters to control the temperature up to 200°C. A schematic of the radiation facility is shown in figure 2. The fibres were irradiated at 700 Gy/h for 71 hours, with the temperature maintained at 40°C. [5]

![Figure 1. GEUSE II spent-fuel gamma irradiation facility.](image1)

![Figure 2. Schematic view of the spent fuel irradiator GEUSEII.](image2)

3. Online experimental set-up
The experimental set-up used to monitor the attenuation in the fibres in-situ during irradiation can be seen in figure 3. Two commercially-available PMMA-based plastic optical fibres, with 1mm core, were prepared, each with a length of 20m and terminated using SMA connectors. The fibres were
passed through a hose into the irradiation container for exposure to gamma radiation. One fibre was used as a reference fibre, in which 1m of the fibre was irradiated. The second fibre had a 7m length of the fibre irradiated. A tungsten halogen white light source ANDO AQ4303A was used to illuminate the fibres, with a bifurcated fibre being used to split the light between the two fibres. An Ocean Optics S2000 Dual-Channel Spectrometer was used to spectrally resolve the optical signal from both PMMA fibres.

4. Results
The transmission spectra of the fibres were monitored during irradiation, a sample of which can be seen in figure 4 [6]. It was found that over time, as the gamma radiation dose increased, the light intensity decreased in the fibres. Due to the difference in length being irradiated of the reference fibre and test fibre, the rate at which the spectra attenuated differed. The test fibre, which has a 7m length of fibre irradiated, shows a considerably larger attenuation when compared with the reference fibre, which has a 1m length of fibre irradiated. It is apparent that the lower wavelengths are more significantly affected, which is agreeable with previous off-line tests [7].

Figure 3. Online experimental set-up.

Figure 4. Transmission spectra of the test and reference fibres prior and during irradiation at 910 Gy.
4.1. Radiation-induced attenuation

Radiation-induced attenuation (RIA) calculations were performed on the transmission spectra in real-time. A number of different wavelengths were selected to determine the different ranges of sensitivities of the PMMA optical fibres. The results of this on-line analysis can be seen in figure 5.

![Radiation Induced Attenuation](image)

**Figure 5.** Real-time Radiation-Induced Attenuation (RIA) at varying wavelengths.

The results indicate a linear radiation-induced attenuation response. The sensitivity of the PMMA optical fibre to the radiation is seen to be dependant on the wavelength, with the sensitivity increasing with decreasing wavelength. The sensitivity, the linear regression fit and the dose range are given in table 1.

| Wavelength (nm) | Sensitivity (dBm⁻¹/kGy) | Linear fit, \( R^2 \) | Dosimetry range (kGy) |
|-----------------|-------------------------|-----------------|----------------------|
| 530             | 0.4                     | 0.9983          | 0-3                  |
| 570             | 0.2                     | 0.9972          | 0-5                  |
| 600             | 0.1                     | 0.9936          | 0-10                 |
| 650             | 0.05                    | 0.9904          | 5-20                 |
| 680             | 0.03                    | 0.9913          | 5-50                 |

**Table 1:** Wavelength dependence of the gamma sensitivity of the POF fibers

It is clear that there is a very high sensitivity at 530nm, compared to a significantly lower RIA response at 680nm. Consequently, the sensitivity of the gamma dosimeter can be determined by the precise selection of the monitoring wavelength. Due to the high gamma radiation-induced attenuation of the PMMA fibre at wavelengths below 600nm it was found that the optical signal was attenuated completely in a very short time and thus it was no longer possible to monitor the effects of the radiation on the fibre at these wavelengths for higher doses. Figure 6 shows the RIA at doses between 47 kGy and 50 kGy at 680nm. Although the sensitivity at these wavelengths is low, the attenuation in the fibre is still evident, demonstrating the ability to monitor gamma radiation doses up to 50 kGy. As saturation of the fibre has not yet been reached at 50 kGy, it is envisaged that even higher doses can be measured. The difference in the sensitivity at the higher dose is due to the low optical signal at these doses, giving a high signal-to-noise ratio. Figure 7 shows the radiation-induced attenuation at doses up to 300 Gy at 530nm. The high sensitivity of the fibre to radiation at this wavelength is evident and demonstrates the ability to measure doses as low as 50 Gy. This gives an overall range for the
dosimeter of between 50 Gy and 50 kGy. This exceeds the range of any low cost gamma dosimeter currently available.

![Figure 6. Radiation-induced attenuation at high doses (sensitivity: 0.04 dBm/1 kGy, R²: 0.8985).](image)

![Figure 7. Radiation-induced attenuation at low doses (sensitivity: 0.4 dBm/1 kGy, R²: 0.9313).](image)

4.2. Recovery of the fibre

The fibres were also monitored over 14 days in real-time after the irradiation ceased to evaluate their recovery post-irradiation. Figure 8 shows the initial recovery of the fibre over 67 hours. As the optical signal is still fully attenuated at some wavelengths it was only possible to monitor wavelengths at 650 nm and 680 nm. The results show that the fibres begin to recover immediately after irradiation has ceased as the radiation-induced attenuation decreases.

![Figure 8. Radiation-induced attenuation measured online, monitoring post-irradiation recovery, for the initial 3 days.](image)

![Figure 9. Radiation-induced attenuation measured online, monitoring post-irradiation recovery, from 90-330 hours.](image)

The long-term recovery of the fibres is shown in figure 9. As the fibre begins to recover the optical signal improves and so it is possible to begin monitoring the lower wavelengths after 200 hours. The radiation-induced attenuation decreases linearly indicating a linear recovery within the fibre. After 280 hours, the recovery of the fibre appears to slow down considerably. This is due to the reference fibre having completely recovered, while at some wavelengths the test fibre is still recovering. In order to obtain a more in-depth analysis of the recovery of the fibre a different set-up is required, whereby the reference fibre is not irradiated.
5. Conclusions
The ability to monitor gamma irradiation in real-time has been demonstrated. The fibres exhibited a linear radiation-induced attenuation response, at various wavelengths, corresponding well to the Beer-Lambert Law. Due to the intrinsic nature of the PMMA plastic optical fibre, it was possible to monitor the light between 500nm and 700nm. The sensitivity of the fibres to the radiation dose was seen to be wavelength-dependant. Due to this variance in sensitivity, it was also found that the dose range was also wavelength dependant, as the fibre was completely attenuated at lower wavelengths while at higher wavelengths, where RIA sensitivity was less, there was still a measurable signal. The fibres exhibit good sensitivity, as high as 0.4 dBm-1/kGy, and are capable of monitoring dose ranges between 50 Gy and 50 kGy. This exceeds the sensing range of all currently available sensors. The exact sensitivity and dose range can be chosen by careful selection of the monitoring wavelength. The fibres begin to recover immediately after irradiation, although they do not fully recover at all wavelengths. Due to the low cost of these PMMA fibres it is possible to consider such dosimeters as disposable sensors, similar to the PMMA slabs currently in use. Further work will involve increasing the integration time during the course of the irradiation. This will allow for an increase in the optical signal, thereby allowing the attenuation due to irradiation to be monitored at higher doses. This will significantly improve the dose range at lower wavelengths. [6]

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