Plastic scintillator-based fibre dosimeters for measurement of X-ray pulses in a clinical setting

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ABSTRACT

This work presents the development of plastic scintillator (BCF-10) based optical fibre sensors for medical radiotherapy dosimetry. Two different designs of BCF10 joined to PMMA (Polymethyl methacrylate) fibre were considered, based on simple Plug and Play designs for the rapid and effective assembly of radiation sensors. The first design was a simple butt-coupling arrangement sheathed in tubing, with an outer diameter of <2 mm. The second design explored the coupling joint of a cylindrical protrusion and hollow part of BCF10-PMMA that were achieved using femtosecond laser machining; the purpose of which was to maintain the original 1-mm fibre diameter for the sensor probe. The two fibres were pressed together and sealed with UV curing, hence the reference to a Plug and Play architecture. Both sensors exhibit higher output counts at the higher dose rate (due to the higher number of radiation pulses), although a discernible signal is observed at 50 MU/min for 6 MV, 15 MV energies and both sensors. When comparing both sensors with the different joint coupling designs, the flat surface connection of BCF-10 to PMMA demonstrates slightly higher photon counts compared with the micro-machined sensor (Plug n Play). However, the difference is small and the Plug n Play sensor benefits from the smaller sensor diameter (1 mm diameter), which is suitable for inserting into a small applicator or in-vivo monitoring. In the second section, micro-pulses of X-Ray radiation from Siemens Linear Accelerator (linac) were obtained and compared for two different energies and dose rates. Both of the sensors demonstrate the feasibility to be used for characterisation of X-ray pulses from a clinical linac.

Keywords: Optical fibres, BCF-10, X-ray, Radiation Sensor, Femtosecond laser micro-machining

1. INTRODUCTION

Radiotherapy is a cancer treatment option that uses high energy radiation beams to treat tumours or cancer cells. The aim of radiotherapy is to maximise radiation into the targeted tumour with minimal radiation exposure to healthy neighboring tissue or organs at risk (OAR). The use of a radiation dosimetry system is essential to allow for effective and safe radiation therapy for each patient. There are many types of dosimetry systems and herein, we focus on the discussion of optical fibre dosimeters.

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The most common fibre dosimeter employs scintillating material at the tip of the fibre. When the fibre is exposed to ionizing radiation, the scintillating tip converts the radiation into a visible light wavelength, guided towards the distal end of the fibre to a detector. These scintillators are developed based on inorganic scintillators or organic (plastic) scintillators [1, 2]. An inorganic scintillator has higher light-production efficiency and larger X-ray absorption [3]. However, the high Z-number of inorganic materials and slow response time pose challenges for dosimetry applications. Organic scintillators on the other hand are water-equivalent, where the use of water-equivalent dosimeters allows for accurate measurement of radiation dose deposited in tissue. Using plastic scintillators also has an advantage that light generated is linearly proportional to the energy deposited in them by photons and electrons [4].

For radiation therapy applications, there is a high demand for small and accurate fibre probes for real time measurement of radiation, particularly for *in vivo* monitoring. The fibre is inserted into the patient intravenously to measure the dose applied to the patient during radiation therapy. For some cases, where small-sized detectors are needed, the scintillators were spliced together with non-scintillating fibre. In practice, the overall size of the scintillator-fibre probe could be large to assure that the sensor has good coupling efficiency and is robust (e.g. using UV glue or a polymer tube to join both fibres). To overcome the size requirement and at the same time increase the collection efficiency of the scintillating light, some dosimeters incorporate a coating of reflective paint at the scintillator tip e.g. BC-620 to increase the light capture [5, 6]. However, the use of these paint materials may reduce the water-equivalence of the probe, scattering more radiation than lower Z materials.

This paper presents the use of specially coupled BCF10-PMMA design fibre dosimeters employing laser processing of the fibre using a femtosecond laser for X-ray radiation dose measurement in a clinical setting [7]. The coupling joint design using femtosecond laser micro-machining would provide new opportunities to overcome the shortcomings of the conventional dosimeters, to physically improve the robustness of the sensor probe at the joint, without compromising on the size of the dosimeter. The sensor was compared with a standard butt-coupling BCF10-PMMA assembly for real-time radiation detection. Both sensors have been investigated using a linac for radiotherapy treatment.

2. METHODOLOGY

2.1 Fibre Fabrication - Femtosecond laser

Two different designs of BCF10 joined to PMMA fibre were considered, based on a simple butt-coupling with tube and a Plug and Play design for the rapid and effective assembly of radiation sensors as illustrated in Figure 1. The first design was a simple butt-coupling arrangement sheathed in a tight fitting tubing, with an outer diameter of <2 mm; the fibre was fabricated using a 1 m PMMA fibre with a short length of 5 mm plastic scintillating fibre BCF-10. The butt-coupled fibres were flat cleaved and joined to realize a BCF-10:PMMA fibre sensor. In order to reduce the outer sensor diameter further, without compromising sensor robustness, we explored and employed laser processing of the fibres using a femtosecond laser and each fibre underwent laser micro-machining. In the 5 mm length of BCF-10 fibre, the femtosecond laser selectively removed fibre cladding until a central cylindrical protrusion was realized ("male" joint). The 1 m length of PMMA fibre underwent core/cladding removal at one end in order to produce a cylindrical hollow (a "female" joint). The outer and inner dimensions of the cylindrical protrusion and hollow were precisely micro-machined to enable a coupling joint to be made when the fibres were pressed together, hence the reference to a Plug and Play architecture (Figure 1(b)). A small amount of UV curing was used to seal the joint and the outer diameter was reduced to only 1 mm, which is ideal for dosimetry applications. The BCF-10 scintillating fibre emits blue light at peak wavelength of 432 nm during irradiation.

Figure 1: Schematic diagram of two BCF10-PMMA joint design (a) butt-coupling in a tight tubing , (b) Plug and play architecture.

2.2 Experimental Setup

The 1-m length BCF-10: PMMA fibre sensor was inserted into the centre of a solid water phantom as shown in Figure 2. To allow for a more accurate and constant dose of energy delivered, the sensor was placed at the depth of maximum dose (d_{max}) region for each energy; which is 1.5 cm for 6 MV and 3 cm for 15 MV energy photon beams in our case. Field size was set to be 10x10 cm^2 and 100 cm source to surface distance (SSD). The fibre sensor is extended using a 20-m PMMA fibre to allow for connection to the C13366GU multi-pixel photon counter (MPPC) located outside the bunker room. This MPPC allows reading of time resolved photon intensity through a connection to a PC using a standard USB cable. The data was captured with a gate time setting at 100 ms and at 0.5 p.e. threshold. The MPPC enables the reading of analog signal output by connecting the port to an external oscilloscope or a frequency counter. To investigate the analog pulse from the fibre dosimeter during irradiation, a Teledyne Lecroy WaveSurfer oscilloscope was used to capture the pulse shape and to calculate the pulse repetition rate during irradiation.

Both fibres were exposed to two different energies of X-ray pulses, namely 6 MV and 15 MV, from a Siemens Oncor Avant Garde linear accelerator in a clinical setting. For each energy, high dose rate (HDR) pulses of 300 MU/min for 6 MV and 500 MU/min for 15 MV were used, whereas low dose rate (LDR) pulses of 50 MU/min for both energies were also investigated. All measurements were performed with a radiation dose of 100 Monitor Units (MU), where 1 MU equated to 1 cGy at D_{max} for the 10x10 cm^2 fields. All measurements were taken in Galway clinic, Ireland.

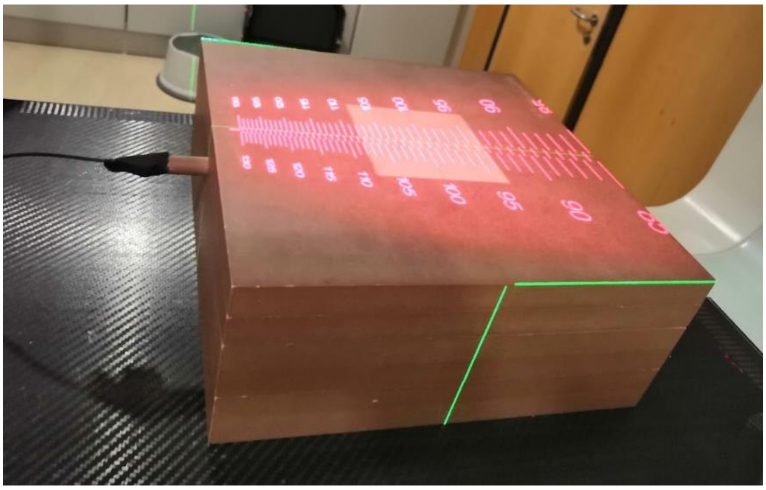

Figure 2. Experiment setup, fibre dosimeter inserted into the centre of water equivalent phantom and irradiated with field size of 10 x 10 cm^2.

3. RESULTS AND DISCUSSION

Figure 3 illustrates the results of the photon counts comparing two different sensor designs, namely Plug and play (PnP) in blue and simple butt-coupling sensor in tube (tube) in red. The rectangular plateau at each graph represents the signal (counts) detected when the radiation beam was on. The length of the radiation beam on is dependent on the dose rate and radiation dose delivered. The average dark count rate (DCR), i.e. the background noise when there is zero light input for the measurement at 0.5 pe threshold, was calculated to be 1158.6 counts during the PnP measurement and 1177.9 for the sensor in tube.

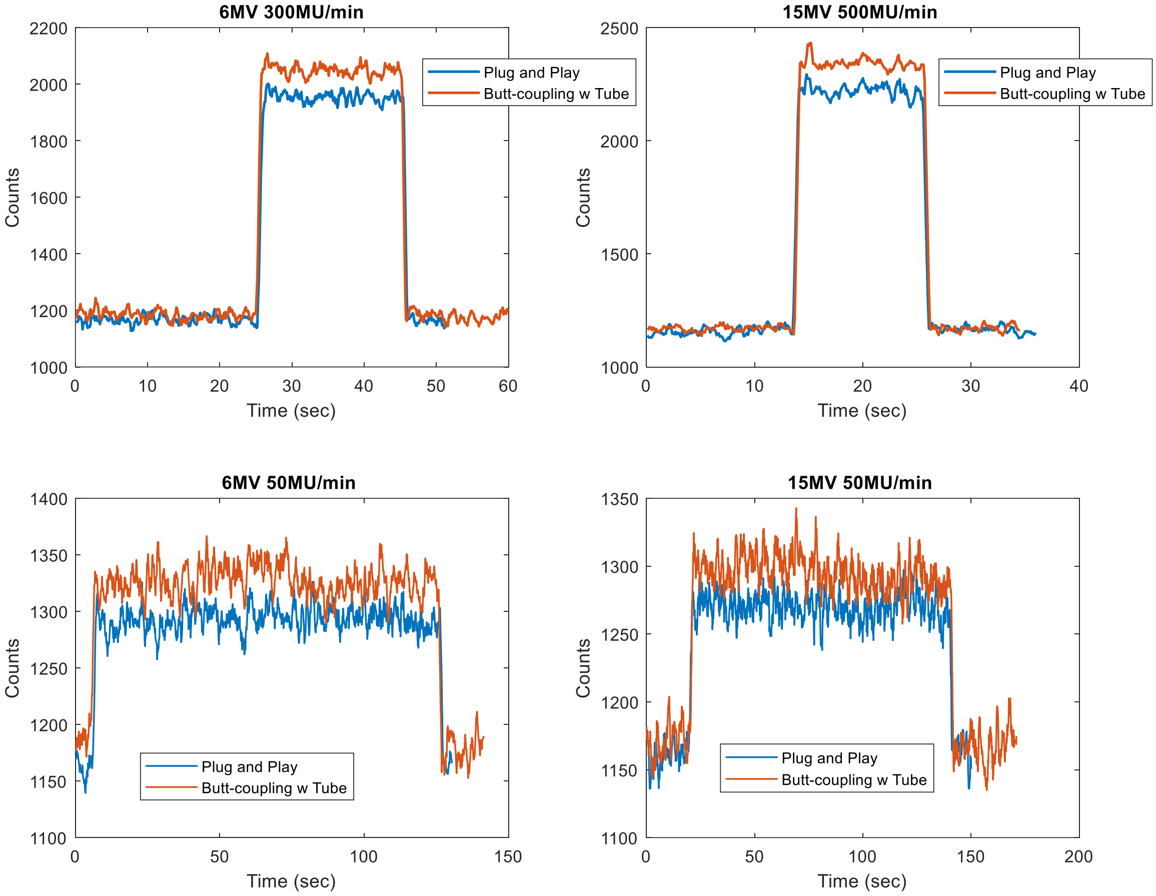

Figure 3. Output signal of two BCF-10 based fibre sensor with plug and play design and simple butt-coupling design.

Both sensors exhibit a good signal with higher output intensity for the measurement performed with high dose rate and lower output intensity for both energies with low dose rate at 50 MU/min. The sensor with simple butt-coupling design exhibits a slightly higher output intensity compared with the PnP configuration. To allow for a fair comparison and to investigate energy dependence, the optical signal corresponding to the total dose was calculated by integrating the signal for the “beam on” duration (rectangular plateau). To perform the integration of the rectangular plateau, the average output signal during irradiation is deducted by the background noise and multiplied with the total time duration of irradiation for 100 MU. The integrated area for all measurement categorized by the different energies and dose rates are summarized in Table 1 below:

Table 1. Summarized table for integrated output signal for both sensor configuration.

Energy	6 MV			15 MV			Energy dependence Difference
Dose Rate	300 MU/min (HDR)	50 MU/min (LDR)	% Difference	500 MU/min (HDR)	50 MU/min (LDR)	% Difference	
Plug &Play	15889.21	16167.77	1.73%	12746.88	13394.7	4.48%	2857
Butt-coupling with tube	17411.1	17894.11	2.74%	13938.55	14123.57	1.16%	3621

The output response (signal integration for beam on) between HDR and LDR for each energy and fibre type has very small differences, which indicates that the integrated output is independent of the dose rates for plastic scintillators [8]. The overall integrated beam on output for low dose rate conditions is slightly higher compared to the high dose rate, possibly due to the lower signal to noise ratio, where the output signal in excess of the DCR as in Figure 3 is lower for the case of 50 MU/min. Overall, the discrepancy between HDR and LDR is low with a maximum difference of 4.48%.

Table 1 also illustrates the energy dependence characteristic shown using the organic scintillator based fibre. For the PnP design sensor, the integrated output signal demonstrates an increase of 22. 6% for the 6 MV energy compared to 15 MV, while the tube design sensor showed an increase of 25.8% from 15 MV to 6 MV. This illustrates the energy dependence characteristic and feasibility of both sensor design for conversion of the output signal into measured dose during patient treatment.

As discussed previously, the overall output signal is slightly higher for the fibre with tube compared with the PnP design sensor. However, the PnP design with smaller sensor diameter of 1mm offers significant advantages e.g. where it is easily guided within existing brachytherapy equipment, such as biopsy needle or catheter. The feasibility of plug and play design for radiation dose measurement with energy dependence characteristic during external beam radiotherapy (EBRT) will allow for optimization of the radiation treatment and result in high quality treatments.

3.1 Analog Output From Oscilloscope

This section presents the analog output pulses captured using an oscilloscope during irradiation. Although a full radiation duration of pulse range cannot be captured by the scope due to the scope limitation, the pulse repetition rate over a selected time range captured can be observed and calculated for comparison. Figure 4 illustrates the analog pulses captured using an oscilloscope during irradiation on PnP sensor. The timescale was set to capture a range of multi-pulses for calculation of pulse repetition rate during irradiation at different energy and dose rates. A higher pulse frequency was observed for the high dose rate (Figure 4(a) and (c)), with a relatively lower pulse frequency for the case of LDR radiation (Figure 4(b) and (d)). The analog output pulse repetition rate was calculated for both types of sensors and is summarized in
Table 2. Both sensors measured the similar analog pulse frequency of 230 Hz, 38 Hz, 224 Hz and 22 Hz for 6 MV 300 MU/min, 6 MV 50 MU/min, 15MV 500MU/min and 15 MV 50 MU/min, respectively. The periodic pattern of the sensor pulse demonstrates the feasibility of using the sensor to profile pulses of X-rays delivered from the Siemens Linac for all settings (2 energies and 2 dose rates).

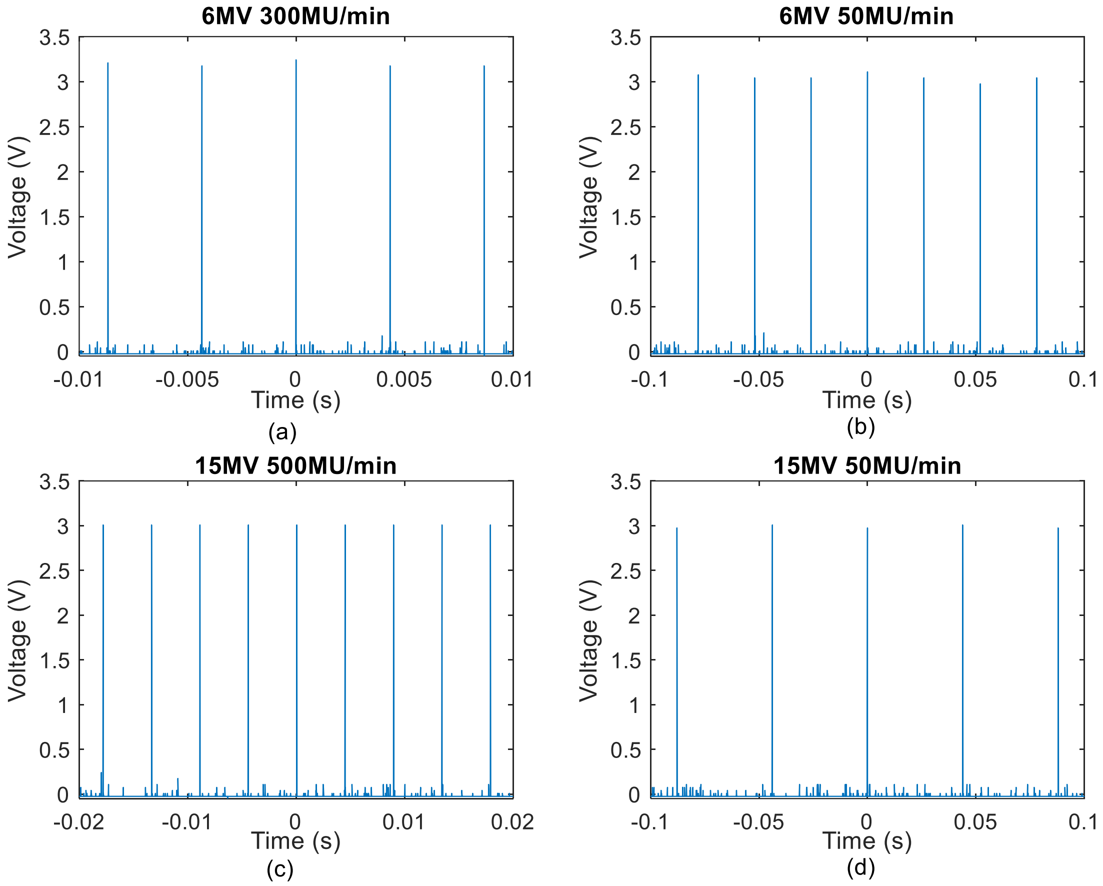

Figure 4: Analog output pulses captured at different energy and dose rate during irradiation on Plug and Play sensor.

Table 2: Summarized table of pulse repetition rate captured at energy level 6 MV, 15 MV , high dose rate and low dose rate for both dosimeter.

Energy	Dose Rate	Pulse Repetition Rate (Hz)	
		Plug and Play	Butt-Coupling with Tube
6 MV	300 MU/min	230.68	230.2
6 MV	50 MU/min	38.45	38.52
15 MV	500 MU/min	224.1	223.0
15 MV	50 MU/min	22.76	22.60

Figure 5 illustrates the single pulse waveform captured during irradiation on PnP sensor for different energies and dose rates. To allow for a higher resolution of the pulse waveform, the analog signal was captured with a smaller temporal resolution (the sampling interval is 0.5 ns). Each pulse has the same pulse width (FWHM) of around 3.5 µs, which is close to the size of a single micro-pulse of the X-ray linac used, which is reported to be in the range of 3 µs ± 0.2 µs [9]. The observed analog single pulses in Figure 5 all have a very sharp negative slope of the pulses, which represents the short decay time of the scintillator used. Since both dosimeter designs use the same scintillating fibre tip, and are irradiated with the same Siemens Linac machine, the analog pulse width from both sensors is, as expected, similar, at approximately 3.56

μs. The short decay time of organic scintillator enables fast response of the pulse to identify dose delivered from a Linac machine. The scintillator -BCF-10 used in the fibre dosimeter has a decay time of 2.7 ns [10], which provides discernible peaks for high dose rate radiation and makes it suitable for real-time pulse dose measurement.

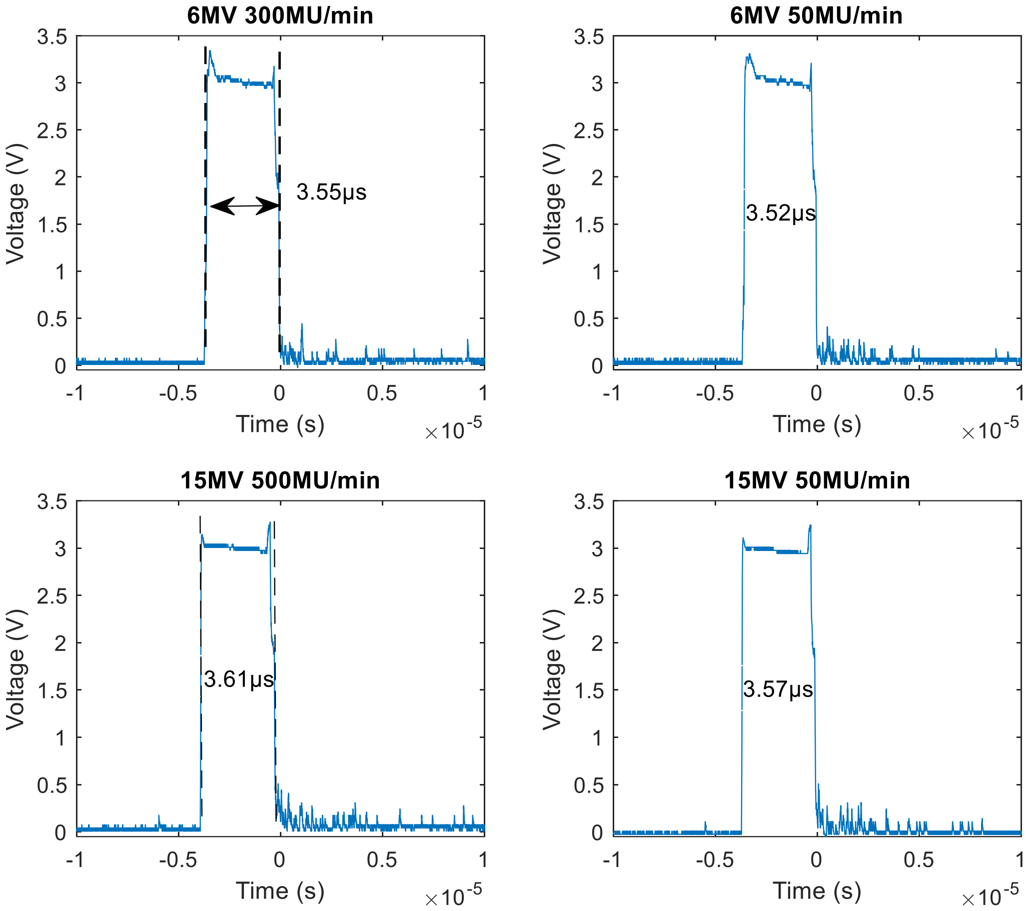

Figure 5. Enlarged peak of a single analog pulse from 6 MV, 15 MV, HDR and LDR.

4. CONCLUSION

In this report, two BCF-10 based sensors with different joint coupling designs were explored when subjected to X-ray radiation from a clinical linac. One sensor was made through a simple Butt-coupling BCF10-PMMA in a tube design, and another was formed with coupling joint of a cylindrical protrusion and hollow part of BCF10-PMMA, achieved using femtosecond laser machining (Plug and Play architecture). Both sensors demonstrate good energy dependence characteristics demonstrating their potential in the characterisation of linac machine in a radiotherapy setting. The butt-coupling sensor, with tube, illustrates a slightly higher output intensity compared with the Plug and Play sensor. However, the difference is small and the Plug and Play sensor benefits from the smaller sensor diameter. The scintillator-fibre coupling method using femtosecond laser micro-machining provides possibility for a more robust and smaller size fibre dosimeter. We are further investigating how to improve coupling efficiency between fibres. The analog output measurement demonstrates that both sensors allow fast response to radiation source with different energies and dose rates. The consistent pulse repetition rate between both sensors enables the identification of radiation doses irradiated from the Siemens Linac machine. Both of the sensors demonstrate the capability to be used for measurement of X-ray pulses in a clinical setting.

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