Thermoluminescence response of flat optical fiber subjected to 9 MeV electron irradiations

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HIGHLIGHTS

- TL performance of pure silica flat optical fiber (FF) and TLD-100 rod to electron.
- TL glow curve with a single prominent peak between 230 and 255 °C.
- The sensitivity of FF is approximately 16% than TLD-100.
- The minimum detectable dose was 0.09 mGy for TLD-100 rod and 8.22 mGy for FF.

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ABSTRACT

We describe the efforts of finding a new thermoluminescent (TL) media using pure silica flat optical fiber (FF). The present study investigates the dose response, sensitivity, minimum detectable dose and glow curve of FF subjected to 9 MeV electron irradiations with various dose ranges from 0 Gy to 2.5 Gy. The above-mentioned TL properties of the FF are compared with commercially available TLD-100 rods. The TL measurements of the TL media exhibit a linear dose response over the delivered dose using a linear accelerator. We found that the sensitivity of TLD-100 is markedly 6 times greater than that of FF optical fiber. The minimum detectable dose was found to be 0.09 mGy for TLD-100 and 8.22 mGy for FF. Our work may contribute towards the development of a new dosimeter for personal monitoring purposes.

1. Introduction

Many radiation detectors have been developed over the last few decades and some are being used routinely for environmental and personnel dose control. Some detectors make use of materials that emit light when heated after exposure to radiation. This technique is known as thermoluminescence dosimetry (TLD). Because of its simplicity and suitability for automation much research and development work has been put into this type of dosimetry, which has also turned out to be useful in fields other than radiation protection (Bradley et al., 2012).

In radiotherapy the aim of dosimetry is to make sure that the dose to the tumour is as prescribed while minimizing the dose to the surrounding normal tissue. The most commonly used energy range for electrons in radiotherapy is 6–20 MeV. At these particular energies, the electron beams are used to treat superficial tumors that are located down to 5 cm in depth. For instance, the treatment of skin or lip cancers, chest wall irradiation for breast cancer and the treatment of head and neck cancers. Electron beam irradiation is preferably compared to superficial X-rays, brachytherapy or tangential photon beams to treat these tumors, since it offers several advantages such as dose uniformity in the target volume and the ability to minimize dose to deeper tissues. (Khan, 2003, Wagiran et al., 2012).

The potential use of commercially available single mode doped SiO_2 optical fibers has been investigated by a number of workers, for

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photons (Abdulla et al., 2001, Abdul Rahman et al., 2011; Issa et al., 2011), electrons (Hashim et al., 2009; Yaakob et al., 2011; Abdul Rahman et al., 2011 and Alawiah et al., 2013), protons (Hashim et al., 2006), alpha particles (Ramli et al., 2009), fast neutrons (Hashim et al., 2010) and synchrotron radiation (Abdul Rahman et al., 2010). In all such studies the TL performances of irradiated fibers have shown considerable potential for dosimetric applications. The Ge-doped optical fibers show linear dose response for 6, 9 and 12 MeV electron irradiations up to 4 Gy, encompassing the range of fractionated doses normally used in radiotherapy (Hashim et al., 2009). The Ge-doped optical fiber exhibits sensitivity 23 times higher than the Al-doped fiber (Yaakob et al.,2011). The electron response of both Al- and Ge-doped fibers was found to be about 1.3 times that of photon irradiation over the dose range 0.2–4.0 Gy, due to the greater linear energy transfer (LET) of the electrons in the doped fibers compared to photons.(Wagiran et al., 2012). With regard to energy response, a slight reduction in TL yield is observed for the electron beams, decreasing by 11% when comparing the TL yield at 16 MeV with that at 9 MeV for a dose rate of 400 cGy $\min^{-1}$ (Abdul Rahman et al., 2011). The optical fibers also demonstrated good reproducibility (± 1.5%), low residual signal and minimal fading (Abdul Rahman et al., 2011).

The pure silica FF preform is a hollow silica tube that contains the core and cladding deposited layers. FF has been fabricated to combine the structural advantages of optical fibers and the functional benefits of planar devices. The ribbon-like planar shapes, with an extended length and flexibility, can be used to develop multiple functional optical components such as splitters, couplers and multiplexers. On the other hand, FF offers a platform for the multi-functionality of integrated optics, while trying to retain many mechanical, chemical and optical properties characteristic of the optical fiber (Dambul et al., 2012).

Herein, we report the efforts made by our group in introducing the FF as a new TL media. The comparison being made with the commercially available radiation dosimeter i.e. TLD-100. The present work describes several attractive features of the proposed dosimeters such as dose response, TL glow curve and minimum detectable dose subjected to 9 MeV electron irradiations.

2. Materials and methods

2.1. Sample preparation

The dosimetry system herein was based on TLD-100 rods size with the dimension of 1 mm × 6 mm and FF with dimension of approximately 3.9 mm × 3.9 mm × 0.9 mm (Table 1). The FF is fabricated using a conventional 5 m fiber drawing tower located at the Flat Fiber Laboratory, Department of Electrical Engineering, Universiti Malaya (UM), Malaysia. Unlike normal optical fiber preform that resembles a solid rod, the FF preform is a hollow silica tube that contains the core and cladding deposited layers (Fig. 1(i)). Table 1 shows the dimensions of the FF used in this study shown in Fig. 1(ii). In this work, the preform (outer diameter=26.5 mm, inner diameter=22.8 mm and length=60 mm) used is a commercially available uncollapsed silica tube. The temperature of the furnace was initially set at 2100 °C, which is silica's melting temperature. When the temperature of the furnace reaches silica's melting temperature, the preform starts to drop. Then, a capillary cane with a diameter of 2-3 mm was pulled from the bottom of the furnace. The capillary cane was then re-pulled to form the desired FF by applying a low vacuum pressure from the top of the capillary, while the furnace temperature was maintained at 2000 °C. A review of the facilities offered by the UM fiber drawing tower is covered in Chow et al., 2012 and Alawiah et al., 2013.

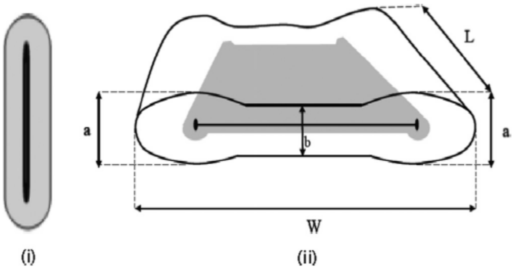

Fig. 1. (i) The cross-sectional area of FF (ii) The FF is a hollow silica tube that contains the core and cladding deposited layers (Alawiah et al., 2013).

Table 1
Dimension details of pure silica FF in Fig. 1(ii).

Parameter	Dimension (mm)
Outer thickness (a)	1.0
Inner thickness (b)	0.8
Length (L)	3.9
Width (W)	3.9

The mass of FF and TLD-100 were determined using an analytical balance BSA224S-CW, (Germany) obtaining values equal to 18.74 mg and 23.62 mg (± 0.05 mg), respectively. The measured TL yield was normalized to unit mass of the TL media. Vacuum tweezers were used for handling and grouping of TL materials (Hashim et al., 2009).

2.2. Annealing

The fibers were annealed in a furnace (Harshaw) in order to standardize their sensitivities and background. The fibers, retained inside an alumina container were oven annealed at 400 °C for 1 h. Following the annealing cycle fibers were kept inside the oven allowing their natural cooling down for 24 h to avoid thermal stress, finally the samples were equilibrated at room temperature (Hashim et al., 2010). After cooling, the samples were placed inside an opaque plastic container in order to minimize exposure to potentially high ambient light levels (which could promote detrapping, otherwise referred to as bleaching), both prior to and after irradiation.

2.3. Irradiation

The electron irradiations were conducted at Universiti Malaya Medical Centre (UMMC) using a Linear Accelerator (LINAC) Varian Model 2100C. The samples were irradiated using the most commonly used electron energies for radiotherapy at this centre i.e. 9 MeV; doses in the range 1 to 4 Gy were delivered to the TL materials. These samples were sandwiched between slabs of a solid water phantom. The solid water phantom is a soft matter medium that can be considered to be a standard tissue-equivalent medium for use in radiation dosimetry. The field and applicator size was set to 10 × 10 cm^2 and positioned at the standard Source-Surface Distance (SSD) of 100 cm. The dose delivered by LINAC is set at a constant dose rate of 600 MU $\min^{-1}$, where MU signifies Monitor Units with 1 MU being equivalent to 1 cGy.

2.4. TL measurements

In the present TL measurements, a Harshaw 3500 TL reader (USA) was used together with WinREMS software, enabling one dosimeter to be read out per loading. During readout the following parameters were used: preheat temperature of 50 °C for 10 s

(Yaakob et al., 2011b); acquisition temperature 300 °C for 14 s and a heating rate cycle of 25 °C s^{-1}. These settings have been shown to provide an optimal glow curve, free of the effects of superficial traps i.e. flushed out by the pre-heat cycle (Hashim et al., 2014). Finally, in the present investigations, an annealing temperature of 300 °C was applied for 10 s to sweep out any residual signal (Hashim et al., 2014).

3. Results and discussions

3.1. TL glow curve

The important physical factor in order to determine the stability of the TL material for dosimetry is the temperature at which the peak of the glow curve occurs. Most commercially available TL dosimeters have high glow peak temperatures (i.e. deep electron traps), so that they are stable for several months or years. An example of a TL glow curves obtained from FF after 9 MeV electron irradiations is shown in Fig. 2.

This typical pattern of the glow curves obtained from FF is the representation of all those measured fiber samples. It is composed of a broad, dominant peak located between 230–255 °C, which is sensitive to the amount of absorbed dose. This convenient position at relatively high temperature allows us to measure absorbed dose, both at room and high temperature. The general structure of the TL glow curve remains unchanged by repeating the cycles of annealing and irradiation at various doses. By comparison, the TLD-100 has five typical peaks at 65 °C, 120 °C, 160 °C, 195 °C and 210 °C (Portal, 1981). Our findings agrees closely with the TL glow peak of SiO_2 optical fibers at 230 °C subjected to ^{60}Co gamma radiation (Espinosa et al., 2006), Ge-doped fibers broad component peaking at 257 °C after X-ray irradiation (Benabdesselam et al., 2013) and the unknown doped INO-optical fiber had one well-defined glow peak at 327 ± 2 °C from a MeV electron beams linear accelerator (Ong et al., 2009).

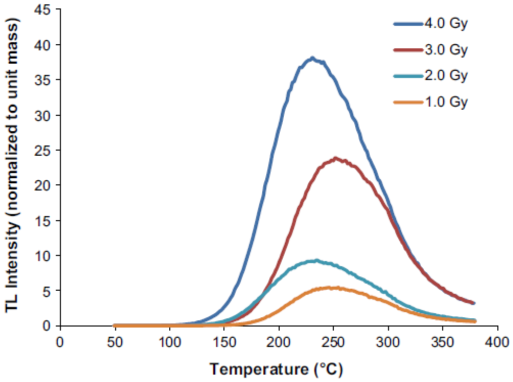

Fig. 2. The TL glow curve of FF at various radiation exposures.

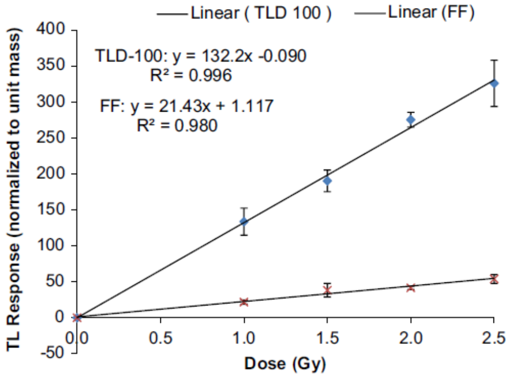

Fig. 3. TL response of FF optical fibers and TLD-100 at 9 MeV electron versus dose.

3.2. Dose response

The sensitivity of a TLD material can be expressed in one of two ways, namely, by the TL yield normalized to the mass of dosimeter or by the TL yield normalized to the mass of the dosimeter and its absorbed dose (McKeever et al., 1995). In this work, the latter approach was utilized to determine the TL sensitivity (TL response.mg^{-1} Gy^{-1}). Fig. 3 shows the TL dose response of TL materials to electron irradiations.

The TL response of the FF was relatively small compared to that of TLD-100 i.e. the change in TL yield per unit absorbed dose or slope for FF and TLD-100 are 21.43 mg^{-1} Gy^{-1} and 132.20 mg^{-1} Gy^{-1},respectively. We found that the FF sensitivity is approximately 16% of TLD-100 media. This clearly indicates that the TLD-100 rod has a better sensitivity and capability in producing higher TL signals compared to FF (by a factor of 6). Our result was comparable with the TL sensitivity of TLD-100 subjected to electron irradiation of 6-, 15- and 21 MeV i.e.~5 times that of FF (Alawiah et al., 2013).

Fig. 4 shows the $f(D)$ supralinearity function of FF where $f(D)$ is a measure of deviation from linearity, given by Eq. (1):

$$f(D) = \frac{F(D)/D}{F(D_l)/D_l} \tag{1}$$

where $F(D)$ is the TL signal intensity as a function of dose D and $F(D_l)$ is measured at low dose D_l, i.e. somewhere in the linear region of $F(D)$ (Mahajna and Horowitz, 1997). By using Eq. (1), the linear behavior is achieved when $f(D)=1$; supralinearity $f(D)>1$ and in sublinearity the $f(D)<1$.

Fig. 4 shows the data point is clustered close to 1 for doses of 1 Gy up to 2.5 Gy. Then, supralinearity ($f(D)>1$) appears to start at doses greater than 3 Gy. Each data point in Fig. 4 is obtained by taking an average of three individual fiber readings. The linear/supralinear behavior may be attributed to the non-uniform spatial ionization density following electron irradiation. This phenomenon have been successfully introduced as the Unified Interaction Model (UNIM) (Horowitz, 2014). In TLD-100, $f(D)=1$ only up to a few gray. Above this we have $f(D)>1$ (supralinearity) reaching values as high as ten at approximately 100 Gy. At even higher doses $f(D)$ decreases due to recombination, saturation and/or radiation damage and reaches

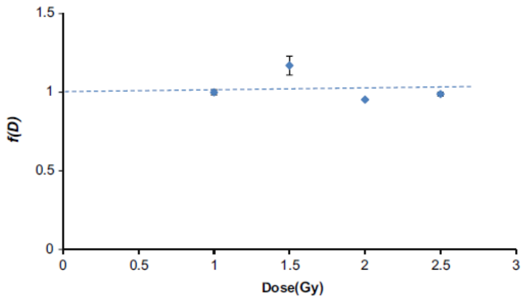

Fig. 4. Supralinearity function of FF subjected to 9 MeV electron irradiations.

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