The thermoluminescence characteristics and the glow curves of Thulium doped silica fiber exposed to 10 MV photon and 21 MeV electron radiation

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HIGHLIGHTS

- A sub-linear response of Tm doped silica CF was measured at dose range of 0.2–10 Gy.
- The TL sensitivity of Tm doped silica CF is 2 times higher as compared to pure silica CF.
- Tm-doped silica CF glow curve consists of 5 individual glow peaks.
- The glow peak area and peak height of Tm-doped silica CF are highly dependent on dose.
- The kinetics parameters are highly dependent on dose.

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ABSTRACT

The thermoluminescence (TL) glow curves and kinetics parameters of Thulium (Tm) doped silica cylindrical fibers (CF) are presented. A linear accelerator (LINAC) was used to deliver high-energy radiation of 21 MeV electrons and 10 MV photons. The CFs were irradiated in the dose range of 0.2–10 Gy. The experimental glow curve data was reconstructed by using WinREMS. The WinGCF software was used for the kinetic parameters evaluation. The TL sensitivity of Tm-doped silica CF is about 2 times higher as compared to pure silica CF. Tm-doped silica CF seems to be more sensitive to 21 MeV electrons than to 10 MV photons. Surprisingly, no supralinearity was displayed and a sub-linear response of Tm-doped silica CF was observed within the analyzed dose range for both 21 MeV electrons and 10 MV photons. The Tm-doped silica CF glow curve consists of 5 individual glow peaks. The E_a of peak 4 and peak 5 was highly dependent on dose when irradiated with photons. We also noticed that the electron radiation (21 MeV) caused a shift of glow peak by 7–13 °C to the higher temperature region compared with photons radiation (10 MV). Our Tm-doped fibers seem to give high TL response after 21 MeV electrons, which gives around 2 times higher peak integral as compared with 10 MV photon radiation. We concluded that peak 4 is the first-order kinetic peak and can be used as the main dosimetric peak of Tm-doped silica CF.

1. Introduction

Optical fiber based sensors are promising devices to be used in radiation dosimetry such as in the measurement of the absorbed

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dose in radiotherapy (Jang et al., 2009) and brachytherapy (Suchowerska et al., 2007), radiation dosimetry in computed tomography (Jones and Hintenlang, 2008), distributed radiation dosimetry for beta and gamma rays, and neutrons (Naka et al., 2001).

Previous researchers had observed that the TL performance of an irradiated optical fibers is influenced by the type of fiber including the type of dopant material, diameter of the fiber core, the shape of fiber and the type of radiation (Hashim et al., 2010; Ramli et al., 2009; Abdul Rahman et al., 2011; Yaakob et al., 2011; Ong et al., 2009; Alawiah et al., 2013, 2015).

However, not many reports describe the TL response and the glow curve properties of the Thulium (Tm) doped silica cylindrical fibers (CF). It is interesting to see the effect of Tm in the pure silica CF on the TL response and the glow curve properties. Furthermore, studies of the Tm doped silica CFs are not as extensive as that of the germanium doped optical fibers. This paper reports on TL measurements of the Thulium doped silica CF and its dosimetric properties in comparison to the most common LiF based TL material, TLD-100.

2. Materials and methods

2.1. Fiber fabrication

The Tm doped silica CFs with a diameter of 195.7 μm (Fig. 1) were used in this study. The fibers were cut into 1.0 cm length samples and the average mass of the sample was 0.84 mg. The dopants were induced into the fiber by using a Modified Chemical Vaporized Deposition (MCVD) technique. The fibers were fabricated using a conventional 5 m fiber-drawing tower located at the Flat Fiber Laboratory, Department of Electrical Engineering, University of Malaya, Malaysia. A scanning electron microscope with an energy dispersive x-ray fluorescence (SEM-EDXRF) capability was used to determine the elemental composition of the fibers (Table 1).

2.2. Pre irradiation annealing

Thermal annealing was carried out in order to stabilize the sensitivity and the background signal of the fibers. In this study, the silica CFs were annealed using a Nabertherm Program Controlled S27 Furnace (Nabertherm, Germany). The fibers were wrapped in aluminum foils and annealed at 400 °C for 1 h. The fibers were then removed and allowed to cool to room temperature.

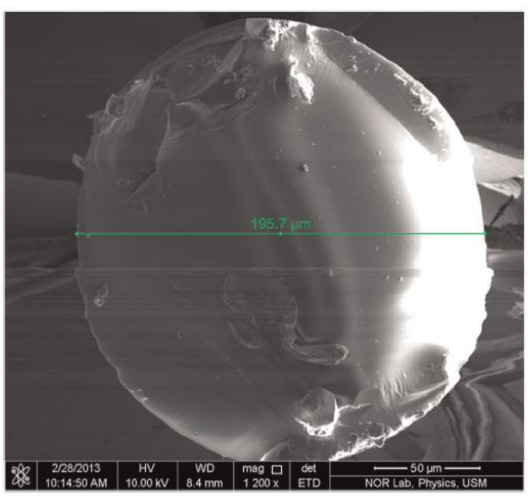

Fig. 1. An image of Tm doped silica CF taken by a scanning electron microscope with energy dispersive x-ray fluorescence (SEM-EDXRF).

Table 1
Elemental composition of the Tm doped silica CF.

Element	% composition by weight
O	75.55
Si	24.15
Tm	0.30
Total	100.00

2.3. Irradiation

The Tm doped silica CFs were irradiated using a Siemens Mevatron MD2 (Siemens, Germany) linear accelerator (LINAC), providing high-energy radiation of 21 MeV electrons and 10 MV photons, within the dose range of 0.2–10 Gy. For each dose a minimum of 10 fibers were irradiated, allowing assessment of statistical variation and reproducibility. The source to sample surface distance (SSD) was at 100 cm, with a field size of 15×15 cm^2 selected for electron irradiations. In all cases, the fibers were placed at the center of the field. A Gammex RMI solid water™ phantom (Gammex, U.S.A.) (30 cm lengthx30 cm width) was used to ensure calibration conditions. The applicator size was 15×15 cm^2. To provide for charged particle equilibrium at the sample position, the samples were located at the depth at which, in use of a single stationary beam, the maximum dose is deposited, D_{max}. Another 10 cm slab of the solid water™ phantom was placed below the sample fibers to provide for full backscattering conditions (Fig. 2).

2.4. TL measurements

The TL yields as a function of temperature, referred to as the TL glow curve, were measured using a Harshaw 3500 TLD reader (Thermo Fisher Scientific Inc., U.S.A.). The following time-temperature profile (TTP) was applied: 5.0 s preheat at the temperature of 60 °C, the linear heating rate profile up to the maximum temperature of 400 °C, heating rate of 16 °C s^{-1} and results in acquisition time of 25 s. All readings were taken under N_2 gas flow, suppressing oxidation and potential triboluminesence. The homogeneity test was performed for all samples with the method described by Alawiah et al. (2015).

The fibers were readout after 24 h from the irradiation in order to eliminate the low temperature peak contribution in TL glow curves. The glow curves were analyzed with a curve fitting computer program that is known as WinGCF. Then, the experimental glow curves were deconvoluted into individual peaks using WinGCF software in order to evaluate the glow peak kinetic parameters.

3. Results

The measured TL glow curves and deconvoluted glow peaks are presented. Computerized glow curve deconvolution (CGCD) has established itself as a powerful tool in the analysis of glow curves and WinGCF is mainly based on the first order kinetics equation (Randall and Wilkins, 1945).

The uncertainty has been determined as ± 1 standard error of the mean and the coefficient variation does not exceeded $\pm 5\%$, as

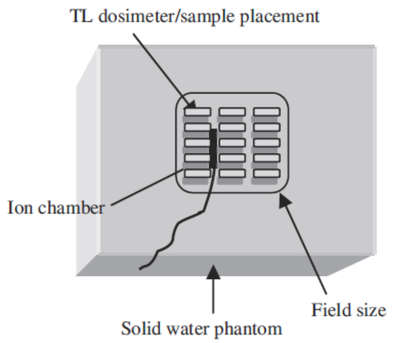

Fig. 2. The dosimeter and sample experimental setup on a solid water phantom. Another solid water layer was placed on top of the set-up to provide for charged-particle equilibrium (Alawiah et al., 2015).

required for radiotherapy clinical applications (ICRU, 1976) and the homogeneity of fiber samples is maintained. The fibers also show good reproducibility with a standard deviation less than 3.0%.

3.1. *TL linearity and sensitivity of Tm-doped silica CF and pure silica CF*

Fig. 3 shows the degree of linearity of Tm-doped silica CF and pure silica CF as a function of radiation dose range following 21 MeV electrons and 10 MV photons. Symbols represent experimental data (measured TL) while dot-dashed lines indicate linearity (calculated).

Surprisingly, no supralinearity is displayed by these data and we observed a sub-linear response of Tm-doped silica CF at the dose range of 0.1–10 Gy for both 21 MeV electrons and 10 MV photons.

The sensitivity of the fiber was calculated from the dose response relation for 21 MeV electrons and 10 MV photons as shown in Fig. 4. We noticed that the sensitivity of Tm-doped silica CF is 2 times higher as compared with pure silica CF. TL sensitivity of both fibers is highly dependent on the radiation dose at the lower dose range 0.2–1 Gy but becomes more constant with dose increasing above 2 Gy. Thulium seems to be more sensitive to 21 MeV electrons than 10 MV photons, while our pure silica CF presents an opposite characteristics.

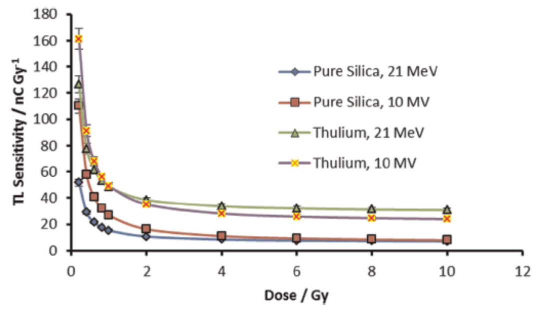

Fig. 4. TL sensitivity of Tm doped and pure SiO_2 fiber for the dose of 0.1–10 Gy of LINAC radiation of 21 MeV electrons and 10 MV photons.

3.2. *Glow curve analysis of Tm-doped silica CF*

The experimentally measured glow curves were deconvoluted into its individual peaks in order to evaluate the kinetic parameters associated with the TL mechanism in our samples. These parameters include the activation energy, E_a, maximum peak temperature, T_{max} and peak integral, *PI*.

Fig. 5 presents the measured glow curves (left side) and the deconvoluted glow peaks (right side) of Tm-doped CF. Let us now compare in details the glow curves and its deconvoluted glow peaks for doses of 0.2, 1, 6 and 10 Gy, separately.

Analysis of the glow curves by WinREMS can be done based on its Region-of-Interest (ROI) as the following: ROI #1 (Channel 0–50), ROI #2 (Channel 51–100), ROI #3 (Channel 101–150) and ROI #4 (Channel 151–200). Within the dose range of 0.2–1 Gy, we have 5 deconvolved peaks by WinGCF, as shown in Fig. 5. We determined the location of deconvoluted glow peak at the dose of 0.2 Gy, peak 1 was located at ROI #1, peak 2 at ROI #1 and 2, peak 3 at ROI #2 and 3, peak 4 at ROI #3 and peak 5 at ROI #4. We noticed that peaks are highly overlapped at ROI 1–3. As the dose increases from 0.2 Gy to 1 Gy, the TL intensity of the glow curve shows a significant increase in each ROI. Based on the maximum temperature of the peak, we have classified peaks 1, 2 and 3 as the low temperature peaks (LTP) which are located at ~130 °C, 160 °C and 220 °C, respectively. Whereas peak 4 and peak 5 are the high temperature peaks (HTP) which are located at ~280 °C and 330 °C, respectively.

We noticed that peaks 1, 2 and 3 tend to overlap throughout the studied dose range. Our WinGCF program successfully

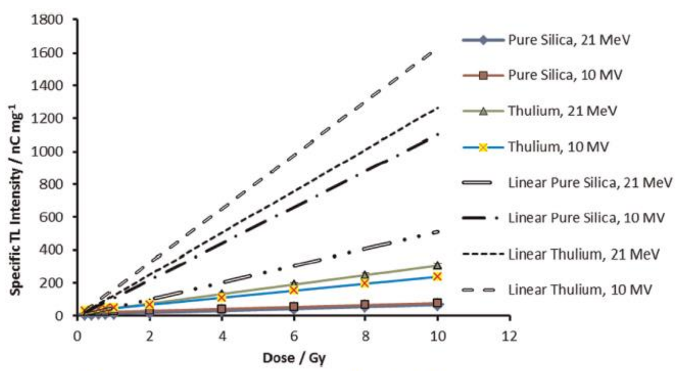

Fig. 3. Dose–response dependence (measured and calculated) of Tm-doped and pure silica CF for the dose of 0.2–10 Gy of LINAC radiation of 21 MeV electrons and 10 MV photons.

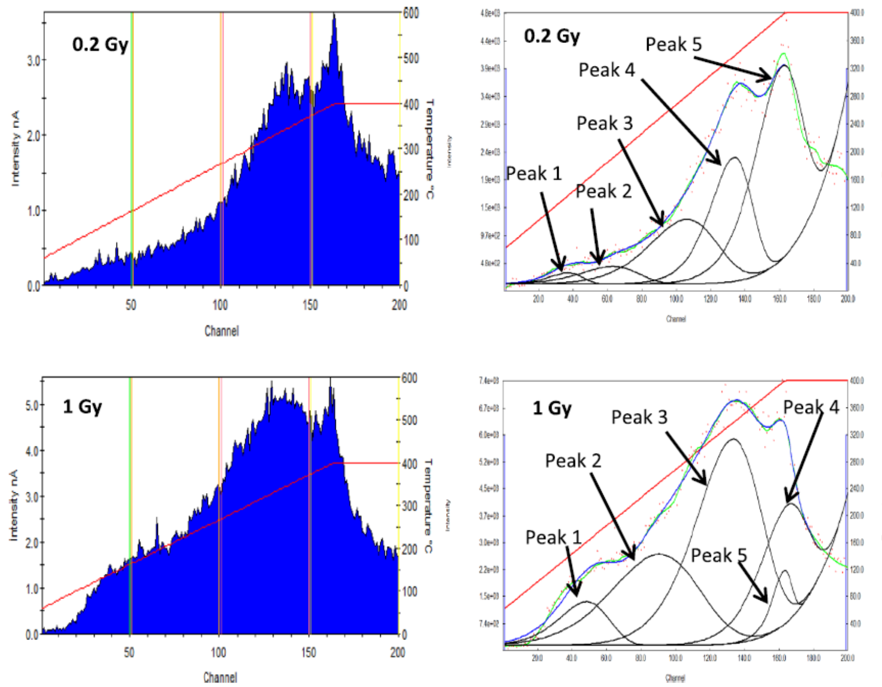

Fig. 5. The typical glow curves (left) and glow peaks (right) of Tm-doped CF for doses of 0.2 Gy and 1 Gy.

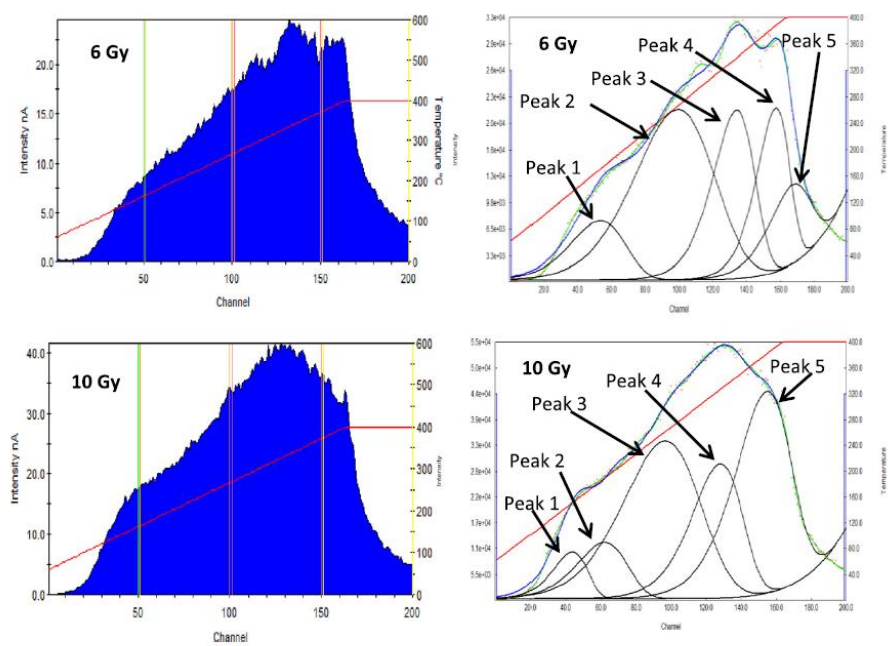

Fig. 6. The typical glow curves (left) and glow peaks (right) of Tm-doped CF at the doses of 6 Gy and 10 Gy.

extracted the kinetic parameters of the glow peaks and their evaluation based on the TL model will be discussed in Section 3.3.

We observed a significant increase of TL intensity by 2 times as the dose increases from 6 Gy to 10 Gy. Clearly seen in Fig. 6 that peak height of the glow curve in ROI #3 increased by 2 times with dose. We also notice that the area of glow curve increased with increasing dose. The area under the glow curve was found to be highly dependent on dose.

Fig. 7 showed that the TL intensity of Tm-doped silica CF increases with increasing dose (0.2–10 Gy). We found that, as the dose increases, our high temperature peaks (HTP) appeare clearly and become dominant peaks at the temperature range of 317–327 °C, which does not exceed 400 °C. We also noticed that the glow curve area and peak height of both LTP and HTP showed a significant increase with increasing dose. The LTP at 280 °C starts to be noticeable at the dose of 1 Gy. We concluded that the glow peak area and peak height of the Tm-doped silica CF TL glow curve are highly dependent on the dose.

3.3. Kinetic parameters evaluation of Tm-doped silica CF

The most important characteristic of all first-order TL glow curves according to the first order kinetics in TL model of Randall and Wilkins (1945) is the fixed peak position, while the peak height is directly proportional to the dose.

It is also stated in the first order kinetic that as the activation energy increases, the peak position shifts towards higher temperature region with decreasing peak height and increasing peak width, while keeping the area constant.

On the other hand, based on second-order kinetic model of Garlic and Gibson, which stated that as the dose increases, the peak height shows a significant increase and peak position shifts towards lower temperature region, with more symmetric peak as compared to the first-order peak.

As shown in Fig. 8, the activation energy, E_a of the deconvoluted glow peak 4 showed a significant decrease by 30–60% with increasing dose for both 21 MeV electrons and 10 MV photons. Moreover, peak 4 showed 3 times higher dependency on photon dose as compared to electrons. In contrast, the E_a of peak 5 seems to increase with increasing dose by 30–58%. It is clearly seen in Fig. 8 that the E_a of peak 4 and peak 5 was highly dependent on dose, when irradiated with photons. We also noticed that the E_a of peak 5 was 5 times greater as compared to peak 4 following the same radiation condition of 10 MV photons.

We observed the first-order kinetic response for all deconvoluted TL glow peaks, as the peak position stayed constant with

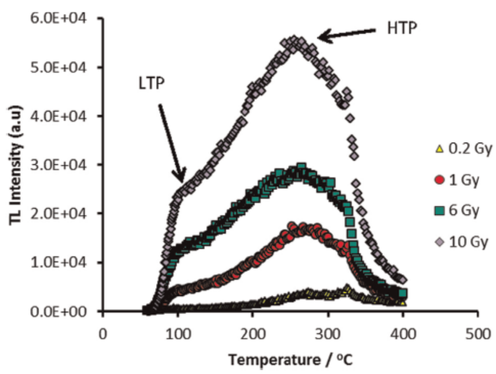

Fig. 7. The TL glow measured for Tm-doped silica CF after irradiation with doses from 0.2 Gy to 10 Gy.

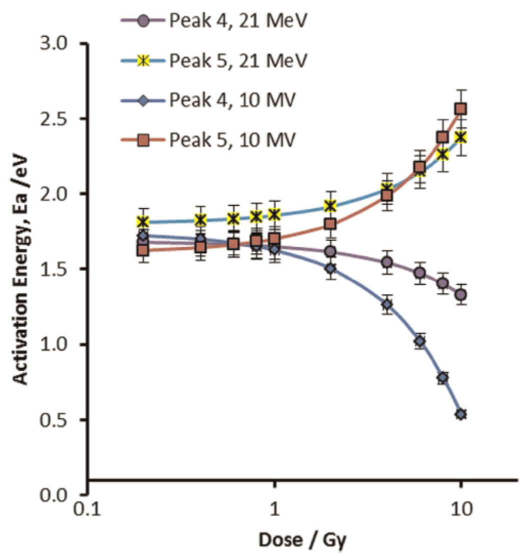

Fig. 8. The variation of the activation energy, E_a, with dose increasing from 0.2 to10 Gy for 21 MeV electrons and 10 MV photons.

increasing dose, as shown in Fig. 9. It is clearly seen that peak 4 is dominant within the temperature range of 280–290 °C, while peak 5 was found to be visible at much higher temperature range, within 317–327 °C. We also noticed that electron irradiation (21 MeV) caused a significant shift of glow peak by 7–13 °C to the much higher temperature region as compared to the photon irradiation (10 MV).

Fig. 10 shows the variation of *PI* with increasing dose for electrons and photons irradiations. We observed that the peak 5 showed a constant response of *PI* with increasing dose for 10 MV photon irradiation. In contrast, for 21 MeV electron radiation peak 5 showed a significant increase of PI with increasing dose. Similar response was observed for peak 4 under electron and photon irradiations. Our Tm-doped fibers give 2 times higher TL response for 21 MeV electrons as compared to 10 MV photon radiations.

Fig. 11 shows the TL sensitivity of peak 4 and 5 as the function of dose for electrons and photons irradiation. Our Tm-doped fibers showed 6 times higher TL sensitivity for photon as compared to electron radiation. Moreover, peak 5 showed a constant TL sensitivity with increasing dose for electron radiation. We observed that peak 4 showed a remarkable increase of TL sensitivity (around 40%), when irradiated with photons as the dose increased up to 10 Gy.

Fig. 12 shows the variation in E_a with changes in *PI*. We observed the first-order kinetic response for peak 4, as the E_a decreases with increasing *PI* by 3.4 times of its initial value, whereas peak 5 showed an opposite response of E_a with *PI* and thus are not showing the behavior of first-order kinetic. We concluded that peak 4 is the first-order kinetic peak and can be used as the main dosimetric peak at the average T_{max} region of 280–290 °C.

4. Conclusion

The TL sensitivity of Tm-doped silica CF is around 2 times higher as compared to pure silica CF. The TL sensitivity of both fibers is highly dependent on the irradiation dose at the lower dose range of 0.2–1 Gy, but becomes more constant with dose

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