Optical fiber based dosimeter sensor: Beyond TLD-100 limits

G. Amouzad Mahdiraji\textsuperscript{a,},\textsuperscript{a}*, M. Ghomeishi\textsuperscript{a}, E. Dermosesian\textsuperscript{a}, S. Hashim\textsuperscript{b}, N.M. Ung\textsuperscript{c}, F.R. Mahamad Adikan\textsuperscript{a}, D.A. Bradley\textsuperscript{d,c}

\textsuperscript{a} Integrated Lightwave Research Group, Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
\textsuperscript{b} Department of Physics, Universiti Teknologi Malaysia, 81310 Skudai, Johor Darul Takzim, Malaysia
\textsuperscript{c} Clinical Oncology Unit, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia
\textsuperscript{d} Department of Physics, University of Surrey, Guildford GU2 7XH, UK
\textsuperscript{e} Department of Physics, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia

\textbf{ARTICLE INFO}

\textbf{Article history:}
Received 11 June 2014
Received in revised form 22 November 2014
Accepted 26 November 2014
Available online 5 December 2014

Keywords:
Single mode fiber
Optical fiber application
Dosimeter
Thermoluminescence

\textbf{ABSTRACT}

This work investigates the suitability of single mode optical fibers (SMFs) as ionizing radiation dosimeter sensors. Thermoluminescence (TL) response studies have been carried out to investigate the performance of two commercial optical fibers, SMF-1 and SMF-2, with different Ge-doping concentrations of 4.9 and 4.3 wt%, respectively, exposed to 0.5 to 8 Gy doses under 6, 9, and 20 MeV electron irradiations. The performance parameters include dose response linearity and sensitivity, energy dependency, glow curve analysis, minimum detectable dose, repeatability, fading effects and optical absorption. The TL dose response of SMF-1, the fiber with the greater Ge concentration of the two, was found to be in excess of 6.3 and 3.2 times that of SMF-2 and TLD-100, respectively. SMF-1 demonstrated capability for detecting a minimum dose of as low as 6 mGy, being some 3.2 times superior to that of TLD-100. The results underline the potential of these optical fibers as next-generation alternative dosimeter sensors for detection of ionizing radiation.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Optical fibers have been shown to offer considerable potential as thermoluminescence dosimeters (TLD), with valuable performance and cost advantage over that of well-established commercial TLD materials such as TLD-100. The advantages include high sensitivity to dose, excellent linearity of response over a wide range of dose and low dependence on dose rate [1–3]. A number of groups have investigated the TL and optically stimulated luminescence performance of silica (SiO\textsubscript{2}) optical fibers as radiation dosimeters for patients undergoing radiotherapy [4,5]. Other research groups have worked on these and nuclear track detectors for fission fragments for in situ measurements of nuclear reactors [6,7]. In addition, others have reported on the designing of special photo-, radio-, and/or thermo-luminescence material with high sensitivity in measuring irradiation dose, including phosphate glasses doped with lithium and barium [8], zirconium oxide (ZrO\textsubscript{2}) [9], copper activated calcium borate (Ca\textsubscript{2}B\textsubscript{4}O\textsubscript{7}:Cu) nanocrystals [10], manganese doped calcium tetraborate (CaB\textsubscript{4}O\textsubscript{7}:Mn) nanocrystal [11], lithium potassium borate glass doped with titanium oxide (TiO\textsubscript{2}) and magnesium oxide (MgO) [12], double potassium yttrium fluoride (K\textsubscript{2}YF\textsubscript{3}) crystals doped with samarium (Sm\textsuperscript{3+}) and terbium (Tb\textsuperscript{3+}) ions [13], all emphasizing the importance of producing a dosimeter with high sensitivity.

Our current work focuses on the investigation of two types of standard single mode fibers, SMF-1 and SMF-2, which have been subjected to 6, 9 and 20 MeV electron irradiations at doses up to 8 Gy, comparison being made with the performance of TLD-100. The intention is to emphasize that these relatively cheap commercially available telecommunication optical fibers can be used as alternatives to the more conventional phosphor-based TL materials such as TLD-100 for dosimetric applications.

2. Materials and methods

2.1. Elemental analysis

Two types of commercially available Ge-doped standard SMFs namely SMF-1 and SMF-2 are used in this study. Both SMFs have similar core and cladding diameters of about 8.5 μm and 125 μm, respectively. Energy dispersive X-ray (EDX) analysis was used for elemental measurement. For each SMF type, five sets of EDX
Table 1
EDX analysis of SMF-1 and -2.

<table>
<thead>
<tr>
<th></th>
<th>SMF-1</th>
<th></th>
<th>SMF-2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight (%)</td>
<td>Atomic (%)</td>
<td>Weight (%)</td>
<td>Atomic (%)</td>
</tr>
<tr>
<td>Sample 1</td>
<td>69.6</td>
<td>25.5</td>
<td>4.9</td>
<td>81.7</td>
</tr>
<tr>
<td>Sample 2</td>
<td>69.6</td>
<td>25.5</td>
<td>4.8</td>
<td>81.7</td>
</tr>
<tr>
<td>Sample 3</td>
<td>72.0</td>
<td>22.7</td>
<td>5.4</td>
<td>83.6</td>
</tr>
<tr>
<td>Sample 4</td>
<td>52.8</td>
<td>42.7</td>
<td>4.6</td>
<td>67.6</td>
</tr>
<tr>
<td>Sample 5</td>
<td>53.1</td>
<td>42.3</td>
<td>4.8</td>
<td>67.7</td>
</tr>
<tr>
<td>Average</td>
<td>63.4</td>
<td>31.7</td>
<td>4.9</td>
<td>76.5</td>
</tr>
<tr>
<td>STD</td>
<td>9.6</td>
<td>9.9</td>
<td>0.3</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Fig. 1. Elemental concentration distribution across the fiber core cross section, obtained using EDX. (a) and (b) Normalized weight (%) Ge concentration for 50 and 42 ROIs measured within fiber core area of five different fiber samples for SMF-1 and -2, respectively. The result of ROIs per fiber sample are identified in (a) and (b), (c), (d), and (e) showing silica, oxygen, and germanium intensity concentration, respectively, measured by line scanning across fiber core area (averaged from fiber Samples 4 and 5 in Table 1). (f) and (g) Show cross section area of SMF-1 and -2 taken by SEM imaging.

measurement were done using different samples of the same fiber type. For each fiber sample, 6–10 region-of-interests (ROIs) are selected within the fiber core area. **Table 1** shows the results of average compositional analysis over all ROIs per fiber sample for SMF-1 and -2. On average, SMF-1 and -2 indicate the presence of Ge at about 4.9 and 4.3 wt%, respectively. Details of the Ge concentration variability per ROI for the five samples are presented in **Fig. 1**(a) and (b) for SMF-1 and -2, respectively. Over and above the overall average value presented in **Table 1**, it is noted that the majority of Ge concentrations in SMF-1 are found to be greater than that in SMF-2. As an instance, 22 out of the 50 readings made in SMF-1 showed a concentration greater than 5 wt% compared to 9 out of 42 readings in SMF-2. In regard to concentrations of ~4 wt%, there are 19 over 42 readings for SMF-2 and 12 over 50 readings.
for SMF-1. This suggests that the concentration of Ge in SMF-1 and -2 can best be characterised as ~5 and 4 wt%, respectively. Fig. 1(c) to (e) illustrate the result of Si, O, and Ge concentrations across the fiber core surface, respectively, obtained as averages of line scanning over the cross-sections of fiber Samples 4 and 5 under EDX inspection. Results in Table 1 and Fig. 1 are in agreement that Ge and O concentrations in the SMF-1 core area are greater than that in the SMF-2 core area, while Si is greater in SMF-2. It should be noted that the EDX analysis over fiber cladding is also performed. However, almost similar Si and O concentrations are observed for both fiber samples in the absence of detecting any other elements. Fig. 1(f) and (g) shows SMF-1 and -2’s cross sections obtained by SEM imaging.

2.2. Absorption

Since the luminescence generated from an optical fiber dosimeter is contributed by the structural defects in the fiber, having fiber spectral absorption would be useful in analyzing the type of defect centers associated in each optical fiber samples. Fig. 2 illustrates the extent of light absorption detected in 8 m of SMF-1 and -2 normalized per unit length. The absorption presented here is obtained by measuring optical fiber attenuation and subtracting the attenuation from the reference light source. The fiber attenuation was measured by directly connecting one end of each fiber to the pigtail of a supercontinuum light source (NKT Photonics) and the other end to an Optical Spectrum Analyzer (OSA). The attenuation spectrum of each fiber is then subtracted from the emitted light source/reference spectrum, which is measured by directly connecting the supercontinuum source pigtail to OSA. The spectrum for SMF-1 shows much greater absorption compared to SMF-2, which implies the presence of more defect centers in SMF-1. Considering the spectral range of TLD reader used in this study (i.e., around 270–630 nm); the main bands in SMF-1 with elevated absorption are around 560–630 nm, 500 nm, 485 nm, 455 nm. In general, the defect centers associated with these absorption bands can be referred to as non-bridging oxygen hole center (NBOHC) with absorption bands within around 550–690 nm and Ge-related defect centers around 570–410 nm [14]. The fiber absorption spectra show greater absorption bands at the longer wavelengths, however, the TL generated from these absorption bands is not detectable with the TLD reader used in this study.

2.3. Sample preparation

Prior to irradiation, the optical fiber samples were prepared, first by carefully removing the outer polymer coating to the optical fiber. This is done by using a fiber stripper that provides for removal of the buffer coating, without scratching or nicking of the glass fiber. A cotton cloth containing methyl alcohol was then used to clean the stripped fibers in order to ensure complete removal of any residual polymer or impurities. The fibers were then manually cut using a diamond cone-point cutter, to the length of (5 ± 0.5) mm as dictated by the maximum size of the square planchet of TL reader.

All fiber samples were then annealed before the irradiation stage in order to standardize their thermal history. This allows for removal of any residual TL signal from previous handling (the so-called mechanical/triboluminescence signal) and elimination of the unstable low-temperature glow curve component [15]. The annealing process for fibers is carried out using a furnace operating with a time-temperature profile of 400 °C for 1 h, subsequently left to cool down to room temperature. The TLD-100 chips were annealed for 1 h at 400 °C and subsequently for 2 h at 100 °C. After cooling, 7–10 pieces of the samples were then placed in small plastic bags, ready for irradiation and subsequent evaluation of the mean TL yield. When not being handled, all samples were placed in a light-tight container to prevent unnecessary exposure to light as this could influence the TL results.

2.4. Irradiation

The SMF-1, SMF-2 and TLD-100 samples were placed at the surface of a solid water™ phantom whose function is to provide for the standardized full-scatter condition (reference conditions) as conventionally adopted and were exposed to 6, 9 and 20 MeV electron beams, 600 cGy/min dose rate, with accumulation doses of 0.5 to 8 Gy, delivered by a Varian Model 2100C linear accelerator (Varian Medical System, Palo Alto, USA) located at the University of Malaya Medical Centre. One monitor unit corresponds to dose of 1 cGy delivered under the reference conditions. Bolus thicknesses of 1.5, 1.5 and 2.5 cm were used as build-up medium during irradiation using the 6, 9 and 20 MeV beams, respectively. A field size of 20 × 20 cm², source to skin distance of 100 cm and applicator size of 20 × 20 cm² were used for all irradiations.

It should be noted that the recorded absolute radiation dose delivered by the linac is based on adoption of the procedures detailed in the International Atomic Energy Agency Report TRS398, the output being ensured to be within ±2% of the intended delivered dose. Measurements of dose from electron beam irradiation have been performed by the in-house medical physicists, supported by monthly quality assurance (QA) checks made using a Roos ionization chamber IBA PPC40 with a Supermax electrometer.

2.5. TL measurements

After the exposures and following a selected delay of 24 h (to allow uniform control of thermal fading), the optical fiber TL yield was read out using a Harshaw 3500 TL reader. In this study, the time temperature profile (TTP) was set as follows: preheat temperature of 50 °C, maximum temperature of 400 °C, acquired temperature rate at 25 °C/s, post annealing of 6 s and total acquisition time of 20 s. The readings were performed under nitrogen gas flow to suppress possible spurious light signals from triboluminescence and also to reduce oxidation of the heating element.

All TL responses were then normalized to the mass of the sample. An accurate electronic balance with 0.1 mg accuracy was used to measure the mass of a group of 10–15 randomly selected fiber samples per fiber type. For simplicity in this study, mean masses of 0.132 mg for SMF-1 and 0.136 mg for SMF-2 were used to normalize the TL yield for individual fiber samples. However, for TLD-100 chips, since the weight per chip is significantly high (~23–24 mg), the normalization is performed individually using actual weight per chip.

3. Results

3.1. Dose response

Fig. 3 shows TL response of the two SMFs for the three different electron energy irradiations, 6, 9 and 20 MeV, in comparison with TLD-100 TL yields. In terms of linearity, all samples show linear response (linear fitting curve r² > 97.8%) over the investigated dose range. 0.5 to 8 Gy for all three energies. Taking TLD-100 as the benchmark, SMF-1 exhibits significantly greater response to the TLD-100, while SMF-2 has approximately half of the response of the TLD-100. On average, SMF-1 has a TL response that is about 3.2 times greater than that for TLD-100 at 6, 9 and 20 MeV, and the results also confirm SMF-1 to significantly outperform TLD-100. The potential of Ge-doped optical fiber as TLD has been reported earlier in the literature. Hashim et al. [15,16] compared the TL response of a Ge-doped commercial SMF with TLD-100, oxygen- and Al-doped fibers under electron and photon energies.
Ge-doped fiber showed significantly better TL response compared to oxygen- and Al-doped fibers but showed a TL yield about 8 times lower compared to TLD-100. In another study, Yaakob et al. [17] confirmed the significant outperformance of Ge-doped fibers compared to Al-doped fiber, while the Ge-doped fiber used in their study could yield a TL half that of a TLD-100 chip. To the best of our knowledge there exist no previous reports showing SMFs to outperform TLD-100, certainly not to the present extent. Recently, Benabdesselam et al. [1] reported TL glow curve analysis of a multimode fiber (MMF) with 62.5 μm diameter with 2-layer Ge-doped fiber compared with TLD-500 and -600. The MMF is shown to be relatively more sensitive compared to TLD-500 and -600. Zahaimi et al. [18] demonstrated that the TL yield in a SMF with 8–9 μm diameter can be improved upon by up to 6 times using a larger core MMF with 50 μm diameter with the same cladding size.

Fig. 2. Absorption spectrum of SMF-1 and -2.

Fig. 3. TL response of two different SMFs in comparison with TLD-100 irradiated to 6, 9 and 20 MeV electrons. SMF-1 shows significantly greater TL response than SMF-2 and TLD-100.

Fig. 4 (left side) show the energy dependency of the two SMFs compared to that of TLD-100 at 6, 9 and 20 MeV. Both SMFs show low sensitivity to change in radiation energy, sharing this dosimetrically favorable behavior with that of TLD-100. On the other hand, Fig. 4 (right side) show the sensitivity curve of the optical fibers and TLD-100 calculated from their TL response divided by relative applied dose. Besides the irradiation energy insensitivity, both SMF-1 and TLD-100 have a positive sensitivity slope compared to SMF-2. Unlike SMF-2, SMF-1 and TLD-100 have slightly higher sensitivity at the higher doses compared to lower dose, showing them to be slightly dose dependent.

Uncertainty of the slope (ΔS) of the fitted curve in TL response (shown in Figs. 3 and 4 (left)) and dose detection sensitivity (shown in Fig. 4 (right)) is calculated based on the maximum slope (Smax) and minimum slope (Smin) calculated based on the variation or standard deviation (STD) in TL response as
\[ \Delta S = \frac{(S_{\text{max}} - S_{\text{min}})}{2} \]

where 

\[ S_{\text{max}} = \left( \frac{y_{\text{max at } x_{\text{max}}}}{y_{\text{min at } x_{\text{min}}}} \right) \]

and 

\[ S_{\text{min}} = \left( \frac{y_{\text{min at } x_{\text{min}}}}{y_{\text{max at } x_{\text{min}}}} \right) \]

The y_{\text{max at } x_{\text{max}}} is the maximum value in y-axis (mean + STD) at maximum value in x-axis, which here refers to the maximum TL value at dose 8 Gy and the y_{\text{min at } x_{\text{min}}} is the minimum value in y-axis (mean − STD) at minimum value in x-axis, which here refers to the minimum TL value at dose 0.5 Gy.

Table 2 shows the slope of fit and its uncertainty for TL response (Table 2(a)) and dose sensitivity (Table 2(b)) for SMF-1, -2, and TLD-100 for the three radiation energies. The highest variation in the slope of the fit to the TL responses for SMF-1, -2 and TLD-100 are 6%, 2% and 5%; and to the dose sensitivity are 2%, 0.4% and 1%, respectively. These low variations in the slope of the fit reconfirm the stability of the SMFs in terms of both energy independency and dose sensitivity, comparable with commercially available TLD-100.

Table 3 shows the average sensitivity of SMFs compared to TLD-100, obtained by dividing the TL response by its corresponding dose...
over the three radiation energies. SMF-1 offers a dose sensitivity 3.2 and 5.6 times that of TLD-100 and SMF-2, respectively, and TLD-100 shows about 1.7 times more sensitivity compared to SMF-2. The response variation in the dosimeter samples with greater sensitivity is greater than that of the dosimeters with lower sensitivity.

Since the fiber samples were cut manually to a mean length of 5 mm with a tolerance of 0.5 mm, for both SMFs the non-uniformity in length results in a greater variation in TL response compared to TLD-100. Due to very low mass of individual fibers, in present practice the mean mass has been used to normalize each fiber sample, instead of seeking to obtain individual fiber corrections. It should be noted that although, the fiber samples are cut manually, the highest measured TL variation observed was less than 8%, which is related to 6 Gy, 9 MeV, SMF-1 (Fig. 3(b)) with STD of 0.7 and TL yield of 8.9 μC/mg. This variation in TL yield of optical fiber can be reduced by cutting the fiber samples with an automated fiber cleaver.

3.2. Glow curve analysis

Fig. 5 shows the glow curves of SMF-1, -2, and TLD-100 resulting from electron irradiation at 6 MeV, delivering doses of 0.5, 2, 4, 6, and 8 Gy. To provide intercomparison between all three samples, the curves have been normalized to dosimeter mass, the time-temperature profile covering temperatures from 50°C to 400°C. Compared with TLD-100, with thermal luminescence at well-defined temperatures, at around 170, 220, 260 and 330°C, it is apparent that the SMFs exhibit a broad range of thermal excitation, as expected of an amorphous system.

Using the so-called computerized glow curve deconvolution (CCGD) method, second derivative deconvolution of the glow curve of SMF-1 and -2 has been carried out, Fig. 6, respectively, showing the resultant component peaks. The trap parameters associated with the component peaks are shown in Table 4, a mixture of first and second order kinetics being applied. It is found that the first half of the glow curve follows first order kinetics since while the second half follows second order kinetics. The deviation of the fitted sub-component peaks from the gross glow curve is about 0.04%, with a figure of merit of 2.8%.

In SMF-1, glow curve peak number 1, with activation energy 1.6 eV, could be associated with Si nanoclusters, while peak number 2, activation energy 1.8 eV, could also be related to Si nanoclusters and the oxygen-deficiency center (ODC) in the silica. Peaks numbers 3 and 4, activation energy 2.6 and 2.4 eV respectively, are probably due to the ion dopants Ge⁺ and/or Si⁺, peak number 3 being also probably related to the self-trapped excitation (STE) defect in silica. Peak number 5, with energy 2.2 eV, could be due to the STE, Si implantation, Si nanoclusters, and/or hydrogen defects [19].

In SMF-2, peak numbers 1 and 5 with 1st and 2nd order activation energy of 2.5 eV could be associated with the STE, Si implantation, and/or Si nanoclusters. Peak number 2, with activation energy 1.5 eV, is suggested to be due to Si nanoclusters in the fiber. Peak number 3 and 4, with activation energy 2.0 and 2.2 eV, is suggested to be mainly due to the STE, the ion dopant Si and C implantation, Si nanoclusters and/or hydrogen defects [19].

3.3. Minimum detectable dose

Minimum detectable dose (MDD) or the lower dose detection limit of a dosimeter is of clear importance in efforts toward reducing the limit of a dosimetric system for lower dose applications. In addition to the slope of TL response (m) of a dosimeter, the MDD also depends on the TL background signal, calculated as

\[ \text{MDD} = \frac{1}{m} (B_{\text{mean}} + 2\sigma) \]  

where \( B_{\text{mean}} \) is the average of the TL background signal combined with the photo-multiplier tube (PMT) noise signal obtained from TL samples annealed but unirradiated or the TL value provided by the TL reader in the absence of any TL sample within the reader and \( \sigma \) is the standard deviation of the background signals. The average and STD of background noise for the TL reader used in this study are 7.9 nC and 0.83, respectively. On the other hand, the variation in the slopes of the fit in the TL response reflects uncertainty on the MDD. Considering the slope of the fitted curve and its variation presented in Table 2, the MDD and its variation for SMF-1, -2, and TLD-100 over three applied energies are estimated based on Equation (1)

Table 5

<table>
<thead>
<tr>
<th>Minimum detectable dose (mGy)</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMF-1</td>
<td>6 ± 0</td>
<td>6 ± 0</td>
<td>6 ± 0</td>
</tr>
<tr>
<td>SMF-2</td>
<td>39 ± 3</td>
<td>38 ± 2</td>
<td>39 ± 3</td>
</tr>
<tr>
<td>TLD-100</td>
<td>19 ± 1</td>
<td>19 ± 2</td>
<td>19 ± 2</td>
</tr>
</tbody>
</table>
as shown in Table 5. Considering the average MDD obtained over 6, 9, and 20 MeV electron irradiations, SMF-1, -2, and TLD-100 have MDD values of 6 ± 0, 39 ± 3, and 19 ± 2 mGy, respectively. SMF-1 shows a detection threshold some 3.2 and 6.5 times lower than that of TLD-100 and SMF-2, pointing to considerable utility in detecting environmental doses.

3.4. Repeatability

In consideration of the potential repeated reuse of the samples, repeatability tests were performed on six samples from each of the SMF samples and TLD-100 each irradiated with 8 Gy dose at 6 MeV. Subsequent to each readout cycle, the same samples were re-annealed and re-irradiated for a total of four irradiation-readout cycles. The same annealing conditions and parameters presented in Section 2.3 for fiber samples and TLD-100 chip, are used here for subsequent readout cycles. The variation from the first TL yield is represented in Fig. 7, the error bars on the y-axis values provided as the STD in TL yield. From the six samples per dosimeter type, the highest variation observed in SMF-1, -2, and TLD-100 are 13.1%, 13.1% and 10.9%, where the average repeatability variation over the six samples is 11.0%, 8.7% and 9.7%, respectively. The low variations suggest the SMFs to offer reusability as radiation dosimeter sensors. It should be noted that the TL response difference between samples 1 to 6 are due to the cut length of the fiber samples as mentioned earlier.

3.5. Fading

The results of signal fading in the irradiated SMF samples are shown in Fig. 8. In this experiment, initially, the fibers were irradiated at 6 MeV to a dose of 6 Gy and stored in a dark place under room temperature. The readout was started after 24 h and continued up to 6 weeks from irradiation. The readout conditions and parameters were fixed for all measurements. The percentage of signal reduction after every 10 days is presented in the figure based on the exponential curve fitting. The TL signal of SMF-1 and -2 showed about 4 and 6% reduction after 10 days from irradiation, 21 and 30% after 60 days, respectively.

A comparison study is made with TLD-100 based on the reported works in literature, suggesting higher fading in optical fibers compared to TLD-100 especially for the longer period of time. Izak-Biran et al. [20] have shown the fading in TLD-100 is about 11%, 19%, and 22% after 10, 30, and 90 days by using 100 °C preheat temperature, respectively. They claimed that the fading in TLD-100 can be reduced to 4%, 7%, and 11% after 10, 30, and 90 days by using preheat temperature of 150 °C, respectively. Vasilache et al. [21] reported a fading of about 12% and 19% for TLD-100 after 10 and 25 days respectively, keeping the samples in a dark room. Noor et al. [22] presented fading analysis comparison between Ge-doped SMF and MMF with TLD-100, where after 133 days of storage, a TL loss of 11%, 8%, and 5% is observed with a preheat temperature of 160 °C, respectively.

3.6. Discussion

In standard optical fibers, to obtain the total internal reflection (TIR) required for effective light guiding for telecommunication, the core or cladding needs to be doped to obtain the necessary refractive index situation. Fortuitously it is the presence of the dopant that provides the defect centers for TL dosimeter applications, to first order a greater concentration of defects being expected to produce the greater TL response, albeit with saturation occurring (due to self-absorption) above a certain level. The EDX results of Table 1 show SMF-1 to contain the greater Ge doping concentration compared to SMF-2, supporting the superior TL response of SMF-1 over that of SMF-2. It is remarkable that a small increment of about 10% in Ge concentration in SMF-1 compared to SMF-2, caused a large TL response difference of 6.3 times, important in designing high-sensitivity optical fiber with optimum Ge concentration. Additionally, Fig. 2 shows the absorption of the two SMFs in the visible range, with SMF-1 exhibiting some two times the
absorption of SMF-2, again supporting the superior TL generated by SMF-1. Elevated absorption in the fiber suggests the availability of elevated defects/impurities in the fiber. It is important to note that a region of elevated absorption in optical fibers occurs at the longer wavelength infrared region, outside of the detectable wavelengths typical of TLD readers. This suggest a reader with wider detectable bandwidth would be more suitable for fiber TLDs, potentially providing for a higher photon count. Also, the presence of oxygen in the core of SMF-1 is slightly greater than that in SMF-2, while the Si concentration is opposite. Oxygen (O2) influences the absorption in optical fiber, as an example at around 630 nm. This agrees with present results, the higher absorption in SMF-1 at 630 nm being due to the higher oxygen concentration in SMF-1 compared to SMF-2. In mapping of the absorption curve in accord with the elemental content of the optical fiber core, what is missing here is a study of the dependencies of the optical fiber drawing parameters upon fiber properties, a matter which we intend to pursue. Hibino et al. [23] have shown that fiber attenuation increases as a result of increasing drawing tension. Elevated absorption over a wide spectral range, observed for SMF-1 (Fig. 2), suggests observation of the effect of fiber drawing-induced absorption in the fiber. Hibino and Hanafusa [24] have also shown significant absorption induced at 630 nm due to fiber drawing tension. This absorption in SMF-1 is some 3 times greater than that of SMF-2, which again suggests that a higher fiber drawing tension has been used for SMF-1 compared to SMF-2.

In terms of dosimeter performance, SMF-1 significantly outperformed TLD-100 with 3.2 times greater TL response and dose detecting sensitivity. SMF-1 has capability in detecting a minimum dose of 5.7 ± 0.2 mGy. In addition, this fiber shows highly linear TL response with regression fitting ($R^2$) of greater than 97.8%, relative independence to irradiation energy, low fading of less than 4% per 10 days, and repeatable dose measurement with an average variation of about 10%. These and other inherent advantages of optical fibers as mentioned in the introduction confirm the considerable capability of these optical fibers as dosimeter sensors. Thus said, comparison of the TL response of SMFs and MMFs in this study suggests that designing a larger core optical fiber like MMF, with Ge concentration similar to SMF-1, would significantly improve dose detection sensitivity of an optical fiber sensor.

4. Conclusions

The commercially SMFs with about 8.5 μm core diameter used herein reveal a linear dose response for 6, 9 and 20 MeV electron irradiations, up to at least 8 Gy, encompassing the range of fractionated doses normally used in radiotherapy. From this study, the SMF-1 produced elevated TL yields compared to SMF-2 and TLD-100, by a factor of around 6.3 and 3.2 times. Analysis shows SMF-1 to contain slightly higher germanium and oxygen concentration compared to SMF-2. Further, the absorption peak at 630 nm suggests that SMF-1 has been drawn with higher drawing tension compared to the SMF-2. These results confirm that by using optical fiber technology irradiation dose sensors with sensitivity beyond TLD-100 is possible. The output of this study strongly suggests optical fiber technology to provide a promising basis for developing next generation high sensitivity irradiation dosimeters.

Acknowledgements

The authors would like to acknowledge UM-MOHE High Impact Research (HIR) grants number A000007-50001 that financially supported this project, mydosimeter group members for their suggestions and discussions, and UM-MOHE HIR grant number UM.C/625/1/HIR/33 that partially contributed in this study.

References

Biographies

Ghafour Amouzad Mahdizadeh received his B.Eng. degree in Electrical Power Engineering from Iran in 2002 and his M. Eng. degree in Communication and Computer Engineering from University Kebangsaan Malaysia in 2006. In 2009, he received his Ph.D. degree from the Universities Putra Malaysia (UPM) in the field of Communications and Networks Engineering major in optical communication. From May 2009 to Aug. 2010 he was lecturer in the School of Engineering, UCSI University. Afterward, he joined to the Centre of Excellence for Wireless and Photonics Networks in UPM for around 1 year as Postdoc. From Nov. 2011 to 2012 he worked as Visiting Research Fellow in the optical fiber fabrication group in Integrated Photonics and Materials Research Group (ILRGI), Department of Electrical Engineering, University of Malaya. Since then, he is working in the same department as Senior Lecturer. Apart of optical communication system, his current research interests are on radiation dosimetry, design and fabrication of microstructured optical fiber for sensing applications.

Mostafa Gholmeshi was born in Tehran, Iran in 1982. He obtained his B.S. degree in Applied Physics from Ferdowsi University, Iran in 2005. He received his M.Sc. degree from University of Tabriz, Iran in 2008. He is currently pursuing the Ph.D. in the field of photonics research and technology at Integrated lightwave research group (ILRGI), department of electrical engineering, University of Malaya. His broad research experiences covered dosimetry, high energy beam spectroscopy, hot-plasma technology, and statistical analysis. Mostafa has membership in the global societies as OSA, and IEEE.

Elian Dermosenian received B.Eng. degree with Honours in Electrical Engineering in 2013 from University of Malaya, Malaysia. After graduation, she worked for 6 months as research assistant and then start her M.Sc study in the Integrated Lightwave Research Group (ILRGI) at University of Malaya. Her current research interest is design and fabrication of Microstructured Optical Fibers for dosimeter applications.

Subhailor Hashim (Ph.D. in Physics, UTM, 2009) Senior Lecturer at Universiti Teknologi Malaysia (UTM), medical radiation physics. He obtained his B.Sc. (Hons) in Nuclear Science from Universiti Kebangsaan Malaysia (UKM) in 2001 and M.Sc. in Medical Physics from University of Surrey, UK (2005). He completed his Ph.D. at the Universiti Teknologi Malaysia (UTM) in March 2009. Upon completing his Ph.D. research, he was awarded the Research/Postdoctoral Fellowship at Centre for Nuclear and Radiation Physics, University of Surrey, UK (from 1 May 2009 to 16 October 2010) funded by Kansas State University, USA and UTM. Currently, he is a Senior Lecturer at Physics Department, Faculty of Science, UTM and the Head of Nuclear and Dosimetry Laboratory. His current research interests include radiation physics, material sciences, medical physics/imaging and radiation dosimeters. He has worked for the last five years on the development of TL dosimeters. This has led to highly encouraging results for optical fibers and borate glass samples to be used in radiation dosimetry fields.

Ung Ngie Min is a senior lecturer and medical physicist at the Department of Clinical Oncology, University of Malaya Medical Centre. He possesses Bachelor of Biomedical Engineering and Master of Medical Physics from the University of Western Australia in collaboration with Genesis Cancer Care (formerly known as Perth Radiation Oncology). His PhD work revolved around the investigation of uncertainties in fiducial markers tracking during image-guided radiotherapy (IGRT) of prostate cancer. Apart from IGRT, his other current research interests include dosimetry, brachytherapy and advanced radiotherapy techniques.
Faisal Rafiq Mahamd Adikan received the Ph.D. degree from the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., in 2007. His Ph.D. research was focused on flat fiber and produced an international patent. He is currently the Head of the Photonic Lightwave Circuit Group in the Photonics Research Centre, University of Malaya, Kuala Lumpur, Malaysia, and is involved in developing novel fabrication processes to incorporate optically active materials into a glass matrix. He specializes in glass-based integrated optical devices for use in telecommunication and sensing applications. Apart from research and teaching, he is also an active member of the Faculty of Engineering, holding a number of administrative posts including the Coordinator of the Telecommunication Engineering program. He has published more than 70 journal and conference papers on optics and engineering education. He also deputy-chaired two Technical Postgraduate Symposia, and is the current chairman for the Sports and Recreational Club, Faculty of Engineering. He also established the Junior Lecturer Forum, an informal platform for young staff members to discuss matters concerning career development. Dr. Rafiq was the recipient of the Section Prize for the Best Engineering Research during Presentations at the House of Common (British Parliament) in 2006. He also received the SPIE Educational Scholarship in Optical Science and Engineering in 2004, and the Best Paper for Photonic Category during an international conference in 2003.

David Bradley (Ph.D. (USM), MSc (London), B.Sc. (Exeter)) is Professor of Radiation and Medical Physics at the University of Surrey. He has taught and researched in Universities for some 35 years. For some 14 years he Directed MSc programmes in Medical Physics. He was also for six years the Secretary of the International Radiation Physics Society (IRPS). Presently he is Editor-in-Chief of the British Journal of Radiology and Consulting Editor to the Elsevier journals ‘Applied Radiation and Isotopes’ and ‘Radiation Physics and Chemistry’. Dr. Bradley is the author of over 250 publications and has made more than 150 presentations at conferences. His interests are in researching the fundamental interactions of radiation in matter as well as their applications in biomedical areas and in industry.