The thermoluminescence response of Ge-doped flat fibre for proton beam measurements: A preliminary study

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Abstract. The aim of this study was to investigate the thermoluminescence (TL) response of fabricated 2.3 mol% and 6.0 mol% germanium (Ge) doped flat optical fibres to proton irradiation. The fundamental dosimetric characteristics of the fibres have been investigated including dose linearity, reproducibility and fading. The thermoluminescent dosimeters (TLDs) were used as a reference dosimeter to allow the relative response of the fibres. The results show that Ge-doped flat fibres offer excellent dose linearity over the dose range from 1 Gy up to 10 Gy with correlation of determination (R^2) of 0.99. The fibres also demonstrated good reproducibility within the standard deviation (SD) of 0.86% to 6.41%. After 96 days post-irradiation, TLD-100 chips gave rise to the least loss in TL signal at around 18% followed by fabricated 2.3 mol% Ge-doped flat fibres about 24%. This preliminary study has demonstrated that the proposed fabricated Ge-doped flat fibre offers a promising potential for use in proton beam measurements.

1. Introduction

Protons were first employed in medical treatment in 1946 [1] with the first attempts to treat patients began in 1954 [2]. Since then, proton beam therapy provides an advanced level of radiation treatment and is widely used nowadays in treating cancers. In radiotherapy, the reason of using proton beams instead of photon or electron beam is due to their physical characteristics of the Bragg curve. Proton beams loss their energy rapidly in the last few millimeters of penetration which results in a very precise localized dose peak at a target area, so-called Bragg peak. Changing the Bragg peak depth allows the desired dose to be sharply placed at any point in the patient. However, small changes can make a large difference on accuracy of the dose delivered, particularly in the distal fall-off region [3].

Therefore, verification of dose distribution in proton therapy before the treatment is very important to avoid any radiobiological effects to the patient. To achieve this, there is a need for accurate dosimetry systems which able to verify the radiation dose given to the patient. Over the past few years, a number of research groups have attempted to evaluate the use of doped silica optical fibre in photons [4-7], diagnostic X-rays [8-9], electrons [10], alpha particles [11], fast neutrons [12], and synchrotron radiations [13]. In all such studies, the studied optical fibres have shown considerable potential to be developed as radiation dosimeter in radiotherapy.

Although the dosimetric characteristics of the doped silica optical fibre for various types of irradiations have been reported in the literatures, their investigation in the proton beam has not yet been extensively studied. In the present study, we investigated the dosimetric characteristics of the proposed fabricated germanium (Ge) doped flat optical fibre with respect to dose linearity, reproducibility and signal fading for the proton beam and to compare it with TLD-100 chips.

2. Materials and methods

2.1. Fabrication of Ge-doped flat optical fibre

The tailor-made flat optical fibres studied herein were fabricated to produce 2.3 mol% and 6.0 mol% Ge-doped flat fibres with dimension of 643 × 356 μm^2 and 272 × 69.5 μm^2 respectively. The fibre preform was fabricated using modified chemical vapour deposition (MCVD) method at MCVD Laboratory in Telekom Research & Development (TM R&D) Sdn. Bhd., Cyberjaya, Malaysia with subsequent fibre pulling process at Flat Fibre Laboratory, Department of Electrical Engineering, Faculty of Engineering in University of Malaya (UM), Malaysia [14]. Figure 1 shows a cross-sectional image of the selected flat fibre and distribution of the germanium at the center of the fibre core.

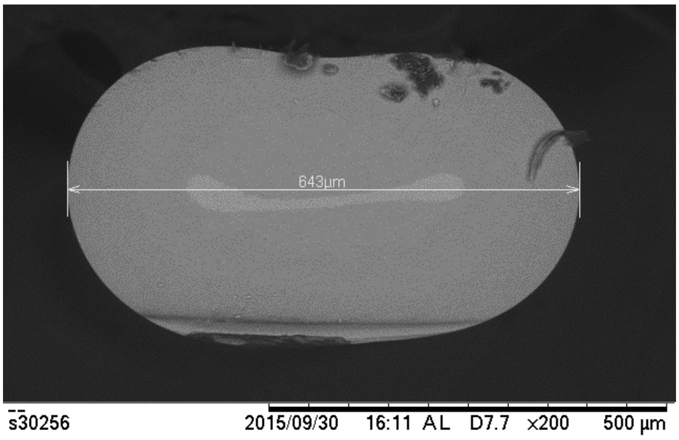

Figure 1. Cross-sectional image of a selected fabricated Ge-doped flat optical fibre obtained from a scanning electron microscope (SEM) analysis.

2.2. Preparation of samples

The fabricated flat fibres were cut using a diamond cutter (Thorlabs, USA) into 6.0 ± 1.0 mm length to easily accommodate within the planchet (the heating plate of the TLD reader). A vacuum tweezer (Dymax 5, UK) was used to minimise surface abrasion and deposition of dust or finger oil to the samples during handling. Prior to irradiation, the unscreened fibres were annealed using a furnace (Carbolite, UK) at temperature of 400 °C for one hour to erase any pre-irradiation TL signals. Whilst, TLD-100 chips (Thermo Fisher Scientific, USA) with dimension of 3.2 mm × 3.2 mm × 0.89 mm were annealed using a TLD annealing oven for one hour at 400 ºC and subsequently 16 hours at 80 ºC [15]. Following annealing procedures, the fibres and TLD-100 chips were retained inside their furnaces to finally cool down to reach room temperature to avoid thermal stress. The samples were kept in a light-tight box at room temperature to minimise exposure to ambient light prior to and following irradiation as it may affect the TL readings.

2.3. Irradiation setup

A total of five units of flat fibres and three units of TLD-100 chips were encased into their respective radiolucent gelatin capsules, used to provide homogeneity in the irradiation. The samples were placed horizontally in between water-equivalent slab phantoms and perpendicularly to the beam axis as shown in figure 2. A slab equivalent in thickness to maximum dose (d_{max}) was placed on top of the sample arrangement and another 10 cm of solid water was placed below the sample to provide the build-down for backscatter attenuation. The experiment was carried out based on the clinical treatment source-to-surface distance (SSD) of 100 cm and beam field size of 10 × 10 cm^2. Table 1 shows a summary of irradiation settings for proton, gamma, photon and electron beam used in this study.

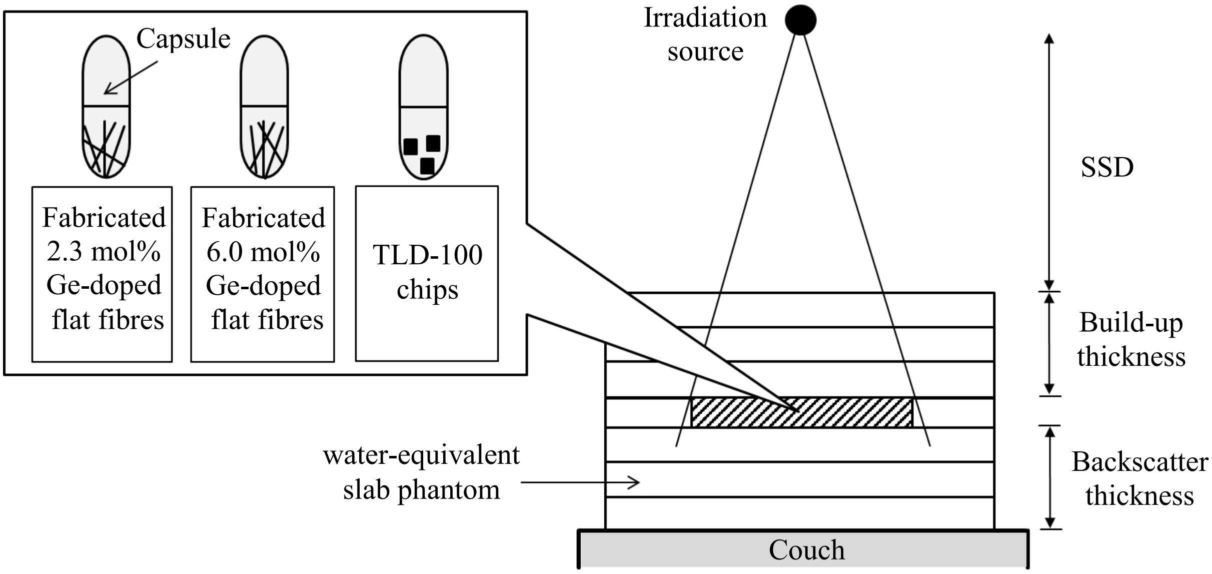

Figure 2. Schematic illustration of the experimental setup for sample irradiation.

Table 1. Summary of irradiation settings for proton, gamma, photon and electron beam.

	Proton	Gamma	Photon	Electron
Energy	150 and 210 MeV	1.25 MeV	6 MV	9 MeV
Dose	1-10 Gy	5 Gy	5 Gy	5 Gy
Dose rate	4 Gy/min	0.0427 Gy/min	600 MU/min	600 MU/min
Build-up thickness	14 cm (for 150 MeV) and 25 cm (210 MeV)	Nil	1.5 cm (bolus)	2 cm (bolus)
Applicator	Nil	Nil	Nil	10 × 10 cm^2

2.3.1. Dose linearity. The measurement of dose response for proton beam was evaluated over a dose range from 1 up to 10 Gy at a constant energy of 150 MeV.

2.3.2. Reproducibility. The samples were irradiated with proton, gamma, photon and electron beam at energy of 210 MeV, 1.25 MeV, 6 MV and 9 MeV respectively at a constant dose of 5 Gy. The same set of samples was reused, subsequent to re-annealing for each irradiation.

2.3.3. Signal fading. The samples were irradiated with proton beam at 150 MeV for 5 Gy and readout at day 3, 4, 7, 13, 20, 26, 34, 59 and 96. Throughout the storage period, the samples were stored in a light-tight box at room temperature until readout to avoid thermally stimulated release of trapped electrons.

2.4. Readout
A Harshaw TLD™ Model 3500 (Thermo Fisher Scientific, USA) reader was used to measure the TL signals from the flat fibres and TLD-100 chips, with nitrogen gas atmosphere at 0.5 bar to supress spurious light signals from triboluminescence and minimise surface oxidation. The flat fibres were readout with the time-temperature profile (TTP) at a preheat of 120 °C, acquired at a temperature ramp-rate of 30 °C s^{-1}, with an acquisition time of 13 seconds and maximum temperature of 400 °C. Whilst, the TTP for TLD-100 chips was set to preheat at 145 °C for 10 seconds and a temperature ramp-rate of 17 °C s^{-1} up to a maximum temperature of 300 °C for 10 seconds [5].

3. Results and discussion

3.1. Dose linearity
In figure 3, the fabricated 2.3 mol% and 6.0 mol% Ge-doped flat fibres were found to show a good linearity with correlation of determination (r^2) of 0.9911 and 0.9912 respectively over the investigated dose range. In line with expectation, TLD-100 chips show excellent and relatively flat TL response with r^2 of 0.9962 as compared to the flat fibres.

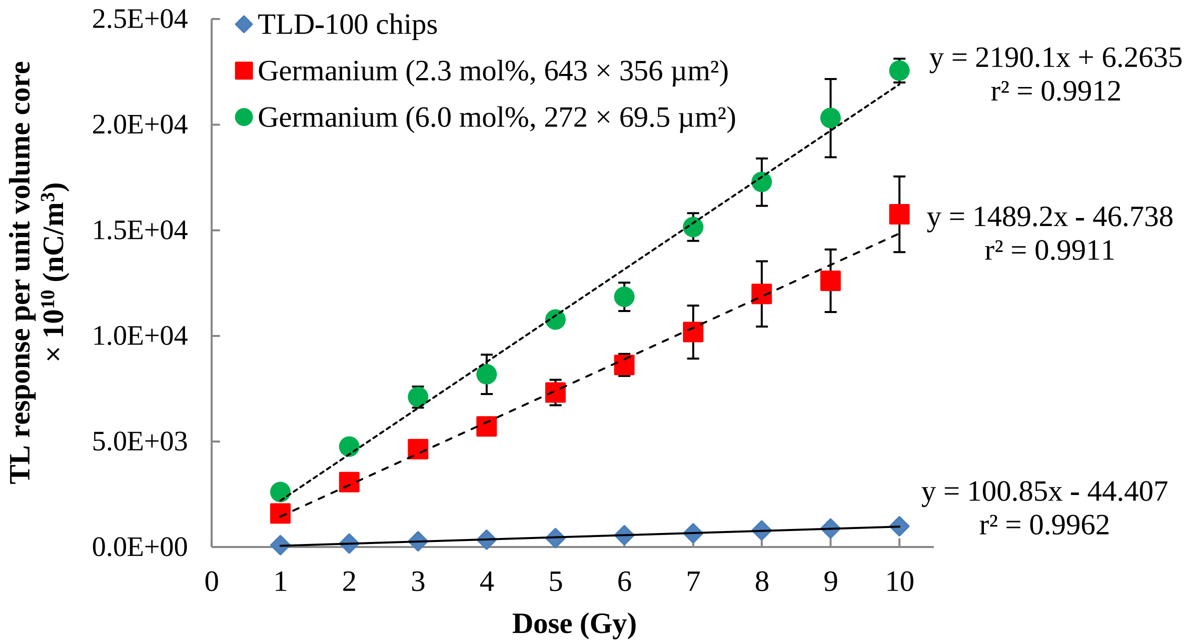

Figure 3. Dose linearity of Ge-doped flat fibres compared to that of TLD-100 chips.

3.2. Reproducibility
In table 2, it was apparent that both types of flat fibres show good reproducibility response with the standard deviation (SD) to be within 0.86% to 6.41%, whilst the TLD-100 chips show reproducibility to be always better than 1.06%. The SD value for 6.0 mol% Ge-doped flat fibres (6.41%) obtained in this study is better than the results reported by a previous study which is 7.56% [7].

Table 2. Reproducibility response of Ge-doped flat fibres and TLD-100 chips at dose of 5 Gy.

Sample	Irradiation source	TL response per unit volume × 10^{10} (nC/m³)		
		Mean	SD	SD (%)
TLD-100 chips	1.25 MeV gamma	379.98	4.03	1.06
	9 MeV electron	376.85	3.03	0.80
	210 MeV proton	420.31	2.87	0.68
	6 MV photon	399.40	0.16	0.04
2.3 mol% Ge-doped flat fibre	1.25 MeV gamma	89.83	2.77	3.08
	9 MeV electron	119.14	1.25	1.05
	210 MeV proton	125.25	1.08	0.86
	6 MV photon	129.83	1.45	1.11
6.0 mol% Ge-doped flat fibre	1.25 MeV gamma	106.72	6.84	6.41
	9 MeV electron	151.95	7.13	4.69
	210 MeV proton	126.65	6.43	5.07
	6 MV photon	174.09	7.14	4.10

3.3. Signal fading
Over 96 days post-irradiation, TLD-100 chips gave rise to the least loss in TL signal at around 18% followed by 2.3 mol% Ge-doped flat fibres about 24% as shown in figure 4. The largest signal loss was suffered by 6.0 mol% Ge-doped flat fibres at around 58%.

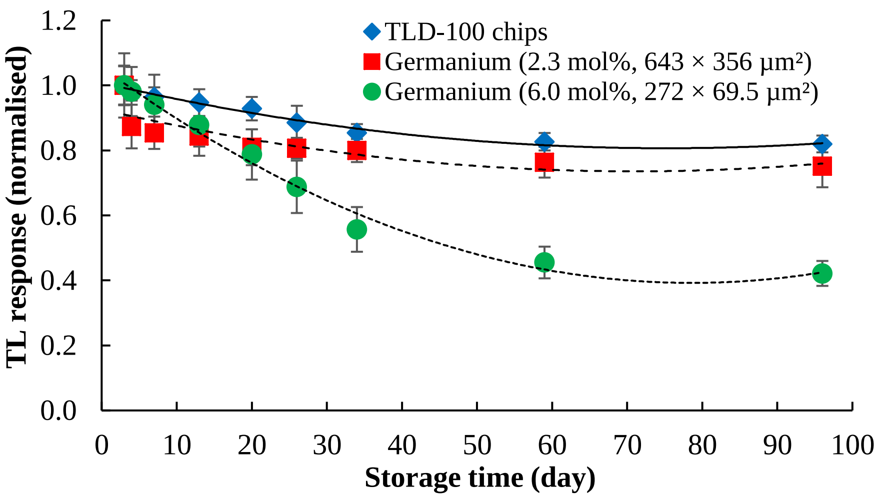

Figure 4. The loss of TL signals after normalised to day three post-irradiation.

4. Conclusion and future work
Results of the study represented several important key dosimetric characteristics of novel fabricated Ge-doped flat fibres including dose linearity, reproducibility and signal fading. Apparently, flat fibre with 2.3 mol% Ge-doped shows promising dosimetric characteristics as compared to 6.0 mol% Ge-doped. This is mainly due to 2.3 mol% Ge-doped flat fibres have better dose response, good reproducibility with SD better than 3.08%, and least signal loss about 24%. This preliminary study has demonstrated that the proposed fabricated Ge-doped flat fibre offers a promising potential for use in proton beam measurements. In future work, we suggest studying other dosimetric characteristics in more details including measurement of depth-dose distribution of the fabricated fibres in proton beam.

5. References
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