Characterisation of sensitive Ge-doped silica flat fibre-based thermoluminescence detectors for high resolution radiotherapy dosimetry

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Abstract: Present study focuses on characterisation of SiO\textsubscript{2} optical fibers as a potential thermoluminescence (TL) system for radiation therapy dosimetry. Irradiations were made using 6 MV photon beams from a linear accelerator. Flat SiO\textsubscript{2} optical fibers of various dimensions with 8\% concentration of germanium doped were used. The dimensions of the flat fibers were 270x60 $\mu$m, 360x73 $\mu$m, 100x510 $\mu$m and 160x750 $\mu$m. Flat SiO\textsubscript{2} optical fibers were characterised for TL dose response in terms of linearity, sensitivity, fading and reproducibility. The uncertainty measured was ±1 standard error of the mean and the coefficient variation was within ±4\%, as required for clinical radiotherapy dosimetry. Results shown a good distribution of TL response measured by flat SiO\textsubscript{2} optical fibers with uncertainties less than 4\%. Linearity of TL comes out with a coefficient of determination ($r^2$) of each fibers that is better than 99\% which resulted in high percentage of confidence level. The loss of TL response due to fading, for photon irradiation at fixed energy and constant dose was found to be (20.4 ± 0.2)\% over a post irradiation period of 30 days. The TL fading well, showing rapid loss in the first seven (7) days (17.8 ± 0.2)\% followed by a more linear like loss subsequently the following day (3.2 ± 0.2)\%. A perfect selection of fibers can enhance the accuracy of radiation dosimeter in order for better determination and measurement of radiation doses with a linear response over wide range therapeutic dose.

1. Introduction
Recent technological gains in radiation therapy, including intensity modulated radiation therapy (IMRT), image-guided radiation therapy (IGRT) and recent attempts to implement intensity-modulated proton therapy (IMPT) \cite{1,2}, enable delivery of more complex and conformal treatment plans and the use of tighter margins to irradiate smaller treatment volumes with higher doses. Correctly delivered radiotherapy dose ensures the possibility to improve survival rate and reduce toxicities to normal tissues for better quality of life. Any slight miss in the dosimetric verification may defeat the whole aims for better tumour control. The challenge in advanced dosimetry is to have a
system that is able to verify those complex plans. Obviously, not all dosimeters can satisfy all the characteristics, therefore, the choice of a radiation dosimeter and its reader must be made sensibly, taking into account the requirements of the measurement situation, such for beam calibrations, for the evaluation of the dose distribution or for dose verification. Therefore, study will investigate a potential TL dosimetry system for radiation therapy application. These preliminary studies will characterise the new candidate for dosimetry system of germanium doped silica flat fibers in term of its feasibility.

Characteristics of dosimetric properties of germanium doped silica glass optical fibre have been undertaken and established by a several groups for various applications in radiation therapy [3-18]. Commercially available germanium doped silica glass optical fiber has been shown to possess a number of desirable TL characteristics, in terms of dose stability, linearity of response, and sensitivity to dose. Previous studies have examined the performance of tailor-made doped silica cylindrical glass optical fibre and its dopant concentration effect on TL response due to photon and electron irradiation [4, 19]. Present study will focus on characterisation of tailor-made doped silica flat fibre at therapeutic doses.

2. Material and methods

2.1. Sample preparation

The dosimeter used is made of Ge-doped SiO$_2$ flat fibre (FF), which has been fabricated using MCVD process, with ultra-pure fused silica Suprasil F300 glass tube as the substrate (University of Malaya). The Ge-doped SiO$_2$ flat fibre has been fabricated by applying a vacuum pressure of 10 kPa from the top of the hollow preform during the drawing process [20]. The Z$_{eff}$ of the flat fibre is in the range of 11.3-11.8, based on Field Emission Scanning Microscope (FESEM) and Energy Dispersive X-ray Spectroscopy (EDXRS) analysis [21]. Five different dimensions of flat fiber have been used as shown in Table 1. Fibers were cut into approximately 5 mm length and average mas of each fiber have been measured.

| FLAT FIBRE | DIMENSION (um) | Ge - DOPANT (%) | MASS (gram) |
|------------|----------------|-----------------|-------------|
| FF-A       | 180 X 45 um    | 8               | 0.074       |
| FF-B       | 270 X 60 um    | 8               | 0.151       |
| FF-C       | 360 X 73 um    | 8               | 0.311       |
| FF-D       | 100 X 510 um   | 8               | 0.913       |
| FF-E       | 160 X 750 um   | 8               | 1.325       |

The flat fibers were annealed using a furnace (Carbolite CWF 23L Laboratory Chamber Furnaces). Fibers are placed in an alumina ceramic boat and annealed at 400 °C for an hour. The fibers were then removed and allowed to cool to room temperature at the rate of 10 °C/min. Thermal annealing is intended to erase accumulated radiation signal and stabilise the background of the medium such that dosimetric properties of flat fibers used are being controlled at the same state before any irradiation.

2.2. Irradiation Setup

The characterisation of Ge-doped SiO$_2$ flat fibres were investigated using 6 MV photon beam from an Synergy linear accelerator (Elekta, Crawley, UK) at Advances Medical and Dental Institute (IPPT), Universiti Sains Malaysia. Flat fibers were placed in a water phantom at 2.0 cm depth. A field size of 10 x 10 cm$^2$ and standard Source-Surface Distance (SSD) of 100 cm was applied.

Uncertainty: 100 samples of each Ge-doped SiO$_2$ flat fibres were characterised for TL sensitivity selection within a standard division of mean distribution. Provided at 3 Gy dose at constant dose rate of 400 cGy/min.

Dose Response: Each capsule (contained ~25 flat fibers) irradiated to 6 MV photon energy at a fixed dose rates of 400 cGy/min in the dose range of 1 to 10 Gy.
Reproducibility: To allow a study on reproducibility and repeatability of the dosimeter, the irradiations of each group of flat fibers have been repeated for several times.

Fading Effect: It is significant to know how long the information of radiation deposition can be stored by the flat fibre. Fading effect of the flat fibers has been investigated up to a month beyond the time of irradiation.

2.3. TL Measurement
The measurement of thermoluminescence (TL) yield response of the irradiated flat fibres has been performed using a Harshaw 3500 TLD reader. Measurements being carried out under nitrogen (N\textsubscript{2}) gas atmosphere. The TLD reader has been set up to a preheat temperature of 50°C for 10 s, an acquired temperature rate of 40°C/s, an acquisition time of 13.33 s and maximum anneal temperature of 400°C. This readout parameter was set up to ensure optimal data acquisition and radical sweep-out of any residual signal. The TL readings were normalised to the mass of flat fiber, to obtain results in µC/mg.

3. Results and discussions
Figure 1 shows the selected Ge-doped silica flat fibres are capable of producing a uniform TL response of better than 3% (1 S.D).

The above irradiation has been repeat consequently four time with the same set up of 6MV photon energy at the fixed dose delivered of 3 Gy at the dose rate of 400 cGy/min. Figure 2 shows that Ge-doped silica flat fibres are also capable of reuse, the TL response varying by about 0.3 % (1 S.D). The flat fibers dosimeter is able to shows a better uncertainty and reproducibility compared to cylindrical fibres obtained by [15, 19].

A linear response is obtained over the dose range 1 – 10 Gy, with a correlation coefficient of 0.994 or better. The least-squares straight line fits to the measured data, revealing a TL light yield (in counts per second per unit mass of fiber) corresponding to a dose-dependency of ~26 time the absorbed dose, measured in Gy, for photon irradiations. Each group of flat fibers provide the basis for sensitive dosimeter throughout this range, the TL yield increasing by on average 95 % per additional 1Gy of dose delivered for photon irradiation. The results show a small but systematic difference between the TL response at lower and higher dimension of Ge-doped silica flat fibres for photon beams, as shown by the various least-squares straight line fits in Figure 3.
The loss of TL response due to fading, for photon irradiation at fixed energy and constant dose was found to be (20.4 ± 0.2)% over a period of 30 days post irradiation. The TL fading well showing rapid loss in the first seven (7) days (17.8 ± 0.2)%, followed by a more linear like loss subsequently the following day (3.2 ± 0.2)%. The fading response of Ge-doped optical fibers investigated is shown in Figure 4.

Figure 2. The reproducibility and repeatability of Ge-doped silica flat fibres irradiated for four times consequently at a fixed dose of 3 Gy delivered at a dose rate of 400 cGy/min of 6MV photon energy.

Figure 3. Dose response of Ge-doped optical fibers of cross-section dimensions 180 × 5 µm (FF-A), 270 × 60 µm (FF-B), 360 × 73 µm (FF-C) and 100 × 510 µm (FF-D) and 160 × 750 µm (FF-E), provided together with the standard error of the mean. The solid lines are least square fits to the data, obtaining respective correlation coefficients of better than 0.994. The irradiation has been made used of 6 MV photon energy at 400 cGy/min for a dose range 1 – 10 Gy. (Note: in some cases, the error bars are smaller than the data points).
4. Conclusions
Ge-doped SiO$_2$ flat fibers produce the greatest sensitivity of all of the fiber samples, also displaying uniform sensitivity over the full range of measured doses (1 – 10 Gy). The various features in term of high spatial resolution, impervious to water, reproducibility and low signal loss over 30 days post irradiation (0.14% per day make these tailored Ge-doped SiO$_2$ flat fibers a promising TL material for use as a dosimetric system in radiotherapy.

5. References
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