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_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_2 optical fibers of various dimensions with 8% concentration of germanium doped were used. The dimensions of the flat fibers were 270×60 µm, 360×73 µm, 100×510 µm and 160×750 µm. Flat SiO_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_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) [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

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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 fiber 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.

Table 1. Physical properties of fabricated germanium doped silica flat fibers

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 to10 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_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).

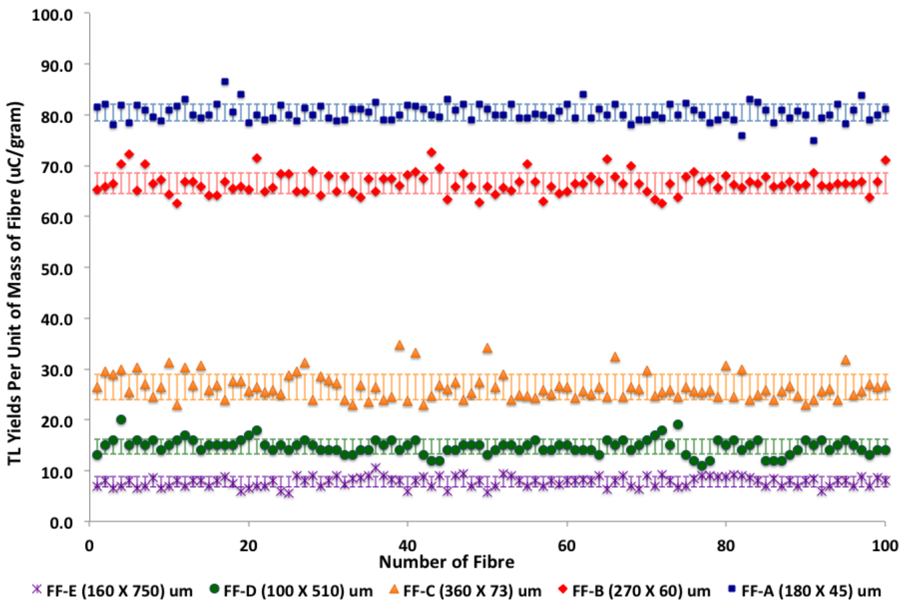

Figure 1. TL response of Ge-doped silica flat fibres irradiated with 3 Gy dose of 6MV photon energy at 400 cGy/min dose rate.

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.

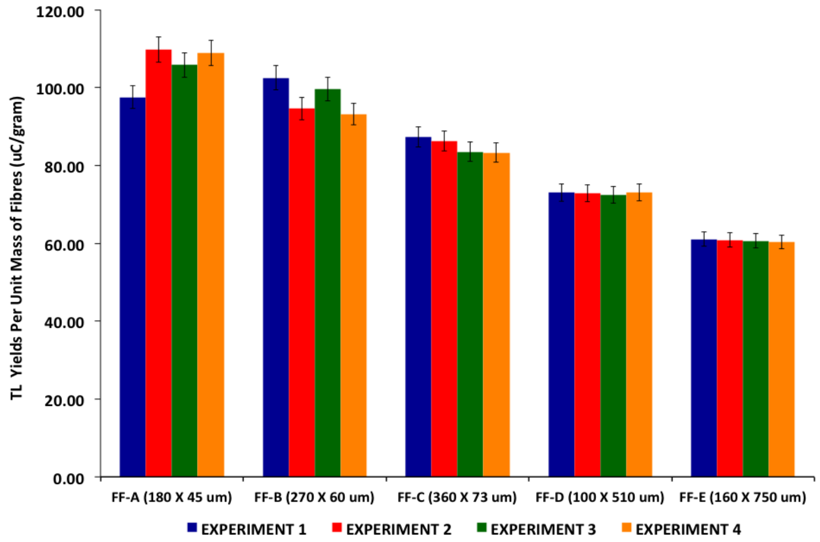

Figure 2. The reproducibility and repeatability of Ge-doped silica flat fibres irradiated for four times consequently at a fixed dose of 3 Gy delivered at a dose rate of 400 cGy/min of 6MV photon energy.

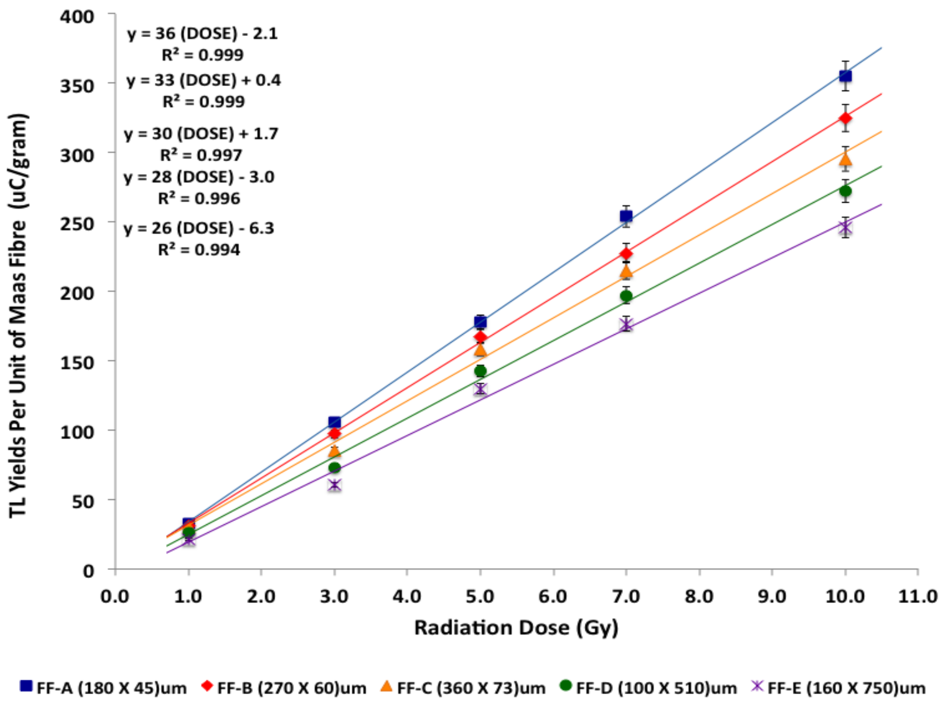

Figure 3. Dose response of Ge-doped optical fibers of cross-section dimensions 180 × 5 μm (FF-A), 270 × 60 μm (FF-B), 360 × 73 μm (FF-C) and 100 × 510 μm (FF-D) and 160 × 750 μm (FF-E), provided together with the standard error of the mean. The solid lines are least square fits to the data, obtaining 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).

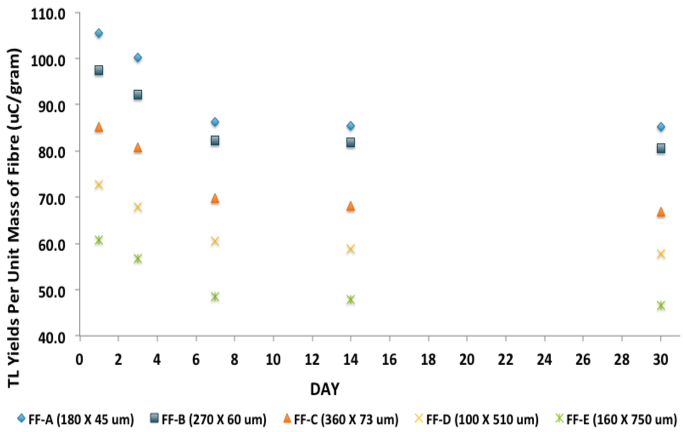

Figure 4. The loss of TL yield over a period of 30 days post-irradiation for the variously dimensioned Ge-doped optical fibers of cross-section dimensions 180 × 5 µm (FF-A), 270 × 60 µm (FF-B), 360 × 73 µm (FF-C) and 100 × 510 µm (FF-D) and 160 × 750 µm (FF-E). The irradiation has been made used of 6 MV photon energy at 400 cGy/min for a fixed dose 3 Gy.

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

[1] Michael Baumann, Mechthild Krause, Jens Overgaard, Jürgen Debus, Søren M. Bentzen, Juliane Daartz, Christian Richter, Daniel Zips and Thomas Bortfeld, *Radiation oncology in the era of precision medicine.* Nat Rev Cancer, 2016. **16**(4): p. 234-249.

[2] Saif S Ahmad, Simon Duke, Rajesh Jena, Michael V Williams and Neil G Burnet, *Advances in radiotherapy.* BMJ : British Medical Journal, 2012. **345**.

[3] N A Zahaimi, H Zin, G A Mahdiraji, A L Abdul Rahman, D A Bradley and A T Abdul Rahman, *Characterisation of the thermoluminescence (TL) properties of tailor-made Ge-doped silica glass fibre for applications in medical radiation therapy dosimetry.* Journal of Physics: Conference Series, 2014. **546**(1): p. 012012.

[4] N A Zahaimi, M H R Ooi Abdullah, H Zin, A L Abdul Rahman, S Hashim, M I Saripan, M C Paul, D. A. Bradley and A T Abdul Rahman, *Dopant concentration and thermoluminescence (TL) properties of tailor-made Ge-doped SiO2 fibres.* Radiation Physics and Chemistry, 2014. **104**: p. 297-301.

[5] Bradley D. A. Abdul Sani Siti F, Alalawi Amani I. Jafari, S. M. Noor Noramaliza, M. Hairul Azhar, A. R. Mahdiraji, Ghafour Amouzad, Tamchek Nizam, Ghosh S, Paul M. C, Alzimami Khalid S, Nisbet A. Maah M. J, *Development of tailor-made silica fibres for TL dosimetry.* Radiation Physics and Chemistry, 2014. **104**: p. 3-9.

[6] Abdul Sani, Siti. F.; Alalawi, Amani I.; Azhar, Hairul A. R.; Amouzad Mahdiraji, Ghafour; Tamchek, Nizam; Nisbet, A.; Maah, M. J.; Bradley, D. A., *High sensitivity flat SiO_2 fibres for medical dosimetry.* Radiation Physics and Chemistry, 2014. **104**: p. 134-138.

[7] Hossain, I., H. Wagiran, and N.H. Yaakob, *Thermoluminescence of Ge- and Al-Doped SiO_2 Optical Fibers Subjected to 0.2–4.0 Gy External Photon Radiotherapeutic Dose.* Journal of Applied Spectroscopy, 2013. **80**(4): p. 620-623.

[8] Bradley DA, Hugtenburg RP, Nisbet A, Abdul Rahman AT, Issa F, Mohd Noor N, Alalawi A, *Review of doped silica glass optical fibre: Their TL properties and potential applications in radiation therapy dosimetry.* Applied Radiation and Isotopes, 2013(0).

[9] Fatma Issaa, A.T. Abdul Rahmana, Richard P. Hugtenburg, David A. Bradleya, Andrew Nisbet, *Establishment of Ge-doped optical fibres as thermoluminescence dosimeters for brachytherapy.* Applied Radiation and Isotopes, 2012. **70**(7): p. 1158-61.

[10] Abdul Rahman, A.T., Siti Fairus Abdul Sani, and D. A. Bradley, *Doped Silica telecommunication fibre as a 1-D detector for radiation therapy dosimetry.* AIP Conference Proceedings, 2012. **1423**(1): p. 347-353.
[11] Noor, Noramaliza M; Hussein, M; Bradley, D.A; Nisbet, A., *Investigation of the use of Ge-doped optical fibre for in vitro IMRT prostate dosimetry.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2011. **652**(1): p. 819-823.
[12] Issa, Fatma; Latip, Nur Atiqah Abd; Bradley, David A.; Nisbet, Andrew, *Ge-doped optical fibres as thermoluminescence dosimeters for kilovoltage X-ray therapy irradiations.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2011. **70(7), 11**
[13] Abdul Rahman, A.T., S.F.A. Sani, and D. Bradley, *Doped Silica Telecommunication Fibre as a 1-D Detector for Radiation Therapy Dosimetry*, in *IX Latin American Symposium on Nuclear Physics and Applications (IX-LASNPA 2011)*2011, AIP: Quito, Ecuador.
[14] A.T. Abdul Rahman, R.P. Hugtenburg, Siti Fairus Abdul Sani, A.I.M. Alalawi, Fatma Issa, R. Thomas, M.A. Barry, A. Nisbet, D.A. Bradley. *An Investigation of the Thermoluminescence of Ge-doped Silica Optical Fibres for Application in Interface Radiation Dosimetry*. in *8th Industrial Radiation and Radioisotope Measurement Applications (IRRMA)*. 2011. Kansas City, USA.
[15] Abdul Rahman, A.T., A. Nisbet, and D.A. Bradley, *Dose-rate and the reciprocity law: TL response of Ge-doped SiO_2 optical fibers at therapeutic radiation doses.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2011. **652**(1): p. 891-895.
[16] Noor, NM, Hussein, M, Bradley, DA and Nisbet, A, *The potential of Ge-doped optical fibre TL dosimetry for 3D verification of high energy IMRT photon beams.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2010. **619**(1-3): p. 157-162.
[17] S. Hashim, D. A. Bradley, M. I. Saripan, A. T. Ramli, H. Wagiran, *The thermoluminescence response of doped SiO_2 optical fibres subjected to fast neutrons.* Applied Radiation and Isotopes, 2010. **68**(4-5): p. 700-703.
[18] D. A. Bradley, R. P. Hugtenburg, Suhairul Hashim, O. O. Okoya, A. L. Yusoff, A. Aziz Mat Hassan, A. T. Ramli, and H. Wagiran, *The Development of Doped Radiosensitive Glass.* AIP Conference Proceedings, 2007. **909**(1): p. 9-18.
[19] A.T. Abdul Rahman, R.P. Hugtenburg, Siti Fairus Abdul Sani, A.I.M. Alalawi, Fatma Issa, R. Thomas, M.A. Barry, A. Nisbet, D.A. Bradley, *An investigation of the thermoluminescence of Ge-doped SiO_2 optical fibres for application in interface radiation dosimetry.* Applied Radiation and Isotopes, 2012. **70**(7): p. 1436-1441.
[20] Entezam, A., Khandaker, M. U., Amin, Y. M., Ung, N. M.; Maah, J., Bradley, D. A., *Thermoluminescence response of Ge-doped SiO_2 fibres to electrons, X- and γ-radiation.* Radiation Physics and Chemistry, 2016. **121**: p. 115-121.
[21] S. Hashim, S. S Che Omar, S. A. Ibrahim, W. M S Wan Hassan, N. M. Ung, G. A. Mahdiraji, D. A. Bradley, K. Alzimami, *Thermoluminescence response of flat optical fiber subjected to 9 MeV electron irradiations.* Radiation Physics and Chemistry, 2015. **106**: p. 46-49.

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