Characterisation of the thermoluminescence (TL) properties of tailor-made Ge-doped silica glass fibre for applications in medical radiation therapy dosimetry

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Abstract: We have investigated the characterisation of new fabricated material Ge doped silica glass thermoluminescence TL dosimeter (Photonic Research Centre, University of Malaya) for medical radiation dosimetry at therapy energy. Previously, the dosimeter has been studied to provide ideal dosimetry system, suitable to ensure an accurate delivery of radiation doses to tumour tissue while minimising the amount of radiation administrated to healthy tissue. Both energies of photon and electron were used in this experiment for a dose range of 1 to 5 Gy. The various sizes of core diameter Ge doped silica glass (120, 241, 362, 483 and 604 µm) were exposed by using linear accelerator at Pantai Medical Centre. For both energies, the optical fibres were found to produce a flat response to a fixed photon and electron doses to within 4% (S.D) of the mean of the TL distribution. In terms of dose response, the fibres provide linear response over the range investigated, from a fraction of 1-5 Gy. The finding shows 120 µm fibres have 1.82 greater dose response than 604 µm fibres irradiated at 6 MV photon with a fixed dose of 3 Gy. While for electron energy 12 MeV, the response shows 120 µm fibres have 1.58 greater dose response compared to 604 µm fibres. The good responses are suitable to make these tailor-made doped silica fibres a promising TL material for use as a dosimetric system in medical radiation therapy.

1. Introduction

Radiation therapy is the use of high energy radiation to shrink tumors and destroy cancer cells. The treatment is delivered by giving high radiation dose to the cancer tissue using a linear accelerator.
However, the dose is also deposited to normal tissue surrounding the cancer and this should be constrained to within acceptable levels.

Desirable characteristics and properties of doped silica glass for use in radiation therapy dosimetry system was studied by [1]. Thermoluminescence properties to be considered in choosing a suitable dosimetric system for radiation therapy dosimetry are linearity between radiation dose and response, sensitive to the signal, TL glow curve, acceptable accuracy and precision, and a good characterized relationship between the dosimeter response in the medium in which dose is to be measured and the calibration radiation field.

Recently, a number of research groups have started to study the potential use of doped silica glass as a radiation TL dosimeter to determine the absorbed dose by patients, in particular overcoming spatial resolution limitations of existing TL dosimetry systems [2]. One of the advantages doped silica glass fibre is its impervious to water and in some instances, like study by [3] about radiation induced attenuation, radioluminescence and optically stimulated luminescence (OSL) [4-6] it has also become possible to locate the fibres within a particular tissue needed [7].

In recent year, the thermoluminescence responses of doped silica glass fibres have been studied for various radiation sources including photon [8-10], electron [9, 11], alpha particles [12], fast neutrons [13] and synchrotron radiation [14]. In all investigation of TL performances of irradiated fibres have shown considerable potential for dosimetric application in radiotherapy, however the study made use of commercial optical fibres available in market which intestinally produce for telecommunication purposes. Therefore, this study will focus on investigation of new tailor-made Ge-doped silica glass fibres produced by Photonic Research Centre, University of Malaya. This study has been made use of 8 mol% of Ge doped silica glass fibre compared to commercial fibres used previously [8-10] which is ~3.1% mol. Literature shows that TL response of doped silica glass fibre relies on dopant concentration at core fibre [8-10].

2. Materials and methods

2.1. Sample preparation
An unclad of 8 % mol Ge doped silica glass with various sizes of core diameter namely 120, 241, 362, 483, 604 µm has been used as the basis of TL dosimetry system. These tailor-made doped silica glass fibres were fabricated at Photonic Research Centre, University of Malaya. The samples were cut with an approximately length of 5.0 ± 0.1 mm by using a cutter. The vacuum tweezer (Dymax 5 Charles Austen Pumps Ltd Surrey, UK) was used to handle the optical fibres. The study involved annealing, sample irradiation, TL measurement and data analysis.

2.2. Annealing process
Annealing process was performed at 400 °C for an hour and cut fibres were placed in alumina ceramic. Annealing process is used to remove any irradiation signal from thermoluminescence material, stabilise the trap structure and reset the dosimeter to initial conditions prior to irradiation. To avoid thermal stress, the fibres were left inside the slowly cooling furnace for a period of 24 hour to finally equilibrate at room temperature. After cooling, the fibre were placed in gelatin capsule, each made to contain 10 pieces of fibre to provide mean value of dose obtain at each irradiation condition. Electronic balance was used to weight each capsule, allowing TL yield to be normalized to unit mass of irradiated fibre (±0.02 mg). The weight of each fibre varied in the range of 0.10-0.35 mg.

2.3. Exposure process
The Ge doped silica glass fibres and TLD-100 were placed at the surface of solid water phantom and were irradiated with 6 MV photon and 12 MeV electron beam at a fixed nominal dose rate of 400 cGy/min using a LINAC (Elekta Synergy™) at Pantai Hospital Kuala Lumpur, Malaysia. Samples were placed in solid water phantom at Dmax of 1.5 cm and 2.5 cm depth for both photon energy and
electron energy respectively. The dose delivered by LINAC with field size of 10 cm x 10 cm at SSD of 100 cm.

2.1 Instrumentation
The optical fibre TL yield was readout by a Harshaw 3500 TL reader (Waltham, MA, USA) located at Universiti Teknologi MARA Pulau Pinang, Malaysia. An N₂ atmosphere was used to suppress possible spurious light signals from triboluminescence and also to reduce oxidation of the heating element: preheat temperature is 160 °C for 10s; readout temperature of 300 °C for 13.33s and heating rate cycle of 25 °C s⁻¹. Then, annealing temperature of 300 °C was applied for 10s to erase any thermoluminescence signal. This setting was set to provide an optimal glow curve and free of the effects of superficial traps.

3. Results and discussion

3.1. TL glow curve
Shallow traps, those nearest to the conduction band, are easily emptied at room temperature (RT), leading to measurable fading of the TL signal. The dosimetric traps require somewhat more energy to release trapped electrons, normally forming the peak within which maximum TL yield is obtained and hence are used as the principal peak in dosimetric evaluation. The deep seated traps require appreciable energy in order to be emptied, obtained by high temperature annealing. Figure 1 (a-c) shows the examples of TL glow curve for 120 µm core diameter for increase in absorbed dose from 1 Gy up to 5 Gy.

![Figure 1. TL Glow Curve of 120 µm for (a) 1 Gy (b) 3 Gy (c) 5 Gy and (d) TL glow curve for TLD-100 irradiated at 3 Gy for 6 MV photon energy.](image)

The maximum peak of TL intensity from 1 Gy to 5 Gy were appeared at approximate channel number 50 and the maximum number of peak TL intensity increase with increasing the irradiation dose. Comparing with the glow curve obtained for TLD-100 at delivered dose of 3 Gy at 6 MV photon energy.
irradiation, it shows that the peak number intensity is greater (Figure 1(d)) than fabricated 120 µm core diameter Ge doped silica glass.

3.2. TL response

One of the important characteristic to be a good thermoluminescence dosimeter is linear relationship between TL emission and the absorbed dose. The particular thermoluminescence material gives the great effect to the linearity range. Generally, the response of TL phosphors is linear at low absorbed dose value than becomes supralinear and finally saturates at high values [15]. The fabricated Ge doped silica glass with various sizes of core diameter (120, 241, 362, 483 and 604 µm) were exposed to 6 MV photon energy and 12 MeV electron energy. Figure 2 (a) and Figure 2 (b) displays a linear TL absorbed dose response from 1 Gy up to 5 Gy with respect to sizes of core diameter. The regression ($r^2$) remains 0.998 or better for both energy irradiations.

![Figure 2](image)

(a) (b)

**Figure 2.** TL response of Ge doped silica glass irradiation of 120, 241, 362, 483, and 604 µm for dose in range 1-5 Gy of (a) 6 MV of photon irradiation energy (b) 12 MeV of electron irradiation energy.

3.3. Energy dependence

To obtain the energy dependence, the sensitivity of Ge doped silica glass was calculated from the dose response relation for different photon and electron energies. The energy response that used in this study is 6 MV photon and 12 MeV electron, the available photon and electron energies for radiotherapy at Pantai Hospital in which the irradiations were carried out. Figure 3 shows that the energy response of 6 MV photon is ~ 5 % greater compared to 12 MeV electron energy. This may be explained by dependence of electron beam scattering and the range of the electron upon density and atomic composition, the effects of heterogeneity upon dose distribution being more pronounced for electron beams than for photons. Electrons being charged particles, energy is lost continuously as they pass through matter and also undergo significant scattering as electrons are light mass particles. The other significant reason is about the effect of air cavities in the loaded gelatin capsule on the dose distribution. It is important to take such factors into account in providing for the precision and accuracy of radiotherapy dosimetry. The need for calibrations carried out under conditions similar to that for field conditions is of great importance [16].
3.4. Sensitivity

TL sensitivity can be defined [17] as the amount of light released by phosphor per unit of radiation exposure. There are many factors that affect to TL sensitivity dosimeter such as kind and concentration of activators, system of the readout, heating rate, etc. The least square fit of the change in TL response in count per unit mass for 120 µm core fibres irradiated at 6 MV to be 1.82 greater than that obtained for 604 µm core fibres irradiated at same photon energy (Figure 2 (a)). While for electron energy, the least square fit of the change in TL response in count per unit mass for 120 µm core fibres irradiated at 12 MeV to be 1.58 greater than that obtained for 604 µm core fibres irradiated at same energy as shown in Figure 2 (b). Therefore, the average ratios finds that 120 µm core diameter Ge doped silica glass has better response and is more sensitive compared to 604 µm core diameter Ge doped silica glass for both energy irradiations.

4. Conclusion

At 6 MV and 12 MeV, the tailor-made Ge doped silica glass fibres fabricated by Photonic Research Centre, University of Malaya, provide good characteristic dosimeter that used in medical treatment in terms of linearity, dose response, energy dependence and sensitivity point to favorable applications within the dose ranges studied. The Ge doped silica glass fibres is an attractive viable dosimeter in radiotherapy due to its small physical size, flexibility and low cost. Further study on its application is significant to establish this tailor-made Ge doped silica glass fibres for potential use in medical treatment applications to be alternative TL dosimeter available.

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References

[1] Zahaimi, N.A., et al., Dopant concentration and thermoluminescence (TL) properties of tailor-made Ge-doped SiO2 fibres. *Radiation Physics and Chemistry*, 2014. **104**: p.297–301.
[2] Hashim, S., et al., The thermoluminescence response of doped SiO2 optical fibres subjected to photon and electron irradiations. *Appl Radiat Isot*, 2009. **67**(3): p. 423-7.
[3] Huston, A.L., et al., Remote optical fiber dosimetry. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2001. **184**(1–2): p. 55-67.
[4] Aznar, M.C., et al., Real-time optical-fibre luminescence dosimetry for radiotherapy: physical characteristics and applications in photon beams. *Phys Med Biol*, 2004. 49(9): p. 1655-69.

[5] Justus, B., et al., Optically stimulated luminescence radiation dosimetry using doped silica glass. *Radiation Protection Dosimetry*, 1997. 74(3): p. 151-154.

[6] Benevides, L.A., et al., Characterization of a fiber-optic-coupled radioluminescent detector for application in the mammography energy range. *Med Phys*, 2007. 34(6): p. 2220-7.

[7] Yusoff, A.L., R.P. Hugtenburg, and D.A. Bradley, Review of development of a silica-based thermoluminescence dosimeter. *Radiation Physics and Chemistry*, 2005. 74(6): p. 459-481.

[8] Abdulla, Y.A., Y.M. Amin, and D.A. Bradley, The thermoluminescence response of Ge-doped optical fibre subjected to photon irradiation. *Radiation Physics and Chemistry*, 2001. 61(3–6): p. 409-410.

[9] Abdul Rahman, A.T., A. Nisbet, and D.A. Bradley, Dose-rate and the reciprocity law: TL response of Ge-doped SiO2 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.

[10] Issa, F., et al., 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. 652(1): p. 834-837.

[11] Hashim, S., et al., The thermoluminescence response of doped SiO2 optical fibres subjected to photon and electron irradiations. *Applied Radiation and Isotopes*, 2009. 67(3): p. 423-427.

[12] Ramli, A.T., et al., The thermoluminescence response of doped SiO2 optical fibres subjected to alpha-particle irradiation. *Applied Radiation and Isotopes*, 2009. 67(3): p. 428-432.

[13] Hashim, S., et al., The thermoluminescence response of doped SiO optical fibres subjected to fast neutrons. *Applied Radiation and Isotopes*, 2010. 68(4): p. 700-703.

[14] Abdul Rahman, A.T., et al., The thermoluminescence response of Ge-doped silica fibres for synchrotron microbeam radiation therapy dosimetry. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2011. 619(1–3): p. 167-170.

[15] Yaakob, N.H., et al., Electron irradiation response on Ge and Al-doped SiO2 optical fibres. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2011. 637(1): p. 185-189.

[16] Bradley, D.A., et al., Review of doped silica glass optical fibre: Their TL properties and potential applications in radiation therapy dosimetry. *Applied Radiation and Isotopes*, 2012. 71, Supplement(0): p. 2-11.

[17] McKeever, S.W.S. and P.D. Townsend, Thermoluminescence dosimetry materials: properties and uses. 1995: *Nuclear Technology Pub.*