Enhancing the radiation dose detection sensitivity of optical fibres

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HIGHLIGHTS

- Improved TL yield of irradiated silica-based optical fibres.
- A range of forms of silica fibre have been fabricated.
- Large TL yield enhancement strongly suggests surface-strain defects generation.
- Novel forms with TL yields many times that of undoped capillary-fibre.

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ABSTRACT

A method for improving the thermoluminescence (TL) yield of silica-based optical fibres is demonstrated. Using silica obtained from a single manufacturer, three forms of pure (undoped) fibre (capillary-, flat-, and photonic crystal fibre (PCF)) and two forms of Ge-doped fibre (capillary- and flat-fibre) were fabricated. The pure fibre samples were exposed to 6 and 21 MeV electrons, the doped fibres to 6 MV photons. The consistent observation of large TL yield enhancement is strongly suggestive of surface-strain defects generation. For 6 MeV irradiations of flat-fibre and PCF, respective TL yields per unit mass of about 12.0 and 17.5 times that of the undoped capillary-fibre have been observed. Similarly, by making a Ge-doped capillary-fibre into flat-fibre, the TL response is found to increase by some 6.0 times. Thus, in addition to TL from the presence of a dopant, the increase in fused surface areas of flat-fibres and PCF is seen to be a further important source of TL. The glow-curves of the undoped fibres have been analysed by computational deconvolution. Trap centre energies have been estimated and compared for the various fibre samples. Two trap centre types observed in capillary-fibre are also observed in flat-fibre and PCF. An additional trap centre in flat-fibre and one further trap centre in PCF are observed when compared to capillary fibre. These elevated-energy trap centres are linked with strain-generated defects in the collapsed regions of the flat fibre and PCF.

1. Introduction

To-date, wide-ranging investigations have been made of the radiation dose detection capability of various types of passive dosimeters (Bradley et al., 2014; DeWerd et al., 2014; Halperin et al., 2014; Jafari et al., 2014; Marcazzó et al., 2013; Page et al., 2014; Pugliesi et al., 2014; Sahare et al., 2014; Salah et al., 2011; Twardak et al., 2014). The type of base material and constituent concentrations are the dominant factors influencing dosimeter performance. In recent years several materials have been the basis of new dosimeters with sensitivity and/or properties that improve upon existing capabilities, as for instance glass-based dosimeters doped with rare-earth materials. Examples of dopants and compounds include aluminium, copper (I), germanium, manganese, tin, zinc (Yusoff et al., 2005), lithium and barium (Timar-Gabor et al., 2011), zirconium oxide (ZrO_2) (Salah et al., 2011), copper activated calcium borate (CaB_4O_7:Cu) nanocrystals (Erfani Haghiri et al., 2013a), manganese doped calcium tetraborate (CaB_4O_7:Mn) nanocrystal (Erfani Haghiri et al., 2013b), lithium potassium borate glass doped with titanium oxide (TiO_2) and magnesium oxide (MgO) (Alajerami et al., 2013), dipotassium yttrium fluoride

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(K_2YF_5) crystals doped with samarium (Sm^{3+}) and terbium (Tb^{3+}) ions (Marcazzó et al., 2013). An additional form of glass based dosimeter that has attracted considerable and growing attention are silica-based optical fibres (Bradley et al., 2014), offering a range of advantages over other passive dosimeter types. These include high spatial resolution, by virtue of their very small size ($\sim 125\ \mu m$) relative to many other forms of dosimeter, linear dose response in both the low and high dose regimes (Alawiah et al., 2013a, 2013b; Girard et al., 2013), capability for real time remote monitoring (Fernandez et al., 2008; O'Keeffe et al., 2007), lower cost (Espinosa et al., 2006) and relatively high dose sensitivity (Abdul Sani et al., 2014).

A standard optical fibre has a core with higher refractive index compared to the cladding, typically provided for by doping with rare earth elements. The structural defects thereby produced within the fibre core represent the main basis for TL radiation dosimeter applications. Over and above the defects generated by the dopant impurities in the core, additional defects are induced in the optical fibre core during the fibre drawing process, influenced by fibre tension and the neck-down shearing effect (Friebele et al., 1976; Hanafusa et al., 1987; Hibino and Hanafusa 1986; Lee et al., 1998). These defects provide additional dose detection sensitivity of optical fibres, a situation not observed in sol–gel based or other forms of glass dosimeter. Other than these types of defects contributed from the choice of elements and their concentration doped in optical fibres or from the fibre drawing condition, additional new defects can be generated in optical fibres by fusing optical fibre wall surfaces during the drawing process. To-date, such defect generating mechanisms have not been harnessed in a controlled way in producing elevated sensitivity optical fibre TL dosimeters, a matter to be addressed in this paper.

The approach is entirely novel, to the best of our knowledge there being no other published reports showing such method for improvement in the TL yield of undoped optical fibres. The proposed method can be further applied to doped optical fibre preforms (the doped silica starting material, prior to fibre production) to further enhance TL yield. The main objective of this study is to demonstrate the proposed method for improving dose detection sensitivity in optical fibres, both pure and in silica fibre of arbitrary dopant concentration. For this purpose, three types of undoped optical fibres namely capillary optical fibre, flat fibre, and photonic crystal fibres, have been fabricated and tested for radiation dose detection. The thermoluminescence (TL) responses of these fibres are compared under 6 and 20 MeV electron iradiation and their glow curves are presented. Finally, the TL response of a doped capillary and flat fibres are presented and compared with that of the undoped capillary and flat fibres.

2. Materials and methods

2.1. Fibre fabrication

Five different types of optical fibre have been fabricated for this study (Fig. 1), three made using undoped preform and two with doped preform. The undoped fibres include capillary optical fibre, flat fibre, and photonic crystal fibre are shown in Fig. 1a–c, respectively. The doped fibres are capillary and flat fibre are shown in Fig. 1e and f, respectively. The undoped fibres are made from an ultra-pure silica glass tube termed Suprasil-300 (Heraeus Holding GmbH, Hanau, Germany), with outer and inner diameter of 25 mm and 19 mm, respectively. The doped fibres are made with ultra-pure glass tube as the substrate (obtained from the same manufacturer) and the doping is applied using the modified chemical vapour deposition (MCVD) process. Germanium of about 8.5% by weight (referenced to the applied gases in the MCVD process) were applied to the fibre preform. It should be noted that the concentration and material used in this study has been adopted with the restrictive intent of demonstrating the utility of the proposed method. As such, the doping recipe used herein does not

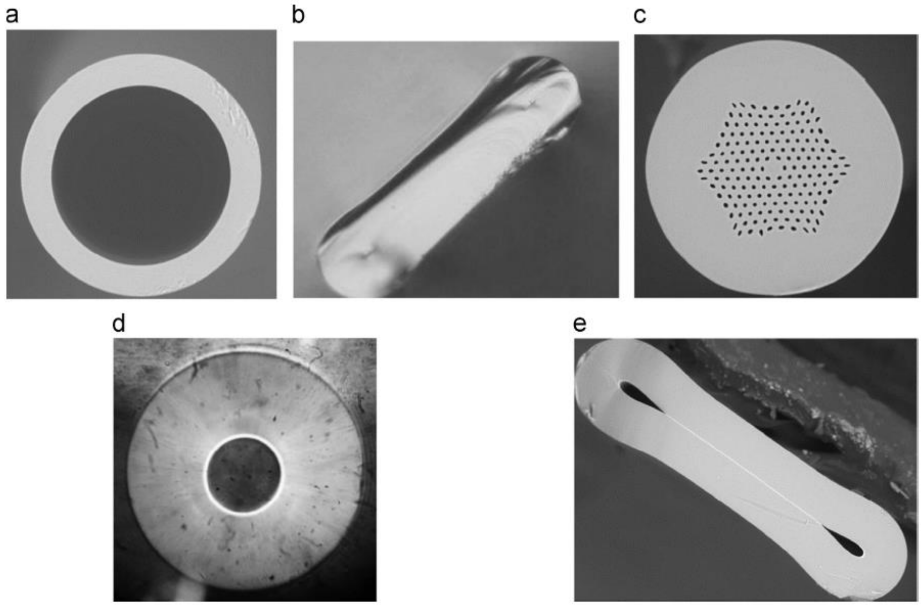

Fig. 1. Optical fibre images: (a) undoped capillary fibre; (b) undoped flat fibre; (c) undoped PCF; (d) doped capillary fibre; and (e) doped flat fibre. See text for information on the dimensions of the various fibres.

infer it to be optimal for dosimeter applications.

The optical fibres are fabricated using a lab-based drawing tower located at the University of Malaya. In use of this facility efforts have been made to maintain constant pulling parameters from one fibre production run to another. Thus said, small variations in drawing parameters resulting from the nature of different optical fibres (as in for example the fibres becoming more brittle with the addition of dopant) can be considered to have negligible effect on the outcome compared to the very large differences in performance of the different fibres, as presented in the following sections.

The capillary form has been fabricated at a temperature of 2000 °C by pulling a 25 mm diameter silica glass tube into a fibre of diameter ~200 µm. The flat fibres have been fabricated in a similar way, the one difference being the use of a vacuum pressure of ~10 kPa applied from the top of the glass tube in order to collapse the tube into a flat shape, the faces of the internal walls coming into contact with each other. The undoped and doped flat fibres used in this study have respective cross-sectional dimensions of 300 µm × 70 µm and 180 µm × 60 µm.

The PCF has been fabricated by using the stack-and-draw method, stacking a hexagonal shaped array of small diameter capillaries within a larger diameter tube and then pulling the assembly into a single fibre of diameter ~200 µm. Fig. 1 shows the cross sections of the various fabricated fibres.

2.2. *Sample preparation and irradiation*

Prior to irradiation, the samples were first cleaned using methyl alcohol and then long fibre strands were divided into individual lengths of 5 ± 1 mm, these being sufficiently small to hold within the heating tray of the TL readout device while also being sufficiently large to provide for ease of handling. To standardize the thermal history of the fibre samples, for instance removing any residual triboluminescence (mechanically as opposed to radiation induced) due to the preparation procedures outlined above, the samples have been annealed at 400 °C for a duration of 1 hour and then allowed to slowly cool to room temperature.

The fibre samples were subsequently irradiated using a Varian Model 2100C linear accelerator (Varian Medical System, Palo Alto, USA) located at the University of Malaya Medical Centre. The undoped fibre samples were exposed to 6 and 20 MeV electron radiation, with doses ranging from 0.5 to 8 Gy. During the radiation, the samples were placed at the surface of a *solid water*™ phantom of dimensions prescribed for accurate dosimetry, use also being made of an irradiation field size of 20 cm × 20 cm, a source to (phantom) surface distance (SSD) of 100 cm and an applicator size of 20 cm × 20 cm. In a similar fashion the doped fibre samples were exposed to a dose of 8 Gy, this time to 6 MV photons (the linear accelerator being set up for such delivery at the time).

2.3. *TL Measurements and normalization*

The TL yield of the irradiated fibres were read out using a Harshaw 3500 TLD reader, setting the time–temperature profile (TTP) of the reader to a preheat temperature of 50 °C, a heating rate at 25 °C s^{-1} and an acquisition time of 20 s. The TL responses were normalized to the mass of the sample, measured using an accurate electronic balance. For simplicity, the mean mass of 10 fibre samples was used for normalization.

3. Results and discussion

3.1. *TL analysis of pure silica fibre*

The TL response of capillary and flat fibres (FF) following 6 and 20 MeV electron beam irradiations, for doses in the range 0.5–8 Gy, are shown in Fig. 2. As expected, the capillary fibre shows minimal TL response, approaching that of the prevailing background noise. By collapsing the capillary into a flat shape, the resulting TL responses for 6 and 20 MeV irradiations has been observed to be some 12.0–12.5 times that of the capillary fibre. The approximate accord between the results for electron and photon irradiation is in line with the equivalent linear energy transfer (LET) provided by these sources. It should be noted that both fibres were fabricated from the same preform, simultaneously exposed and read out on the same day, the latter reducing potential drift effects of the TL reader. The results strongly suggest the dominant TL mechanism to be associated with the generation of new defects in the FF, the inner surfaces of the capillary fusing together during the drawing process, with subsequent strain relaxation on cooling and defects generation. To seek support for this, a PCF has been fabricated, the resulting TL to be then compared with that of the capillary and FF. In the present PCF there are a bundle of 168 capillary fibres, their outer surfaces being fused together. Thus, even greater TL response is expected to result from the PCF compared to that from the capillary fibre or FF.

For the same irradiation conditions as previously, Fig. 3 shows the TL response of flat fibre and PCF. The TL response of PCF is between 17.5 and 17 times that of capillary optical fibre for both 6 and 20 MeV irradiations, respectively. Compared to FF, the PCF provides a TL yield some 1.4 times greater. This strongly reaffirms the suggestion that the TL response in FF and PCF is predominantly generated from the fused surfaces of the collapsing region.

All three types of fibres represented up to this point show strong linear TL response, with $R^2 > 96\%$. Further, for the energy range applied, the fibres are seen to be insensitive to radiation energy. The variation of TL response at a given dose is primarily due to variation in fibre details, the variation being reduced to a certain extent by the mass normalization procedure. A length variation of about 5 ± 1 mm can lead to a 20% variation in TL response of fibre samples. Such variation can be reduced by characterizing individual response to dose, a rather laborious procedure.

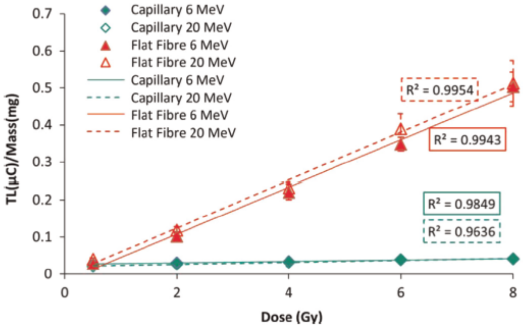

Fig. 2. TL response of capillary and flat fibre under 6 and 20 MeV electron irradiation, for doses in the range 0.5–8 Gy. All fibres show linear TL response and low energy dependency. While capillary shows very low TL response with almost flat response, FF provides multiple times higher TL.

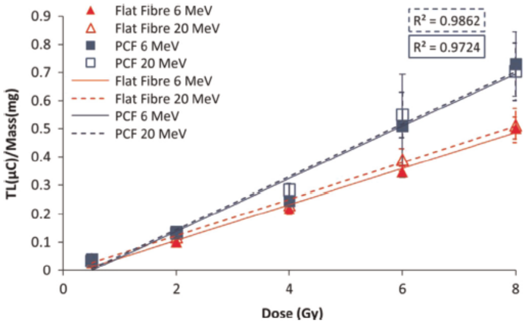

Fig. 3. TL response of flat fibre and PCF following 6 and 20 MeV electron beam irradiation for doses covering the range 0.5–8 Gy. While PCF is more sensitive than FF, both fibres show linear TL response and minimal energy dependence.

3.2. *TL analysis of doped silica fibre*

In the previous experiments, we have shown that the TL response of undoped capillary fibre can be improved, either by collapsing the inner wall surfaces into a flat shape or fusing the outer surface of an array of capillaries formed into a PCF. In this section, the performance of two forms of doped silica fibre are compared subsequent to 6 MV photon radiation to a dose of 8 Gy. A Ge-doped capillary and flat fibres (Fig. 1d and e), have been fabricated from a preform, the germanium being doped in the inner layer of the preform. Fig. 4 shows the TL response of the Ge-doped capillary and flat fibre in comparison with 'gold-standard' TLD-100 chips. Compared to the undoped capillary, which shows a response under electron radiation approaching that of background noise, at a photon dose of 8 Gy the Ge-doped capillary produces a TL yield some 10 times greater. This result confirms that doping of the optical fibre significantly increases the number of defect centres and thereby the TL response. When the capillary wall surfaces of the doped fibre are collapsed into a flat shape the TL response is improved by a factor of the order of 6. This result again confirms that by collapsing and fusing optical fibre surfaces, the TL response of the fibre will be substantially improved. Compared to the commercially available TLD-100 chip, the Ge-doped flat fibre has a response some 50% lower. The TL response in optical fibre can be further improved by using an optimum doping concentration. However, in this study and as previously noted, the Ge-doped fibre has been chosen simply to demonstrate the effect of wall surface collapse upon the TL yield of a doped fibre.

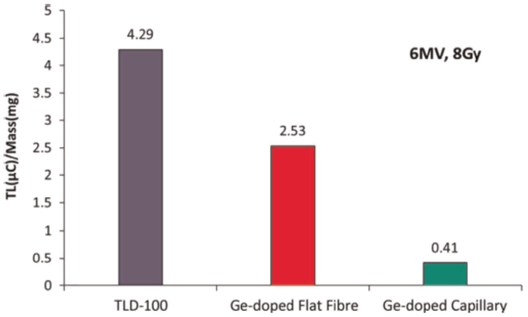

Fig. 4. TL response of Ge-doped capillary and flat fibre compared to TLD-100 under 6 MV photon irradiation at a dose of 8 Gy. Although the TL response of Ge-doped FF is not as great as that of TLD-100, its TL response is significantly improved compared to its original capillary shape.

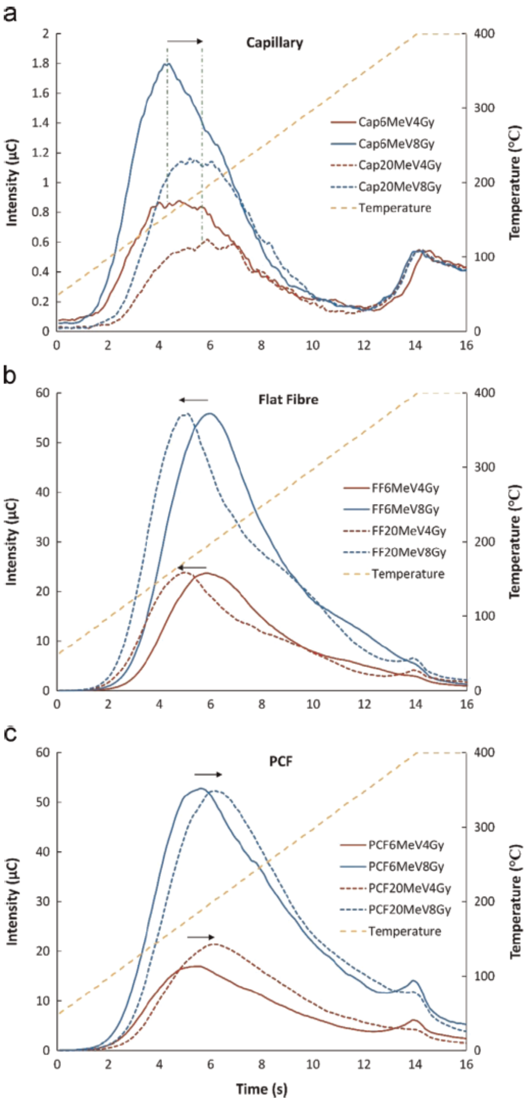

Fig. 5. Glow curves of undoped fibres following 6 and 20 MeV irradiation at doses of 4 and 8 Gy: (a) capillary optical fibre, (b) flat fibre, and (c) PCF. Glow curves were shifted by changing the radiation energy.

Based on observations for the undoped-silica fibres, as recorded in Section 3.1, it is expected that by fabricating PCF out of Ge-doped capillaries, the TL sensitivity will increase to a more pronounced degree. Moreover, this can be further enhanced by collapsing the PCF holes, and creating multiple flat fibres within a fibre.

3.3. *Glow curve analysis*

Fig. 5(a)–(c) show representative glow curves for undoped capillary fibre, flat fibre and PCF, respectively subsequent to 6 and 20 MeV electron irradiation at doses of 4 and 8 Gy. Compared to

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