Developments in production of silica-based thermoluminescence dosimeters

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HIGHLIGHTS

- Review of developments in doped silica dosimetry.
- Overview of fabrication and irradiation dependent defects.
- Application to proton radiotherapy dosimetry.
- Applications in environmental radioactivity.

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ABSTRACT

This work addresses purpose-made thermoluminescence dosimeters (TLD) based on doped silica fibres and sol–gel nanoparticles, produced via Modified Chemical Vapour Deposition (MCVD) and wet chemistry techniques respectively. These seek to improve upon the versatility offered by conventional phosphor-based TLD forms such as that of doped LiF. Fabrication and irradiation-dependent factors are seen to produce defects of differing origin, influencing the luminescence of the media. In coming to a close, we illustrate the utility of Ge-doped silica media for ionizing radiation dosimetry, first showing results from gamma-irradiated Ag-decorated nanoparticles, in the particular instance pointing to an extended dynamic range of dose. For the fibres, at radiotherapy dose levels, we show high spatial resolution (0.1 mm) depth-dose results for proton irradiations. For novel microstructured fibres (photonic crystal fibres, PCFs) we show first results from a study of undisturbed and technologically modified naturally occurring radioactivity environments, measuring doses of some 10 s of μGy over a period of several months.

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1. Introduction

Over the past three years we have been exploring the association between design and performance of silica-based media, our interest being in the utility of the latter in sensing ionizing radiation and in radiation dosimetry. Our efforts stem from earlier adventitious use of commercially available Ge-doped single mode telecommunication fibres (SMF) in such applications, the design of these being entirely unrelated to the needs to which the fibres were put. The SMFs, as well as other telecommunication fibres such as multi-mode fibres (MMF) and variants of these including Bragg gratings, are fabricated from low-defect silica, as an example, very pure SiO\textsubscript{2} in the form of Suprasil F300, a product of Heraeus (Hanau, Germany). Doped fibre fabrication starts from a

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hollow capillary (of a few cm diameter), doped using the Modified Chemical Vapour Deposition (MCVD) process. This process requires the introduction of gases (typically germanium tetra-chloride, GeCl₄, and silicon tetrachloride, SiCl₄) into a rotating hollow silica capillary, at the same time applying highly elevated temperatures, typically between 1800- and 2100 °C, to allow a deformable material and the deposition on the inner walls of SiO₂ and GeO₂. The preform resulting from this MCVD process can then be pulled into fine diameter (~0.1 mm) cylindrical fibres, a form typically used in telecommunications, again using elevated temperatures to soften the silica. The pulling requires use of a rig typically referred to as a pulling tower. For telecommunications the extrinsic dopant creates a change in refractive index between the birefringence of the doped silica core and the silica cladding, light within a particular band of wavelengths suffering total internal refraction, transporting the light forward with very low losses from as low as 0.2 dB km⁻¹ to perhaps ~few dB km⁻¹.

The presence of defects extrinsically introduced into such silica-based insulator media provides for the trapping of electrons that have been excited by incident radiation, with these then being stored as a luminescence signal pending stimulated de-excitation. Storage of the trapped electrons in such media is typically good, providing integration of the irradiation-mediated signal, strongly preserved over a period many orders of magnitude greater than the duration of the exposure. The situation is imperfect, a fraction of the trapped electrons spontaneously relaxing, due to sources of ambient energy, a loss referred to as fading. The fractional loss of TL signal depends on the depth of traps, deep traps (~few eV) suffering markedly less fading than more superficial traps. Practical systems of readout through stimulated de-trapping can either function through the application of heat, producing thermoluminescence (TL), or exposure to a controlled source of light, producing optically stimulated luminescence, the emission spectrum that reflects the trapping levels being picked up by a photomultiplier tube. Such systems provide a passive form of detection, contrasting with active devices such as diodes or ionisation chambers.

Present interest is in TL, a less favourable practical feature of such systems is the lack of on-line monitoring capability. For a well-behaved TL medium, one that can be used for radiation dosimetry, it is desirable for the system to respond sensitively to the radiation levels of interest and to provide TL yield linear with radiation dose. The range over which this occurs is referred to as the dynamic range. A highly sensitive medium points to lower limits of detection, the tendency being for the available defects to become occupied at relatively low doses. Indeed, we are currently pursuing doses down to a small fraction of a mGy as will be shown later. Conversely, the benefit of a less sensitive dosimeter for a particular source of radiation is that it can be used beyond the upper limit of linearity of the more sensitive dosimeters. As such, the question as to whether a dosimeter is considered good or poor is ultimately linked to the level of dose and range of dose that one wishes to detect, the arbiter of utility being whether it can be used as a monitor of environmental radioactivity, accumulating annual doses of as low as a few mGy, in dosimetry of synchrotron microbeam therapy beams delivering doses at a rate of the order of 10 kGy min⁻¹ (Abdul Rahman et al., 2010), or applied to radiation processing facility dosimetry, with doses of 10 s of kGy delivered over a period of an hour or less.

With this brief overview, it is perhaps clear that there exist a number of issues that need to be addressed in seeking high performance TL media. As an example, among the issues confronting use of commercially available fibres such as SMFs, are:

(i) undoped silica cladding, a low-defect unproductive component that also acts to attenuate the TL signal exiting the doped region, as indeed will the doped volume itself (Nawi et al., 2015);
(ii) dopant concentrations that yield sub-optimal TL levels;
(iii) geometric formation that offers sub-optimal net TL yield;
(iv) a potential inhomogeneously doped medium, with additional need to establish whether the fibres yield the designed-for dopant concentrations, measured using techniques such as refractive index profiling (RIP), scanning electron microscope energy-dispersive x-ray analysis (SEM-EDX) and also proton-induced x-ray emission/proton-induced gamma emission (PIXE/PIGE) techniques, the PIGE depending on nuclear reactions and their analysis;
(v) light transmitted through the cladding depending on the incident irradiation and spectra, trap depth so defining the net luminescence exiting the fibre;
(vi) recognition that the thermal conductivity of SiO₂, which while not small, is less than that of LiF, pointing to potential need for use of a temperature ramp-rate lower than that typically applied in use of phosphor dosimeters (LiF has a particularly high thermal conductivity).

In regard to (vi), with fibres popularly cut to 5 mm lengths for ease of handling, to-date the fibres have been read-out with their long dimension in contact with the planchet (the heating plate of the TL reader), not least allowing good thermal contact between the heating plate and TL medium. With TL light transporting preferentially along the fibre, normal to the photomultiplier tube, this sub-optimal readout situation has nevertheless been shown to offer excellent capability for radiotherapy applications (with doses from a fraction of a Gy to 10 s of Gy and beyond). A further issue in design of silica fibres is that the MCVD and fibre pulling facilities are expensive to establish and operate. Thus said, access to such facilities provides for novel microstructured assemblies that offer particularly high levels of sensitivity, a matter which we are presently testing at low (environmental) levels of dose, as will be discussed towards the end of this article.

In what is to follow we review the MCVD-based fabrication method and a wet-chemistry sol–gel nanoparticle approach that offers lower costs of fabrication, summarizing what we know from the characterization of defects and the radiation performance parameters. We will then provide example situations, our choices being limited by the length restrictions placed upon the invited article.

2. Silica production routes

Understanding the origin of luminescence from the various silica fibres involves study of intrinsic defects in the starting material, as well as those that result from fabrication, eg strain-related defects and extrinsic doping, and those that arise from exposure to ionizing radiation, all existing in differing concentrations and charge states. As intimated, commercial optical telecommunication fibres can lead to a poorly posed situation, the fabrication parameters having been set up to provide for optimum telecommunications. As such, the primary intent of the present collaboration has been to work with preforms and fibres based on use of the MCVD process, in particular those that have been tailored towards radiation detection, contrasting this route towards production with the surface decorated nanoparticle sol–gel approach. The sol–gel route offers a very much cheaper processing technique for production of doped glass developed for TL purposes (Rivera et al., 2007a; Siti Shaﬁqah et al., 2015; Wang et al., 2012) but as with the MCVD product it provides a solution that is not entirely without issues, not least in seeking to obtain closely similar quality product from each production batch. The variant of
the sol gel technique of interest herein involves producing surface-decorated/surface-coated silica nanoparticles, the surface decoration/coating creating luminescence centres. Herein we report on production of Ag-doped silica nanoparticles. Our analytical approaches in investigating the utility of the two forms of doped silica media involve:

1. elemental composition and morphological studies, to-date the sol–gel media being limited to use of SEM-EDX and x-ray diffraction (XRD);
2. defects characterization via optical properties (UV–vis, Raman spectroscopy, photoluminescence spectrometry, RIP and X-ray photo spectroscopy, XPS), to-date limited to the optical fibers;
3. dosimetric performance, for the MCVD fibres including the challenging situations of exposure to alpha particles and neutrons in aqueous environments.

Given article length restrictions and noting that previous publications by this group have detailed results from optical and ionizing radiation spectroscopies, we choose here to limit materials analysis results to those arising from use of XRD for the sol gel media. SiO2, be it crystalline (e.g. quartz, coesite, moganite) or amorphous (e.g. opal, hyalite, and silica glass, the latter being the main focus of our interest), is formed of a 3D network of four oxygen atoms surrounding each Si ion. The amorphous oxide lattice closely matches siliconin size, the tetrahedral structure with oxygen covalent bonding Si by sharing oxygen atoms in a six-membered ring (Fig. 1).

The physical properties of SiO2 include:

i. high melting point, ∼1700 °C, the silicon–oxygen covalent bonds throughout the structure needing to be ruptured before melting occurs;
ii. being an insulator, with electrons tightly held between atoms; iii. being insoluble in water and organics solvents, of particular interest for in vivo applications and those involving aqueous environments.

Defects underpin the mechanism of TL, the electrons and holes released by radiation being trapped at defect sites, giving rise to optical absorption and luminescence (Chen and McKeever, 1997). Notwithstanding the many types of defects in silica, present interest concerns those causing significant TL, intrinsic and extrinsic. Prime examples of the intrinsic are the broken or dangling bond, the oxygen/silica deficient centre and the self-trapped exciton. The former are dangling orbitals populated by unpaired electrons, detectable through electron spin resonance (ESR) (Jafari et al., 2014). Non-bridging oxygen gives rise to oxygen dangling bonds (potential hole traps) and empty Si orbitals. The oxygen broken bonds have been identified to be the source of 7.6 eV absorption which, while too deep for direct TL readout, is nevertheless potentially accessible by photo-transferred TL, PTTL; (see Zulkepely et al., 2015). Expected to be present in as-grown materials, as in silica, the broken bonds are also readily created by ionizing radiation. In disrupted SiO2 tetrahedra the absence of oxygen or silicon atoms creates oxygen deficient and silicon deficient defects. The oxygen-deficient centre (ODC), familiarly designated E, is representative of =Si–Si= with Si–Si indicating electron bonding in a chemical reaction. Analysis of the E centre indicates the presence of an unpaired spin, localized at the tp3 orbital of the silicon atom, with orbital orientation towards the oxygen vacancy position (Silsbee, 1961). If two adjacent silicon atoms relax asymmetrically, the most likely occurrence in vitreous glass givenits inherent asymmetry, then one electron can stabilize itself on one of the silicon atoms (Beall Fowler and Edwards, 1997). ESR studies in silica glass have shown the same E structure (Griscos, 1979). The Si–Si centre is capable of forming a hole–trap (Tsai et al., 1988). At annealing temperatures the E centre can transform into a Si–Si centre, while at even greater temperature the Si–Si centres tend to transform into excess silicon atoms in SiO2. These excess silicon atoms will then no longer produce luminescence (Rebohle et al., 1998).

In regard to the self-trapped exciton, when an electron is excited in a lattice it leaves a hole in the valence band. This electron will experience a Coulombic interaction with the hole, screened by ions and other electrons. The electron–hole pair, termed an exciton, can propagate through the crystal. In SiO2, the electron–hole pair is strongly bound due to the low dielectric constant of the base compound. The presence of the self-trapped exciton in silica leads to energy levels inside of the normal bandgap. Tsai et al. (1988) have estimated the exciton binding energy in SiO2 to be about 1.3 eV. Further, the existence of a photoluminescence (PL) band at 440 nm in SiO2 supports the suggestion that excitons are trapped in the SiO2 matrix, a phenomenon absent in an ideal crystal. It is now accepted that the mechanism for this defect in silica is motion of oxygenatoms in the crystal. The motion, first proposed by (Fisher et al., 1990) is an oxygen atom rotation about another Si–O bond of a neighboring silicon atom. This motion causes a lattice distortion that significantly changes the local energy level in the crystal.

In regard to extrinsic defects or impurity centres, when impurities are introduced into the SiO2 substrate it involves a model in which the impurity centres become either substitutional atoms, interstitial atoms or an impurity–intrinsich complex, with any of these being present inside the material. Apart from the possibility of introducing a new luminescence band, impurity atoms might also change the number of electron or hole traps or else provide much deeper traps in the media. One of the main desirable properties involving Ge impurities is its photosensitivity. Much attention has been paid to the defect produced by the

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![Fig. 1](http://www.iue.tuwien.ac.at/phd/filipovic/node26.html)
photosensitivity, known as the germanium oxygen deficient centre (GODC). This defect is commonly considered to be responsible for the changes in the refractive index in germanosilicate glass (Dianov et al., 1996). Concerning the absorption optical activity of these germanium related defects, it has been observed to have connection with the band peaks at 240 nm and 245 nm, referred to as the GODC and NOV (neutral oxygen vacancy) respectively. These two defects have sometimes been assigned to the wrong bond, such as Ge—Ge, Si—Ge, rather than the usual Si—O—Ge bond in Ge-doped silica media. It is found that these defects can be bleached with UV irradiation, producing defects such as GeE′, Ge (1) and Ge (2), GeE′, Ge (1) and Ge (2) are the most common Ge related paramagnetic defects that can be detected by electron paramagnetic resonance (EPR) in irradiated Ge-doped silica media. The GeE′ is representative of (≡ Ge≡), associated with an absorption band at 6.2–6.4 eV. The Ge (1) defect consists of an electron trapped at the site of a substitutional 4-fold coordinated Ge precursor (GeO₄⁻) (Chiodini et al., 1999; Neustreue, 1994; Pacchioni and Mazzeo, 2000), attributed to the absorption band at 4.4–4.6 eV. The Ge (2) defect is assigned as ionized twofold coordinated Ge (≡ Ge≡⁻). Based on EPR analysis, the presence of GeE′, Ge (1) and Ge (2) are found to be in the region g = 1.9937, 1.9933 and 1.9866 respectively.

The photosensitivity of Ge-doped silica material is found to be correlated with a defect observed in the photoluminescence spectrum, known as the Ge Lone Pair Centre (GLPC) with microscopic structure that has been illustrated to be similar to the Ge (2) defect. This defect can be observed in two band peaks in the photoluminescence spectrum, at 3.2 eV and 4.3 eV, with the absorption band referred to as transitions from a point defect ground singlet state (S⁰) to the first single state (S¹) (Hosono et al., 1992; Skuja, 1992).

2.1. Ge-doped optical fiber produced via MCVD technique

The fibers used by us in TL studies have employed the MCVD technique, produced in a high temperature environment using GeCl₄ and SiCl₄ as the precursor (Jacqueline et al., 2004; Liu et al., 1997; Mat-Sharef et al., 2013). The TL response of commercial SiO₂ doped optical fiber has been investigated for photons (see for instance, Abdul Rahman et al., 2011; Yussef et al., 2001), electrons (e.g. Abdul Rahman et al., 2011; Hashim et al., 2009) and alphas (e.g. Ramli et al., 2009) in each case showing considerable potential in dosimetric applications. Abrulla et al. (2001a, 2001b) carried out a study on commercially available Ge-doped optical fiber using a gamma source, the response being found to be linear from 1–120 Gy. Under electron irradiations, the Ge-doped fibers were shown to have a TL response superior to that of Al doped optical fiber, with linearity over the range of doses 0.02–0.24 Gy (Yaakob et al., 2011), tying in with the fact that Ge in the core allows increase in the value of the refractive index due to the photosensitivity.

Developments beyond the commercially available telecommunication fibre, also obtained using the MCVD technique, have included fabrication of hollow cylindrical fibres, collapsed fibres, photographic crystal fibres and flat fibres, with various Ge dopant concentrations extrinsically introduced and with various dimensional structures. As an instance, Ghomeishi et al. (2015) have investigated three types of Ge-doped optical fibres: conventional cylindrical fibre, capillary fibre, and flat fibre, all fabricated using the same optical fibre preform. For electron and photon irradiated fibres at doses from 0.5 to 8 Gy, the results show for capillary fibre collapsed into a flat shape that the TL yield is increased by a factor of 5.5, also some 3.2 times that of the cylindrical fibre. This suggests a strain-generated means of production of suitably sensitive TLD for in-vivo dosimeter applications, with changes in the form of glow curve also being noted. Begum et al. (2015) have also been among those who have shown that the sensitivity of FF constructs can be made to be competitive with phosphor-based TLD, in the particular case that of TLD-100 and TLD-700 (doped LiF). Further investigations have concentrated on novel microstructured fibres, one example being the photonic crystal fibre (PCF), produced by what is referred to as a stack and draw method (multiple doped fibres stacked together, as for example in a hexagonal array and then pulled into a fine fibre form), the TL arising from the dopant (Ge and B as an example) and induced strains (Dermosesian et al., 2015). Here, an interesting question concerns whether methods might be developed that could apportion the fractional TL yield due to the strain-related defects and extrinsic dopant(s). Glow curve analysis would seem to hold the key to this. The report of Dermosesian et al. shows that PCFs can markedly improve upon the sensitivity of an SMF, in one instance by a factor of some 30 ×.

2.2. The sol–gel technique

Chemical precursors are applied in this low temperature technique, providing a means of producing ceramics and glasses with purity and homogeneity greater than that achievable using the conventional high temperature MCVD technique. The method has been used to produce a wide range of compositions, mostly oxides, in various forms including powders (Rivera et al., 2007b, 2007c), fillers (Wen and Mark, 1994), coatings (Kurz et al., 2006; Natsume and Sakata, 2000) and thin films (Kajitvichyanukul et al., 2005; Marikkanam et al., 2015). The technique starts from mixtures of a chemical solution, the precursors acting as the source of elements to be incorporated into the final product. The most common precursor used for silica glass is tetraethylorthosilicate, Si(OEt)₄, commonly referred to as TEOS. The main chemicals in the mixture are then made to undergo chemical processes with the intent of forming a colloidal suspension known as sol. After going through a sequence of chemical reactions the sol stiffens to form a gel, subsequently heated and dried to form solid (sometimes as powders). In fabrication, Dabbaghian et al. (2010) found ethanol co-solvent to have the most significant effect on particle size and size distribution of the synthesized silica nanoparticles. Park et al. (2002) reported that smaller sized silica particles can be obtained by employing a small ratio of ethanol in the mixture. The synthesis of mono-dispersed silica particles have been explained in detail by Bogush et al. (1988). To-date, most TL in nanoparticle form have been made of ceramics such as ZrO₂ and ZnS. Purpose-made for TL studies, these have been demonstrated to have good performance under UV light (Azorín et al., 2005). Fewer studies have reported on the TL response of silica nanoparticles, Carvalho et al. (2010) reporting on the TL response to gamma rays of natural quartz at nm particle size and Mendoza-Anaya et al. (2003) discussing the TL performance of pure silica nanoparticles, comparing these with Fe and Cu-doped material. Pandey et al. (2004) investigated TL from pure silica nanoparticles supported by results from photoluminescence spectroscopy for defect characterization.

2.2.1. Ag-doped silica nanoparticles

What is to follow we abbreviate nanoparticles to np and focus on Ag as the dopant of interest. Elsewhere, CdS and ZnS have been doped with Ag (Tiwari et al., 2014), the TL intensity increasing with increase in UV exposure time, indicative of TLD potential. The use of Ag nanoparticles in ZnO₂ has resulted in modification of the kinetic parameters, inducing a shift of the TL temperature towards higher values (Villa-Sanchez et al., 2007), being of particular importance in ensuring a low fading rate of the stored TL signal.

One concern in introducing dopants into SiO₂ in the form of molten glass is the solubility. While in principle any element can...
mix with the SiO₂ precursor during the solution stage. The doping of Ag in SiO₂ is advantageous. SiO₂ reduces the tendency towards Ag Np agglomeration, important in achieving mono-dispersal of the AgNp. There is already a good deal of experience in working with Ag nanoparticles. As an example, coating of nanoparticles of this metal with a SiO₂ shell has been studied in attempts to enhance colloidal and chemical stability (Niitsoo and Couzis, 2011). SiO₂ coatings have also been successfully produced in forming a controlled dielectric environment around the AgNp, improving precision in surface plasmon resonance (SPR) sensing. Ag-doped SiO₂ has also been applied in surface enhanced Raman scattering (SERS), with Ag as one of the plasmonic materials, light excitation enhancing the local electromagnetic field (Feng Xian Liu et al., 2001; Long et al., 2012). In Fig. 2, the Cu Kα XRD pattern shows a broad distribution peaking at 2θ = 23°, indicating successful production of amorphous silica and agreeing with others (Gorji et al., 2012; Tabatabaei et al., 2006).

The results of Fig. 3 reveal crystalline peaks for the Ag-doped medium, at 2θ = 38.2, 44.4, 64.7 and 77.5°, confirming the presence of Ag nanoparticles in agreement with others (Hilonga et al., 2012; Mie et al., 2014; Torres et al., 2007) (Table 1).

In Fig. 4, it is apparent that particle size manifestly influences the TL properties of the silica nanoparticles, smaller particles, with proportionately greater surface area, exhibiting the greater TL yield compared to that of larger samples (Siti Shafiqah et al., 2015). As such, there are a proportionately greater number of light-emitting ions on the surface. The TL response of the nanoparticles increases with dose, pointing to the possibility of using silica nanoparticle powder as a dosimetric base-material. Mendoza-Anaya et al. (2003) report silica gel glow peaks to achieve an intensity maximum at much lower temperature compared to present results, indicative of the control issues needing to be confronted in product generation.

With Ag as the extrinsic impurity, effects are revealed in Fig. 5 that contrast with the use of Ge, one similarity being that with both Ag- and Ge-dopants saturation appears at much greater dose, beyond 500 Gy, compared to that of pure silica samples. For the latter, saturation starts at around 300 Gy. For present samples the AgNPs reduce the TL signal, with response less than that of the pure silica samples. Here the Ag multilayer coating the silica surface acts not only as a promoter of TL yield on the silica nanoparticles surface but also as an attenuator, absorbing and scattering a fraction of the incident radiation. Additionally, the layer acts as an inhibitor, reducing the efficiency for transport of TL from the silica nanoparticle surface. Thus said, a particularly attractive feature of the Ag is the extended dynamic range, providing greater versatility of the Ag-doped medium in radiation technology applications at elevated doses, as are found in radiation processing.

3. Examples of fibre TL applications

Here we choose two situations, the first being that of modulated and unmodulated proton beams, illustrating the considerable
spatial resolution (0.1 mm) capability of fibres in making depth-dose measurements, in this case of a 62 MeV proton beam. Use was made of commercial Ge-doped silica fibres, purchased from CorActive (Canada), the fibres having a core diameter of 50 μm and a cladding diameter of 125–127 μm. In order to use the fibres, the coating was first carefully removed through use of a fibre stripper (Miller, USA). The fibre was then cleaned to remove any residual polymer. The product was then cut into small fibre lengths of approximately 0.3 ± 0.1 cm, use being made of a scalpel.

The measurements (Fig. 6) were made in a thin window (0.1 mm mica) water phantom, the irradiations being carried out using the UK National Health Service Clatterbridge proton therapy facility. The results have been compared against gold standard parallel plate ionization chamber measurements. In measuring the Bragg peak, the commonly observed issue of a quenching effect is evident, with a decreased response with increasing ionization density of the radiation field. This dose underestimation in the Bragg peak of heavy charged-particles (Rah et al. 2012), also referred to as the quenching effect (Azangwe et al. 2014), has been reported most for chemical dosimeters such as polymer. The product was then cut into small 0.1 cm, use being made of a scalpel.

The upper graph shows the outcome for an undmodulated beam, the parallel plate ion chamber measurements. The lower graph shows the outcome for a modulated beam, the fibres producing a range that closely agrees with parallel plate ion chamber measurements.

Fig. 6. Depth dose distribution of a modulated and un-modulated 62 MeV proton beam. The upper graph shows the outcome for an undmodulated beam, the parallel plate ion chamber achieving the predicted peak to plateau ratio of some 5:1 while the fibres approach a ratio of 4:1. The lower graph shows the outcome for a modulated beam, the fibres producing a range that closely agrees with parallel plate ion chamber measurements.

The graphed results of Fig. 7 relate to the second set of situations, showing mass-normalised data from irradiations of fibres of various form and also of phosphor-based TLDs, obtained using a tube x-ray facility (model ERESCO 200 MF4-RW) located at the Physics Department of the University of Malaya. For present work the tube x-ray facility was operated at 80 kVp nominal tube potential, with doses to the samples ranging from 0.5 mGy to 10 mGy, verified through use of a calibrated ionisation chamber. The fibre results are for doped PCFs (Ge and B doped), PCF_Ge and PCF_B, the subscript c indicating that under the action of a vacuum, the fibres have been collapsed down from hollow bores into a solid assembly (see for instance, Ghomeishi et al., 2015; Dermosesian et al., 2015), inducing strain-related defects and thus additional TL sensitivity. The inset shows the sensitivity of the PCFs to greatly exceed that of TLD-100 (a doped LiF medium) while the phosphor, a material notable for its ability to sense environmental levels. Under the well controlled situation of x-ray irradiations, the sensitivity of TLD-200 is seen to out perform the present capability of LiF: Mg, Ti (TLD-100) phosphor-based medium.

The irradiated fibres show variations about the mean of up to ± 10%, an outcome that is highly competitive with results obtainable using the well-established LiF: Mg, Ti (TLD-100) phosphor-based medium.

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months. Mean above-ground dose-rates in air at 1 m of some 11 nGy/h correspond to a dose of ∼32 μGy over a four month period (Tikpangi Kolo et al., 2015). Samples of each type of TLD were collected two and four months after burial (with R1 representing the first sample collection and R2 the second sample collection).

The results, in histogram form (Fig. 8), are accompanied by glow curves for the various TL media (Fig. 9), soils analysis at the five specific locations including high-resolution gamma-spectrometry using a shielded high-purity Ge (HPGe) detector. The choice of locations were guided by the gamma-spectrometry analysis and hand-held survey meter findings, obtained regularly over a two-year period, identifying potential elevations (of a factor of up to 2) of NORM over undisturbed soil values (sampling location L1, L2, L3 offering particular examples). For the second sample collection (R2), the TLD results are typically greater than those from first sample collection (R1). The PCFc_Ge samples offer greater TL yield compared to PCFc_GeB, the converse of that found in using 80 kVp x-ray irradiations, PCF offers the greater TL yield compared to PCF. For R2 data, the peak maximum is observed to occur between 255 to 260 °C for both PCFs. The glow curves for the PCFs show the beginning of a high temperature shoulder indicative of strain-related defects.

4. Conclusions

The collaboration whose work is represented herein have made progress towards understanding a number of the major issues guiding development of silica based media for TLD. We have discussed fabrication issues and how these can influence defect types and concentrations. We have subsequently illustrated the discussion by providing examples from our most recent TLD results, pointing to the potentials of such media.

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