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Abstract: Review is made of dosimetric studies of Ge-doped SiO₂ telecommunication fibre as a 1-D thermoluminescence (TL) system for therapeutic applications. To-date, the response of these fibres has been investigated for UV sources, superficial X-ray beam therapy facilities, a synchrotron microbeam facility, electron linear accelerators, protons, neutrons and alpha particles, covering the energy range from a few eV to several MeV. Dosimetric characteristics include, reproducibility, fading, dose response, reciprocity between TL yield and dose-rate and energy dependence. The fibres produce a flat response to fixed photon and electron doses to within better than 3% of the mean TL distribution. Irradiated Ge-doped SiO₂ optical fibres show limited signal fading, with an average loss of TL signal of ~0.4% per day. In terms of dose response, Ge-doped SiO₂ optical fibres have been shown to provide linearity to x- and electron doses, from a fraction of 1Gy up to 2 kGy. The dosimeters have also been used in measuring photoelectron generation from iodinated contrast media; TL yields being some 60% greater in the presence of iodine than in its absence. The review is accompanied by previously unpublished data.

Editor-in-Chief

International journal Applied Radiation and Isotopes (ARI)

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10 December 2011

Dear Chief Editor

I would like to submit the attached manuscript, **Review of Doped Silica Glass Optical Fibre: Their TL Properties and Potential Applications in Radiation Therapy Dosimetry** for consideration for possible publication in **International journal Applied Radiation and Isotopes (ARI)** section of Special Issue ISSSD 2011 (Research Paper Proceeding).

This paper was presented at XXII NATIONAL CONGRESS ON SOLID STATE DOSIMETRY which held on 5th- 9th September 2011. The paper has been modified reflected the comment received during the symposium. This paper (or closely related research) has not been published or accepted for publication. It is not under consideration at another journal.

Sincerely,

Noramaliza Mohd Noor on behalf of Professor David Bradley

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Highlights

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Review of Doped Silica Glass Optical Fibre: Their TL Properties and Potential Applications in Radiation Therapy Dosimetry

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Abstract

Review is made of dosimetric studies of Ge-doped SiO₂ telecommunication fibre as a 1-D thermoluminescence (TL) system for therapeutic applications. To-date, the response of these fibres has been investigated for UV sources, superficial X-ray beam therapy facilities, a synchrotron microbeam facility, electron linear accelerators, protons, neutrons and alpha particles, covering the energy range from a few eV to several MeV. Dosimetric characteristics include, reproducibility, fading, dose response, reciprocity between TL yield and dose-rate and energy dependence. The fibres produce a flat response to fixed photon and electron doses to within better than 3% of the mean TL distribution. Irradiated Ge-doped SiO₂ optical fibres show limited signal fading, with an average loss of TL signal of ~0.4% per day. In terms of dose response, Ge-doped SiO₂ optical fibres have been shown to provide linearity to x- and electron doses, from a fraction of 1Gy up to 2 kGy. The dosimeters have also been used in measuring photoelectron generation from iodinated contrast media; TL yields being some 60% greater in the presence of iodine than in its absence. The review is accompanied by previously unpublished data.

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1. Introduction

Advances in the delivery of brachytherapy fields and external therapeutic beams continue to place considerable demands on the performance of dosimetric systems, for both point-dose and dose distribution evaluations. Challenges include obtaining a well-behaved characterised response across the large dynamic range of dose (the so-called high field gradient) presented at for instance tissue interfaces (eg as in radiation synovectomy), close up to brachytherapy sources, in intensity modulated radiotherapy (IMRT) and in tomotherapy. The spatial resolution and dynamic range required of a dosimeter to accurately evaluate the radiotherapy dose distribution of such complex three-dimensional geometries, especially at the micro spatial resolution scale, is indeed becoming increasingly challenging. When judged against the maintained effort to reduce patient morbidity and improve clinical outcome, the relatively large size of currently commercially available field dosimeters mitigates against their use in such challenging situations. This has been true of both active dosimeters such as ion-chambers and diodes and also of passive devices such as the phosphor-based thermoluminescence dosimetry (TLD) systems typified by LiF TLD-100. Herein, we detail efforts by the current group in utilising the highly promising TL characteristics of commercially available Ge-doped telecommunication fibres in confronting the various challenges outlined above.

1.1. History of TL Dosimetry

Thermoluminescence (TL) is a phenomenon involving the emission of light when particular media are heated following exposure to energetic radiations. TLD systems use TL materials for the measurement of integrated absorbed radiation dose, a fraction of the absorbed energy being conserved in metastable energy levels, either in localised electron bands of ordered media or also non-localised electron traps in the case of amorphous media. The conserved energy is subsequently released by heating, the sum of the light yields being related to the absorbed dose.

An account of historical studies of the TL phenomenon has been given by Becker (1973). As an instance, mediaeval alchemists knew that fluorite and some other minerals showed a transient glow when heated in the dark. The earliest recorded scientific observations of TL were apparently those of Boyle (1663), who wrote about his experiments on diamond, and similarly by Elsholtz in 1676 on the mineral fluorite (calcium fluoride) (McKeever, 1988).

Extensive development of TL as used today in TLD can be traced back to Wiedemann and Schmidt (1895), studying a wide range of inorganic compounds as well as natural minerals, using a

beam of electrons for the initial irradiation of the phosphors (Kron, 1999). Trowbridge and Burbank (1898) showed that X-rays could restore the property of TL to fluorite, which had previously been heated to remove emissions due to environmental radiation (McKeever, 1988). Madame Curie (1904) described the use of radium for the same purpose in her doctoral thesis, "certain bodies such as fluorite, becoming luminous when heated. Their luminosity disappears after some time, but the capacity of becoming luminous afresh through heat is restored to them by the action of a spark and also by the action of radiation".

Morse (1905) investigated the TL of fluorite, in particular the spectrum of the emitted light. Wick (1924, 1925) described TL stimulated in fluorite and many other materials by X-rays. He observed that the emission of light occurred at lower temperatures following exposure to X-rays, then following natural (environmental) irradiation. (This is due to more rapid fading of the lower-temperature peaks at ambient temperatures, although Wick merely noted the effect and did not offer an explanation) (McKeever, 1988). Urbach (1930) observed TL from alkali halides, suggesting that the temperature of maximum light emission was related to electron trap depth.

The foundations of TL theory appear to be due to Randall and Wilkins (1945) and by Garlick and Gibson (1948) (McKeever, 1988, Frame, 2004), providing expressions for the shape of a glow peak in terms of temperature, heating-rate, and the characteristic of the trap. TL materials, apparatus, mechanisms, and a wide range of potential applications, including dosimetry, identification of minerals, studies of catalysis and radiation damage, TL stratigraphy and age determination of rocks and pottery has been discussed by Daniels in 1953 (McKeever, 1988). This paper was the source of the often repeated claim that of over 3000 rocks and minerals studied, about 75 per cent showed visible TL. For dosimetry, the authors also recommended the use of LiF from the Harshaw chemical company. Thus this paper can be seen as the foundation of much of modern research and development in TLD.

LiF has been developed commercially by Harshaw Chemical Company and made available as TLD100, TLD100H, TLD600 and TLD700, depending on the quantity of Li present. The Li concentration determines how the element will respond to neutrons, and an activator is required for the material to be thermoluminescent. The effective atomic number of LiF ($Z_{\text{eff}} = 8.04$) is close enough to the value of Z_{eff} for tissue make it almost tissue equivalent. LiF has a complicated glow curve due to a complex of energy traps, use being made of the most stable of these in dosimetry (Cameron et al., 1968) while the least stable is short lived and decays rapidly (referred to as fading). The sensitivity of LiF, lower than some materials, is able to measure doses down to 0.1 mGy and is sufficient for most dosimetry applications in diagnostic radiology. Another regular use is for thermal neutron studies (Cameron et al., 1968; Chen and McKeever, 1997). Incorporating magnesium (Mg), copper (Cu) and phosphor (P) as dopants, prepared LiF can become a highly sensitive dosimeter for photons and neutrons within the useful range of 1 μGy up to 20 Gy, covering protection levels through to radiotherapy dosimetry.

CaSO_4 is well known as a high sensitivity phosphor. Applications involving Mn or rare earth dopants such as Sm and Dy (referred to commercially as TLD900) or Tm have been noted since 1960 (Chen and McKeever, 1997; Becker, 1973). The Mn-doped CaSO_4 has a single glow peak at 90°C. This low-temperature peak fades rapidly by approximately 30% within 10 hours and by up to 85% within three days (Becker, 1973). Therefore the readout should be performed as soon after the exposure as possible. This has made the Mn-doped CaSO_4 suitable for short duration experiments. This can be contrasted with Sm-doped CaSO_4 which produces a single peak at the higher temperature of 200°C, giving a low thermal fade rate. The other two doped material (Dy and Tm) have a similar response to that of the Mn-doped, where the glow curves of both produce unstable peaks at 80°C and 100°C, at lower dose but also produce a main glow curve peak at 250°C after exposures exceeding several Gy and show a sensitivity some 15 times that of LiF. Dy-doped CaSO_4 , responding in the useful range 1 μGy up to 100 Gy. Thermal fading for both materials have been found to be about 8% six months post irradiation. The effective atomic number of CaSO_4 , $Z_{\text{eff}} = 15.3$ is quite large, demonstrating strong photon energy dependence that necessitates the use of filters or sensitization in order to overcome this (Chen and McKeever, 1997).

A commercial TL material produced by Harshaw and familiar as TLD-500 is carbon-doped aluminium oxide ($\text{Al}_2\text{O}_3\text{:C}$). This has been shown to be highly sensitive for radiation dosimetry purposes, being first developed and produced in the form of single crystals (Bos, 2001). The TL sensitivity is 40– to 60 $\times$ greater than LiF at the same heating rate of 4°C/s (Bos, 2001) and shows good linearity in the useful range 0.05 μGy to 10 Gy. This material also shows a low thermal fade of 3% per year. The main glow curve peak occurs at about 250°C but is quite complex.

Other materials for TL dosimetry have also been extensively studied. These include CaF_2 , the sulphates groups MgSO_4 , CaSO_4 and BaSO_4 , and the oxides group (one of which, Al_2O_3 , has already been mentioned) including BeO and SiO_2 . In present study investigation is made of the TL

phenomenon in silica glass for radiation therapy applications. Previous investigation by Yusoff et al. (2005) shows this to offer promising TL response. Other studies involving photon irradiation of silica based optical fibres were carried out by a number of others (Friebele et al., 1980; Friebele et al., 1984; Friebele and Griscom, 1979, Ellis et al., 1989, Khanlary and Townsend, 1993). These investigations have determined that the TL performance of an irradiated optical fibre is influenced by the type of fibre and by the radiation parameters. Interest herein concerns use of Ge-doped silica optical fibre as a potential 1-D detector for radiation therapy applications.

1.2. Doped Silica Glass Optical Fibre

Studies of potential radiation therapy applications of the optical fibre TL dosimetric system have been undertaken by several groups. Various aspects have been studied (Abdulla et al., 2001; Yusoff et al., 2005; Espinosa et al., 2006; Abdul Rahman et al., 2010a, Abdul Rahman et al., 2010b, Abdul Rahman et al., 2011a, Abdul Rahman et al., 2011b), as for instance, radiation induced attenuation (Huston et al., 2001), radioluminescence (RL) and optically stimulated luminescence (OSL) (Justus et al., 1997; Aznar et al., 2004; Benevides et al., 2007). Useful TL emission has been observed at the radiation levels familiarly applied in high dose radiation-medicine procedures.

A simple explanation of the optical features of silica, SiO_2 , (the glass being an amorphous system, albeit sometimes with microcrystalline inclusions) is based on the trapping processes usually described for crystalline media, dependent on the presence of structural defects in the material i.e. due to the presence of the dopants (Yusoff et al., 2005). The TL response of doped SiO_2 optical fibres has been investigated by a number of workers; for photons (Abdulla et al., 2001; Abdul Rahman et al., 2010b; Issa et al., 2011; Noor et al., 2010; Noor et al., 2011b), for electrons (Hashim, 2009; Abdul Rahman et al., 2010b), for protons (Hashim et al., 2006), for alpha particles (Ramli et al., 2009), for fast neutrons (Hashim et al.) and for synchrotron radiation (Abdul Rahman et al., 2010a). In all such studies the TL performances of irradiated fibres have shown considerable potential for dosimetric applications in radiotherapy.

The TL dosimetric system used in this study is commercial telecommunication fibres (produced for instance by CorActive, Canada), and most specifically Ge-doped SiO_2 glass. Optical fibre usually has a circular symmetry and is most often fabricated from very pure silica (SiO_2). This has a refractive index of $n = 1.458$ at $\lambda_0 = 850$ nm. Selective doping within the centre of the fibre (the core) produces material of greater refractive index than the surrounding region (the cladding), thus forming a waveguide. Figure 1 illustrates the typical geometry of commercial optical fibre. While most of the previous studies performed by members of the present group of authors have been made using 9 μm core diameter fibres, our more recent studies have investigated the effect of different core diameters (8, 11 and 50 μm) on TL sensitivity (Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b).

Ge-doped silica glass optical fibres have several advantages compared to the popularly used phosphor-based TL dosimeters. These include their spatial resolution, ~ 120 μm , their water impervious nature pointing to potential applications in intercavitary and interstitial measurements and the fact that in their production the fibres can be tailored for TLD sensitivity using the Modified Chemical Vapour Deposition (MCVD) method that introduces dopants at selected concentrations. Based on recent studies performed by this group, the selected doped silica glass fibres are capable of producing a uniform TL response of better than 4% (1 S.D) of the mean value (Figure 2) (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b). Ge-doped SiO_2 optical fibres have been also demonstrated to provide excellent reproducibility and reusability; calculated as the percent error (1 S.D.) of the means of five individual sets of measurements, the variation has been found to be less than 0.59 % (ibid.) In terms of TL fading, the average loss of signal is $\sim 0.4\%$ per day within the first week post irradiation increasing to 1.2% per day in the second week (ibid). A t-test of paired means for any pair was used to determine whether the arithmetic means of two sets of data were significantly different from one another. The result showed an insignificant difference between the sets of measurements (ibid.).

Figure 1: (a) A schematic diagram of typical geometry of commercial optical fibre. (b) Examples of cut fibres. (c) A cross-sectional image of a cut fibre obtained in SEM analysis (ibid.); the SEM has been used with EDXRF facilities to obtain elemental analysis of the silica and dopant (see below).

In regard to the potential of Ge-doped optical fibre for therapeutic dosimetry application, studies have been carried out to investigate the TL response of this candidate dosimeter for various types of radiation beam, covering the energy range from a few eV to several MeV. In several dosimetry

studies, the main purpose has been to obtain a full performance characterisation of this new candidate TL material for radiation therapy dosimetry applications including interface radiation applications (Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b), brachytherapy dosimetry (Issa et al., 2011), IMRT verification (Noor et al., 2010; Noor et al., 2011a), external beam radiotherapy dosimetry audits by mailed dosimeters (Noor et al., 2011b) and UV radiation dosimetry. In so doing, it is important to investigate the possible linear dose response between absorbed dose and TL intensity over a wide dose range, at least over the range of interest for applications as well as the energy response of the dosimeter. The preliminary results obtained are discussed below.

2. Dosimetry System

The dosimeter used has been chosen to have a length of 5.0 ± 0.1 mm, easily accommodated within the TLD reader. Prior to cutting the fibres were stripped away from the 250 ± 10 micron buffer coating using an optical fibre stripper, avoiding scratching or nicking of the glass fibre that might result in triboluminescence. A cotton cloth containing methyl alcohol was used to clean the stripped fibres, to minimize the possibility of there being any remnant polymer cladding (Hashim et al., 2009; Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b). The optical fibres were then placed inside a light proof plastic container for routine storage and handling. The optical fibres were handled using vacuum tweezers (Dymax 30 – Charles Austen pump Ltd). The mass of each fibre was determined using an electronic balance (B303-S METTLER TOLEDO), allowing TL yield to be normalized to unit mass of irradiated fibre (± 0.02 mg).

The sensitivity of a TL dosimeter has been described in terms of TL yield per unit dose per unit mass of sample. This sensitivity is typically determined by the concentrations and types of activators and defects present in the TL material. If the medium has a high concentration of luminescent centres, then high energy conversion efficiency may be expected to be obtained. Differences in sensitivity, even from dosimeters belonging to the same production batch, can be encountered in practice. These may be due to variation in the dopant concentration from sample to sample, variation in the mass of the detectors and variations due to contamination of the sample surface. In this study the mean of mass of each fibres investigated was measured to be in the range 0.23 mg – 0.25 mg.

3. Readout System

In present studies a standard TL reader system was used with the following parameters; preheat temperature of 160°C for 10 s; readout temperature of 300°C for 25 s and a heating rate cycle of $25^{\circ}\text{C s}^{-1}$. These settings have been shown to provide an optimal glow curve, free of the effects of superficial traps (flushed out by the pre-heat cycle). The heating rate cycle, sometimes also referred to the ramp rate, determines the time-temperature profiles that ensures complete capture of the TL glow curve. Finally, in the present investigations, an annealing temperature of 300°C was applied for 10 s to sweep out any residual signal. The TL yield obtained was then normalized to unit mass of the particular TL medium. All dosimetric data storage, instrumentation control, and operator inputs are performed in the reader and PC based control system. The software provides real time monitoring of the instrument operating conditions in terms of displaying the TL glow curve and TL response values.

Annealing was performed by further heating in a separate oven operated at up to 400°C for an hour to ensure radical sweep out of deeply trapped electrons. This is generally recognized to be desirable following the TL reader annealing phase as it is fast and stable, all samples being put together at one time rather than individual heating provided in the TL reader.

4. Dosimetric Characterisation of Doped Silica Based optical Fibre

Irradiations included high megavoltage photons and electrons from linear accelerators, low energy kilovoltage photons from an orthovoltage unit, use of radioactive sources for brachytherapy treatments and UV sources as used in dermatological treatments.

4.1. Screening Process

In present studies, the optical fibre used is a commercial Ge-doped SiO_2 optical communication fibre manufactured by CorActive High Tech, Canada. In any such system it is well recognized that the dopant concentration will vary from point to point along the length of an optical fibre, leading to measurable dB loss in respect of light transport. As a result of the dopant variation, and in the absence of a process of radiation sensitivity selection, for a fixed dose of radiation there will result a commensurate range of TL emissions, a situation largely paralleling that for phosphor TL systems. Therefore it is important to select to obtained fibre dosimeters of uniform sensitivity for further

investigation. This is included in a selective study of dosimeters, incorporating reproducibility and reusability of dosimeters and TL signal fading of the dosimeters.

Selection of Ge-doped SiO₂ optical fibres was performed by irradiating large sample groups at a fixed dose as well as at fixed dose rate. The irradiations were made to provide a dose of 3 Gy at a constant dose rate of 400 cGy min⁻¹; a field size of 10 cm × 10 cm was used, from clinical photon and electron beams of energies 6 MV and 9 MeV respectively. The dosimeters were placed in a water phantom at a D_{max} of 2.0 cm and 1.5 cm depth for the photon and electron irradiations respectively, using a standard source-surface distance (SSD) of 100 cm.

Selection of dosimeters was made in an effort to eliminate outlier data, retaining optical fibres within ±1σ of the mean value for subsequent use. The selection procedure has been performed for every new group or batch of Ge-doped SiO₂ optical fibre introduced. The variability of the dosimeter system was then further tested by performing the same irradiation conditions as before. This procedure was repeated to examine the reproducibility and reusability of the dosimeter. Fading of the system was also measured, for a period of up to 15 days beyond the time of irradiation. At a fixed dose-rate the TL response of non-selected commercial Ge doped SiO₂ optical fibres were found to vary by up to 10% of the mean value. As a result of the screening process, the selected Ge-doped SiO₂ optical fibres were subsequently found to produce a flat response, to within better than 4% (1 S.D) of the mean of the TL distribution (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b).

4.2. Elemental Mapping of Doped Silica Glass Optical Fibre

Figure 2: In a cleaved sample examined face-on, use of a scanning electron microscope with energy dispersive x-ray fluorescence (EDX) facilities has helped demonstrate the presence of a centrally-located core of Ge-dopant embedded in the silica fibre. The upper part of the figure shows the cleaved face of a fibre with a 50 μm Ge-doped core; observations have been made of the Kα1 x-ray fluorescence (XRF) emissions of oxygen and Ge in this particular case. The lower part of the figure shows the relative XRF emissions of O, Si and the Ge dopant, indicative of their relative presence in the silica.

4.3. TL Response of Doped Silica Glass Optical Fibre

The TL response of doped silica glass optical fibres have been studied by this group for various types of radiation beam, from several eV to MeV energies, including for photons (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Hashim, 2009; Issa et al., 2011; Noor et al., 2010; Noor et al., 2011b), electrons (Abdul Rahman et al. 2010a; Abdul Rahman et al., 2010b; Hashim, 2009), neutrons (Hashim et al. 2010), protons (Hashim et al., 2006), betas and alpha particles (Ramli et al., 2009).

4.3.1. Photon and Electron Irradiation

For photon and electron response, the selected Ge-doped SiO₂ optical fibre were irradiated over the dose range 1 – 50 Gy at various electron and photon beam energies, the dose being delivered at a constant dose-rate of 400 cGy min⁻¹. For photon beam irradiations use was made at each of the nominal energies of 6, 10 and 15 MV while for electron beam irradiations use was made at each of the electron energies 9, 16 and 20 MeV. The dosimeters (held in gelatine capsules) were placed in an epoxy resin solid water phantom at 2.0 cm and 1.5 cm depth for the photon and electron irradiations respectively, using a field size of 10 cm × 10 cm and a standard Source Surface Distance (SSD) of 100 cm. A total of 20 samples of Ge-doped SiO₂ optical fibres were placed in each gelatine capsule for each dose delivered. Figure 3 shows previously unpublished dose response linearity curves for a dose range familiar in conventional radiation therapy and beyond, from 1 - 50 Gy. One set is for photon beams, specifically at nominal energies of 6, 10 and 15 MV, while the other is for electron beams, specifically at energies of 9, 16 and 20 MeV. Over the range of doses delivered, linearity of TL yield has been obtained, the correlation coefficient (r^2) being observed to be better than 0.998 and 0.999 (at the 95% confidence level) for photon and electron beams respectively (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b).

Figure 3: TL response of silica based optical fibres obtained in the nominal photon energy range 6 - 15 MV (represented by square and x symbols) and the electron energy range of 9 - 20 MeV (represented by the triangle and + symbols). The lines are least-squares straight line fits to the data; the greatest gradient corresponds to 6 MV irradiations, while that with the least gradient corresponds to 20 MeV irradiations (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b).

The least-squares straight line fits of Figure 3, reveal a TL light yield (in counts per second per unit mass of fibre, × 10⁶), corresponding to a dose-dependency of ~ 4 × the absorbed dose, measured

in Gy, for photon irradiations and $\sim 3 \times$ the absorbed dose, measured in Gy, for electron irradiations. It is evident that the fibres provide the basis for sensitive dosimetry throughout this range, the TL yield increasing by on average 90 % and 94 % per for each additional 1Gy of dose delivered for photon and electron energies respectively. In regard to energy response, a marked reduction in TL yield is observed for the electron beams, decreasing by 23 % in comparing the TL yield at 20 MeV with that at 9 MeV for a dose of 50 Gy. For photon beams at a dose of 50 Gy, an approximate 6 % decrease is observed between the TL yield obtained at 6 and 15 MV. In addition it is noted appreciable energy dependence for both electron and photon beams (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b).

In comparing the TL response of Ge-doped SiO₂, for electron beams the sensitivity is lower than for photon beams. 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 effect of air cavities in the loaded gelatine capsule on the dose distribution could also be significant. 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.

4.3.2. Synchrotron X-Ray MRT Irradiation

Further studies have been made to investigate the TL sensitivity of Ge-doped SiO₂ optical fibres at incident energies of several tens of keV, for a wide range of doses, from 1 Gy to 10 kGy (Abdul Rahman et al., 2010a). For this, the irradiations have been carried out at the European Synchrotron Radiation Facility (ESRF) on the ID17 Biomedical Beamline. This beamline uses a wiggler source to produce an intense, highly collimated synchrotron X-ray beam from the 6 GeV electrons circulating at a beam current of approximately 200 mA. The beam was a filtered white beam spectrum, the lower energies being cut off through use of 1.5 mm of aluminium and 1.0 mm of copper. This resulted in a maximum intensity at 83 keV, the energy spectrum covering the range 50 to 350 keV with a mean energy of 107 keV (Brauer-Krisch et al., 2005). After the passage through a Be window, the beam is in air and passes through an ionization chamber before impinging on a single set of slits placed at 41.051 m from the source. The opening of the single slits can be varied in width from a few microns up to several mm and the entrance dose on the samples can similarly be varied over several orders of magnitude. The Ge-doped silica optical fibres were placed in gelatine capsules of 0.30 ml volume with 40 fibres in each capsule to allow dose reproducibility to be investigated at each delivered dose. Each capsule was then passed through the beam, providing investigation of dose response for on-sample doses of between 1 Gy and 10 kGy, delivered at a dose rate of ~ 80 Gy per second per mA in the machine. The irradiations were performed by moving the samples through the beam to provide a treatment field of 18 mm width and 12 mm high, at a distance of ~ 1 m from collimator.

The increase in TL yield with dose is seen to remain linear over a wide range of values, specifically from 1 Gy up to 2 kGy, showing saturation of yield beyond that (Figure 4; previously unpublished). Over the range of doses for which linearity with TL yield has been obtained, the correlation coefficient (r^2) was observed to progressively reduce from 0.999 to 0.997 (at the 95% confidence level). Over the dose range 1 – 30 Gy the TL light yield (in counts per second per unit mass of fibre, $\times 10^6$) corresponds to a dose-dependency of $[(5 \times \text{the absorbed dose, measured in Gy}) + 0.3]$. It is evident that the fibres provide the basis for sensitive dosimetry throughout this range, the TL yield increasing by 89% per additional 1 Gy of dose delivered. For a dose of 5 kGy and present irradiation conditions, there is a loss in TL yield through saturation of 30 % compared with that of linear behaviour. The saturation effect is almost certainly due to manifest filling of available defect (dopant) centres. The dependency of TL yield upon absorbed dose in this saturation region takes on a well-behaved quadratic form that allows an extended calibration for dose to be made for doses well in excess of 8 kGy, for present irradiation conditions (Abdul Rahman et al., 2010a).

Figure 4: (a) Dose response for Ge-doped optical fibres irradiated using the ESRF microbeam radiation therapy facility for doses in the range 1-2 kGy. The solid line is a least-squares fit to the data, obtaining a correlation coefficient of 0.997. (b) Dose response curve for Ge-doped optical fibres irradiated using the ESRF microbeam radiation therapy facility for doses in the range 1-10 kGy. The least squares curve reveals a quadratic dose dependency offering an extended calibration for doses of up to ~ 8 kGy (Abdul Rahman et al., 2010a).

Comparison can be made with measurements using the same type of Ge-doped fibres. In irradiations using a conventional therapy linear accelerator, delivered at a nominal photon energy of 6, 10 and 15 MV over a dose range of 1 – 50 Gy (Fig. 5), linearity with dose is in accord with a TL response (in counts per second per unit mass of fibre, $\times 10^6$) of $[(4 \times \text{the absorbed dose, measured in Gy}) + 0.2]$. In the linear region, present results are thus some 1.25 times greater in TL yield per unit dose than measurements obtained using the same type of Ge-doped for irradiations made at nominal photon energies of 6, 10 and 15 MV. This is in line with expectation, given the greater detection efficiency of fibres at the lower photon energies used herein (Abdul Rahman et al., 2010a).

It can be concluded that commercially produced Ge-doped SiO₂ telecommunication fibres of ~ 125 μm diameter offer high spatial resolution dosimetry, with linear response over the dose range 1 Gy – 2 kGy, adequate for the needs of synchrotron microbeam radiotherapy dosimetry, with entrance doses of typically ≤ 2 kGy. What is not yet established is whether there is reciprocity between TL yield and dose over a wide range of extreme dose-rates. Similarly, it would seem essential to examine the energy response of the Ge-doped silica fibre dosimeters for incident energies between a few keV up to in excess of 100 keV (Abdul Rahman et al., 2010a).

4.3.3. Superficial X-Ray Irradiation

At the kilovoltage energy of superficial X-ray beam, the linearity of TL yield over the dose range 1 Gy to 35 Gy has been examined. The irradiation was delivered at dose-rate of 222 cGy min⁻¹ using a PANTAK Superficial X-ray. The beam energy used was 90 kVp (HVL = 2.5 mm Al) with a field size of 8 cm diameter and surface to source distance (SSD) of 30 cm. The variability in TL response of the Ge-doped SiO₂ optical fibres has been described in a previous section for both megavoltage photon and electron irradiations. Figure 5 shows a previously unpublished calibration curve of Ge-doped SiO₂ optical fibres for 90 kVp superficial X-ray for the dose range investigated (1 – 35 Gy). The TL response shows good linearity, with a correlation r^2 of 0.998. The solid lines shown in Figure 5 are least-squares straight line fits to the measured data, revealing a TL light yield (in counts per second per unit mass of fibre, $\times 10^6$) corresponding to a dose-dependency of $\sim 20 \times$ the absorbed dose, measured in Gy, for low energy photon irradiations (Abdul Rahman et al., 2010a; Abdul Rahman et al., 2010b; Abdul Rahman et al., 2011a; Abdul Rahman et al., 2011b).

Figure 5: Comparison of dose response linearity for Ge-doped optical fibres irradiated at 90 kVp superficial X-ray energy and 107 kVp mean energy of synchrotron X-ray at the ESRF for doses in the range 1-30 Gy. The solid line is the least-squares fit to the data, obtaining a correlation coefficient of better than 0.999 (Abdul Rahman et al., 2010a, Abdul Rahman et al., 2010b, Abdul Rahman et al., 2011a, Abdul Rahman et al., 2011b).

Present results can be compared with that obtained using synchrotron X-ray microbeam radiation therapy facility in ESRF, delivered at a mean energy of 107 kVp over the energy spectrum 50 to 350 keV (Abdul Rahman et al., 2010a). Over the dose range 1 – 30 Gy the TL light yield (in counts per second per unit mass of fibre, $\times 10^6$) corresponds to a dose-dependency of $5 \times$ the absorbed dose, measured in Gy. The fibres provide the basis for sensitive dosimetry throughout this range with the TL yield increasing by 89% per additional 1 Gy of dose delivered. As a result, the TL response of Ge-doped SiO₂ optical fibres irradiated to PANTAK Superficial X-ray shows 4 times greater. This can be explained by non-reciprocity resulting from the elevated synchrotron beam dose rate. The PANTAK Superficial X-ray was delivered at dose rate of 222 cGy min⁻¹, compared to the dose rate of 80 Gy s⁻¹ delivered using the synchrotron X-ray microbeam radiation therapy facility in ESRF. A small dose rate applied in PANTAK Superficial X-ray required more time irradiation, in the same time allowed ample time interaction in doped silica material which able to produce more TL light yields within the irradiation period. This has been explained as reciprocity effect or “Schwarzschild effect” (Abdul Rahman et al., 2010b).

Further studies have been made to investigate the TL sensitivity due to different core diameter size of Ge-doped silica optical fibre. For this three different core diameter fibres were used, there are 8, 11 and 50 μm . Irradiation have been delivered using Gulmay Superficial X-Ray at 80 and 250 kVp beam energy. The least squares fit show that the change in TL response in count per second per unit mass for 50 μm core fibres irradiated at 80 kVp to be 39 times greater than that obtained for 8 μm core optical fibres also irradiated at 80 kVp (Figure 6; previously unpublished). This is in line with expectation, the relative number of dopant between the two core diameters being of the same order (i.e. a factor of ~ 39). The implication is that, for the same response, a dose of 1 Gy delivered to the 8 μm core fibre can be reduced by the factor of 39 for the optical fibre of 50 μm core diameter, namely 0.025 Gy. With respect to energy dependence, it is apparent that at higher photon energy (i.e. that

associated with a potential of 250 kVp), the TL yields response decreases due to the lower mass energy absorption coefficient at higher photon energy. The least square fit show that the change in TL yield per unit mass per Gy is 2.33 at 80 kVp irradiation, being six times that of fibres irradiated at 250 kVp. As expected, fibres of any core diameter have a higher response at lower energies than at higher photon energies.

Figure 6: (a) Dose response of Ge-doped silica fibers of 8, 11 and 50 μm core diameter, irradiated at 80kVp X-ray, the solid lines are least square fits to the data, obtaining correlation coefficients of 0.999, 0.994 and 0.992 respectively and (b) irradiated at 250 kVp X-ray, the solid lines are least square fits to the data, obtaining correlation coefficients of 0.995, 0.992, and 0.998 respectively. (Note: the y-axis to the right represents the TL yield of 11 μm core fibres; the error bars are smaller than the data points) (Abdul Rahman et al., 2010a, Abdul Rahman et al., 2011a, Abdul Rahman et al., 2011b, Abdul Rahman et al., 2010b)

5. Potential Applications of Doped Silica Based optical Fibre

Highly sensitive *in vivo* dosimetry systems are needed in order to measure the dose in tissues. Commercially available purpose made thermoluminescence dosimeters (TLDs) offer limited spatial resolution of the order of a few millimetre (mm). Relatively small diameter (several tens of μm) Ge-doped SiO_2 optical fibres make possible thermoluminescence (TL) dosimetry offering high spatial resolution. It is expected that such fibres will provide radiation measurements close to that of an ideal Bragg–Gray cavity. In the accurate evaluation of absorbed radiation dose this is important, being a critical consideration for non-tissue equivalent probes such as Ge-doped SiO_2 optical fibres.

The concentration of Ge in doped SiO_2 optical fibres used in this study is 0.15 – 0.19 mol % based on SEM and EDXRS analysis (Ramli et al., 2009, Hashim et al., 2006). The effective atomic number, Z_{eff} for Ge-doped SiO_2 optical fibres is 11.4, determined using SEM and EDXRF analysis (Ramli et al., 2009, Hashim et al., 2006), the value of Z_{eff} in soft tissue being 7.42 and the value of Z_{eff} for bones 11.6 - 13.8 (McKeever, 1988). One further advantage of Ge-doped SiO_2 optical fibres dosimeters is that they are water resistant and therefore it becomes possible to locate the fibre dosimeter within a particular tissue of interest; this suggests the possible use of Ge-doped SiO_2 optical fibres in a variety of interface dosimetry situations, as in for instance for dosimetry application in radiation synovectomy and brachtherapy. Other applications have been also studied in mapping 3-D distribution of IMRT delivery and finally used of doped silica glass optical fibre in mail dosimetry system (Noor et al., 2010, Noor et al., 2011b).

5.1.1. Interface Radiation Dosimetry

In recent times considerable interest has been shown in optical fibers as a novel form of TLD for radiation therapy dosimetry. Commercially available germanium (Ge) doped silica optical fibers have been characterized in terms of a number of factors including reproducibility, linearity and energy dependence. Present interest is in the potential of such dosimeters in measuring photoelectron dose enhancement resulting from the use of moderate to high-Z media, in particular in regard to iodinated contrast media as might be applied in radiation synovectomy (Abdul Rahman et al., 2011a, Abdul Rahman et al., 2011b, Bradley, 2008). For irradiation, use has been made of 90 kVp x-rays delivering a dose of 30 kGy at a dose-rate of 222 cGy/min, produced by a PANTAK Superficial X-ray unit (HVL = 2.5 mm Al) for an 8 cm diameter field size and with the surface of the phantom arranged at 30 cm distance from the beam source.

A model membrane synovial treatment setup has been created using a specially designed phantom made from a polyurethane medium in the form of a cylinder (60 mm diameter x 60 mm height) and also separately a Perspex cube (60 mm x 60 mm x 60 mm), each with a centrally located reservoir of iodine. The setup provides for measurement of dose enhancement resulting from intimate surface contact between optical fibers and the iodine contrast medium (NIOPAM (270I) 370 mg, l/mL). Comparison has been made with measurements of dose away from the iodine reservoir using a stepped-design phantom that allows insertion of the fibers within the phantom, obtaining the dose deposited in soft tissue. Verification of measurements has been obtained using Monte Carlo simulation, using MCNP.

In two independent measurements, enhancement due to photoelectron production has been observed for fibers placed in intimate contact with iodinated contrast medium, the enhancement being 60 % above the photon dose component measured in the absence of the contrast medium, at the depth of measurement within the phantom. The measurements of percentage depth dose (PDD) away from the iodine have been compared in both cases and agree with each other to within 5%,

being also bounded by the PDDs obtained from BJR Supplement No 25 at 80 kVp and 100 kVp (BJR Supplement 25, 1996). The results indicate that TL enhancement due to photoelectron production is measureable using doped fibers. In addition it is possible that use of iodinated contrast medium can provide for a promising technique in radiation synovectomy treatment (Abdul Rahman et al., 2011a, Abdul Rahman et al., 2011b).

5.1.2. Brachytherapy Dosimetry

In brachytherapy the desire is that a high dose is delivered to the tumour with a low dose being delivered to surrounding normal tissue. Dose measurements around brachytherapy sources at distances very close to the source are very difficult to obtain due to the high dose gradients. Therefore, most efforts have been placed on dose measurements at distances greater than a few cm and/or to perform dose calculations instead, typically adopting the Sievert integral approach incorporating an assumed inverse square law and Monte Carlo simulations for distances less than 5cm. Ge-doped optical fibre dosimeters show good dosimetric response for low photon energies (Issa et al., 2010). In addition, Ge-doped silica fibres offer good spatial resolution ($\sim 120 \mu\text{m}$), are of low cost and are impervious to water. In the present work Ge-doped optical fibres are used as thermoluminescence dosimeters in order to measure the dose distribution around a Low Dose Rate (LDR) I-125 seed (model 6711) for distances very close to the source (less than 5cm). I-125 seeds are commonly used for treatment of early stage prostate cancers. The irradiations are performed in both Perspex and water phantoms. For verification, doses are calculated in the same points of measurement using Monte Carlo simulation, use being made of the EGSnrc \ DOSRZnrc codes (Issa et al., 2011).

5.1.3. IMRT Verification

In this study, the TL yield of Ge-doped optical fibres for in vitro dosimetry has been investigated for the verification of Intensity Modulated Radiation Therapy (IMRT) three-dimensional (3D) dose distributions. IMRT verification plans using the Varian Eclipse treatment planning system for two prostate cancer patients were created using Alderson Rando Anthropomorphic Phantom CT data-sets. Measurements were performed using the Rando phantom at nominal energies of 6 MV and 15 MV. Ge-doped optical fibres TL yields were compared with dose determined through use of the treatment planning system and also with the well established TL lithium fluoride (LiF) dosimetry system (Harshaw TLD-100 and TLD-700). Results show the Ge-doped optical fibres to verify *in vitro* doses within 3% of the Eclipse predicted doses and LiF TLDs for the particular high energy photon beams used (Noor et al., 2010, Noor et al., 2011a).

5.1.4. Ultra Violet Radiation

A good number of UV measurement devices are supported by photodiode sensors. Thus said several studies have been performed in order to investigate the potential of passive UV sensitive materials for UV dosimetry applications. A tissue equivalent radiochromic gel material (FXG) has been shown to have good sensitivity to UVA dose measurement, detecting exposure levels equivalent to the natural solar UVA spectrum (Abukassem and Bero; Abukassem, 2009); a relationship between change in optical density and UVA radiation dose has been established. Some studies have also been conducted of the radiochromic film dosimeter Gafchromic-MD-55-2 film, showing it to be a useful dosimeter for UVA, able to provide reproducible results within 3% (Martin and Et Al., 2000).

Considerable interest in UV dosimetry has also lead to investigation of the potential TL response of phosphors. Six types of commercial TL dosimeter have been used (TLD-100H, TLD-200, TLD-400, TLD-500, TLD-700H and TLD-900) irradiated by a deuterium lamp as the UVR source. The results show TLD-200 and TLD-900 to have good dose linearity over the UVR range but inferior to TLD-500 which shows high sensitivity to UVR (Noh et al., 2001). While the UV sensitivity of doped silica fibres has previously been noticed in several studies (Espinosa et al., 2006), their TL sensitivity has not been well established. Present study seeks to define the TL sensitivity of Ge-doped SiO_2 optical fibres and represents the first tentative investigation of the possible applicability of the fibres as a possible effective but cheap method of UV measurement.

UV irradiation of Ge-doped SiO_2 optical fibres has been performed in the University of Surrey Advanced Technology Institute (ATI) clean-room, designed for photolithography with UV safe lighting. The irradiation made use of UVA radiation of 365 nm wavelength, produced from a 100 W Hg arc lamp (Omnicure UV series 1000). The UV lamp was set up at 10 cm vertically above the irradiation surface and the UVA intensity measured using a UV probe was $10.50 \text{ mW cm}^{-2} \pm 1\%$. Investigation was made of the TL response of Ge-doped SiO_2 optical fibres over a range of UVA dose by simply increasing the time of exposure, from 0 to 300 minutes.

Figure 7: TL yield response of Ge-doped SiO₂ optical fibres to 365 nm UVA radiation with UV intensity measured to be 10.50 mW cm⁻² ± 1% at 10 cm from a 100 W mercury arc lamp source.

Irradiated Ge-doped SiO₂ optical fibres were evaluated using a Solaro TL Reader immediately after irradiation. Figure 7 shows the normalised TL yield response due to UVA irradiation for a dose range 19 – 190 J cm⁻². Result shows the TL response of Ge-doped SiO₂ optical fibres increases with increasing of UV radiation exposure time. The reproducibility observed was within 5.7%. However the TL yield response due to UV radiation range investigated is lower compared to TL yield response of photon and electron beams irradiation. The maximum TL yield obtained was 3.27 x 10⁶ counts per second per unit mass of fibre, 23% lower than the TL yield obtained for 1 Gy dose of photon irradiation from a linear accelerator. This initial study shows promising to use Ge-doped SiO₂ optical fibres for UV radiation dosimetry. In term of sensitivity, is likely due to the dopant distribution in the fibre, for future study using 50 µm diameter size of core fibre might show a better response (Ong et al., 2009). Further work may establish by consider to the UV energy range used in treatment for the potential use of Ge-doped SiO₂ optical fibres in PUVA cabinet dosimetry.

6. Discussion and Conclusions

In this review, the very many highly favourable TL characteristics of commercially available Ge-doped telecommunication fibres have been demonstrated in terms of applications in medical therapies involving energetic radiation exposures. It is envisaged that these same favourable characteristics can be harnessed towards development of even more sensitive TLDs than presently available, in production of non-commercially available fibres, a matter that the Surrey group is now actively pursuing in collaborations with others. It is further envisaged that irradiated Ge-doped optical fibres can be interrogated through optically stimulated luminescence, opening up many new avenues of applications, medical and otherwise, being again a matter that the Surrey group are pursuing in collaborations with others

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Dose response in term of TL yields for a dose range 1 - 2 kGy

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