Sensors and Actuators A 264 (2017) 30–39

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Ge-doped silica optical fibres as RL/OSL dosimeters for radiotherapy dosimetry

A.K.M. Mizanur Rahman[a,b,*], Mahfuza Begum[a,c], H.T. Zubair[a], H.A. Abdul-Rashid[a], Z. Yusoff[a], N.M. Ung[d], D.A. Bradley[e,f]

[a] Fibre Optics Research Centre, Faculty of Engineering, Multimedia University, Jalan Multimedia, 63100, Cyberjaya, Malaysia
[b] Health Physics Division, Atomic Energy Centre, Bangladesh Atomic Energy Commission, 4 Kazi Nazrul Islam Avenue, Shahbag, Dhaka, 1000, Bangladesh
[c] Health Physics & Radioactive Waste Management Unit, Institute of Nuclear Science and Technology, Atomic Energy Research Establishment, Bangladesh Atomic Energy Commission, Ganakbari, Savar, Dhaka, Bangladesh
[d] Clinical Oncology Unit, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia
[e] Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom
[f] Sunway University, Institute for Healthcare Development, 46150 PJ, Malaysia

ARTICLE INFO

Article history:
Received 26 February 2017
Received in revised form 20 June 2017
Accepted 18 July 2017
Available online 22 July 2017

Keywords:
In-vivo dosimetry
Radioluminescence
Radiotherapy
Ge-doped optical fibre

ABSTRACT

Various tailor-made doped-silica optical fibres are investigated as dosimeters in support of radiotherapy, based on radioluminescence (RL) and optically stimulated luminescence (OSL) technology. Investigations focus on the development of these glassy dosimetric media, offering a number of advantages going well beyond their water impervious nature and excellent spatial resolution (~few microns). An RL/OSL photomultiplier-tube (PMT)-based reader was assembled, providing for study of the influence on the RL/OSL signal of different Ge-dopant concentrations (3.59, 4.74 and 7.03 wt%) in silica fibres exposed to medical LINAC photon beams. Among the three arbitrary choices of dopant concentration, those fibres containing the least concentration of Ge (3.59 wt%), denoted as Ge-1, gave rise to the greatest RL yield, at 1.67 and 2.34 times that of Ge-2 (fibres Ge-doped at 4.74 wt%) and Ge-3 (fibres Ge-doped at 7.03 wt%) respectively, reducing in yield with increasing Ge-dopant concentration. At 7.3×10^3 counts Gy^{-1} min at 22 °C, the Ge-1fibres provided the superior sensitivity, also being found to be reusable without noticeable variation in RL signal (<1%; 1 SD) for X-ray exposures delivered at a dose-rate of 600 cGy/min. The RL signal was found to be free from spectral superposition or noise, also exhibiting energy independence in the use of X-rays generated at 6- and 10 MV. In regard to percentage depth-dose (PDD), in measurements made using optical fibre dosimeters and 6 MV X-ray photon beams, the maximum value of PDD, d_{max}, was obtained at a depth of 1.5 cm, in accord with ionization chamber measurements. Using green stimulation light, for all three concentrations of Ge-dopant, linearity between the OSL signal and dose was observed across the 0.5- to 8 Gy dose range investigated. Results from this ongoing study are intended to assist in efforts towards improving the performance of RL/OSL fibre sensors for radiotherapy dosimetry.

1. Introduction

The 2014 World Cancer Report of the International Agency for Research on Cancer (IARC) made the estimate that annual deaths from cancer would rise from 8.3 million in 2012 to 13 million by 2034 [1]. Radiotherapy, an effective treatment option, has been identified as one of the possible therapeutic solutions. Advanced cancer treatment modalities such as volumetric modulated arc radiotherapy (VMRT) and intensity modulated radiotherapy (IMRT) have made highly conformal treatment plans possible, offering reduced risks to healthy tissues. The reliability of dose verification for these complex clinical routines requires real-time *in-vivo* dosimetry [2], in recent years radioluminescence (RL) dosimetry becoming of increasingly popular use in such circumstances [3]. However, when the dosimetric probe is placed in a radiation field an unavoidable consequence is that a portion of signal carrier fibre is also exposed, producing an additional contribution to the overall signal, a situation commonly referred to as the "stem effect". This contribution is mainly due to Cerenkov radiation, as well as fluorescence or luminescence light emission, superimposed onto

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[*] Corresponding author at: Health Physics Division, Atomic Energy Centre, Bangladesh Atomic Energy Commission, 4 Kazi Nazrul Islam Avenue, Shahbag, Dhaka, 1000, Bangladesh.
E-mail address: mizanbaec14@gmail.com (A.K.M.M. Rahman).

http://dx.doi.org/10.1016/j.sna.2017.07.038
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the RL signal from the dosimetric sensor [4,5]. In addition to the real-time RL dosimetry technique, the possibility also arises that optically stimulated luminescence (OSL) can be harnessed to provide "post irradiation" readout, representing an independent signal for dose estimation. The basis of OSL measurement is to stimulate a pre-irradiated sample with an appropriate wavelength of light and to monitor the consequent emission from the sample at a different wavelength [6,7].

To detect ionizing radiation, further acting as dosimeters, use is currently being made of a number of luminescence-based devices, one form of which is the focus of present interest. Such devices can be in the form of solids, liquids or gases. Metal-oxide-semiconductor field-effect transistors (MOSFETs), p-type diodes, ionization chambers, diamond detectors, TLDs, film (radiographic and radiochromic) and the chemically-based Fricke detector system have all been adopted as reference-, relative-, on-line, active- and passive-dosimeters (see for instance, Izewska and Rajan [8]). Active dosimeters are typically electronic devices, providing direct (on-line) dose evaluation, whereas the passive dosimeters (which include thermoluminescence, optically stimulated luminescence, and numerous other diverse forms) store the irradiation information (a form of non-permanent radiation damage), each giving subsequent dose information through use of an off-line form of readout. Each category and form of device offers advantages and disadvantages in accord with the particular applications, not least in respect of expense and convenience.

For radiotherapy, in seeking to approximate the performance of an ideal dosimeter, such devices should be small in size (down to sub mm) yet highly sensitive, also offering large dynamic range (a wide range of response to dose, from mGy to of the order of some 10 s of Gy). Among the above-mentioned sensors, none meet all such requirements [9]. In recent times silica-based optical fibre dosimeters have gained popularity as radiation dosimeters, due in no small part to their excellent spatial resolution (with dimensions of a few tens of microns), water insolubility, chemical inertness, free of risk from various hazards (fire, explosions, electromagnetic interferences) and affordability. Such optical fibres typically consist of an optically transparent doped core surrounded by a transparent cladding material. In traditional application for use in communications, to ensure total internal reflection the refractive index of the core of the fibre is made greater than that of the cladding by the addition of the dopant. It is with respect to such construction, namely of a doped core insulator, that as a matter of serendipity, the selectively doped silica fibre core also forms the basis of a passive radiation dosimeter (see for instance [10]). The dosimetric properties of SiO_2 optical fibres depend on the trapping processes caused by the occurrence of structural defects in the material [11].

The radiation sensitivity (hammering) of telecommuncation fibres has now been known for many years. Specifically, for optical fibres exposed to ionizing radiation, it is known that the data transmission capability of the fibre can be affected (attenuated) through radiation induced ionization and formation of traps (colour centres), created by the presence of impurities within the optical fibre core [12,13]. More recently it has been realized that the presence of the colour centres can be correlated with the radiation dose. By using the associated mechanism of radiation hammering, optical fibres can be evaluated for their utility as radiation detectors rather than in study of the deterioration of their optical communication capability. Three intimately related luminescence phenomena, RL, OSL and thermoluminescence (TL), all based on the energy band structure of materials, can be independently harnessed for use in radiation dosimetry. RL is the spontaneous fluorescence emitted from scintillating material by recombination of the electron-hole pairs caused by the immediate irradiation, also being directly associated with the dose rate. In an RL type dosimetry system the active portion of dosimeter can be made for instance of a small (sub mm^3) piece of scintillator optically attached to the tip of a long polymethyl methacrylate (PMMA) fibre cable. When the sensor is exposed to ionizing radiation, an optical (light) signal is generated and is guided through the PMMA fibre towards a detecting device placed at a distance (metres and more) from the radiation zone. RL type sensors provide real-time information. Conversely, pre-existing traps, populated for instance as a result of absorbed dose, can lead to luminescence emission upon receipt of additional energy from an external source of stimulation of the appropriate wavelength of light (generally in the visible range), termed OSL, or by heat stimulation, termed TL, both with intensity related to the amount of absorbed dose.

The luminescence properties of Ge-doped SiO_2 fibre are affected by dopant concentration along the core of the fibre. Owing to the presence of Ge-atoms (impurities) in the silica glass matrix, colour centre formation is facilitated: since the energy of the Ge—O bond (~3.6 eV) is lower than that of the Si—O bond (~5 eV), the rupture of these bonds by incident radiation is more probable than that of the Si—O association [14].The details of both the nature and the molecular structure of radiation-induced point defects in pure and doped glassy silica has been described elsewhere [15,16].

Present dosimetric study focuses on the RL and OSL characteristics of lab-fabricated Ge-doped fibres of core diameter 100 μm, manufactured using the Modified Chemical Vapour Deposition (MCVD) process. In seeking to fulfill the requirements of a sensitive form of dosimetry there is need to investigate dependency on the quantity of Ge-dopant, a situation that is not usually to be attained through use of commercially available telecommunication optical fibres, these generally being of a particular dopant concentration. The particular interest is investigation of the effect of doping concentration of SiO_2 glass based on the RL/OSL method, pointing to optimum Ge-dopant concentrations for sensitive radiotherapy dosimetry. This will depend on source types, in present study these being penetrating (energetic, ~MeV) X-ray photons.

2. Materials and methods

2.1. Dosimeter fibre fabrication and characterization its quality standards

Three different Ge concentrations were selected in the doping of silica optical fibres, guided by the relatively limited amount of *a priori* information available on luminescence yield for such systems. Here it should be mentioned that several of the research team within this group have also been involved in the investigation of the TL properties of different Ge-concentrations in silica optical fibres [17,18], it being known from those studies that the TL yield for Ge-doped silica are close to optimum at around the value choices that have been retained herein. Doping was through use of the MCVD method, with details of the fabrication procedure also being available elsewhere [19,20]. The fibre fabrication process consists of two steps: preform fabrication wherein the doping takes place and the drawing process to produce fibres. The preforms were pulled into fibre with core/cladding diameters (100/604) μm. It is expected that larger cross-sectional fibre samples will provide greater number of traps [21], cross-sections that would need to be compatible with the larger core-sized PMMA fibre used herein.

In previous studies, SEM (Scanning Electron Microscope)-based EDX (Energy Dispersive X-ray Spectroscopy) analyses have been used in X-ray mapping and line-scan profiling, performed to determine the relative presence of doping material in the silica fibre core. With use of an optical cleaver, the fabricated optical fibres were cut into 1 cm lengths for SEM-EDX analysis. Ease of incident electron flow to the ground was ensured through use of carbon tape attached to the sample, also the low atomic number of carbon ensuring min-