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The thermoluminescence response of doped SiO_2 optical fibres subjected to fast neutrons

S. Hashim [a,*], D.A. Bradley [b], M.I. Saripan [c], A.T. Ramli [a], H. Wagiran [a]

[a] Department of Physics, Universiti Teknologi Malaysia, 81310 Skudai, Johor Darul, Takzim, Malaysia
[b] Department of Physics, University of Surrey, Guildford GU2 7XH, UK
[c] Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

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ABSTRACT

This paper describes a preliminary study of the thermoluminescence (TL) response of doped SiO_2 optical fibres subjected to ^{241}AmBe neutron irradiation. The TL materials, which comprise Al- and Ge-doped silica fibres, were exposed in close contact with the ^{241}AmBe source to obtain fast neutron interactions through use of measurements obtained with and without a Cd filter (the filter being made to entirely enclose the fibres). The neutron irradiations were performed for exposure times of 1-, 2-, 3-, 5- and 7-days in a neutron tank filled with water. In this study, use was also made of the Monte Carlo N-particle (MCNP^{TM}) code version 5 (V5) to simulate the neutron irradiations experiment. It was found that the commercially available Ge-doped and Al-doped optical fibres show a linear dose response subjected to fast neutrons from ^{241}AmBe source up to seven days of irradiations. The simulation performed using MCNP5 also exhibits a similar pattern, albeit differing in sensitivity. The TL response of Ge-doped fibre is markedly greater than that of the Al-doped fibre, the total absorption cross section for Ge in both the fast and thermal neutrons region being some ten times greater than that of Al.

1. Introduction

Neutron dosimetry finds importance in a number of fields of endeavour, prime among which are radiation oncology and the nuclear fuel-cycle industry. Such applications give rise to continuing interest in the development of systems of sensitive dose measurement, particularly those that are robust and yet provide for ease of use. The need for sensitivity is in large part due to the energy variability of the radiation weighting factor, reflected in the fluence to ambient and personal dose equivalent conversion factors (Roberto et al., 2006). The associated desire for any such measurement system to imperceptibly perturb the radiation field also implies particular interest in small volume dosimeters. It is in this context that present interest focuses on the thermoluminescence produced by short lengths (~0.5 cm) of commercially available doped optical fibres subjected to neutron irradiations. It was reported that the useful TL properties of the SiO_2 commercial optical fibre is appear to be an excellent candidate for use in TL dosimetry of ionising radiation (Espinosa et al. (2006)).

In regard to neutron irradiations, it is to be noted that all presently available neutron sources, regardless of type, emit photons as well as neutrons. Thus the detector system needs to be characterized for both neutron (fast, thermal, etc.) and photon response. For the particular example of ^{241}AmBe, an important characteristic of this (α, n) source is that only one neutron is produced per reaction, the alpha particles emitted from ^{241}Am interacting with the target material, ^{9}Be, to form a compound nucleus having overcome the Coulomb barrier. The ^{9}Be atom transforms to ^{13}C which immediately decays to ^{12}C by emitting neutrons. The ^{12}C atom can be left in an excited state (predominant emission 4.4 MeV gamma rays) or go straight to the ground state. The reaction can be written as

$$ {}_{2}^{4}\alpha + {}_{4}^{9}Be \rightarrow {}_{6}^{12}C + {}_{0}^{1}n \tag{1} $$

The Monte Carlo technique is a numerical method for obtaining an estimate of a solution which depends on random processes. A well-known method for simulating such a situation in this research is the Monte Carlo (MCNP^{TM} V5) technique developed and maintained by the MCNP team at the Los Alamos National Laboratory (Briesmeister, 2003). Monte Carlo physics simulation packages attempt to provide essentially a 'physics-library' of possible interactions, the user being required to specify the geometry of the system, the source to be used and the manner in which the resulting data are to be recorded. In the case of the MCNP code, one can define various geometric primitives, set-up the source situation and use one of the many tallies to record the resulting data, also specifying the total number of events for the simulation to take place. During execution, the MCNP code generates individual particles and tracks them through the user-defined geometry recording the various interactions occurred.

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[*] Corresponding author.
E-mail address: suhairul@utm.my (S. Hashim).

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Many such ‘particles histories’ are then simulated in order to build up a statistically valid result, which may be in any forms, for instance, an image or a deposited energy spectrum.

2. Materials and methods

2.1. Sample preparation

Present research has focused on the TL response of commercially produced single-mode telecommunication optical fibres. Use has been made of optical fibres manufactured by INOCORP (Canada), these being SiO_2 doped with Ge or Al at concentrations appropriate for total internal reflection, as required for telecommunication fibres. It is to be noted that dopant concentrations are not included among the data provided in the accompanying product data sheets. Each of these INOCORP fibres has a core diameter of $125.0 \pm 0.1\,\mu m$. In preparation for irradiation, the outer polymer coating to the optical fibres was removed using a fibre stripper (Miller, USA) to allow investigation of the TL yield of the fibre core. Following removal of the outer cladding, the optical fibre was cleaned by means of a cotton cloth containing a small amount of methyl alcohol to completely remove any remnant polymer cladding. Subsequently, the fibre was cut into 0.5 cm long pieces using an optical fibre cleaver (Fujikura, Japan). The mass of each fibre, $\sim 0.20 \pm 0.02$ mg, was measured using an electronic balance (PAG, Switzerland). Vacuum tweezers (Dymax 5, Surrey, UK) was used for handling and grouping of the TL materials.

Before making any irradiations and subsequent TL measurements, the fibres were first annealed in an oven in order to standardise their sensitivities and backgrounds. This allows removal of any residual TL signal, the establishment of TL sensitivity and elimination of unstable low-temperature glow peaks. Annealing was performed with the fibres positioned in an oven set at 450 °C for a period of 1 h, the fibres being retained in an alumina container during this time. To avoid thermal stress following the annealing cycle, the fibres were left inside the slowly cooling oven for a further 10 h to finally equilibrate at temperature of 40 °C. For the TLD-100, the annealing routine was to place these in a stainless steel plate and to anneal for 1 h at 400 °C and subsequently 2 h at 100 °C.

After cooling, the fibres were placed inside vegetable-based gelatin capsules and held within a light tight box in order to minimize exposure to potential high ambient light levels. A typical mass of each pieces of the fibre is 0.2 mg per fibre.

2.2. Irradiation

The first series of doped fibres to be irradiated were retained in two separate gelatine capsules, one for Ge and one for Al-doped fibres. The materials inside their gelatine capsules were then both placed inside a thin-walled water-tight plastic container; the results providing for estimation of the gamma photon and neutron dose. In a second series of experiments, use was made of 0.2 cm thick cadmium foil filtration to remove the thermal neutron contribution and practically all of the 59.54 keV gamma photons, the samples then being wrapped in polythene tape to ensure that the package was again water-tight. As an aside, it is well known that cadmium filtration can be made to be virtually opaque to thermal neutrons (0.025 eV) while being reasonably transparent to epithermal and fast neutrons.

The Ge- and Al-doped fibres were exposed in the neutron tank, the dosimeters being positioned directly over the 10.6 GBq source (the fibres being at an estimated 1 cm from the surface of the source) for periods of time of 1-, 2-, 3-, 5- and 7-days.

2.3. MCNP5 simulation

Given that MCNP calculations can be CPU time intensive, there are a number of simplifying assumptions that can be made to the practical set-up. In the present situation, in making practical measurements the cadmium and plastic containment of the fibres are each located close to the neutron source, the latter being located in a water tank. Hence, in the MCNP simulation no account has been taken of the presence of any minimal amount of intervening water. The use of cadmium and plastic containment has also been omitted in this simulation, it being possible for the fast neutron component to be extracted using a filtered tally (tally f1) in the MCNP code. Tally f1 provides the details of the number of particles crossing surfaces. By setting different surfaces with their own number, the number of particles crossing different surfaces can be distinguished easily.

In this simulation, the particles emission from ^{241}AmBe is simulated using a source definition located below the fibre. Due to the variance reduction facility in MCNP, the MCNP calculation boundary can be set to limit the particle tracks. With these various assumptions, it is an expectation that the results of simulation will be higher than the measured values due to reduced account of the intervening attenuating material. Thus said, since that the volume of the omitted attenuating materials is constant, it is also expected that the simulation will yield the same dose response trend as that observed in actual measurements.

2.4. TL measurements

After each set of exposures, and following a selected delay of 12 h (to allow uniform control of thermal fading), the optical fibre TL yield was read out by using a Solaro TL reader (Vinten TLD, Reading, UK); N_2 atmosphere being used to suppress spurious light signals from triboluminescence and also to reduce oxidation of the heating element. According to the TL reader manual, it is recommended to use the following parameters during readout process: preheat temperature 160 °C for 10 s; readout temperature 300 °C for 25 s and heating rate cycle of 25 $^{\circ}C\,s^{-1}$. Finally, an annealing temperature of 300 °C was applied for 10 s to sweep out any residual signal. It should be noted that the complete annealing prior irradiation was done separately in a furnace at 450 °C for 1 h and further cooling for another 10 h (Hashim et al., 2009). The TL signal from Ge-doped fibre has a fast fading characteristic of about 2% within 6 h and a slow fading of 7% within 30 days (Abdulla et al., 2003). The TL yield obtained was then normalized to unit mass of the particular TL medium. The TL measurements of fast neutron dose were obtained by subtracting the TL value obtained in the presence of Cd filtration from the total value of TL obtained in the plastic containment only.

3. Results and discussion

3.1. Dose response

Based on dose calculations obtained on the basis of the known activity of 10.6 GBq for the ^{241}AmBe source, an MCNP5 simulation was performed using the ratio two neutrons:three photons (based on the experimental results, two neutron particles were emitted for every three photons from ^{241}AmBe source). This being required since in MCNP the source emission is not allowed to consist of both neutrons and photons in a single calculation. Using different SDEF for photons and neutrons will be resulting independent sources emissions between SDEFs and therefore, it will need different tally records for neutrons and photons, respectively.