FABRICATION OF GERMANIUM-DOPED SILICA OPTICAL FIBRES USING MCVD TECHNIQUES TO ENHANCE DOSIMETRIC CHARACTERISTICS FOR GAMMA-RAY DETECTION IN BLOOD IRRADIATOR

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Article History: Received March 22, 2025; Revised April 23, 2025; Accepted May 5, 2025

ABSTRACT: This study explores the fabrication of germanium-doped silica optical fibers using Modified Chemical Vapor Deposition (MCVD) techniques to enhance dosimetric properties for gamma-ray detection in blood irradiators. Accurate dose mapping, essential for preventing graft-versus-host disease, requires radiation exposure in the range of 15 Gy to 50 Gy. We investigate the dosimetric characteristics of Ge-doped silica fibers as passive radiation dosimeters for blood irradiators using a Cs-137 source. Key dosimetric parameters, including linearity, sensitivity, fading, and glow curve analysis, were tested on cylindrical (CF) and flat (FF) fibers, irradiated with doses from 5 to 50 Gy. Thermoluminescence (TL) measurements showed a linear dose response ($R^2 > 99\%$) and consistent sensitivity, with Coefficients of Variation improving from 12.8% to 5.57% for CF and 13.8% to 5.91% for FF. After 28 days of storage, TL fading was 11.5% for CF and 9.2% for FF. The MCVD technique, along with germanium doping, significantly improved the dosimetric properties of the fibers, making both CF and FF Ge-doped optical fibers promising candidates for passive dosimetry in gamma-ray blood irradiators.

KEYWORDS: *Fabricated Ge-doped optical fibres; Cesium-137 irradiator; Gamma dose mapping; Thermoluminescence; and Dosimetry*

1.0 INTRODUCTION

Abdulla [1] and Noor et al [2] have explored the potential of silica optical fibres as new TL materials compared to conventional TLDs. These fibres have shown promising TL characteristics in ionising radiation dosimetry, including water resistance [3]. Additionally, optical fibres doped with germanium have shown higher radiation sensitivity than those doped with other elements [4]. The MCVD technique is used to create undoped silica cladding around a centrally doped silica core region in commercial fibres, leading significant advances in radiation detection. This technique aims to maintain a constant dopant concentration, encouraging the development of novel fibres for clinical applications. MCVD technology provides numerous advantages to optical fibres, particularly those doped with germanium, improving their homogeneity and sensitivity, thus facilitating the advancement of TL silica-based materials [5-6].

Researchers have extensively studied the properties of fabricated Ge-doped optical fibres for dosimetry, proving their versatility in various fields, such as postal radiotherapy dose audit characteristics [6-8]. The study explores various methods for assessing patient dose in various diagnostic procedures, including x-ray diagnostics [6], low dose particle irradiation [9], small fields dosimetry [10-11], proton beam measurements [12-13], computed tomography [14], electron beams [15-16], and food irradiation dosimetry [5]. Irradiation is used to deactivate viable lymphocytes in cellular blood components to reduce the risk of Transfusion-associated Graft-versus-Host Disease (TA-GVHD), a rare but fatal disease [17]. According to several authorities, the maximum dose is 50 Gy, and the blood in the canister should receive 25 Gy, with no point in the irradiated region receiving less than 15 Gy [18]. Ionising radiation dosimetry is crucial to quality assurance and blood irradiation in medicine [19]. There is a lack of studies on using optical fibres to detect gamma-ray radiation in blood. This study examines the radiation dosimetry of 2.3 mol% germanium (Ge) doped silica preforms, as radiation dosimeters. These dosimeters are then exposed to gamma beam Cesium-137 blood irradiation for further analysis.

2.0 METHODS

2.1 Preparation of Fabricated Ge-Doped Optical Fibres using MCVD technique

The fabrication process consisted of two phases. The preforms were produced using MCVD at the Photonics Laboratory, Faculty of Engineering, Multimedia University (MMU), Cyberjaya, Malaysia. The fusion of gases ($GeCl_4$, $SiCl_4$, and O_2) into a rotating hollow substrate tube composed of high-purity silica was conducted using a lathe equipped with an oxy-hydrogen burner. MCVD was performed at temperatures ranging from 1800 to 2100°C. The uniform rotation of the high-purity silica substrate tube facilitated the deposition of the inner wall layer. Ge-doped preform rods exhibited both collapse and recovery at elevated temperatures. The introduction of $GeCl_4$ to the rotating tube modified the Ge concentrations in the optical fibre to various mol% levels. Subsequently, following MCVD, both collapsed and uncollapsed Ge-doped preform rods were drawn into CF and FF optical fibres using pulling tower facilities at the Flat Fibre Laboratory, University of Malaya (UM), Malaysia. Temperature, pulling speed, and pressure can be manipulated to create fibres with varying TL responses [1].

The fibres in this study had different geometries due to their structures and with 2.3 mol% germanium dopant. Cylindrical fibres were identified by diameter, while flat fibres by height and width. The cylindrical fibre (CF) had a diameter of approximately 481 μm. Conversely, the flat fibre (FF) measures approximately 643 × 356 μm. The physical properties of the 2.3 mol% germanium-doped fibres were studied using a scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDX). Comparing the geometric characteristics of the CF and FF to the core volume and precise composition of the optical fibres as a whole. Each optical fibre is 6 mm long, with a 124 μm core diameter for CF and 348 × 12.6 μm^2 for FF. The estimated volume of the doped-core region for CF is 2.6 × 10-11 m^3, while for FF it is 6.79 × 10-11 m^3.

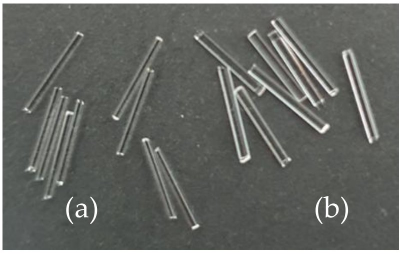


Figure 1: Fabricated Ge-doped cylindrical optical fibres (a) Cylindrical fibres, (b) Flat fibres

Before gamma irradiation, optical fibers underwent a thermal treatment process known as annealing in a CarboliteGero CWF 1200 Heating Chamber (Figure 2(a). The samples were heated inside a brass plate and wrapped in aluminium foil (Figure 2(b)) at 400°C for 1 hour. Subsequently, the samples cooled naturally to room temperature. The purpose of this treatment was to eliminate any potential thermoluminescence (TL) signal present in the optical fibres.

(a) (b)

Figure 2: (a) CarboliteGero CWF 1200 Heating Chamber, (b) Sample fibres are inside the brass plate in the furnace.

2.2 Irradiation Setup

All fibres in this study were exposed for basic dosimetric characterisation tests at the Malaysia Nuclear Agency's Secondary Standard Dosimetry Laboratory (SSDL) using a Colbalt-60 source with gamma rays. Fabricated optical fibres are exposed to a gamma ray machine at a source-to-surface distance (SSD) of 80 cm, a 10 cm × 10 cm field size, and a dose rate of 479.23 mGy/min. To receive 1 Gy, 2.09

minutes is required. Each type of CF and FF was held in multiple gelatine capsules stacked on a board to expose the fibres. The Ge-doped optical fibres received a horizontal gamma beam (Figure 3).

(a) (b)

Figure 3: Irradiation setup for basic dosimetric characterisation of fabricated Ge-doped optical fibres (a) a gamma Cobalt-60 machine, (b) Samples fibres CF and FF in gelatine capsules.

2.3 Read-Out of Fabricated Optical Fibres

The Harshaw™ 3500 TLD reader is employed following optical fibre irradiation, located at the Pusat Pengimejan dan Diagnostik Nuklear (PPDN), Universiti Putra Malaysia (UPM).

2.4 Sensitivity and Glow Curve

The optical fibre was irradiated for 1 Gy using the gamma Colbalt-60 machine for dose sensitivity and TL Glow curve test. Select fabricated Ge-doped fibres with similar mass, length, and sensitivity will be grouped into a ± 10% sensitivity range. Windows®-based Radiation Evaluation and Management System (WinREMS) was used to obtain TL signal glow curves for CF and FF glow curve analysis. This TLD reader software is integrated. After irradiation, a hot planchet inside the TLD reader heats the TL materials, causing the effect. To optimise CF and FF TTP, this study manipulated preheat time-temperature (TTP) parameters. This study evaluated several preheat TTPs, as shown in Table 1. Preheat time, acquisition temperature rate, and time acquired for 13 seconds, heating rate of 30°C s-1, maximum temperature of 400°C, annealing temperature of 400°C, and annealing time of 10 seconds were constant throughout the study. Preheating eliminates the TL signal from rapid low-temperature peak fading. Preheating reduces fading in low trap electron peaks.

Table 1: Various preheat TTP parameter set.

Optical Fibres	TTP Parameter
	Preheat Temperature (°C)
CF	80
	95
	100
	110
	120
FF	85
	92
	95
	10
	110

2.5 Linearity

Both CF and FF optical fibres were irradiated using the Gamma Colbalt-60 machine in the dose range of 5 Gy to 50 Gy. Table 2 displays the fibre exposure time and doses. The coefficient of determination (R-squared) value indicates a linear relationship between dose range and TL intensity. The TLD reader read the optical fibres on day 5 after irradiation. To calculate the normalised TL signal, $TL^{fibre}_{net\_normalised}$ from optical fibre measurements, Equation (1) was used:

$$TL^{fibre}_{net\_normalised} = \frac{(\underline{R}-\underline{B})}{V}, \quad (1)$$

where $\underline{R}$ is the average TL reading of ten optical fibres irradiated at a given dose in water-equivalent phantom, $\underline{B}$ is the average TL background reading of 10 unirradiated optical fibres, both given in units of nanocoulomb (nC), and V is the volume of doped-core optical fibre (m^3). Therefore, the normalised TL response is expressed in a unit of nC/m^3.

Table 2: Time of exposure set at Gamma Colbalt-60 machine and doses acquired to the fibres.

Dose (Gray)	Time set for exposure (minutes)
5	10.65
10	21.30
15	31.95
20	42.60
25	53.30
30	63.90
35	75.00
40	85.00
45	96.00
50	107.00

2.6 Fading

The fibres were exposed to 25 Gy Gamma Cobalt-60 radiation to assess TL signal fading. After radiation exposure, the fibres were stored in a light-proof case to reduce trapped electrons that might decrease signals. Readouts occurred across several time intervals at 1, 3, 5, 7, 17, 21, and 28 days.

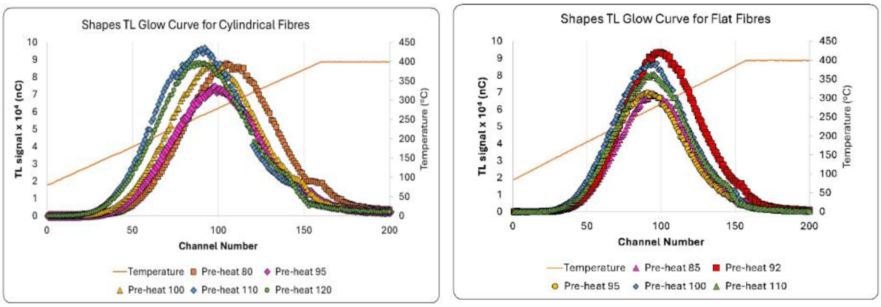
2.7 Statistical Analysis

The statistical analysis was conducted using the Statistical Package for Social Sciences (SPSS) version 29. The t-test was used for sensitivity, simple linear regression for linearity dose response, and the Pearson correlation coefficient (r) for fading.

3.0 RESULTS AND DISCUSSION

3.1 Glow Curve

The glow curve acquired during readout assists in identifying thermoluminescent materials for dosimetry applications. Temperature and TL intensity are correlated in the glow curve. Electrons are released from traps and recombine with holes. Figures 4 show the channel formation glow curve from 0 to 200. Preheating the temperature was initially adjusted in several ranges. The ideal TTP and glow curve formation with a bell-shaped centre of channel at 100 show that this study's TTP set was pre-heat: 95°C for CF Sand 92°C for FF at 10 seconds, acquired temperature: 400°C for 13 seconds, and heating rate: 30°C/s.



(a) (b)

Figure 4: Formation of a glow curve with different preheat temperatures employed (a) CF and (b) FF.

3.2 Sensitivity

The TL sensitivity is measured by TL yield (nC) per dosimeter volume and dosage (m−3. mGy−1). This study normalised sensitivity to fibre core volume for each dosimeter. Before fibre sorting into each sensitivity batch, the coefficient of variation (CV) of CF and FF was more than 10% (CF was 12.82% and FF was 13.86%) for all 520 fibres for each dosimeter. Figure 5 shows that the medium-sensitivity batch's mean TL responses of 290 CF and 280 FF were CV less than 6%, 5.57% and 5.91%, respectively.

The fabricated optical for gamma ray's sensitivity (normalised TL yield) versus dose is shown in Figure 6. As mentioned in a previous study, 2.3 mol% Ge-doped FF had the highest TL sensitivities [5]. FF has increased sensitivity due to collapsed surface structures, which provide more defect sites. This shows that more defect sites increase electron-hole trappings during FF irradiation. Thus, sensitivity is higher than CF [2,3]. The coefficients of variation for optical fibre sensitivity for each 520 group were 0.12% to 1.7% for CF and 0.14% to 1.59% for FF, indicating good TL measurement consistency.

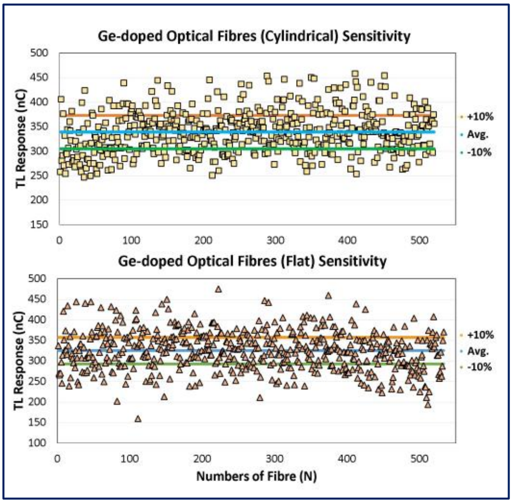


Figure 5: For the medium sensitivity batch, (a) CF CV was reduced to 5.57% (290 fibres) from 12.82% (520 fibres), while that for the (b) FF was reduced to 5.91% (280 fibres) from 13.86% (520 fibres).

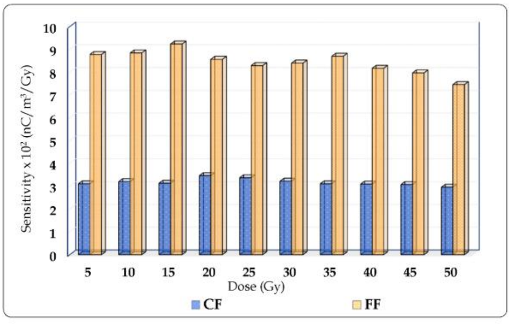


Figure 6: The sensitivity of CF and FF fabricated optical fibres from 5 Gy to 50 Gy gamma ray Colbalt-60 irradiation.

Skewness, kurtosis, and Shapiro-Wilk statistics supported normality distribution for each fibre type. Since Levene's statistic was non-significant ($p > 0.05$), variance homogeneity was not violated. The non-significant variance between CF and FF was determined by a t-test. The one-sample t-test showed that CF (M = 337.7, SD = 18.8) and FF (M = 326.4, SD = 19.3), and the population mean (M = 339.1), $t(289) = 1.3$, p = .202 and (M = 325.5), $t(279) = 0.8$, p =.420, respectively, at $p > 0.05$. Figure 6 reveals that FF optical fiber exhibits significantly higher sensitivity than CF at every dose, from 5 Gy to 50 Gy, demonstrating its capability for monitoring in lower-dose environment applications.

3.3 Linearity

One important characteristic of radiation detectors is dose linearity, which is the property of each material that indicates non-linearity in a thermoluminescence (TL) growth curve within specific dosage ranges. The relationship between TL response and dose delivered for CF and FF exposed to 5 Gy to 50 Gy gamma rays is shown in Figure 7. To eliminate weight factors, all TL responses were normalised per unit volume. The result shows CF and FF TL responses gradually increasing. Both CF and FF demonstrated linear dose-response with a coefficient of determination (R^2) greater than 0.99.

Both fibres have equal Shapiro-Wilk p-values in linear regression, which assumes normality. It is assumed that CF and FF data are normally distributed. Doses in Gray predicted TL normalised per unit volume for FF ($R^2 = 0.99$, $F(1,8) = 710.45$, $p < .001$) and CF ($R^2 = 0.99$, $F(1,8) = 1221.26$, $p < .001$). Overall regression is significant at 0.05. This correlation also shows a strong direct relationship between doses and TL normalised per unit volume. Figure 7 shows a strong linear relationship between CF and FF, with an R^2 value exceeding 0.99, indicating a high correlation across the 5 to 50 Gy range. These results suggest that both CF and FF can effectively detect radiation doses within this range, which is commonly used in blood product applications.

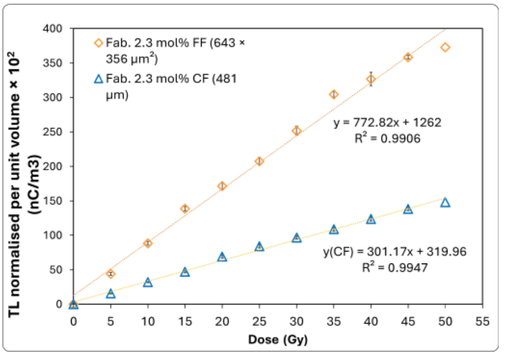


Figure 7: TL response and dose in Gray for CF and FF subjected to gamma ray irradiations for doses ranging from 5 Gy to 50 Gy.

3.4 Fading

TL signal decreases after irradiation and before readout are known in the field. These are called fading or post-irradiation annealing, according to Theinert [20]. Comparing the TL signal from day 1 to 28 post-irradiation revealed fading results. The single exponential decay fitting function in Figure 8 shows that 25 Gy gamma rays reduce the TL signal in both CF and FF. On day 28 after irradiation, CF had 11.5% TL fading loss and FF 9.2%. The presence of the Ge dopant and the fused inner wall of these silica optical fibres during fabrication may cause extra low-energy traps, which may explain their faster fading rate. 2.3 mol% CF faded most due to shallower depths and higher ambient temperature energy production, supporting Ghomeishi [21].

The assumption of normality for Pearson correlation was verified using the Shapiro-Wilk test, which confirmed that the data followed a normal distribution for both CF and FF. Pearson correlation analysis revealed a strong negative correlation between days and TL yield for both fibers: CF $r(7) = -0.930$, $p = 0.02$ and FF $r(7) = -0.806$, $p = 0.002$. This significant negative correlation was consistent for both fibers. Statistical analysis supports the decreasing thermoluminescence (TL) signal, suggesting that both CF and FF fibers exposed to high-dose radiation should wait until after the stability period (in this case, the 5th day) before reading the TL signal (Figure 8). However, a fading correction factor must still be applied to reflect the actual TL readings, allowing the absorbed dose measurements to be established accurately.

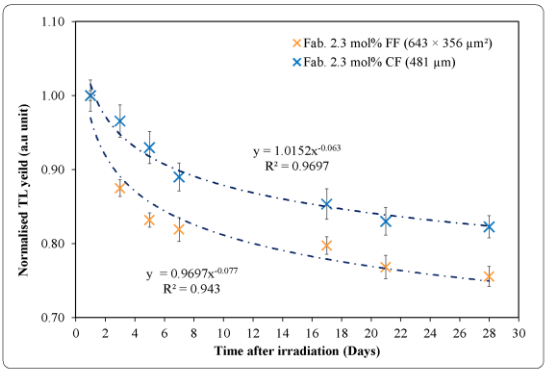


Figure 8: Exponential decay fit graph of normalise TL signal fading for CF and FF 25 Gy gamma ray irradiation.

4.0 CONCLUSION

This study successfully conducted a direct comparison of fabricated germanium-doped silica optical fibers (CF and FF), focusing on their basic dosimetric characteristics. The MCVD technique used in the fabrication of these fibers demonstrated that the germanium element, as a dopant, effectively enhanced the dosimetric properties of the fibers.

For the use of this novel fabricated Ge-doped silica optical fiber system in blood irradiation dosimetry, to ensure sufficient accuracy and precision, appropriate correction factors must be applied, along with adequate preparation of the measurements. Both fiber types, due to their excellent characteristics, exhibit high sensitivity, excellent linearity, and minimal fading of the signal. This technology shows considerable promise as an innovative passive dosimeter for blood dose mapping.

ACKNOWLEDGMENTS

We acknowledge the Malaysian Nuclear Agency's Secondary Standard Dosimetry Laboratories (SSDL) and Universiti Putra Malaysia's Department of Pathology and Medical Physics Unit for their assistance with this study. We also recognize the support from the Prototype Research Grant Scheme (PRGS/1/2021/SKK07/UPM/02/1) of the Ministry of Higher Education Malaysia in completing this research.

CONTRIBUTIONS

K. S. A. K. Bakar: Methodology, Software, Writing-Original Draft Preparation; N. M. Noor: Supervision, Writing-Reviewing and Editing M. T. Dollah: Supervision; D.A. Bradley: Writing-Reviewing and Editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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