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Time-Temperature Profiles Effect on Thermoluminescence Glow Curve Formation of Germanium Doped Optical Fibres

(Kesan Profil Suhu Masa pada Pembentukan Lengkung Cahaya Termoluminesen bagi Gentian Optik Berdop Germanium)

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ABSTRACT

The development of optical fibres technology grows in response to seeking a radiation detector with better thermoluminescence (TL) performance. Concerning the dosimetric characterization study by previous researchers, this research work has widened the exploration to optimize the time-temperature profile (TTP) in connection with the glow curve formation of the optical fibres. Two forms of germanium (Ge) doped optical fibres, namely cylindrical optical fibre (CF) and flat optical fibre (FF) were fabricated, and the TTP were investigated prior to commissioning the optical fibres for fieldwork. CF and FF were irradiated to the dose of 2 Gy using a 6 MV linear accelerator. Various TTP profiles, including preheat temperature, preheat time, acquisition temperature rate, and acquisition time were varied to determine the best thermal profile for the CF and FF based on the glow curve formations. Out of 4 parameters, an increase in preheat temperatures ranging from 40 to 120 °C caused a significant variation in the glow curve formation, thus possibly giving rise to different TL signals of the optical fibres. The maximum glow peak temperature of CF and FF was unvarying when different preheat temperatures employed. These findings support the conceptual idea that manipulating the optical fibres' readout system can alter the glow curve formation. Thus, an optimized TTP will provide the correct glow curve configuration for kinetic parameter analysis.

Keywords: Optical fibres; thermoluminescence glow curve; time-temperature profiles

ABSTRAK

Pembangunan teknologi gentian optik berkembang sebagai gerak balas dalam mencari pengesan radiasi dengan prestasi pendar gerlap terma (TL) yang lebih baik. Merujuk kepada kajian pencirian dosimetrik oleh penyelidik terdahulu, penyelidikan ini telah memperluaskan penerokaan untuk mengoptimumkan profil suhu-masa (TTP) yang berkaitan dengan pembentukan lengkung cahaya daripada gentian optik. Dua bentuk germanium (Ge) dop gentian optik, iaitu gentian optik silinder (CF) dan gentian optik rata (FF) difabrikasi dan TTP dikaji sebelum gentian optik digunakan untuk kerja lapangan. CF dan FF disinari dengan dos radiasi 2 Gy menggunakan pemecut linear bertenaga 6 MV. Pelbagai profil TTP, termasuk suhu pra-pemanasan, tempoh masa pemanasan, kadar pemerolehan suhu dan masa pemerolehan diubah untuk menentukan profil terma yang terbaik untuk CF dan FF berdasarkan penghasilan lengkung berbara. Daripada 4 parameter, peningkatan suhu pra-pemanasan antara 40 hingga 120 °C menyebabkan variasi yang ketara dalam pembentukan lengkung berbara, dan ia akan menghasilkan isyarat TL yang berbeza daripada gentian optik. Suhu maksimum puncak berbara CF dan FF tidak berubah apabila suhu pra-pemanasan yang berbeza digunakan. Penemuan ini menyokong idea konseptual bahawa manipulasi terhadap sistem pembacaan gentian optik boleh mengubah pembentukan lengkung berbara. Oleh itu, TTP yang optimum akan menyediakan konfigurasi lengkung berbara yang tepat untuk analisa parameter kinetik.

Kata kunci: Gentian optik; lengkung berbara pendar gerlap terma; profil suhu-masa

INTRODUCTION

Optical fiber is well-known in the communications and broadcasting industries, where it has been frequently employed to transmit long-distance transmissions (Correia et al. 2018). On the other hand, the use of optical fibre in radiation detection turns up when the silica-based optical fibre possesses thermoluminescence (TL) characteristics similar to that of conventional phosphor-based dosimeter. TL is the emission of light during gradual heating of material following the previous absorption of energy from ionizing radiation. The amount of light produced is directly proportional to the absorbed dose of the radiation given to the material. Sharing the same TL fundamental, the dosimetry research community introduces optical fibre as a new potential TL material with enhanced performance using the specified fabrication process so as to obtain better physical and dosimetric characteristics for different applications (Bradley et al. 2017; Ghomeishi et al. 2015).

Recent research and developments in optical fibre sensor technology have led to a renewed interest in radiation detection. The potential use of germanium (Ge) doped optical fibres in radiation detection has gained much interest. Many profound researchers conducted the evaluation on the dosimetric characteristics of the Ge-doped optical fibre subjected to various types of radiation, including gamma-ray (Entezam et al. 2016), low-dose diagnostic x-ray kV (Rais et al. 2019b), high energy photon (Noor et al. 2016), electron (Zakaria et al. 2020), proton (Hassan et al. 2018), and neutron (Mustafa et al. 2018). Comprehensive reviews by Bradley et al. (2017) and O'Keeffe et al. (2015) provide supportive facts that the Ge-doped optical fibres are feasible to be introduced as a potential dosimeter in numerous applications due in part to their favourable responses to ionizing radiation. Research on the Ge-doped optical fibres flourishes when the studies of Ge-doped optical fibre make a notable leap from passive dosimeter application into the real-time dosimetry system (Bradley et al. 2019; Lam et al. 2021). Notwithstanding that scholarly research was carried out on TL performance of the Ge-doped optical fibres, the use of different time-temperature profiles (TTP) during the TL signal readout process is doubtful. The studies on the Ge-doped optical fibre dosimetry conducted by a consortium of researchers employed different heating cycles, although a similar TLD reader was used (Begum et al. 2018; Ghomeishi et al. 2015; Lam et al. 2017; Noor et al. 2016). Different forms of optical fibres possess a unique energy level of traps in the silica band gap, corresponding to the presence of the defects within the TL material caused by the impurities and fabrication process. Consequently, each type of Ge-doped optical fibres requires a specific TTP for the readout process, as is done for phosphor-based dosimeters (Thermo Electron Corporation 2002). Furthermore, the TL signals extracted from the TLD reader in the form of emitted light as the function of time are affected by various TTP parameters, including the preheat, acquisition and anneal cycles (Rodrigues et al. 2005). This indicates that it is necessary to establish the optimum heating cycles for the Ge-doped optical fibres prior to employing these dosimeters for radiation detection.

Ideal TTP is the critical component in determining the reproducibility of the TL signal, which indicates by the number of electron trapped under the glow curve. Several kinetic parameters can be determined to provide clear insight into the trapping behavior, including activation energy, frequency factor, and peak integral. However, unspecified and inconsistent TTP employed during the readout process causes the electron excitation to happen at different rates, thus resulting in the degradation in the TL reading stability of the Ge-doped optical fibres. Therefore, this study aims to optimize the TTP for TL readout of Ge-doped optical fibres. The experimental work presented here provides one of the first investigations into how heating cycles affect the glow curve formation of Ge-doped optical fibres, leading to a better understanding of the application of thermal treatment in TL dosimeter.

MATERIALS AND METHODS

FABRICATION AND PREPARATION OF GE-DOPED OPTICAL FIBRES

The Ge-doped optical fibres were fabricated into two different shapes: 1) cylindrical optical fibre (CF) with a diameter of ~483 μm and 2) flat optical fibre (FF) with a dimension of ~67.5 × 273 μm. These optical fibres were fabricated through a process called the modified chemical vapour deposition (MCVD) technique involving preform production and optical fibre drawing. Ge is the primary doping agent that was prepared at 6 mol% of weight gas flow rate, has been introduced in the form of germanium tetrachloride ($GeCl_4$) vapour along with silicon tetrachloride ($SiCl_4$) and oxygen (O_2). The details of the fabrication processes of CF and FF were thoroughly outlined by Fadzil et al. (2017) and Noor et al. (2016).

Prior to any irradiation tests, the optical fibres need to be prepared in-house following a multi-stage procedure. First, both CF and FF were cut manually using a diamond cutter into 6.0±1.0 mm lengths to fit the optical fibres to the size of the planchet of the TLD reader. Then, the CF and FF were dipped into the alcohol solution to remove possible carbon deposition and residue on the surface of the optical fibres (Fadzil et al. 2017). A vacuum tweezer was used to handle the optical fibres during the preparation procedure to minimize optical fibres' surface abrasion. Finally, the optical fibres were annealed before the irradiations to eliminate any pre-existing TL signals. Ten pieces of each CF and FF were loaded into a plastic capsule to provide accurate mean values.

OPTICAL FIBRES IRRADIATION

A medical linear accelerator (linac) located at Nilai Medical Centre that operated at a 6 MV photon beam was used to deliver a dose of 2 Gy. The plastic capsules were inserted horizontally into the TLD holder and placed in a water tank with a dimension of 20 20 20 cm as shown in Figure 1. A focus to surface distance (FSD) of 100 cm, a 10 cm depth in the water, and a 10 10 cm field size were employed for the irradiations.

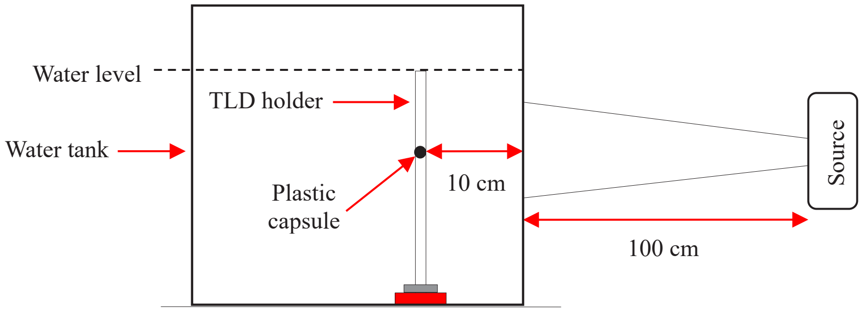


FIGURE 1. Photon beam irradiation set-up for Ge-doped optical fibres

READOUT PROCESS

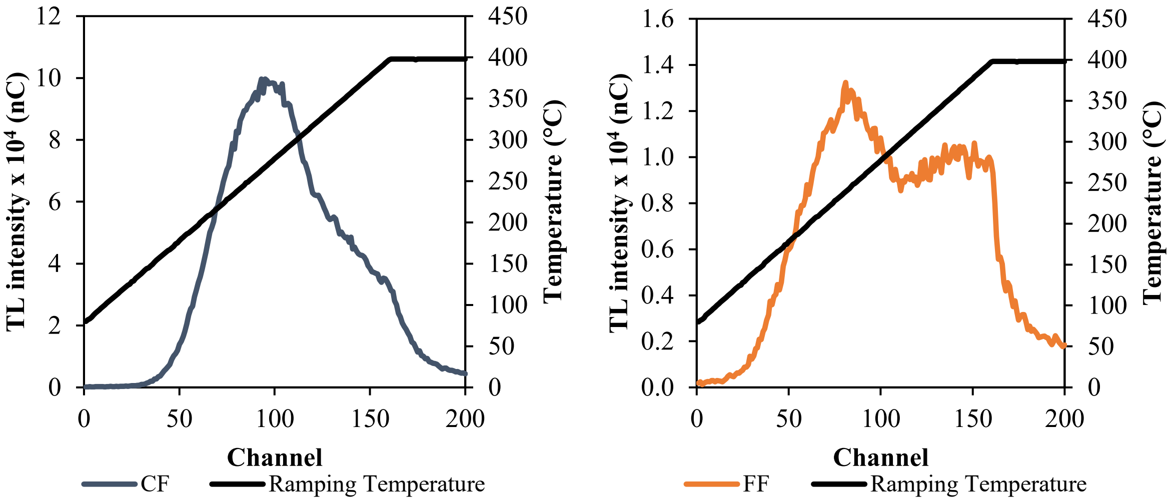
The TL signal of the CF and FF was acquired using a Harshaw 3500 TLD reader after the irradiations completed. The readout was carried out with nitrogen gas at 0.5 bars to avoid oxidation of the heating material (Lam et al. 2017). Various TTP were manipulated in order to examine the optimum thermal profile and temperature ramping time for the CF and the FF, including preheat temperature, preheat time, acquisition temperature rate, and acquisition time (Table 1). Meanwhile, a constant maximum temperature of 400 °C, the annealing temperature of 400 °C and the annealing time of 10 s were set throughout the study. The glow curve formation was extracted using a Windows®–based Radiation Evaluation and Management System (WinREMS) software with subsequent data analysis for comparison purposes. A comparison of these data reveals information about an optimized TTP for Ge-doped optical fibres.

TABLE 1. Various TTP manipulated during the readout process

TTP parameters	Values		
Preheat temperature (°C)	40	80	120
Preheat time (s)	5, 10, 15	5, 10, 15	5, 10, 15
Acquisition temperature rate (°C/s)	-	20, 30, 40	20, 30, 40
Acquired time (s)	-	20, 13.3, 10	20, 13.3, 10

RESULTS AND DISCUSSION

The emitted light intensity defines the glow curve as a result of heat treatment. This graphic representation exhibits the relationship between the temperature used for releasing the trapped electrons and the intensity of the emitted light after the recombination of the released electron. The optical fibres would have dissimilar trap levels in the energy band gap due to their varied features such as the shapes, the sizes and the dopants. The glow curve rises exponentially until it reaches a maximum glow peak at a specific temperature before falling to minimum intensity as the number of trapped electrons continuously decreased. Figure 2 shows the glow curve formation of CF and FF subjected to 6 MV photon irradiation delivering a dose of 2 Gy. CF demonstrates a single-peak curve, while FF exhibits a double-peaks curve. The first peak appears at the low-temperature region (channel 1 to 100) and the second peak at the high-temperature region (channel 101 to 200). These results consistent with the earlier study of Hassan et al. (2018), with the glow curves of CF and FF appeared in a broad range of thermal treatment ranging from 80 °C up to 400 °C. Their findings indicate that the trap levels are widely distributed across the range of thermal treatment in an amorphous structure of Ge-doped optical fibres, with the maximum glow peaks located at temperatures 270 °C to 280 ℃ and 240 °C to 250 ℃ for respective CF and FF.



(a) (b)

FIGURE 2. TL glow curve for (a) CF and (b) FF subjected to 6 MV photon beam with 2 Gy dose

In order to optimize the TTP, the first attempt was made by exploiting the preheat temperature into three different levels: 40 °C, 80 °C, and 120 °C. Preheat temperature was applied to exclude the TL signal generated from the low-temperature regions, represented by low energy electron traps. TL signal produced at the lower temperature region has a higher fading rate than that of high-temperature region. Thus, removing of such low-temperature TL signals using an optimum preheat temperature could result in less variations in the integrated TL signals. A low fading rate is essential for a dosimeter, especially for low dose detection. The remaining TTP parameters were kept unchanged. Figure 3(a) and 3(b) demonstrates the glow curve formation for CF and FF respectively subjected to 2 Gy under 6 MV photon irradiation.

An increase in preheat temperatures has caused the glow curve to shift to the low-temperature region, suggesting that higher preheat temperatures have segregated the low energy traps. Meanwhile, it indicates that decreasing the preheat temperatures has shifted the glow curves to the high-temperature region as the low energy electron traps were incorporated in the formation of the glow curves. In the case of a low preheat temperature of 40 °C, a number of low trapped electrons available for recombination with the holes to give off light at a lower temperature, leading to the glow curve formation closer to the high-temperature region. The TL

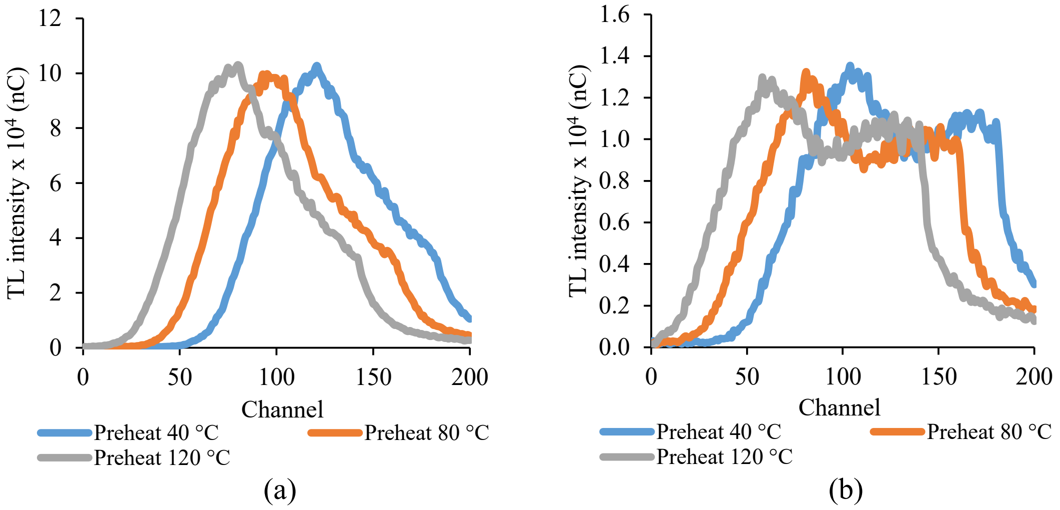


FIGURE 3. Glow curve formation of (a) CF and (b) FF with the use of different preheat temperatures

signals at the end of the high-temperature region of a glow curve were sheared off, indicating that some of the TL signals were not captured by the photomultiplier tube (PMT), considering the maximum possible channel is 200. Removal of the TL signal from the optical fibres results in a lower TL signal (Rais et al. 2019a). A comparison of these findings with another study on the phosphor-based TLD-100 by Yusof et al. (2013) denotes similar behavior where the TL signal of the irradiated TLD-100 will reduce gradually when the lower preheat temperature was applied.

Further detailed analysis was done on the maximum glow peaks temperature, where it refers to the specific temperature required to excite the highest number of trapped electrons, corresponding to the highest TL signal intensity of a glow curve. The maximum glow peak temperature is based on the principle that the higher the temperature at which the TL signal intensity reaches its highest value, the less likely TL fading occurs. Figure 4 displays the relationship between the preheat temperature and the maximum glow peak temperature. Across the investigated preheat temperatures, the maximum in the TL glow curve peak is found to be at approximately the same temperature for each optical fibre type, ~273 and ~239 °C for CF and FF, respectively. The coefficient of variation was found to be less than 3% for CF and FF. The patterns are in agreement with the previous studies (Fadzil et al. 2019; Lam et al. 2017), reflecting the CF and FF possess a unique traps level in the TL signal production.

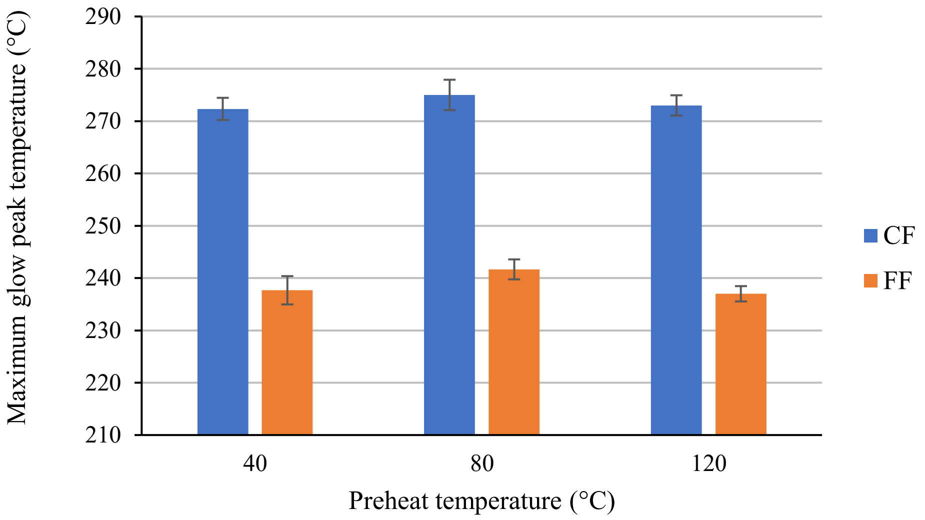


FIGURE 4. Maximum glow peaks temperature for CF and FF

Preheat time is the time duration required to achieve specified preheat temperature prior to the acquisition of a TL glow curve. Manipulation was done on the preheat time ranging from 5 to 15 seconds for several preheat temperatures. As presented in Figure 5, the unvarying glow curves of CF and FF including the glow curve shape and the number of glow peaks reveal that the effect of preheat time is insignificant in present study. According to Horowitz and Yossian (1995), the specific quantity of energy delivered (also known as activation energy) dominates other parameters in the excitation of trapped electrons in TL materials.

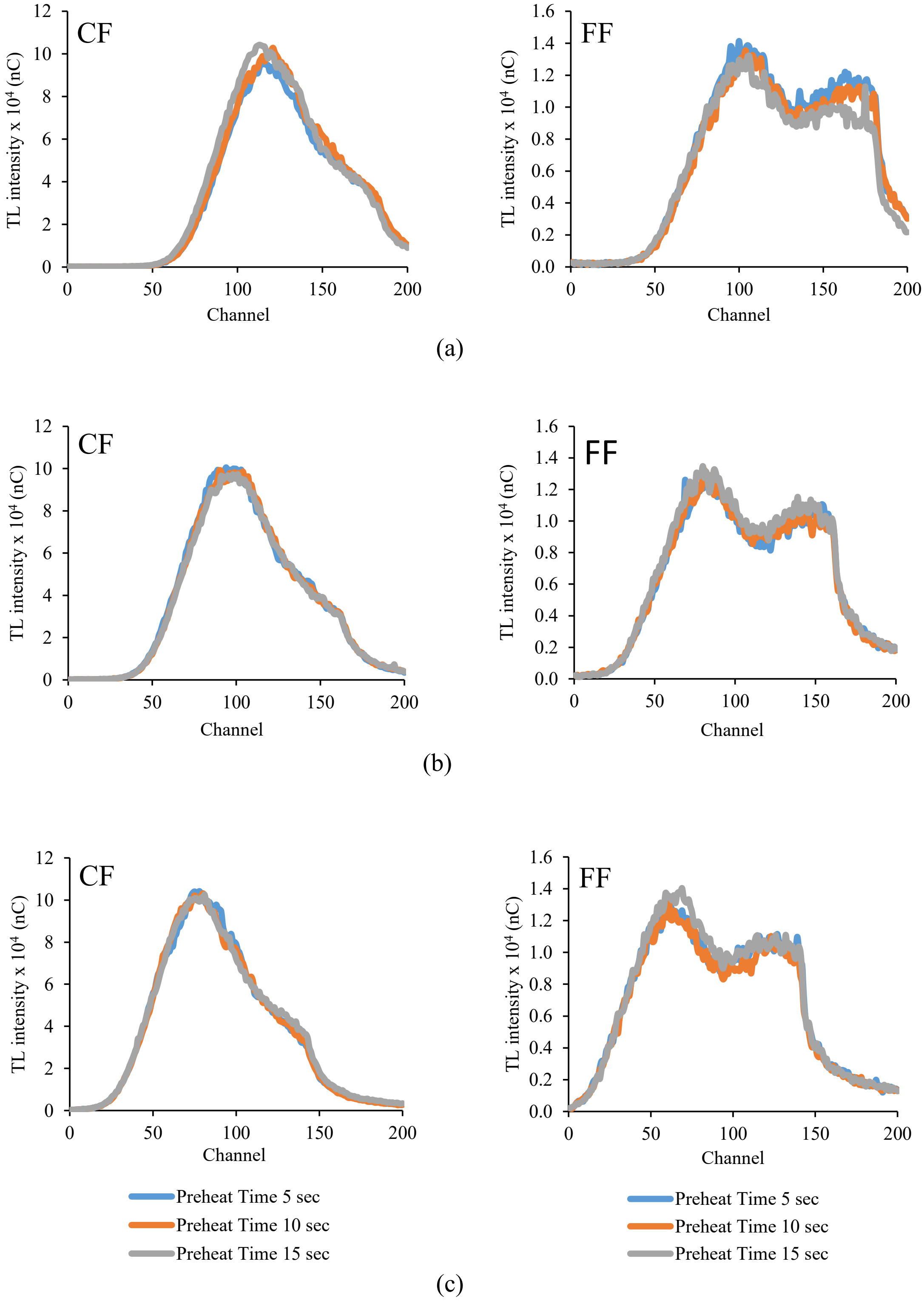
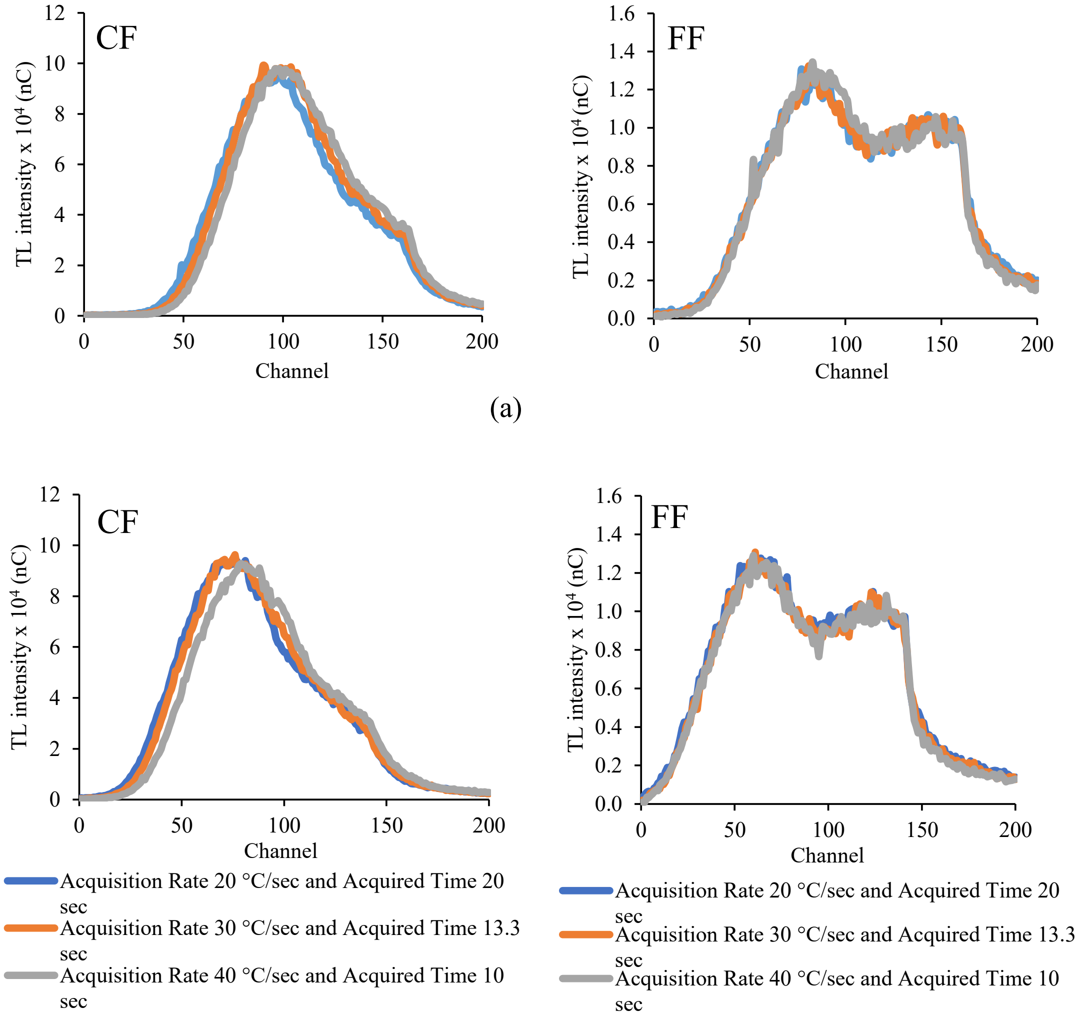


FIGURE 5. The formation of CF and FF glow curves using different preheat time at preheat temperatures of (a) 40 °C, (b) 80 °C, and (c) 120 °C were applied

Besides, the acquisition rates and the acquired times were varied between 20 °C/s and 40 °C/s and 10 to 20 s, respectively. The acquisition rate for a TL glow curve is the time taken to reach the maximum temperature of 400 °C as defined herein. As the acquisition rate increases, the time required for the temperature to achieve 400 °C decreases, allowing fast sample readout within a specific time duration. Figure 6 demonstrates the effect on the glow curve formation for CF and FF subjected to changes in the acquisition rate and acquired time. There is a little shift in the glow curves of CF while the glow curves of FF overlap with each other. The alteration in the acquisition rate and the acquired time during the readout process of FF gives a negligible effect on the shape and magnitude of the glow curves. The maximum glow peaks appear at the transition between low to the high-temperature region (channel 100) for CF and at the low-temperature region (channel 90) for FF as shown in Figure 6. These findings of FF are consistent with the studies of Benabdesselam et al. (2013) and Lam et al. (2017) showing that the use of different acquisition rates results in constant TL signal and glow curve. The difference in outcome between the CF and FF is most likely caused by different trap levels in different shapes of the optical fibres. Note that the collapsing technique has been used to fabricate the FF and thus resulting in the strain-related defects or traps (Lam et al. 2019).



(a)

(b)

FIGURE 6. The formation of CF and FF glow curves subjected to different acquisition rates and acquired times for the applied preheat temperatures of (a) 80 °C and (b) 120 °C

Present TTP study indicates that preheat temperature can significantly change the glow curve formation for CF and FF. However, the use of different preheat times would not affect the glow curves. A minimal change was recorded on the physical appearance of the glow curves of CF using different acquisition rates and acquired times employed, with no variation found in the magnitude of the maximum glow peaks and consistent maximum glow peak temperature. The near ideal glow curves are positioned at around the centre of the total readout channels (i.e. channel 100), not only to eliminate low-temperature traps but also to include the TL signal at the end of the acquisition phase. Besides, the findings of this investigation are in agreement with that of earlier study by Begum et al. (2015), showing that 80 °C is an optimum preheat temperature for the readout of CF. As for the findings related to FF, the first glow peak is prominent in the appearance of the double-peak glow curves due to the high number of low energy traps. This phenomenon is likely to be caused by the additional defects generated by collapsing procedure of the inner wall of the FF during the fabrication process (Fadzil et al. 2018). Therefore, in order to remove low energy traps that contributed to the higher fading rate of FF, a higher preheat temperature of 120 °C is required.

These results provide important insights into the ideal TTP for CF and FF. The ideal TTP for TL signal extraction from CF and FF is presented in Table 2. This TTP is considered an ideal TTP because the maximum glow peak temperature of CF and the two prominent peaks of the FF glow curve appear in the middle of the acquisition channel. This fundamental can be understood as the elimination of low energy electron traps provides more stability and a lower fading rate of TL signal. In addition, an ideal TTP is important to prevent a sudden TL signal abruption at the end of the acquisition phase. The optimized TTP will set the right circumstance for subsequent advanced glow curve kinetic parameter analysis.

TABLE 2. Ideal TTP for TL signal extraction from Ge-doped optical fibres

Time temperature profile	CF	FF
Preheat temperature (°C)	80	120
Preheat time (s)	10	10
Acquisition rate (°C/s)	30	30
Acquired time (s)	13.3	13.3
Maximum temperature (°C)	400	400
Annealing temperature (°C)	400	400
Annealing time (s)	10	10

CONCLUSION

The TTP optimization for CF and FF was done based on the manipulation of the preheat temperatures and time, as well as the acquisition rates and the acquired times. The formation of the glow curve is affected directly by the changes in the preheat temperature. CF requires a lower preheat temperature than that of the FF to segregate the emitted light from those of low energy traps. Besides the time-temperature profiles, it is evident that the optical fibre shapes and dimensions formed during the fabrication processes affect the features of the TL glow curves, portraying a complex relationship between the thermal treatment received by the optical fibres and the TL signal production.

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