International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 3 Issue 7 ǁ July. 2015 ǁ PP.93-96

Thermoluminescence response through the fabrication of novel microstructured fibers

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ABSTRACT: We present a novel technique aimed at improving upon the thermoluminescence (TL) response of optical fibers. The technique, based on the stack-and-draw method, is more conventionally used for micro-structured optical fiber (MOF) fabrication. Utilizing the approach, the TL response of a single micro-structured fiber can be shown to substantially improve upon that of a single capillary fiber, approaching a 30 fold increase in sensitivity. Present results provide strong support for the idea that by collapsing and fusing the surface walls of stacked fibers, strain-related defects are created, increasing the TL yield many times over. The substantial increase in sensitivity of these glass-based systems point to more extensive applications, the production of such detectors allowing versatile use, down to much lower doses than currently available using single capillary fibers.

Keywords: Microstructured optical fiber
Fiber fabrication
Fiber optics sensor
Thermoluminescence
Dosimeter
Ionizing radiation

I. INTRODUCTION

By definition, ionizing radiation provides for removal of elec-trons from bound atomic sites. The associated release of charge has been widely adapted in dosimetric applications, including in regard to environmental radioactivity, radiology, radiotherapy, food sterilization and radiation processing (U. N. S. C. E. A. Radia-tion, 2000). In such applications, precise and accurate measure-ment of dose is crucial, most importantly in that received by hu-man tissue.

In regard to passive dosimeters, typically dose integrating, commercially available phosphor-based thermoluminescence do-simeter (TLDs) are one of the most commonly used forms in medical applications, a prime example being the LiF-based TLD100. Beginning to compete with these in radiotherapy applications are optical fibers, offering potential advantages in terms of sensitivity, stability and reliability. Recent studies have highlighted the use of optical fibers, mostly in radiotherapy dosi-metry applications (Noor et al., 2014) and under a wide range of electron and photon beam irradiations (Alawiah et al., 2015; Wa-giran et al., 2012). In efforts towards improving the sensitivity of optical fibers for radiation dosimetry, a variety of dopants in silica and silica based optical fibers have been examined (Benabdesse-lam et al., 2013; Bradley et al., 2014; Noor et al., 2011; Yaakob et al., 2011), also investigating reproducibility, reusability and the TL fading characteristics. Other than single mode optical fibers, un-doped and germanium–boron-doped tailor-made optical fibers have also been investigated, offering comparable sensitivity to TLD-100 chips in measuring doses at diagnostic levels (Bradley et al., 2014).

Unlike doped silica optical fibers, a pure silica fiber usually has very poor sensitivity in radiation dose detection mainly due to the lower number of available defects. The concentration of the defect centers in an optical fiber strongly depends on the impurity level of fibers, material doped in fibers, and also drawing conditions (Hanafusa et al., 1987).

In this work, a novel method is presented that offers gain in the TL response of silica optical fibers. The proposed method is based on collapsing capillary optical fiber surfaces, which causes addi-tional defects in the fusing area, thereby enhancing TL response. In this study, the method is based on the use of undoped optical fibers. Comparison is made of the TL response of a single capillary with that of a group of capillaries stacked in an outer glass tube, forming what is referred to in the photonics industry as a Photonic Crystal Fiber (PCF). Subsequently, through the combined applica-tion of an external vacuum, heat treatment, and fiber drawing, the array of holes presented within the PCF are gradually collapsed towards completely fused surfaces. By such process, subsequent differential cooling of the resultant fused surfaces can be expected to yield strain relaxed defects and with this enhanced TL genera-tion, the greatest value of which is anticipated in the fully-col-lapsed PCF.

II. MATERIALS AND METHODS

2.1. Fiber fabrication

Three types of optical fibers have been fabricated in this study: capillary optical fiber, glass rod and PCF (Fig. 1(a), (b) and (c), re-spectively). Another three versions of photonic crystal fiber have also been fabricated by drawing down the air holes in PCF as shown in Fig. 1(d–f). The glass rod and capillary fiber were drawn respectively from a large glass rod and glass tube, obtaining the desired optical fiber size at a temperature of around 2000 °C, controlling the preform feed rate and drawing speed, also con-sidering the simplified mass conservation law:

$$A_1 v_f = A_2 v_d \qquad (1)$$

2.2. Sample preparation and irradiation

Prior to irradiation, the fiber samples were cleaned using a cotton cloth containing methyl alcohol, seeking to remove all impurities on the fiber. The fibers were then manually cut into lengths of 571 mm using a diamond cone point cutter. After-wards, the samples were annealed at 400 °C using a Thermo Electron furnace for 1 h. Annealing is carried out to standardize the thermal history within the fibers, removing any residual TL signal (Hashim et al., 2009). After cooling at a very slow rate, usually overnight, to avoid additional strain related defects (cooling to room temperature), 10–15 pieces of each sample were placed in small plastic bags to provide for a mean value at the chosen dose, dealing with potential inhomogeneity issues during irradiation and also for easy handling purposes.

The fiber samples were exposed to a 20 MeV beam using a Varian Model 2100C linear accelerator, irradiating to a dose of 8 Gy. The samples in their plastic bag were placed at the surface of

a Solid-Water™ phantom. A field size of 20 cm 20 cm, a source to sample distance (SSD) of 100 cm and an applicator size of 20 cm 20 cm were used for the irradiation.

2.3. TL measurement and normalization

After irradiating the fiber samples, the TL yield of the fibers were read out using a Harshaw 3500 TLD reader. The time-tem-perature profile (TTP) of the TL reader was set to a preheat tem-perature of 50 °C, the signal was acquired at a temperature ramp rate of 25 °C/s and the acquisition time was 20 s. The mass of the fiber samples were measured by electronic balance and then the TL responses were normalized to the mass of the sample. In this study, the mass of 10–15 fiber samples per species were measured and the average mass was used for normalization.

III. RESULTS AND DISCUSSION

where A_1 and A_2 are the cross-sectional areas of preform and fiber while v_f and v_d are the feeding and drawing speed, respectively.

The PCF was fabricated by stacking 1.26 mm diameter capillary canes into a glass tube with outer and inner diameter of 25 mm and 16 mm, respectively. The PCF was then fabricated in two stages. First, the preform was drawn down to a diameter of about 2 mm PCF cane and then subsequently the cane was re-pulled into a standard fiber size of 12575 mm.

Yet later still, from the same PCF cane, three different versions of PCF were drawn down by applying a vacuum pressure of 5, 10 and 75 kPa during fabrication. The applied vacuum pressure dur-ing the fabrication process causes gradual collapse of the PCF holes. With 5 kPa applied vacuum, the PCF's hole was only partially closed. Further collapse was observed at a vacuum of 10 kPa and finally, the holes were observed to be fully collapsed at 75 kPa, as shown in Fig. 1(d–f).

Fig. 2 compares the TL response of optical fibers at 8 Gy dose under 20 MeV electron beam irradiation. The capillary optical fi-bers show relatively low TL response, at around 0.04 mC/mg. By way of comparison, the glass rod fiber shows a response some 4 times greater than that of the hollow tube form (i.e. the capillary fiber). By stacking capillaries and forming a PCF, the TL response is then observed to improve by some 17.5

times. The results suggest the predominant improvement in TL yield to result from the ad-ditional surface areas of the stacked capillaries, further supported by data obtained in moving towards fully collapsed air-holes in the PCF, as below.

The air-holes in PCF are collapsed in three different stages by applying vacuum pressure of 5, 10 and 75 kPa during the fabrica-tion process. Results show that the TL response of PCF to be im-proved by 15% and 35%, collapsing down the PCF holes in applying 5 and 10 kPa vacuum pressure, respectively. Finally, an improve-ment in TL yield of 47% is obtained by fully collapsing all holes, applying 75 kPa vacuum pressure.

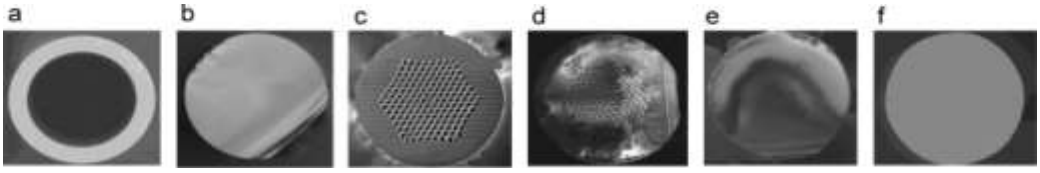

Fig. 1. Cross sectional image of (a) capillary optical fiber; (b) glass rod; (c) PCF; (d) PCF with 5 kPa applied vacuum; (e) PCF with 10 kPa applied vacuum, and (f) fully-collapsed PCF, with 75 kPa applied vacuum pressure.

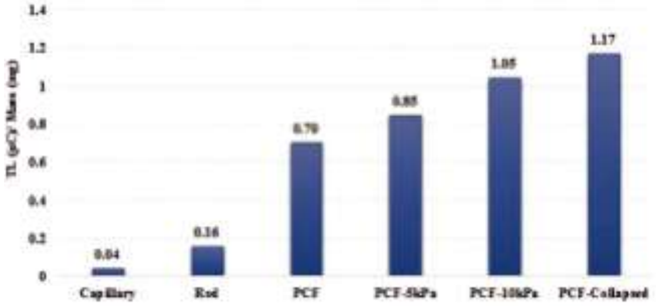

Fig. 2. TL response of capillary, rod, PCF, PCF-5 kPa, PCF10 kPa and PCF-collapsed irradiated under 20 MeV and dose of 8 Gy.

The images in Fig. 1(b) and (f) show two solid rod fibers, the only difference being that the fiber in Fig. 1(b) was originally in rod form while the fiber in Fig. 1(f) was formed into a rod by collapsing the air-holes in the PCF. The TL response of the fiber in Fig. 1(f) is found to be some 7.4 times greater than that of the fiber in Fig. 1
(b). This comparison shows the impact of collapsing to complete surface fusion of the optical fiber, generating additional defects and thereby, greater TL response.

The above results provide a preliminary assessment of the TL yield improvement to be obtained in fiber fabrication manipula-tion. Further investigation is required to find the actual relation-ship between the collapsing area/circumference with fiber TL response.

IV. CONCLUSION

This work has identified a novel method for enhancing the TL response of optical fibers by stack-and-drawing multiple capil-laries into a glass tube. The TL response is improved by collapsing down the air-holes throughout the PCF by vacuuming the fiber during fabrication. The collapsed-hole PCF has about 29 times greater TL response compared to a single capillary. Results suggest the high potential of the proposed method for designing very high sensitive radiation dosimeter by doping suitable rare earth mate-rials into optical fibers.

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