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Rajan, Ginu and Peng, Gang-Ding, "Fabrication and characterization of a polymer micro-fiber bragg grating" (2013). *Faculty of Engineering and Information Sciences - Papers: Part A*. 4346.
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Abstract

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Keywords

bragg, fiber, micro, polymer, grating, characterization, fabrication

Disciplines

Engineering | Science and Technology Studies

Publication Details

G. Rajan & G. Peng, "Fabrication and characterization of a polymer micro-fiber bragg grating," in Proceedings of SPIE - The International Society for Optical Engineering, 2013, pp. 892432-1-892432-4.

Fabrication and Characterization of a Polymer Micro-Fiber Bragg Grating

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ABSTRACT

Polymer micro-fibers with inscribed Bragg gratings are reported in this paper. By implementing a two-stage fabrication process a 16 μm diameter micro-fiber is fabricated with an inscribed 10 mm long Bragg grating which exhibits a peak reflected wavelength circa 1530 nm. The growth dynamics of the polymer micro-fiber Bragg grating are also observed and analyzed. A maximum reflectivity of 5% is obtained after an exposure time of 3 minutes to a 50 mW power He-Cd laser of 325 nm wavelength. The temperature characterization of the micro-fiber Bragg grating with different diameters is also presented. The fabricated micro-fiber Bragg grating can be used as sensors for high sensitivity measurements in a number of application areas.

Keywords: Polymer micro-fiber, Fiber Bragg grating

1. INTRODUCTION

Since their first demonstration in 1999, polymer fiber Bragg gratings [1, 2] have attracted significant interest among engineers and scientists [3] due to their unique advantages compared to their silica counterparts, such as their inherent fracture resistance, high flexibility, large strain measurement range, high temperature sensitivity and biocompatibility. In recent years, advances in the fabrication of single mode polymer optical fiber (POF) have also enhanced the research and development of Bragg grating sensors in POF [4]. Sensors based on polymer micro-fibers and nano-fibers can further exploit the advantages of the characteristic properties of polymer fiber and can provide ultra-high sensitivity measurements compared to existing polymer fiber Bragg gratings.

Previously it has been shown [5] that for silica, Bragg grating sensors written in micro-fibers can considerably improve the measurement sensitivity compared to fiber Bragg gratings written in a conventional single mode fiber. As a result, silica micro/nano-fibers and gratings have been researched and used for a variety of applications including bio sensing and related applications [6]. Polymer micro-fibers could benefit from the superior elastic and high refractive index properties of POF compared to silica fibers. Our recent research work on etched polymer fiber Bragg grating (PFBG) has showed that the force and pressure sensitivity of a Bragg grating sensor can be considerably improved by reducing the diameter of the fiber [7]. By fabricating polymer micro-fibers and inscribing Bragg gratings in them, one can further improve the sensitivity and measurement range of PFBGs. However to do so poses a challenge due to the very thin photosensitive core region left in the micro-fiber after tapering and also the handling issues arising from the very small size of the fiber. Though the photosensitive mechanism and growth behavior of single mode polymer fiber gratings is understood to some extent [8, 9], further detailed study and analysis are required to understand the growth dynamics of Bragg gratings in polymer micro-fibers and to optimize fabrication parameters and conditions, such as UV laser power, duration, uniformity and stability, for high quality PFBGs.

In this paper we report the first results of Bragg gratings inscribed in polymer micro-fibers. The fabrication of polymer micro-fiber is elaborated in section II, in which a two stage process is adopted to retain significant amount of core region inside the polymer micro fiber. The Bragg grating inscription process is explained in section III and the observed growth behavior of the grating is also presented in this section. Temperature characterization of micro-fiber grating with different diameter is presented in section IV and potential applications of the polymer micro-fiber Bragg gratings are discussed in section V. Conclusive remarks are presented in section VI.

2. FABRICATION OF POLYMER MICRO-FIBERS

The polymer fiber used to fabricate the micro-fiber was an in-house produced single mode photosensitive polymer fiber. The fabrication procedure of this poly(methyl methacrylate) (PMMA)-based POF is explained in [9, 10] in which fiber fabrication followed a multiple step process whereby a hollow polymer preform was filled with a core monomer mixture of methyl methacrylate (MMA), ethyl methacrylate (EMA) and benzyl methacrylate (BzMA) which was thermally polymerized. The difference in the refractive index between the core and cladding was 0.0086. The POF fiber sample used had an outer diameter of ~ 250 - $260 \mu\text{m}$ and a $12 \mu\text{m}$ core diameter and the fibers were nominally single mode at the wavelength of operation (1520 - 1570 nm).

To fabricate the polymer micro-fiber a two stage process was adopted, where the fiber was etched to a certain diameter in the first instance and then tapered down by drawing to a final diameter. This two stage process allowed more consistent control of the core-cladding ratio of the polymer fiber and as a result ensured that a sufficient amount of photosensitive core was retained within the fiber to allow inscription of a grating with a usable reflectivity. For this process initially the cladding of the single mode PMMA fiber was etched by the solvent etching method [7]. A lab grade acetone with 99.5% concentration diluted by mixing methanol by 50% volume was used as the etching solution.

To etch the polymer fiber, the middle section (approx. 3 cm) of a 10 cm long POF sample was immersed in the solution for a fixed period then removed and cleaned. The duration of the immersion determined the resulting cladding thickness. For the fiber used in this study the POF was etched to a diameter of $27 \mu\text{m}$ when the fiber was immersed in the solution for approximately 14 minutes.

The etched POF was then carefully placed between two heating plates of 2 cm length with a gap of 3 mm between them. The temperature of the heating element was set to $160 \text{ }^\circ\text{C}$, which is known to provide a temperature of 85 - $90 \text{ }^\circ\text{C}$ at the vicinity of the polymer fiber. The etched fiber was kept at this temperature for 5 min to ensure that the fiber was heated uniformly and was soft enough for effective tapering. The fiber was then smoothly pulled from both ends using a pair of stable and high precision translation stages to form the tapered polymer micro-fiber. The translational stages were driven by two motors which were controlled to achieve appropriate speed and tapering length. The schematic of the tapering setup is shown in Fig 1(a). Using this method the etched fiber with an initial diameter of $27 \mu\text{m}$ was tapered down to a diameter of $16 \mu\text{m}$. The micrographs of the polymer fiber at different stages are shown in Fig 1(b).

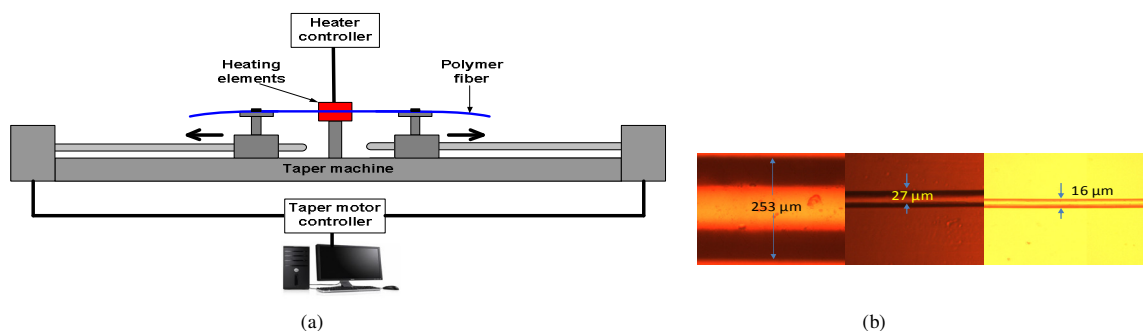


Fig. 1. (a) Experimental setup to fabricate polymer micro-fibers (b) Different stages of fabrication of the polymer micro-fiber

3. INSCRIPTION OF BRAGG GRATINGS IN POLYMER MICRO-FIBERS

The Bragg grating structures were fabricated in the polymer micro-fiber by a phase mask technique using a 50 mW continuous wave Kimmon IK series He-Cd Laser emitting light at 325 nm. The laser beam was irradiated onto the side of the micro-fiber through the phase mask placed parallel to the fiber. The phase mask was 10 mm long and had a pitch of 1030 nm which was designed for an irradiation wavelength of 320 nm and could produce 10 mm long gratings with a peak reflected wavelength of approximately 1530 nm in the POF used in this experiment. Two plano-convex cylindrical lenses were also used in the setup, one to expand the beam to cover approximately 10 mm of the fiber and the other to focus the expanded beam onto the polymer micro-fiber. To measure the reflection and transmission spectra of the grating, a single mode silica fiber pigtail was glued to the POF ends using a UV curable glue. The total length of the POF used was approximately 10 cm with a 2-3 cm section of micro-fiber in the middle of the POF in which the 10 mm long grating was inscribed.

The dynamic growth process of the grating in the polymer micro-fiber is also observed and measured using an optical spectrum analyzer. The Bragg peak started appearing just after the fiber was illuminated with the UV laser and grew

thereafter, reaching saturation and then decreasing. The measured peak reflected wavelength of the grating was 1530.04 nm. The observed growth of the grating reflection peaks in the micro-fiber is shown in Fig 2(a) and the change in peak power of the reflection spectrum with time is shown in Fig 2(b). The maximum reflection power is recorded for an exposure time of three minutes and with further UV exposure the peak power is decreased. This grating growth behavior was similar to that of the original photosensitive polymer fibers, but the exposure time to obtain the maximum peak was lower than that of non-tapered PFBG, which is normally 7-10 min with the same experimental setup. This phenomenon is attributed to the relation between the thickness of the polymer fiber and the UV laser power, where the effective power in the core of the fiber is dependent on the penetration depth. The multiple peaks seen in the spectrum are due to the coupling mismatch effects between the polymer and silica fiber. The spectrum of the grating after readjusting the coupling after the grating inscription is shown in the subset of Fig 2(a).

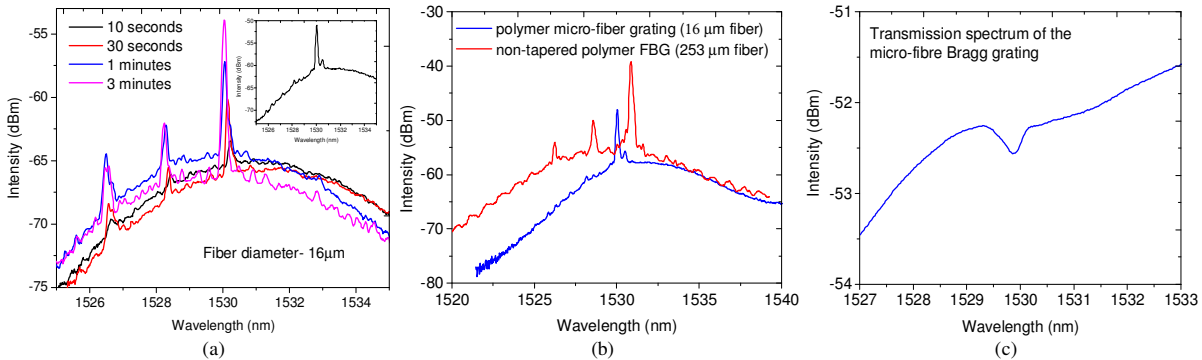


Fig. 2. (a) Observed growth in wavelength peak with UV exposure (b) Comparison of reflection spectra of the original PFBG and the polymer micro-fiber FBG (c) transmission spectrum of a 16 μm diameter (Resolution bandwidth of the OSA was 0.2 nm)

A comparison of the measured reflection spectrum of the micro-fiber grating and a Bragg grating written in the original photo sensitive polymer fiber is shown in Fig 2(b). A small blue shift is observed for the reflection peak of the polymer micro-fiber grating compared to that of the original PFBG. This could be due to the decrease in n_{eff} of the polymer fiber at smaller radii. In order to estimate the reflectivity of the polymer micro-fiber grating, the transmission spectrum of the grating is measured and shown in Fig 2(c). The reflectivity of the grating depends on such things as the UV laser power, laser power uniformity and fiber type. In this experiment it is estimated that the obtained grating reflectivity is approximately 5% for a 16 μm diameter polymer micro-fiber grating.

4. TEMPERATURE SENSITIVITY OF POLYMER MICRO-FIBER BRAGG GRATINGS

In the case of polymer optical fibers, due to the relatively large thermal expansion coefficient and also due to the negative thermo-optic effect and positive grating period effect, the temperature induced wavelength shift of a polymer fiber Bragg grating is far more complex than a silica fiber Bragg grating [11]. In this work the temperature sensitivity of the fabricated micro-fiber gratings were experimentally measured and compared with that of non-tapered gratings written in the same photosensitive polymer fiber. A polymer micro-fiber Bragg grating of 47 μm was also fabricated to have a comparison study. The measured temperature sensitivity of polymer micro-fiber gratings with diameters of 16 μm and 47

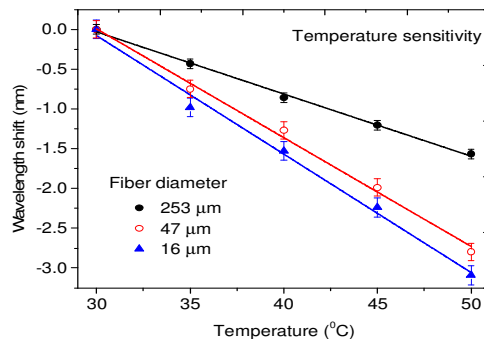


Fig. 3. Temperature sensitivity of gratings made from original polymer fiber and polymer micro fibers

μm and its comparison with the non-tapered grating is shown in Fig 3. The temperature induced wavelength shift appeared linear within the measurement range and the measured temperature sensitivity of micro-fiber gratings with 16 μm diameter was found to be 150.5 $\text{pm}/^\circ\text{C}$, while for the non-tapered grating the sensitivity was 68 $\text{pm}/^\circ\text{C}$. The measured sensitivity of the micro-fiber grating was more than two times larger than that of the non-tapered polymer grating, which could be mainly due to the reduced size of the fiber. It is also expected that the temperature response time of the polymer micro-fiber grating would be faster than that of standard polymer fiber Bragg gratings.

5. POTENTIAL APPLICATIONS OF POLYMER MICRO-FIBER BRAGG GRATINGS

The fabricated PFBGs can be used in a number of applications where high sensitivity measurements are required. Since the temperature sensitivity of the grating is very high compared to other polymer FBGs and silica FBGs, it can be used for high sensitivity temperature measurements up to a temperature range of 80 $^\circ\text{C}$ for medical or biomedical applications such as in medical textiles. Another important advantage of polymer fiber is its intrinsic sensitivity to humidity. PFBGs can significantly improve the response time of humidity sensors, given the temperature effect is properly compensated and can be used in applications such as respiratory monitoring. Another potential application of the sensor is in force and pressure measurements where polymer micro-fiber based sensors can increase the sensitivity many fold times compared to existing PFBGs and silica FBGs due to its very low Young's modulus and smaller size.

6. CONCLUSIONS

Polymer micro-fibers with Bragg gratings inscribed in them for sensing applications are demonstrated. A two stage polymer micro fiber fabrication process is introduced and was used to fabricate a 16 μm diameter micro-fiber in which we successfully inscribed a 10 mm long Bragg grating with peak reflected wavelength of circa 1530 nm. From the observed growth dynamics of the micro-fiber Bragg grating it is estimated that a maximum of 5% reflectivity is obtained after 3 minutes of exposure by a 50 mW and 325 nm wavelength emitting He-Cd Laser. The temperature sensitivity of the polymer micro-fiber Bragg grating is also very high compared to that of standard polymer FBGs. Potential applications of the micro-fiber Bragg gratings are also discussed and could be used as sensors for high sensitivity measurements in a number of application areas.

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