Bragg gratings inscription using PMMA polymer optical fibers drawn from preforms with specific thermal pre-treatment

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Abstract: In this work, fiber Bragg gratings (FBGs) are inscribed in various undoped poly(methyl methacrylate) (PMMA) polymer optical fibres (POFs) using different types of UV lasers and inscription time and their temperature and strain sensitivities are investigated. The polymer optical fiber Bragg gratings (POFBGs) were inscribed using two UV lasers: a continuous UV HeCd @325 nm laser and a pulsed UV KrF @248 nm laser. The PMMA POFs drawn from a preform without specific thermal pre-treatment need more inscription time than the fibers drawn from a preform that has been pre-annealed at 80ºC for 2 weeks. Using both UV lasers, for the latter fiber less than half the inscription time is needed compared with a commercial undoped PMMA POF and other homemade POFs, where the preforms have not had a well-defined thermal pre-treatment. The effect on a POF from a preform that has been annealed prior to drawing is different as previously shown in the literature, where these POFs are much less sensitive to thermal treatment. Also, a proper polymerization process plays a key role as will be discussed. These results indicate the impact of preform thermal pre-treatment as well as polymerization process before the PMMA POFs drawing, which can be an essential characteristic in view of developing POF sensors technology.

1. Introduction

POFs can be considered as a strong alternative to silica fibers in applications such as short distance transmissions, Terahertz waveguides and filters, and mainly in sensing applications [1-4], due to their flexibility, high failure strain, large cores and great elasticity. The mechanical properties provide enhanced sensitivity or longer operational range to intrinsic polymer fibre sensors when they are used for strain, stress, pressure, temperature and humidity monitoring, as well as for transverse force sensing [5-12]. Many POF sensors are based on fibre FBGs, which have been written in different spectral windows in doped and undoped step-index POFs [13], microstructured fibers (including PMMA and TOPAS materials) [13–15], as well as low loss cyclic transparent optical polymer (CYTOP)-perfluorinated POFs [16], and graded-index POFs [17]. Polymer optical fiber Bragg gratings (POFBGs) are inscribed with different laser systems including continuous-wave (CW) HeCd laser (@325 nm) [13-15], pulsed KrF laser (@248 nm) [18], and also femtosecond laser systems [16].
Fabrication of Bragg gratings in mPOF and step-index fibers, with the phase mask technique is a time consuming process. Using a 325 nm UV laser, in undoped mPOFs exposure times from 60 to 270 minutes have been reported [19,20], for up to 10 mm long gratings, with the lowest inscription time reported being approximately 7 minutes [21]. For the step-index fibers times are shorter and typically amount to 45 to 100 minutes [19,22] with the lowest inscription time reported being approximately 20 minutes [13]. The writing time can be reduced by doping the fiber [14] but doped fibers are more difficult and expensive to fabricate, the transmission loss increases and they are less suitable for in-vivo biosensing. Recently, as a way to help manage without the fiber doping, a 248 nm UV laser was used to inscribe Bragg gratings in undoped mPOF, at low fluence and low repetition rate (I = 33 mJ/cm^2; R = 1 Hz) in a record time of around 30 s [18], showing that Bragg grating systems designed for silica fibers can be used to inscribe POFBGs, potentially increasing their take-up in more research laboratories.

In order to understand the fabrication process needed to achieve undoped POFs with good performance as well as reduced FBG inscription time, we compare different undoped PMMA POFs using two different UV lasers: a continuous UV HeCd @325 nm laser and a pulsed UV KrF @248 nm laser.

In this paper, we provide evidence that preform thermal pre-treatment as well as control of the polymerization process can be responsible for a better photosensitivity mechanism of undoped PMMA POF based sensors irradiated with UV light. In the experiments we observed that there is an increase of material photosensitivity in samples subjected to a well-defined preform thermal pre-treatment before the PMMA POFs drawing.

2. mPOFs under investigation and FBG inscription systems

Three different undoped PMMA mPOFs, labeled Fiber 1 to Fiber 3, were drawn in different facilities with different drawing conditions, where Fiber 1 is an mPOF from *Kiriama Pty Ltd* [23,24], Fiber 2 [25] and Fiber 3 (fabricated in *Maria Curie-Sklodowska University*, *Poland*) are homemade mPOFs. The core and cladding dimensions of the fibers are respectively 9/130 µm (Fiber 1), 8/135 µm (Fiber 2) and 9/270 µm (Fiber 3). The core of the fibers is composed of poly-methyl methacrylate (PMMA) with no additional dopants, whilst the cladding is also made of PMMA. All fibers have a three-ring hexagonal cladding structure. For Fiber 1, the air-hole diameter is on average 2.76 µm and the inter-hole pitch is on average 6 µm. For Fiber 2, the average pitch and hole diameter are 4.3 and 1.9 µm, and for Fiber 3 the air-hole diameter is on average 2 µm and the inter-hole pitch is on average 4.6 µm. The draw ratios for fibers 1, 2 and 3 are 20/0.130, 20/0.135 and 11/0.270, respectively. Fiber 1 has been drawn at 30 m/min with a set-temperature of 290 °C and a tension of about 24 g (0.25 N). Fiber 2 was drawn at a rate of 40 m/min with a temperature of 290°C and a tension of 0.2 N. The preform of Fiber 3 was pre-annealed for 2 weeks at 80°C before the fiber was drawn at 290°C with a draw tension between 0.5 N and 1 N and a rate of 30 m/min. For Fiber 1 and 2 the preforms were not annealed. So, the polymerization process for each fiber is different. The parameters of the fibers used are summarized in Table 1.

Table 1. Fiber parameters.

Fiber name	Core/cladding size (µm)	Cladding structure	Hole diameter/ pitch (µm)	Draw ratio (mm)	Pulling speed (m/min)	Drawing Temperature (°C)/Tension (N)	Preform with well-defined annealing?
Fiber 1	9/130	All with	2.76/6	20/0.130	30	290/0.25	No
Fiber 2	8/135	three-ring	1.9/4.3	20/0.135	40	290/0.20	No
Fiber 3	9/270	hexagonal	2/4.6	11/0.270	30	290/0.5-1.0	Yes

Two different inscription systems were used to inscribe FBGs in order to compare their performance in each fiber. The first system is based on a 325 nm UV light from a CW HeCd laser with a power output of 30 mW and a beam diameter of 1.2 mm [8]. The HeCd laser beam was focused vertically downward using a 10 cm focal length cylindrical lens, through the phase mask designed for 325 nm operation, and onto the fiber. 10 cm long POF sections were laid in a v-groove and taped down using polyimide tape to prevent them moving during inscription. With this system, the inscription process was monitored using a broadband light source (provided by Thorlabs ASE-FL7002-C4), and an optical spectrum analyzer connected to an optical coupler. The second system is based on a pulsed KrF Bragg Star^{TM} Industrial-LN excimer laser operating at 248 nm [18]. The laser has a beam spot of 6 mm in width and 1.5 mm in height, with pulse duration of 15 ns. A cylindrical lens, followed by a slit with 4.5 mm width, shapes the beam before it arrives to the phase mask, designed for 248 nm operation. 18 cm long POF sections were placed within two magnetic clamps and kept in strain to avoid undesired curvatures. Here, an interrogation system (provided by Micron Optics sm125) was used to monitor the grating growth.

In all cases, POF sections were cleaved with a hot blade on a hot plate and then a butt-coupled connection was made between one arm of a single-mode silica coupler and the POF using an FC/APC connector on the silica fiber. A small amount of index matching gel was used in order to reduce Fresnel reflections, lowering the background noise. In order to compare the FBG reflected amplitude, all the FBGs used in this work were inscribed at the same distance from the FBG monitoring input. The butt-connection loss was minimized by optimizing the alignment between the two fiber types using a 3D micrometric translation stage. This was controlled from a power measurement in transmission as well as from the noise level in the measured reflected spectrum.

3. Results and discussion

Several FBGs in each fiber type were produced using both FBG inscription systems. Fig. 1 shows the reflected spectra for the three POFs using the 325 nm UV HeCd laser. The inscription times (the time that grating growth stops) for fiber 1, 2 and 3 are on average 90 min, 87 min, and 37 min, respectively. We can notice that for the latter fiber less than half the inscription time is needed compared with Fiber 1 and 2. Although core diameter and three-ring hexagonal cladding structure are very similar for all fibers, the particular grade of PMMA used for each facility must be different (e.g., in terms of molecular weight) and the drawing conditions most probably were different for the three fibers. Besides, we shall recall that the preform of Fiber 3 has been annealed for 2 weeks at 80°C, giving a well-defined thermal pre-treatment when compared with others. The effect of annealing on a POF of which the preform has been annealed prior to drawing is different as reported and discussed recently in [26], where this fiber type is much less sensitive to thermal treatment.

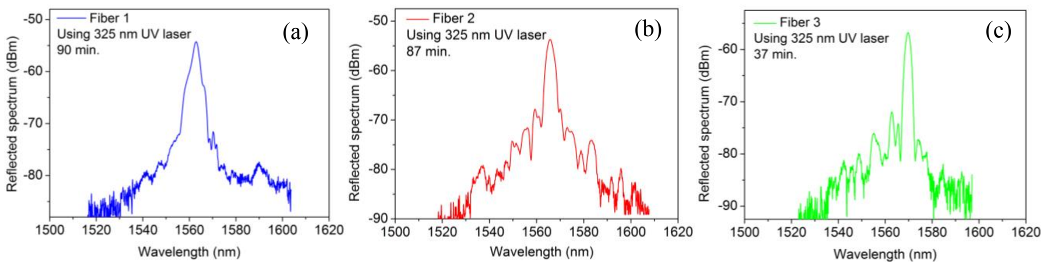

Figure 1. Reflected spectra for POFBGs in (a) Fiber 1, (b) Fiber 2, and (c) Fiber 3 using the CW 325 nm UV HeCd laser.

To substantiate our findings, we repeated the same measurements on the three fiber samples but now using the 248 nm UV KrF laser. The laser parameters were set to a frequency of 1 Hz and a pulse energy of 3 mJ. Fig. 2 shows the reflected spectra and for this case the inscription times for Fiber 1, 2 and 3 are on average 45 s, 40 s and 7 s, respectively. For Fiber 3, the optimum irradiation time was estimated to be 7 seconds meaning that only 7 pulses where needed to produce a saturated refractive index change. In Fiber 3, for which the preform has been annealed prior to drawing, the inscription time is also lower than the inscription time needed for other fibers (indeed we need 5 times less of the total inscription time using Fiber 3), as was the case with inscription using the 325 nm UV HeCd laser.

As is well known, angular orientation of the fiber microstructure has a significant impact on the intensity distribution of the UV beam in the core region, which directly affects the growth dynamics [24]. However, in our case, the success rate of the photo-inscription is quite high – more than 90%.

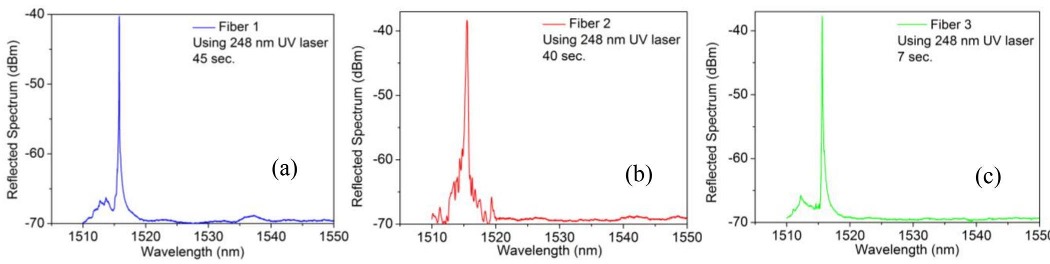

Figure 2. Reflected spectra for POFBGs in (a) Fiber 1, (b) Fiber 2, and (c) Fiber 3 using the pulsed 248 nm UV KrF laser.

The performance in terms of strain and temperature sensitivities was analyzed. A strain characterization was performed in order to show the spectral dependence of the Bragg reflection peak with strain for each fiber using

FBGs inscribed by both laser systems. The results are shown in Fig. 3 and as it can be seen the Bragg wavelength shift was linearly red shifted with 1% deformation. The obtained strain sensitivities for FBGs inscribed were 1.49 pm/με (Fiber 1), 1.33 pm/με (Fiber 2) and 1.24 pm/με (Fiber 3) after using a linear regression model, where the results are similar to the typical values already reported in literature for POFBGs (~1.3 pm/με in the 1550 nm window) using both UV laser systems [17,18]. Additionally, experiments were carried out to explore the temperature response of each fiber containing FBGs. The fibers were placed in an environmental chamber under varying temperatures to study their response. The temperature was increased from 22°C up to 47°C with steps of 5°C. In each step, the temperature was kept constant over 35 min to ensure thermal equilibrium was achieved. There was no control of the humidity level in the chamber. The temperature sensitivities obtained were similar to the values already reported for POFBGs inscribed in Fibers 1 and 2 with 325 nm laser system [17,27], -159 pm/°C and -64 pm/°C, respectively. For Fiber 3, we achieved a temperature sensitivity of -53 pm/°C, which is less than achieved for Fiber 1 and 2, as discussed in [26], suggesting that these POFs are much less sensitive to thermal treatment due to the impact of preform thermal pre-treatment before the PMMA POFs drawing.

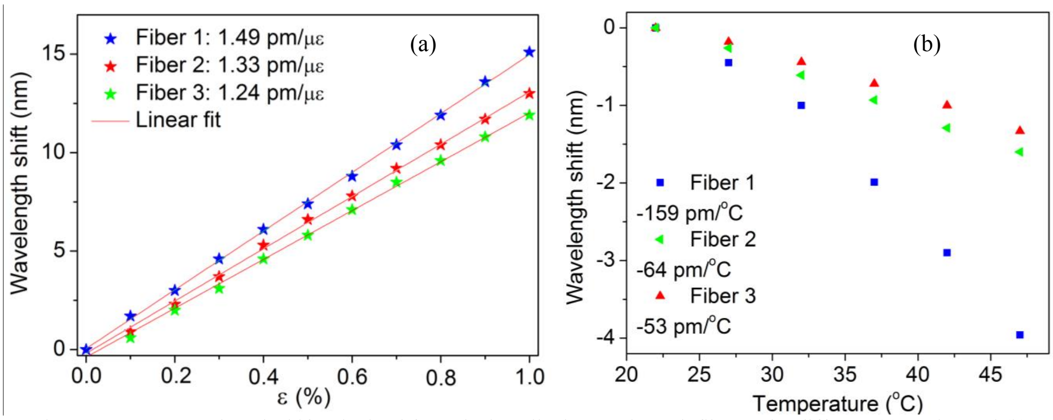

Figure 3. Bragg wavelength shifts obtained from the inscribed FBGs in each fiber under different (a) strains and (b) temperatures.

As well reported in [17], although the temperature sensitivity is lower for annealed fibers than observed in non-annealed fiber, the stability of POFBGs based on annealed fibers is improved, making possible the pre-annealing of fiber prior to FBG inscription in order to extend the quasi-linear operating temperature range. At the same view, the results presented here indicate the impact of preform thermal pre-treatment before the PMMA POFs drawing on the fast inscription of POFBGs, which is an essential characteristic in view of developing stable POFBG based thermo-mechanical sensors. Also, the difference in sensitivity of gratings as well as inscription time in these fibers could be explained by the different polymerization processes, where the thermal pre-treatment of preforms plays a key role to achieve good-quality gratings in less time. The different drawing parameters including drawing tension from which we calculate the draw stress, and the atmosphere surrounding the preform, can also give us a plausible explanation. A more extensive study is required in order to confirm the mechanism(s) behind the observations, and some fibers fabricated in different drawing tensions will be considered in future work.

4. Conclusions

In this work, improvements in the photosensitivity of undoped POFs where there was a well-defined pre-annealing of the preform was reported. We have noticed that with non-annealed preforms, the fiber photosensitivity is lower. The fibers from preforms with specific thermal pre-treatment allow us to achieve less FBG inscription times than fibers with no well-defined annealing, obtaining at the same time FBG sensors with high quality. There are other variables we can further consider in future such as the atmosphere in which the preform is placed during annealing (water content, etc...) and different drawing tensions.

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