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Abstract: In this work, improvements in the photosensitivity of undoped POFs, where there was a well-defined pre-annealing of both preforms in two-step process, were reported. We have noticed that when the primary and secondary preforms are annealed, the fiber photosensitivity is higher; otherwise, if any preform (primary or secondary) is not annealed, the fiber photosensitivity is lower. Two PMMA mPOFs are used where the primary and secondary preforms, during the two-step drawing process, have a different thermal treatment. The PMMA POFs drawn where the primary or secondary preform is not specifically pre-treat need longer inscription time than the fibres drawn where both preforms have been pre-annealed at 80ºC for 2 weeks. Using two different UV lasers, for the latter fibre much less inscription time is needed compared to another homemade POF. The properties of a POF fabricated where there are both preform process with thermal treatment is different from those where just one preform step process is thermal treated, as previously shown in the literature, where these POFs are much less sensitive to thermal treatment. Some important parameters were considered such as drawing tension and water content, where using fibers drawn in different tensions give us a similar FBG inscription time.

1. Introduction

In the last few years, many efforts have been made to increase the quality and diversity of POF sensors for many applications using different methods and techniques [1-18]. Fabrication of Bragg gratings in mPOF and step-index fibres, 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], the lowest inscription time reported being approximately 7 minutes [21]. For the step-index fibres the inscription times are shorter and typically around to 45 to 100 minutes [19,22] with the lowest inscription time reported being approximately 20 minutes [13]. The writing times can be reduced by doping the fibre [14], however doped fibres are more difficult and expensive to fabricate, the transmission loss increases and they are less suitable for in-vivo biosensing. In 2015, as a way to help manage without the fibre 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 short time of around 30 s [18], showing that Bragg grating systems designed for silica fibres can be used to inscribe POFBGs, potentially increasing their take-up in more R&D laboratories. Also, very recently, chirped POFBGs were photo-inscribed after 14 pulses in an undoped POF [23].

In order to understand the fabrication process needed to achieve undoped POFs with good performance as well as to reduce the 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 a specific preform thermal pre-treatment can be responsible for a better photosensitivity mechanism of undoped PMMA POF based sensors irradiated with UV light. In the

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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

Two different undoped PMMA mPOFs, labeled Fibre 1 to Fibre 2, were drawn in different facilities, where Fibre 1 is an mPOF referenced in [24] and Fibre 2 was fabricated in *Maria Curie-Sklodowska University, Poland,* being also an mPOF. The fibre core and cladding diameters of the fibres are, respectively, 8/135 µm (Fibre 1) and 9/270 µm (Fibre 2). The core of the fibres is composed of poly-methyl methacrylate (PMMA) with no additional dopants, whilst the cladding is also made of PMMA. Both fibres have a three-ring hexagonal cladding structure. Both fibres were fabricated from commercial PMMA material. However, we are under the assumption that the amount of unpolymerized monomers and the storage conditions, as well as the preform drilling are the same between the manufacturers. Typically, the drawing process can be done in two-step process where first we draw a cane, then sleeve it, and finally we draw the secondary preform. Both fibres were drawn in this way. However, the preform of Fibre 2 was pre-annealed during both preform two-step process – primary and secondary preforms – for 2 weeks at 80°C in each step before the fibre to be drawn. For Fibre 1, the preform was not annealed at the same way, where only the secondary preform was annealed – at 80ºC during a week. Important parameters of the fibres used (hole diameter/pitch, draw ratio, pulling speed, drawing temperature and tension) are summarized in Table 1.

Table 1. Fibre parameters.

	Hole diameter/ pitch (µm)	**Draw ratio (mm)**	**Pulling speed (m/min)**	**Drawing Temperature (°C)/Tension (N)**	**Both preforms annealed?**
Fibre name					
Fibre 1	1.9/4.3	20/0.135	40	290/0.20	No
Fibre 2	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 fibre. The first system is based on a 325 nm UV light from a CW HeCd laser (KIMMON laser systems) 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 fibre. POF sections 10 cm long were laid in a v-groove and taped down using polyimide tape to prevent them from 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 [23]. The laser has a rectangular Tophat beam spot of 6 mm width and 1.5 mm 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 (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 (at 70ºC) 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 fibre. 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 buttconnection loss was minimized by optimizing the alignment between the two fibre 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 pristine fibre sample were produced using both FBG inscription systems. Fig. 1 shows the reflected spectra for the two POFs using the 325 nm UV HeCd laser. The inscription times (the time that grating growth stops) for fibre 1 and 2 are on average 87 min and 37 min, respectively, after several inscriptions to make sure about the repeatability of the results. We can notice that for the latter fibre less than half the inscription time is needed compared with Fibres 1. We shall recall that the preform from each drawing process of Fibre 2 has been annealed for 2 weeks at 80°C, giving a well-defined thermal pre-treatment when compared with other. 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 [25], where this fibre type is far less sensitive to thermal treatment.

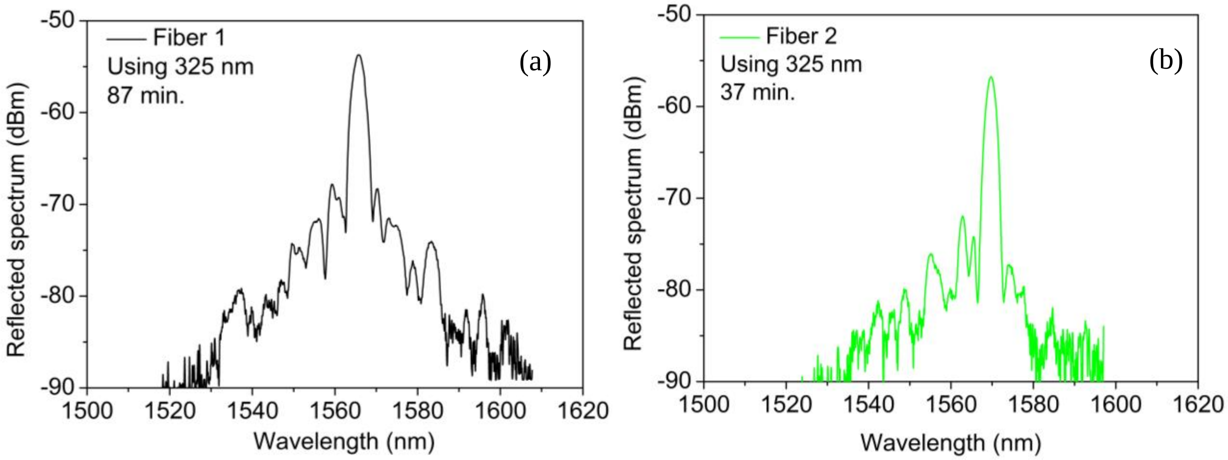

Figure 1. Reflected spectra for POFBGs inscribed in (a) Fibre 1 and (b) Fibre 2 using the CW 325 nm UV HeCd laser.

To substantiate our findings, we repeated the same measurements on the two fibre 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 Fibres 1 and 2 are on average 40 s and 7 s, respectively. For Fibre 2, 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 Fibre 2, for which the both preforms has been annealed prior to drawing, the inscription time is also lower than the inscription time needed for other fibres (indeed we need 5 times less of the total inscription time using Fibre 2), as it was the case with inscription using the 325 nm UV HeCd laser.

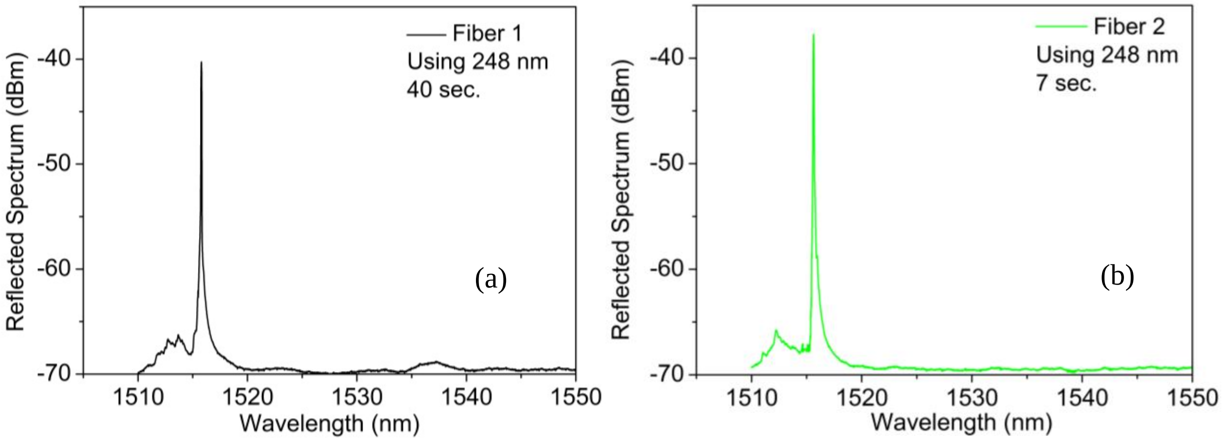

Figure 2. Reflected spectra for POFBGs inscribed in (a) Fibre 1 and (b) Fibre 2 using the pulsed 248 nm UV KrF laser.

The performance of the produced sensors, 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 fibre 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 1.33±0.01 pm/με (Fibre 1) and 1.27±0.02 pm/με (Fibre 2) after using a linear regression fit, 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 inscription systems [17,18].

Additionally, characterization was carried out to explore the temperature response of each fibre containing FBGs. The fibres 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. The temperature characterization was done at a fixed 50% relative humidity. The obtained temperature sensitivities were similar to the values already reported for POFBGs inscribed in Fibre 1 with 325 nm laser system: -74 pm/°C. For Fibre 2, we achieved a temperature sensitivity of -53 pm/°C, which is less than achieved for Fibre 1, as discussed in [25], 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.

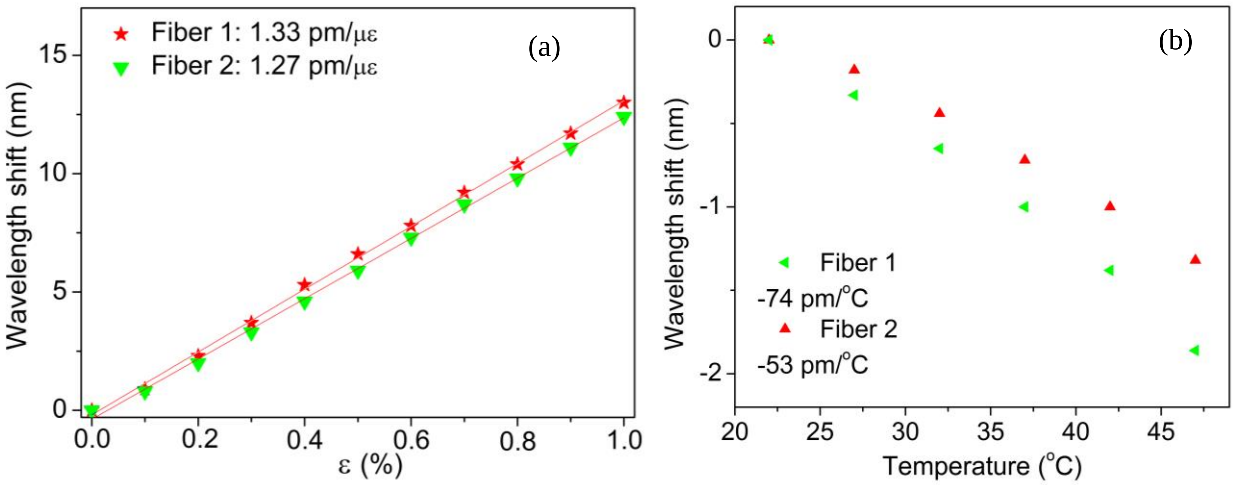

Figure 3. Bragg wavelength shifts obtained from the inscribed FBGs in each fibre under different (a) strains and (b) temperatures.

The results presented here indicate the impact of thermal pre-treatment in both preforms process 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. The different drawing parameters, namely drawing tension from which we calculate the draw stress, and the atmosphere in which the preform is placed during annealing, can also give us a credible explanation. However, using three fibres fabricated at different drawing tensions (from the same facility of Fibre 2) some FBGs were produced and no significant difference was observed in terms of inscription time between all fibres. Any annealing process prevents humidity to be diffused and consequently avoiding some issues during drawing such as bubbling, destabilized conditions or fluctuation on diameter of fibre. With this long time of annealing all water quantity may be removed. So, if there is a fibre drawn from a preform which had not a specific process of annealing in any of two-step process (primary and secondary preforms), it could include a considerable amount of water inside the preform and can affects the final performance of the fibre. However, it does not mean that the final fibre in both cases may have a large different content of water at the end but a slight difference may be sufficient. In both fibres, the humidity of the oven is controlled by argon flow or in vacuum in order to guaranty that the atmosphere, where the fibre is annealed, is free (as possible) of external climatic changes.

On the other hand, after inscribe FBGs on the pristine samples using both laser systems and discuss the obtained results above, in order to explore and understand our findings we then annealed new samples for 12 hours at 80°C before FBGs inscription. PMMA based POFs are well known to be sensitive to humidity [26]. Whilst we could not control the history in terms of exposure to environmental temperature and humidity changes between their fabrication and arrival in our laboratories, we emphasize that we in between the annealing steps carried out in our labs, all fibre samples were stored and measured in the same temperature (20°C) and relative humidity (50%) controlled cleanroom and therefore in the same environmental conditions. Thus, we observed that the inscription times for Fibres 1 and 2 are on average similar to previous case, it means there are no significant improvements in inscription time consumption compared with non-annealed fibres before FBG inscription.

4. Conclusions

In this work, improvements were reported in the photosensitivity of undoped POFs, where there was a well-defined pre-annealing of the both preforms fabricated in two-step process. We have observed that with non-annealed preform in any step process (in this case primary preform), the fibre photosensitivity is lower. The fibres from preforms with specific thermal pre-treatment in both two-step process allow us to achieve less FBG inscription times than fibres with a well-defined annealing of the secondary preform, obtaining at the same time stable FBG sensors with high quality. We also addressed the actual influence of annealing on the strain and temperature sensitivities of the fibres prior FBG inscription, observing that the fibre produced from the preforms with well-defined pre-annealing did not produce any significant difference. Some important parameters were considered such as drawing tension, where using fibres drawn in different tensions give us a similar FBG inscription time. We can also conclude that a fibre drawn from two-step process, where both the primary and secondary preforms are not annealed, may include a slight amount of water inside of preform and this will affect the fibre performance.

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