Fast inscription of long period gratings in microstructured polymer optical fibers

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***Abstract*—We demonstrate 20 dB long period grating (LPG) fast inscription in microstructured polymer optical fibers (mPOFs) using a point-by-point technique obtaining an LPG total length of 25 mm. Two 248 nm UV laser pulses of 15 ns duration have been employed for every inscription point, which means a time reduction by more than 21 times compared with the fastest inscription time already reported in literature. The device has been fabricated in a single-mode mPOF with a core that has been doped with benzyl dimethyl ketal (BDK) for photosensitivity enhancement. Moreover, we characterize the strain and temperature responses and the stability of the fabricated gratings response under different conditions in order to assess the viability for different applications.**

***Index Terms*—Polymer optical fibers, fiber Bragg gratings, optical fiber devices, optical filters**

I. Introduction

DURING the last two decades, long period fiber gratings (LPGs) have attracted significant attention due to their successful applications for both optical communications [1] and sensing [2]. The advantage of LPGs includes low insertion loss, ease of fabrication and low back reflection. Various LPGs based on silica fiber have been explored as WDM channel isolation filter [3], erbium-doped multi-wavelength fiber laser [4], highly sensitive refractometer [5] and sensor for different parameters such as strain [6], temperature [7], refractive index [8] and biochemical sensing [9,10]. Furthermore, properties of polymer optical fibers (POF) such as the large range of strain and small Young's modulus make LPGs even more attractive in these fibers. As a recent application, an all-plastic fiber-based pressure sensor based on LPG in microstructured POF (mPOF) has been explored [11]. However, the fabrication technology of LPGs in POF is still under research. Only a few papers mentioned the fabrication process of LPGs in mPOF [11-14]. The first LPG was fabricated in mPOF by mechanical deformation and heating [12]. UV photo inscription of LPG in mPOF was reported in 2010 with point-by-point technique [13]. Also, trans-4-stilbenmethanol was employed as external cladding dopant and demonstrated a reduced fabrication time down to six times compared to pure PMMA fibers with the same technique, which leads to reduce the coupling points as well as to shorten the irradiation time for each point (42 s against 2 min) [14]. In terms of minimizing fabrication times, which is a critical issue for commercial application, a 248 nm UV laser was used to inscribe a high quality fiber Bragg grating (FBG) in an undoped PMMA mPOF within less than 30 s [15]. Then, this laser type was employed to fabricate FBGs in benzyl dimethyl ketal (BDK) doped fiber with a single UV laser pulse [16] and it holds the minimum inscription time obtained until now. As demonstrated in previous work [16], BDK dopant acts as a photoinitiator which triggers a photo-polymerization process when irradiated with UV light and therefore, the photosensitivity of this fiber is increased.

To the best of our knowledge, in this letter we present the shortest inscription time for the LPG in an mPOF, and we also investigate the temperature and strain sensitivities.

II. Long Period Fabrication Grating Fabrication

A PMMA mPOF with 3 rings of holes and a BDK doped core was used to inscribe LPGs. The three ring cladding microstructure has a hole-to-pitch ratio of 0.47 with an average hole diameter of 1.74 um and an average pitch of 3.70 um [17], which makes it close to endlessly single-moded [18]. A cross-section image of the fiber is shown in Fig. 1. The fiber was annealed for 24 hours at 70 degrees before use in order to improve stability and quality of the inscribed gratings [19]. After cleaving it with a special room temperature cleaver [20] and polishing with sand paper, a long piece of fiber was connectorized and held onto the fabrication setup (see Fig. 2) under 0.1% strain, in order to ensure a good alignment between the fiber and UV beam. Several long pieces of fiber were connectorized to support the results of this work.

A Coherent Bragg Star Industrial-LN krypton fluoride (KrF) excimer laser system operating at 248 nm wavelength was employed for the LPG inscription. The laser pulse duration was 15 ns and the pulse energy was set at 2.95 mJ. The laser beam

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profile was measured as a rectangular Tophat function of 6.0×1.5 mm^2 size and 2×1 $mrad^2$ divergence. It was focused onto the fiber core utilizing a plano-convex cylindrical lens (Newport CSX200AR.10) with focal length of 20 cm. The translation stage was employed to shift the laser beam with a precision of 10 µm and a slit was employed to control the width of the beam where the point-by-point technique was employed to inscribe LPGs.

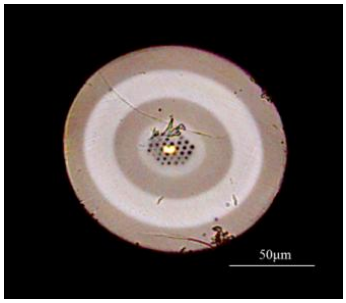

Fig. 1. Cross-section of the mPOF.

The grating transmission spectrum was monitored during fabrication by using a super luminescent diode (Superlum SLD-371-HP1) and an optical spectrum analyzer (Yokogawa AQ6373B) with 0.02 nm resolution bandwidth. According to the slit width, each point was 0.2 mm long, the beam was shifted 1 mm for inscribing every point and a total of 25 steps were completed, obtaining an LPG total length of 25 mm. From these parameters the transmission values at the resonance of the LPG appear in the range of 800 nm to 900 nm, as shown in previous works [13]. Different period values were tested however no significant results were obtained. Each inscription point was irradiated by two 15 ns pulses emitted by the UV laser at 1 Hz frequency repetition rate. Therefore, 2s irradiation time is a significant reduction from the 42s per point writing time reported in a previous work [14].

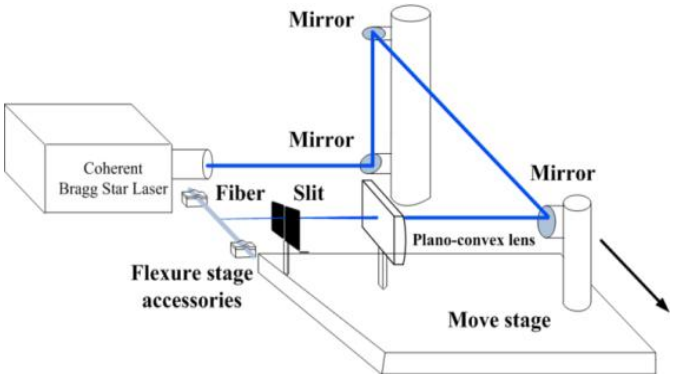

Fig. 2. Experimental setup for LPG inscription.

Fig. 3 shows the transmission of the LPG spectrum with only one irradiated pulse in each coupling point. The transmission of the grating was about -3.0 dB at 870.05 nm just after fabrication. The results are presented as normalised transmission response respect to the output spectrum of the optical source. According with [16], just one KrF laser pulse with a duration of 15 ns introduces a refractive index change in the fiber core with enhanced photosensitivity by the BDK dopant. Also, it shall be noted that some experiments about single and multiple pulses were already explored for FBG inscription in [16]. In this way, both one and two pulses for each coupling point would lead to LPG fabrication, where the LPG inscription of 25 mm is achieved due to the BDK doped core of the fiber.

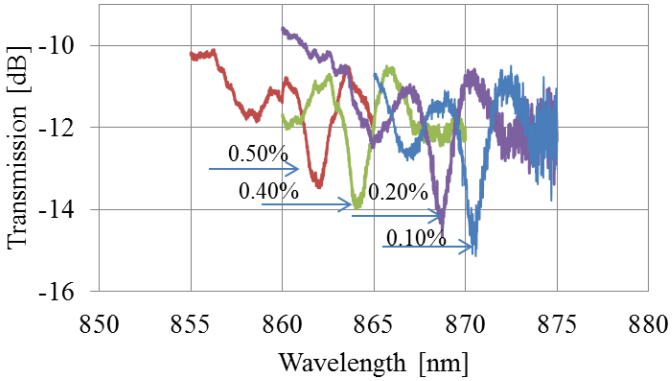

Fig. 3. Transmission of the LPG with one irradiated pulse per coupling point under different strain.

Another LPG was inscribed using two pulses for each coupling point in order to obtain a stronger grating. Fig. 4 shows the LPG transmission spectra just after fabrication when different levels of strain are applied. When the laser is stopped and the fiber is under 0.05 % strain, the grating peak is centered at 869. 5 nm and the transmission only drops 4.5 dB, whereas the grating peak becomes more clear when it is further strained (0.88 % and 1.0 %), and intensity reaches around 9.0 dB.

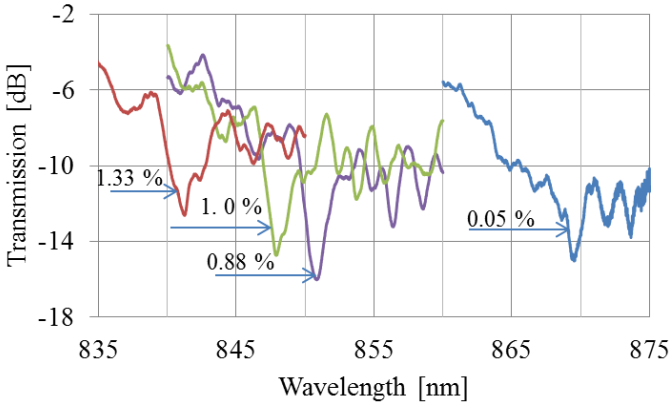

Fig. 4. Transmission of the LPG under different strain after inscription with two pulses for each coupling point.

However, after two weeks, the grating response shows a -20 dB peak centered at 866.9 nm wavelength when a 0.1% strain is applied, as shown in Fig 5. Such intensity growth after fabrication has been previously reported in FBG irradiated in annealed BDK doped PMMA fibers [16] and dye-doped

PMMA polymer fibers [21]. After considerable number of experiments, we found that two UV pulses for each coupling point are a more reliable way to obtain LPGs with significant strength for sensing purposes.

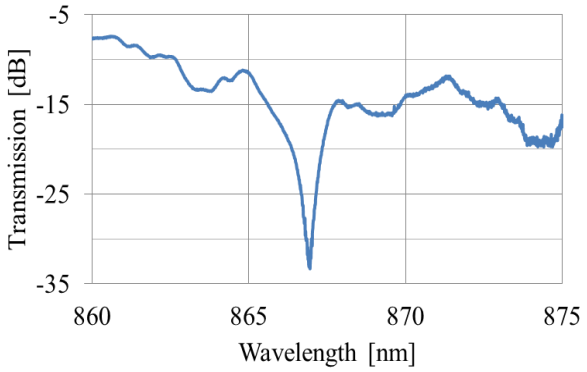

Fig. 5. Transmission of LPG with 0.1% strain two weeks after fabrication.

Transmission spectra were also collected after two weeks with different levels of strain measurement as shown in Fig. 6, and all cases show larger resonant dip than measured spectra just after fabrication, according to Fig. 4.

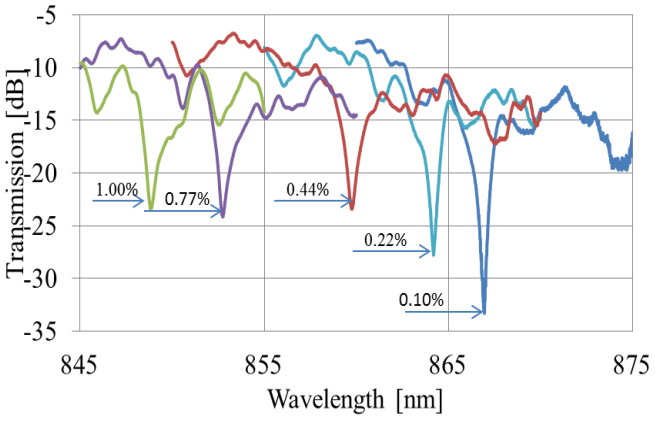

Fig. 6. LPG transmission responses under different strain after two weeks.

To achieve a detailed analysis of the LPG behavior under strain after fabrication (see Fig. 4) and two weeks after fabrication (see Fig. 6), the transmission values and the wavelength shift at the resonance of the LPG for different values of strain have been plotted in Fig. 7 for the sake of comparison. From Fig. 7 (a) we can observe a transmission depression of 20 dB when a 0.1% strain is applied and for 1% of strain the transmission depression decreases for 13 dB. Fig. 7 (b) shows the peak wavelength variation for different strain levels and a sensitivity about -2.21±0.05 nm/mstrain was measured for the LPG after fabrication whereas, -2.15±0.05 nm/mstrain for the LPG two weeks after fabrication.

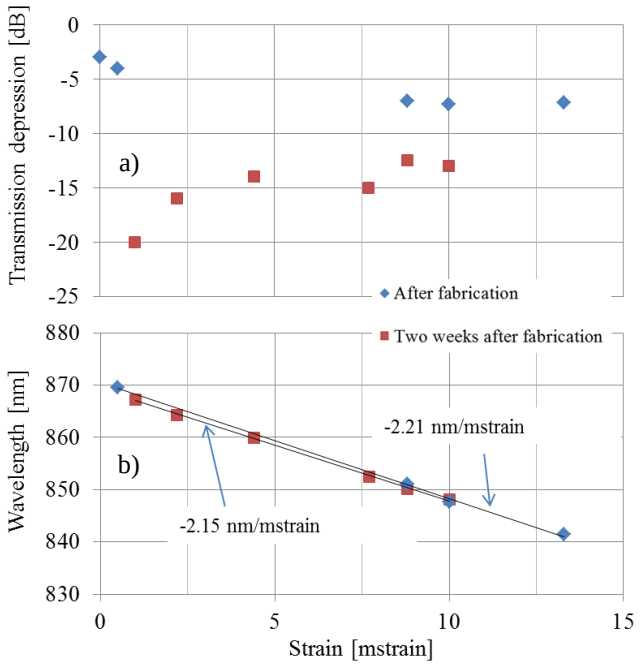

Fig. 7. LPG behavior under strain after fabrication and two weeks after fabrication. (a) Transmission depression of the grating. (b) Wavelength shift of the grating.

III. Strain and Temperature Characterization

In the following, we measured the strain and temperature sensitivities of the fabricated LPGs in order to complete their characterization. To measure the former one, a 22 cm long connectorized fiber including an inscribed LPG was fixed with epoxy glue on the flexure stage accessories (Thorlabs THH001), and then fixed on the translation stage. The flexure stage fixing avoids sliding and also strain can be easily controlled by the translation stage. It shall be noted that we can use sharp blade to separate the fiber and the stage carefully for different experiments. The total fiber length between the glued points was about 18.1 cm and the length was changed by 20 μm (0.1105% strain) in every measurement step. After 12 steps, a total 1.326% strain was applied and then, decreasing strain was applied by using the same steps.

Fig. 8 shows the peak wavelength variation against different levels of strain and sensitivity about -2.30±0.05 nm/mstrain was measured for increasing strain whereas, -2.25±0.05 nm/mstrain for decreasing strain due to polymer hysteresis. The measured sensitivity is slightly larger than presented in the literature, which ranges from -1.40 to -1.44 nm/mstrain for increasing strain and between -1.30 and -1.40 nm/mstrain for decreasing strain [22]. This phenomenon is probably due to fiber annealing for 24 hours at 70 ℃ as reported in [23] since the annealed fibers can produce an increase in the strain sensitivity.

We also studied the temperature response of the LPG inscribed which was fixed on the flexure stage and placed in the climatic chamber (Angelantoni Industrie CH340) with 50%

humidity under varying temperature values. The temperature was increased from 22 ℃ to 52 ℃ with steps of 5 ℃. Each temperature value was held during one hour to ensure stabilization.

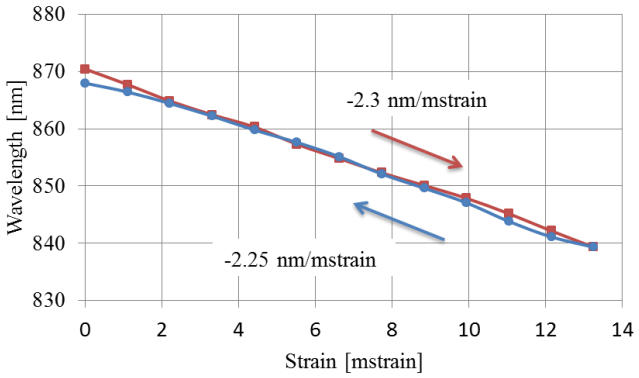

Fig. 8. Wavelength change induced by increasing and decreasing strain.

At the same time, we explored the stable behavior of the grating response during the characterization experiment. As depicted in Fig. 9, when the temperature is changed from 27 ℃ to 32 ℃, the grating needs about 1 hour to become stable and before stability is reached, the grating shifts towards blue and then towards red wavelengths. However, when the temperature is increased from 47 ℃ to 52 ℃, the grating needs less than 10 minutes to become stable and central wavelength only shifts by a small amount.

The large range shift, observed for temperature change between 27 ℃ and 42 ℃ is probably due to the combined effect of humidity and temperature [24] since the water diffusion is a slow process. Oppositely, the grating becomes stable after a short time when the temperature is increased, as reported in [25], when the temperature is increased under 55% relative humidity (RH) conditions.

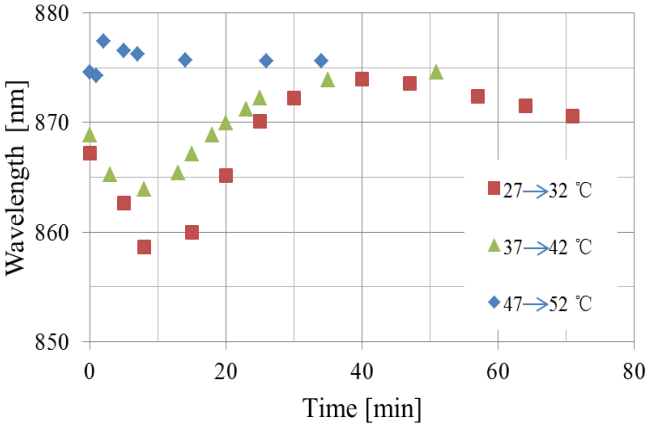

Fig. 9. Time evolution of the LPG central wavelength for different temperature variations.

Provided temperature is stabilized for each measurement, the obtained temperature sensitivity was 0.276±0.02nm/℃, as shown in Fig. 10. The resonance wavelength of the grating shows a linear behavior with temperature. This behavior is different from previous results [22] where high nonlinearity and hysteresis was obtained when measurements were collected after 5 min. The linear behavior is probably due to the larger measuring times employed in our experiment since we also found high nonlinearity in the grating behavior during the first 5 min due to the combination of temperature and humidity. Longer times (~ 1 hour) between each measurement allow to get a stable response and, consequently the wavelength shows a linear behavior with the temperature variation. Such behavior with temperature variation of LPG was also reported in mPOF with trans-4-stilbenmethanol as external cladding dopant [14]. However, the measured sensitivity is slightly larger than presented in the literature. From [14], in the linear part of the temperature characteristics the thermal sensitivity was roughly 0.035 nm/℃, which is almost one order less when compared with our result. It can be due to fiber drawing conditions, chemical composition of polymer and it is dependent of thermal history processing of each fiber.

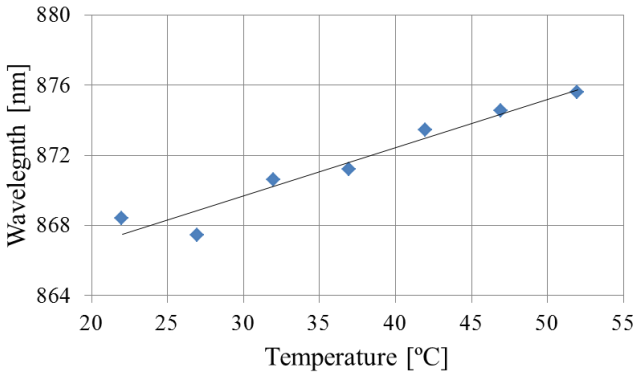

Fig. 10. Central wavelength dependence on the temperature.

Fig. 11 shows the transmission of the LPG after 50 days after fabrication, showing a good stability of the grating. The achieved strain sensitivity is -1.97 ±0.05 nm/mstrain, slightly lower than before, which indicates the sensitivity decreases slowly with time.

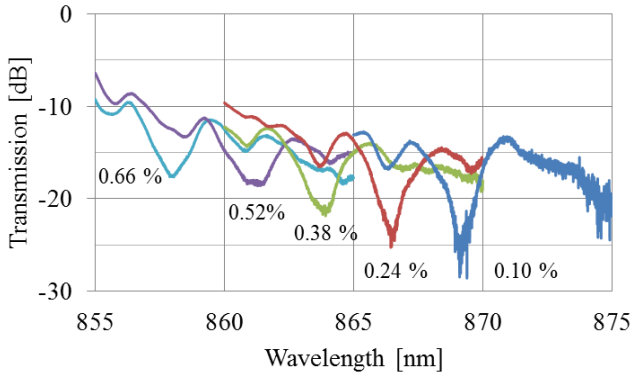

Fig. 11. LPG transmission behavior with strain (50 days after fabrication).

IV. CONCLUSIONS

To summarize, we demonstrated fast inscription of LPGs in polymer optical fibers using two 248 nm UV laser pulses per point by using point–by- point technique. The device has been fabricated in a single-mode mPOF which core has been doped with BDK for photosensitivity enhancement to UV radiation. The inscription time for each coupling point has been shortened by 21 times compared with the best one reported in the literature. The grating response shows a notch depth of 20 dB centered at 866.9 nm wavelength under 0.1% strain. The strain and thermal characterization of the LPG showed the strain and temperature sensitivity of -2.3 ± 0.05 nm/mstrain and 0.276 ± 0.02nm/℃, respectively. Furthermore, we explored the stability of the grating response under different conditions to demonstrate its large potential for telecommunications and sensing applications.

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