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Bragg gratings inscription in TS doped PMMA POF by using 248 nm KrF pulses

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***Abstract*— We demonstrate the Bragg gratings inscription in the 850 nm spectral region by using trans-4-stilbenemethanol (TS)-doped poly (methyl methacrylate) (PMMA) step-index optical fiber and a 248 nm krypton fluoride (KrF) excimer laser system. The gratings inscription only takes 0.4 second. A detailed study of the grating fabrication process using different pulse repetition rates is also reported. Additionally, temperature, humidity and strain sensitivities are measured to demonstrate the potentiality of these components for different sensing applications.**

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

I. Introduction

During the last two decades polymer optical fiber Bragg gratings (POFBGs) have attracted huge attention driven by sensing and communication applications. Polymer optical fibers (POFs) show a smaller Young's modulus and larger thermo-optic coefficient compared with silica counterparts, which make them suitable for different sensing scenarios, such as strain [1], temperature [1], humidity [2], liquid level [3] and ultrasound [4]. The demonstrated biocompatibility also makes them a promising sensing technology for biomedical and bioengineering industry [5].

The first poly (methyl methacrylate) (PMMA) POFBG was reported in 1999 [6]. Since then, great progress has been made in the POFBG fabrication. Different materials such as TOPAS [7], ZEONEX [8], CYTOP [9] or even polycarbonate [10] were introduced for different sensing modalities with unique advantages. Both microstructured and step-index POFs have been investigated. Until now, PMMA remains the preferred material for POFs composition. Due to the low photosensitivity of pure PMMA, a photosensitizer such as benzyl dimethyl ketal (BDK) [11], trans-4-stilbenemthanol (TS) [12] or diphenyl disulphide [5] can be added in the fiber core or cladding to enhance its photosensitivity. Among the various compositions and geometries of POFs, step-index POFs are the easiest ones to connectorize by using silica fibers pigtails [12]. In 2004, 90% reflectivity FBGs were obtained in step-index PMMA POFs with TS doped in the core by using 325 nm UV pulses after ~ 90 min exposure by using the phase mask technique [12]. Moreover, the etching technology allowed to obtain 40 min benefit in a 97% reflectivity grating by using a continuous 325 nm He-Cd laser system [13]. The same group also obtained low reflectivity gratings in 1 second, which have to be stabilized using a post-inscription thermal annealing [14]. Due to the PMMA POF periodic ablation in 248 nm wavelength mentioned by *Xiong et al* in 1999 [6], this wavelength was not considered suitable for POF FBG irradiation until *Oliveira et al* [15] demonstrated the first POFBG in a pure PMMA microstructured fiber by using a 248 nm krypton fluoride (KrF) excimer laser system in few seconds of exposure, which greatly shortened the inscription time for POFBGs. Since then, one high pulse energy (6.3 mJ) was employed to fabricate FBGs in a BDK-doped microstructured PMMA fiber core [16]. Due to the benefits of KrF excimer laser such as high output pulse energy and repetition rate control, several works investigated the fabrication of several types of gratings in different POFs [17-19]. However, until now, no TS-doped PMMA POFBGs fabricated with 248 nm UV wavelength. Gratings at 850 nm spectral region are very suitable for various sensing applications since POF lengths of tens of centimeters are required and losses are much lower compared to the C+L bands. Consequently, our motivation is to study the fabrication of TS-doped POFBGs with the 248 nm laser system and develop fast and stable Bragg gratings inscription to achieve stable and useful optical components with lower transmission loss for sensing applications. In this paper, we report the first TS-doped POFBG inscription under 248 nm UV irradiation with ~17 dB reflection above noise level in less than 1 second of exposure

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time. Moreover, temperature, humidity and strain characterizations are also measured for assessing potential sensing applications.

II. Bragg Gratings Fabrication

In this work, a step-index PMMA POF is employed with a core diameter of 8.2 µm and a cladding diameter of 150 µm. The cladding is pure PMMA, while the core is PMMA doped with diphenyl sulfide (DPS) (5% mole) and TS (1% w.t.). Both dopants are used to increase the refractive index and enhance the photosensitivity. A trans-cis structure change in the TS material under UV irradiation, estimated from 240 nm to 340 nm, leads to a refractive index decrease [12] where DPS facilitates the trans-cis inter-conversion under UV irradiation. A cross-section image of the fiber is shown in the inset of Fig. 1. The fiber was annealed for 24 hours at 70 degrees in order to release the stress that was induced during the drawing process prior to the gratings fabrication. A Coherent Bragg Star Industrial-LN KrF excimer laser system operating at 248 nm wavelength was employed for the Bragg grating inscription. The experimental setup for POFBG inscription is shown in Fig. 1. The laser beam was focused onto the fiber core utilizing a plano-convex cylindrical lens (Newport CSX200AR.10) with focal length of 20 cm. The effective spot size of the beam on the surface of the POF is 32.4 mm (height) and 20.0 mm (width). The UV laser beam illuminated a 567.5 nm pitch phase mask with a total length of 10 mm just before irradiating the fiber and, therefore, the FBG length was 10 mm.

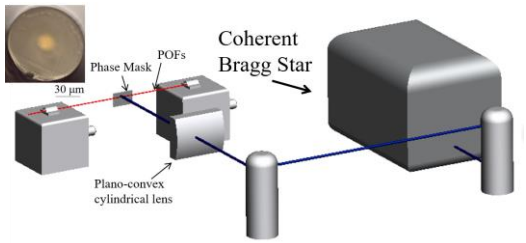

Fig. 1. Experimental setup for POFBG inscription, inset: end face of the POF.

The reflected power spectrum was monitored after irradiation by using a super luminescent diode (Superlum SLD-371-HP1) and an optical spectrum analyzer (OSA) (Yokogawa AQ6373B) with 0.05 nm resolution bandwidth through butt coupling with a single-mode silica pigtail. A small amount of index gel was inserted to reduce Fresnel reflections.

Several previous unfruitful attempts were done by using 1 pulse at 1 Hz repetition rate and 2.5 mJ pulse energy but further optimizations produced a grating with only 0.4 seconds inscription time at 100 Hz pulse rate. As explained below, the pulse repetition rate has strong influence on the POFBG reflected spectral power.

Figure 2 shows the POFBG reflected spectral power obtained with a 10 Hz repetition rate and a 0.50±0.02 mJ pulse energy over 4 seconds (i.e., 40 pulses). We observe a full-width half-maximum (FWHM) bandwidth of 0.38 nm and a 17 dB peak-to-noise difference. The increase of pulse repetition rate is a promising method for grating inscription with shorter inscription time.

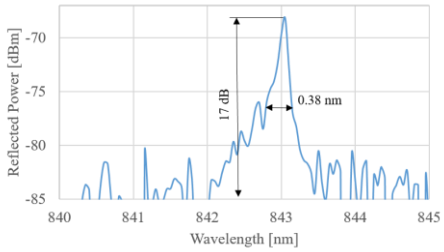

Fig. 2. Reflected spectral power by a POFBG inscribed using 10 Hz repetition rate and pulse energy of 0.50±0.02 mJ in 4 seconds (40 pulses).

Furthermore, in order to obtain shorter inscription times, the repetition rate was set to 50 Hz using the same pulse energy. Fig. 3 shows the reflected power with an FWHM bandwidth of 0.46 nm, and 17 dB of reflectivity obtained in a 0.8 second exposure (40 pulses). The inscription time was reduced by 5 times when compared with the results shown in Fig. 2.

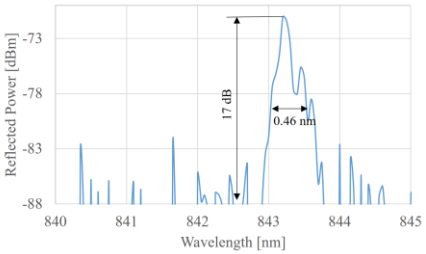

Fig. 3. Reflected spectral power by a POFBG inscribed using 50 Hz repetition rate and pulse energy of 0.50±0.02 mJ in 0.8 seconds (40 pulses).

The repetition rate of the laser was further increased to 100 Hz and Fig. 4 shows the reflected spectral power by the grating after 40 pulses by using the same pulse energy (0.50±0.02 mJ). The POFBG still shows similar reflectivity response as the previous ones but the inscription time has been reduced down to 0.4 s.

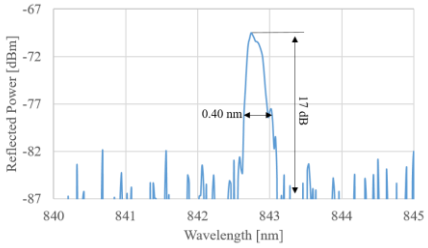

Fig. 4. Reflected spectral power by a POFBG inscribed using 100 Hz repetition rate and pulse energy of 0.50±0.02 mJ in 0.4 seconds (40 pulses).

Oliveira et al [15] mentioned that it is possible to damage POF by using 50 Hz frequency and 3 mJ pulse energy after a few seconds. There are several methods to reduce or avoid damages, such as decreasing the pulse frequency, energy or pulse number. By using 1 Hz of frequency, a good performance is demonstrated in different undoped POFs [19]. Also, a single 6 mJ pulse leads to obtain gratings using BDK doped mPOF [16].

However, in our case, no POFBGs were obtained with a single pulse. Higher pulse repetition rates lead to achieve POFBGs in less than 1 second. As shown in [14], higher pulse repetition rates generate higher cumulative heating, and then higher temperatures are induced in the fiber. So, the aforementioned observation can be attributed to temperature variation. When a single pulse inscription is employed, the temperature is nothigh enough, the movement of polymer chains is confined and no sufficient free volume for the movement of TS molecules is generated. Conversely, when higher repetition rates are employed, higher temperature is achieved and sufficient free volume is enabled for the movement of TS molecules, which could switch from trans to cis forms with the associated negative refractive index change [14]. Fig. 5 indicates that there is neither damage in the fiber core nor in the surface after inscription by using the phase mask technology under 100 Hz repetition rate and pulse energy of 0.50 ±0.02 mJ in 0.4 second (40 pulses). This demonstrates that the TS-doped POF can be useful in a POFBG fabrication setup, controlling the UV laser repetition rate to reduce the irradiation time without damaging the POF.

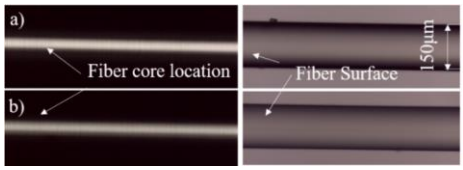

Fig. 5. Microscope images of the TS doped POF surface: a) before irradiation; b) after 0.4 s irradiation by using phase mask technique under 100 Hz frequency and pulse energy 0.50±0.02 mJ (40 pulses).

III. Grating performance

For sensing applications, stability of the grating over time is a critical issue. Fig. 6 shows the reflected spectral power by the grating two weeks after the initial inscription (see Fig.4) at room temperature. We can observe a blue shift of 0.7 nm and a power reduction of 1 dB. The grating profile is also modified, with the appearance of a sub-peak. This sub-peak could be related to coupling issues because the POF used is few-moded. A profitable comparison can be made to gratings inscribed using conventional CW 325 nm HeCd lasers, with exposures of 1 second, which need longer inscription time and present lower stability [14].

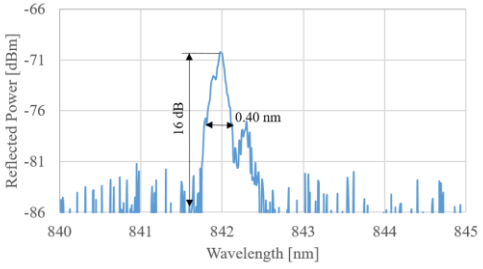

Fig. 6. Grating with 100 Hz frequency and pulse energy 0.50±0.02 mJ condition in 0.4 second (40 pulses) after two weeks.

Several gratings were inscribed with 40 pulses but using different repetition rates (10 Hz, 50 Hz and 100 Hz). In Fig. 7, we can notice that the reflected power keeps stable for a long time showing no considerable impact of the repetition rate on the stability and therefore, it shows that this is an efficient method to obtain reasonable stable gratings with reduced fabrication times.

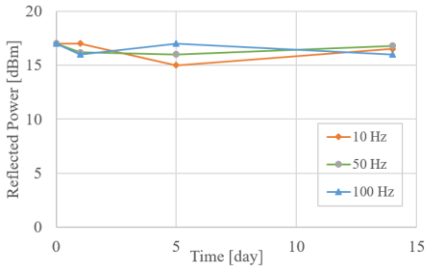

Fig. 7. Reflected power of gratings fabricated with different laser pulse frequencies (10 Hz, 50 Hz and 100 Hz) at 40 pulses during two weeks.

In the following, the POFBG was connected to a single mode silica fiber with UV glue (Norland 78) and placed into a climate chamber (Angelantoni Industrie CH340) at a constant temperature of 22 ℃ and 30% of relative humidity (RH) during 80 min for stabilization. Then the RH was increased up to a value of 90% then decreased to 30 % in 20% step, waiting 80 min between each one. The reflected spectrum was monitored using an 850 nm circulator, a super luminescent diode (Superlum SLD-371-HP1) and an optical spectrum analyzer (Yokogawa AQ6373B). Fig. 8 (a) shows that the central wavelength needs around 80 min to be stable under the 20% humidity change. The stable time could be short with etching technique for decreasing the POF diameter [2] The total wavelength shift was 1.60 nm and the maximum hysteresis detected around 0.06 nm was observed at 70% of RH (see Fig. 8 (b) – increasing and decreasing cycle was collected). The sensitivity was computed as 0.027±0.005 nm/%RH as shown in Fig. 8 (b).

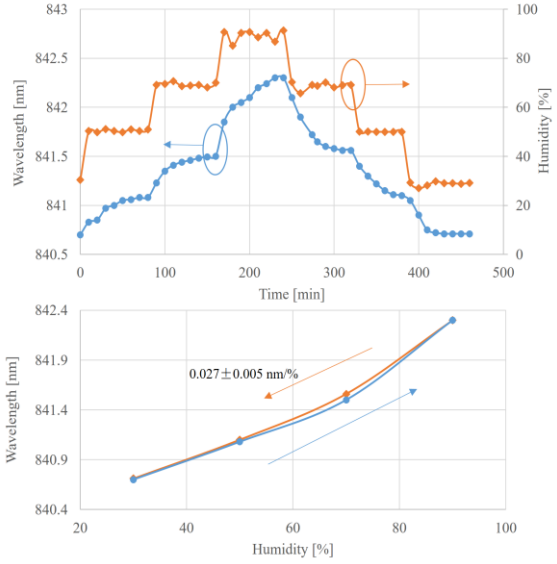

Fig. 8. a) Measured wavelength shift under humidity change. b) Wavelength shift at different humidity levels for increasing and decreasing cycles.

Temperature sensitivity of the same grating was measured by using a Peltier plate, which contains a small v-groove where the temperature is set with a thermo-electric controller. Silicone

grease was placed on the grating position to increase temperature conduction. The central wavelength of the grating was measured from 22 º C to 52 º C, in 5 º C steps, every 10 min. The total central wavelength shift was about 1.22 nm, allowing to estimate a sensitivity of -0.42±0.05 nm/º C, as shown in Fig. 9. A similar value was obtained with Bragg gratings inscribed in the same fiber type but using the 325 nm HeCd laser system [13].

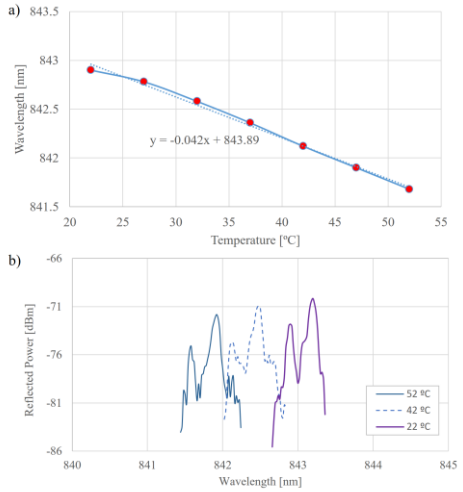

Fig. 9. a) Wavelength shift under different temperatures. b) Reflected spectrum under different temperatures.

In order to characterize the strain sensitivity of the fabricated gratings, a 7.9 cm long fiber containing the grating was placed between two X-Y-Z stages where it was glued. The fiber was strained step-by-step while awaiting 5 min between each step at room temperature. The evolution of the central wavelength was monitored when the strain was changed from 0 to 1.26 % as depicted in Fig. 10. A wavelength shift of 9 nm was observed under strain, which indicates a linear strain sensitivity of 7.18±0.02 pm/με, which is similar with PMMA mPOFBG fabricated at 850 nm spectral region [20]. It shall be noted that we characterized in strain up to 1.26% only due to setup limitations.

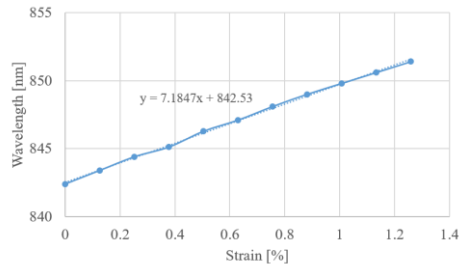

Fig. 10. Wavelength shift under different strain.

As recently confirmed by the literature [19], different undoped POF materials need a maximum of 25 s of inscription time, but BDK-doped mPOF just requires one high pulse with 6.2 mJ of energy due to the high BDK absorption coefficient [16]. Based on these investigations, the performance described here is relevant due to the presence of the TS dopant. Due to the different refractive index change mechanism of BDK and TS dopants at 248 nm wavelength, we were not able to obtain a grating with a single pulse. However, the choice of adequated parameters of the pulsed UV laser allows to obtain FBG with less than 1 second exposure time.

IV. Conclusions

In conclusion, we inscribed FBGs in Trans-4-stilbenemethanol-doped photosensitive step index PMMAPOF at 850 nm wavelength by using phase mask methodology with a 248 nm KrF laser, with inscription times lower than 1 second. Humidity, temperature and strain sensitivities under stable conditions have been measured to assess the fabricated components for potential sensing applications.

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