High-quality phase-shifted Bragg grating sensor inscribed with only one laser pulse in a polymer optical fiber

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Abstract –**We present the first phase-shifted polymer optical fiber Bragg grating sensor inscribed with only one KrF laser pulse. The phase shift defect was created directly during the grating inscription process by placing a very narrow blocking aperture, in the center of the UV beam. One laser pulse with a duration of 15 ns and energy 6.3 mJ is adequate to introduce a refractive index change of 0.69×10^{-4} in the fiber core. The high-quality produced Bragg grating structure rejects 16.3 dB transmitted power, thus providing 97.6% reflectivity, which is well suited for photonic applications. The transmission notch depth is about 10 dB and very sharp notches of 3 dB width ranging from 14 pm is reported. The temperature, strain, and pressure response of the sensor has been characterized showing promising results in applications that require high-precision measurements. The ability to inscribe these high-quality sensors effectively can significantly reduce their production cost in industry.**

Keywords – ***Optical sensors, polymer fibers, fiber Bragg gratings, phase-shift, annealing.***

I. INTRODUCTION

As fabrication technology of FBGs in silica fibers is already well established, the Bragg grating-based phase-shifted inscribed in such fibers were studied for numerous practical applications due to their simplicity, small size and increased measurement resolution. In recent years, the technology of fabrication of FBGs in polymer optical fibers (POFBGs) has been intensively developed using uniform FBGs, tilted FBGs, chirped FBGs, or FBG-based Fabry–Perot interferometer [1,2]. Specific material properties, such as low Young's modulus (about 3 GPa compared to 72 GPa for glass), a wider range of strain that the POFs can withstand as well as biological compatibility open a variety of new applications unattainable for silica fiber [1-4].

In the last few years, there is an increase in the research of POF technology in the biomedical applications [5-8]. Recently, Broadway *et al* showed the scope and potential that POF offers for endoscopic implementation [6]. Also, the same group presented the first opto-acoustic measurements obtained using a mPOF uniform Bragg grating and presented the lateral directivity pattern of an ultrasound sensor over a frequency range of 1-50 MHz [7,8]. These works showed that the acoustic sensitivity for POF is thirteen times higher than for silica fiber. However, they discussed the impact of the use uniform FBGs to mitigate some problems encountered, where a potential transition from uniform FBGs to Fabry-Perot cavities or phase-shifted POFBGs (PS-POFBGs) could be a validated option. The goal with that is to deliver a narrower spectral profile, which it can potential used to achieve higher sensitivities. Until now, the literature only provides a single report on a PS-FBG in POFs with quality, which was for use at THz frequencies by using a point-by-point FBG fabrication method [9]. However, this latter method should be avoided due to long-time consumption and consequently the high cost setup used to produce these gratings at 850 nm or 1550 nm spectral regions.

For the first time, we report high-quality PS-POFBGs inscribed with only one krypton fluoride laser pulse at 850 nm region with high-quality. The device has been inscribed in a single-mode poly (methyl methacrylate) optical fiber, with a core doped with benzyl dimethyl ketal (BDK) for photosensitivity enhancement. The phase shift defect was created directly during the grating inscription process by placing a very narrow blocking aperture, in the center of the UV beam. The high-quality produced Bragg grating structure rejects 16.3 dB transmitted power, thus providing 97.6% reflectivity, which is well suited for sensing applications. The PS-POFBG's temperature, strain, and pressure characteristics are also experimentally studied. These PS-POFBGs can be useful optical devices not only for optical sensing but also for different applications such as in multiple wavelength fiber lasers or filters.

II. EXPERIMENTAL SETUP

A KrF excimer laser system operating at 248 nm wavelength has been used for the PS-POFBGs inscription. The laser pulse duration is 15 ns and the pulse energy can be pre-set; in this study, the energy more suitable for this grating type is 6.3 mJ, where it was investigated with detail in our previous work [10]. Since the fiber core is doped with BDK for photosensitivity enhancement, where the absorption coefficient of BDK is much higher at wavelengths shorter than 325 nm, shorter laser inscription wavelengths enhance its effects [10]. The fiber is 3-ring microstructured with a hole diameter 1.74 µm and average pitch 3.7 µm. Its core size is 8 µm and its external diameter 130 µm. A cross-section image of the POF used in this work is shown in Fig. 1 (a). The laser beam is focused in the fiber core utilizing a plano-convex cylindrical lens with effective focal length of 200 mm. The effective spot size of the beam on the fiber surface is 20 mm in width and 32.4 µm in height. For the PS-POFBG inscription, we used the typical uniform phase mask technique with 10 mm in width with a period of Λ_{PM} =567.8 nm and it can produce gratings with Bragg wavelengths approximately at λ_B = 844 nm.

Before the inscription, POF pieces of length between 15 cm and 35 cm were glued into demountable FC/PC connectors to facilitate the POFBG interrogation. The average loss per connector is less than 1 dB. Different fiber pieces were pre-annealed with the same procedure used in [10], where the fiber was placed for 15 minutes in a container filled with water that was heated at 60±1 °C process and also to remove possible twists present on it. Also, considering our recent results [10], we can conclude that a single laser pulse in a pre-annealed POF is adequate for a POFBG inscription.

The phase shift defect was created directly during the grating inscription process by placing on the phase mask a very narrow blocking aperture (a metal wire with 40 µm diameter) in the center of the UV beam, as it is schematically illustrated in Fig. 1 (b). The phase shift occurs because, where the UV beam is blocked, the mean fibre index is less than in the rest of the grating. It resulted in the inscription of two FBGs separated by a very small gap in a single fabrication process, producing a phase shift on the structure. To observe the grating spectrum in transmission, the POF is connected between the super luminescent diode and the optical spectrum analyzer.

III. Results

Fig.1 (c) gives the transmission and reflection spectra of inscribed PS-FBG after an UV pulse. We can see that there are two main dips in each transmission spectrum because the PS-POFBG is successfully inscribed. The refractive index modulation produced by narrow wire acts as a phase shift of the grating during the inscription process. The transmission losses of the 1st and 2nd dips are about -16.25 dB and -13.17 dB, and the central wavelengths are 844.126 nm and 844.187 nm, respectively. In this case, the channel space of these two dips is about 61 pm, and the transmission notch depth is about 10 dB. We can fabricate the PS-POFBGs in transmission with very sharp notches of 3 dB width (~14 pm) as shown in the inset of Fig. 1 (c) depending the total grating length (in this case with 10 mm length). Fig. 1 (c) also shows a comparison of simulated and experimental results showing a good agreement between them. The simulation of the PS-POFBG spectrum can be accomplished using the transfer matrix method [12]. The success rate of the PS-POFBG photo-inscription is quite high – more than 98% – give us a high repeatability of fabrication. Comparing these PS-POFBG spectra with uniform POFBG ones, the slopes of the PS-POFBG compared with normal POFBG in the linear regions are several orders enhanced, which will result in the same input signal yielding detected signals with amplitudes that differ by a higher factor [11]. Though the dynamic range is smaller in the PS-POFBG because of the narrow peak, for the application of ultrasonic detection, this is not a problem since the strain is always small.

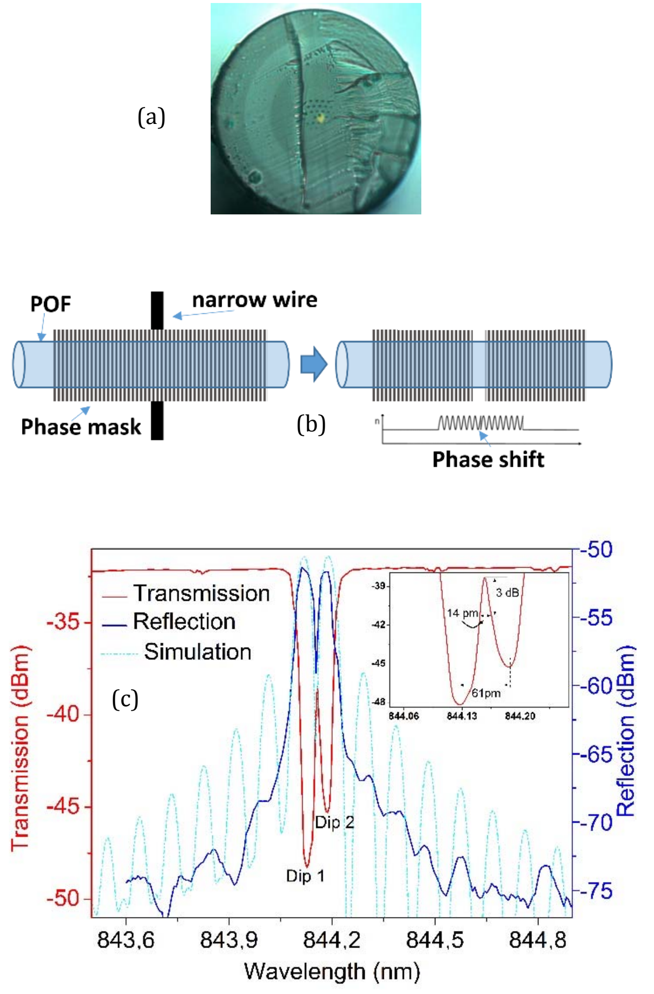

Figure 1. (a) Fiber cross-section. (b) A schematic configuration of the PS-POFBG fabricated with a very narrow metal wire positioned in the center of the UV beam. (c) Transmission and reflection/simulation spectra of inscribed PS-POFBG after an UV pulse UV beam.

After the successful PS-POFBGs inscription a characterization to temperature, strain and pressure was done, in order to show the spectral dependence of the Bragg peak under different external conditions.

The results for the temperature, strain and pressure are shown in Figs. 2 (a)–(c), respectively. The change in Bragg wavelength over the 30°C temperature variation was obtained giving -1.71 nm. The obtained temperature sensitivity was –57.0±4.1 pm/°C, after fitting to a linear model (see Fig. 2(a)). Fig. 2(a) shows that 1.71 nm tuning range can be achieved only with the temperature variation of 30°C, which is larger than the achieved in silica PS-FBG by the several hundred-degree temperature variation. Fig. (b) displays the strain response of the

PS-POFBG shows a good linearity and repeatability, and the strain sensitivity is 0.76±0.01 pm/με, which is a little larger than 0.7 pm/με of the silica PS-FBG reported in the literature [13]. From Fig. 2 (c), we can notice that the central wavelengths shift linearly with increasing and decreasing the pressure for two dips at a pressure sensitivity of 0.46±0.03 pm/kPa, which is more than 2 times sensitive compared with uniform POFBGs [14].

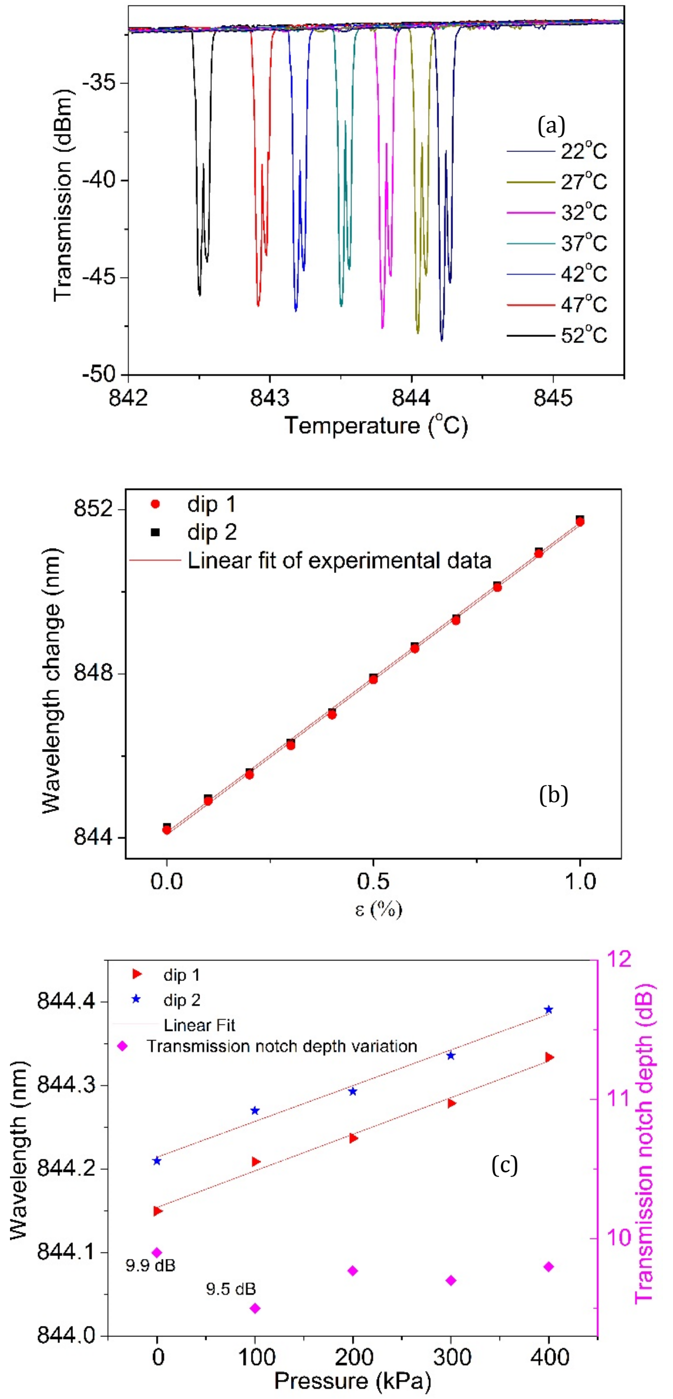

Figure 2. Characterization of a PS-POFBGs for: temperature (a), strain (b) and pressure (c).

IV. CONCLUSIONS

A fast inscription with only one KrF laser pulse of high-quality phase-shifted Bragg gratings in a doped PMMA mPOF is reported for the first time. The gratings were created through the phase mask technique, using 248 nm UV light. The phase shift defect was created directly during the grating inscription process by placing a very narrow blocking aperture, in the center of the UV beam. The PS-POFBGs were created at 850 nm region and produced Bragg grating structure rejects 16.25 dB transmitted power, which is well suited for photonic applications. The spectral dependence of the PS-POFBG with temperature, strain and pressure were analyzed. The optical characteristics of the achieved PS-POFBGs show promising results in applications that require high-precision measurements such as ultrasonic detection. The optimization of the FBG response by changing the narrow wire diameter or placing multiple narrow wires in different zones of the phase mask are in progress.

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