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# Polymer optical fiber Bragg grating inscription with a single Nd:YAG laser pulse

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**Abstract:** We experimentally demonstrate the first polymer optical fiber Bragg gratings inscribed with only one Nd:YAG laser (266 nm) pulse. The gratings have been inscribed in a single-mode *poly (methyl methacrylate)* optical fiber, with a core doped with *benzyl dimethyl ketal* for photosensitivity enhancement. One laser pulse with a duration of 8 ns and energy of 72  $\mu\text{J}$  is adequate to introduce a refractive index change of  $0.5 \times 10^{-4}$  in the fiber core. The stability of the gratings has been confirmed and the strain and temperature sensitivity measurements demonstrate their tunable properties.

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## 1. Introduction

The study and development of Fiber Bragg Gratings (FBGs) began in the 1970s with Hill's work on the non-linear properties of silica optical fibers (SOFs) doped with germanium [1]. In this study, an interference pattern was introduced into the core of an optical fiber, resulting in a periodic modulation of the refractive index of the core. These results led to a huge effort by the scientific community to improve the FBGs manufacturing. In 1989 [2], Meltz et al demonstrated a strong variation in the core's refractive index when SOFs doped with germanium were irradiated by a periodic pattern originated by the intersection of two coherent ultraviolet (UV) beams. The fabrication of FBGs improved drastically in 1993 [3], with the introduction of the phase mask for side inscription, providing a method for mass fabrication due to the simplicity of the technique, easy alignment, stability, reproducibility and flexibility of the process for producing apodized and chirped gratings [4].

Recently, polymer optical fibers (POFs) have been used as an alternative to SOFs in data transmission over short distances and in sensing applications [5]. Although POFs have higher transmission losses, they also have several advantages over SOFs, including lower Young's modulus and higher elastic strain limits [6], enabling them to be used as strain [7], stress [8], bending [9], refractive index [10] and pressure sensors [11]. Additionally, POFs have a negative thermo-optic coefficient and high sensitivity to temperature [12]; and the standard polymer *poly(methyl methacrylate)* (PMMA) has affinity to water [13], allowing to monitor humidity based parameters. Furthermore, polymers display excellent compatibility with organic materials, giving them great potential for biomedical applications [14,15]. The first FBGs were inscribed in POF in 1999 by Peng et al [16], using two illumination wavelengths, 248 and 325 nm, to create different gratings. Since then, the most common UV light used to manufacture Polymer Optical Fiber Bragg Grating (POFBG) remains the continuous wave (CW) low power HeCd laser operating at 325 nm, which is an affordable and accessible laser for grating inscription. It is typically the preferred option to avoid any ablation issues due to high energy [17], and to obtain deeper penetration of the radiation in the material [18]. Lately, other lasers with different wavelengths in the UV region have also been used to fabricate POFBGs, in particular the KrF laser operating at 248 nm [19–21], which allows to decrease the POFBG inscription time due to the higher absorption of the PMMA for shorter wavelengths. However, in ref [22], the authors reported a periodic ablation on the fiber surface when the 248 nm wavelength was used, due to the higher absorption of PMMA in shorter UV wavelengths [21]. Furthermore, using low energy density as well as low repetition rate from a 248 nm laser, a refractive index modification in PMMA bulk material was confirmed without introducing the ablation effect [19]. In this way, the key factors to avoid the ablation effect are the use of low energy density, low repetition rate and also low number of pulses as recently reported in different reports using different polymers [19–21,23], in contrast with the reported in [16,17]. After the first laser pulse with an energy lower than the ablation threshold, the polymer structure changes and there is a refractive index modification. Thus the refractive index change is due to an incubation phenomenon well below the material ablation threshold. This index change could be caused by the complete side chain removal of the material molecule leading to a densification [24]. As most polymers are intrinsically photosensitive, FBG inscription in different polymers is possible without doping [23]. Despite the photosensitivity mechanisms not being fully understood, the chemical structure of the polymer can be altered either by photo-polymerization, or by photo-crosslinking, or by photo-degradation [24,25]. All these mechanisms can possibly co-exist under UV irradiation, and which one prevails over the other depends on the irradiation conditions: laser wavelength, intensity and total exposure time [24]. The fabrication of Bragg gratings in undoped POFs can be a time consuming process, and as the exposure time increases, the higher are the risks of damaging the POF and compromising the stability of the grating [23,25]. Usually, to obtain a strongly reflective signal using the 30 mW CW HeCd laser, the minimum exposure time is about 20 minutes for step-index (SI) PMMA-POF [26], and that time can easily increase for

microstructured POFs (mPOFs) [25]. Increasing the UV beam intensity, the exposure time can drop to a few minutes [27], showing a dependency between grating inscription time and laser power. For the 248 nm excimer KrF laser, the inscription time for undoped PMMA-POF is less than 30 seconds [19,23], due to the higher absorption of the material at this wavelength. The inscription time can be reduced to less than 1 second by doping the core of the POF. The fastest time for POFBG fabrication is 15 ns [21,28,29], the duration of only one UV laser pulse, using a single mode (SM) PMMA-mPOF doped with *benzildimethylketal* (BDK) to enhance the photosensitivity of the core. When the fiber is irradiated by the appropriate wavelengths (about 250 nm and 344 nm) [30], the photo-polymerization process starts, with the BDK acting as a photo-initiator. Exploring the photosensitivity in those UV bands, in particularly around 250 nm where the spectral absorption is higher [30], is possible to use alternative UV sources for fast fabrication of POFBGs. Using this principle, the implementation of smaller dimension and cheaper lasers in the fabrication of POFBGs is increasingly important to develop simple and viable inscription systems and potentially reduce POFBGs fabrication costs.

In this paper, we report the inscription of POFBGs using only one pulse of the fourth harmonic of a Nd:YAG laser system (operating at 266 nm). This wavelength has been implemented before to fabricate Bragg gratings in SOF, through pulsed [31,32] and CW lasers [33]. Regarding the inscription of POFBGs, there are no data available until now, and we believe this is the first demonstration using this wavelength. The Bragg grating was inscribed with one pulse in a BDK-doped mPOF, with a pulse duration about 8 ns, which is to our knowledge the fastest photo-inscription time for POFBGs to date as well as the lowest pulse energy employed for this purpose.

## 2. Experimental setup

The optical fiber used to inscribe the POFBGs was a 3-ring hexagonal step index PMMA-mPOF with a BDK-doped core [34], manufactured at *DTU Fotonik*. The doping process was performed at 51.5 °C, improving the diffusion speed of the BDK and decreasing the time of the process [34]. Because of the smooth nature of the core, we believe the BDK is uniformly distributed in the core, without generating large scatterings. The average hole diameter and pitch in the fiber are 1.5  $\mu\text{m}$  and 3.79  $\mu\text{m}$ , respectively. Thus, the ratio of the hole diameter to the pitch was calculated to be 0.4, confirming that the mPOF is endlessly SM [35]. The diameters of the core and the cladding are 6  $\mu\text{m}$  and 150  $\mu\text{m}$ , respectively. The mPOF pieces of length about 20 cm were cleaved with a hot blade [36] and glued into FC/PC connectors in order to simplify the POFBG interrogation. Before the inscription, the mPOFs were pre-annealed during 24 hours at 70 °C to reduce the internal stress in the fiber originating from the fabrication process. This heat treatment reduces the POFBG sensor hysteresis and the inscription time and increases the grating stability [37,38], which can be further improved by also annealing the preform before drawing [39].

Figure 1 presents the inscription setup, based on the phase mask technique. A pulsed Q-switched Nd:YAG laser system (LOTIS TII LS-2137U Laser) lasing at the fourth harmonic (266nm) was employed to produce the POFBGs, using pump lamp repetition rate of 1 Hz and the Q-Switch mode as single shot. The laser beam profile is circular, the diameter is about 8 mm and the divergence is  $\leq 1.0$  mrad. The laser beam is focused onto the fiber core using a plano-convex cylindrical lens with effective focal length of 320 mm. The effective spot size of the beam on the fiber surface is 8 mm in width and about 30  $\mu\text{m}$  in height. Experimental setup was aligned and tested before the inscription in order to focus the UV beam onto the core of the fiber and obtain an effective POFBG inscription. A single 8 ns pulse with a pump energy of 23.6 J and measured pulse energy of 72  $\mu\text{J}$  was used to inscribe the grating in a pre-annealed PMMA-mPOF. It shall be noted that this pulse energy is the lowest value reported for the Bragg gratings inscription and it is several orders lower than the pulse energy used in the recent published reports using 248 nm laser system [21,28,29]. The phase mask employed

is 10 mm in length with a period of  $\Lambda_{PM} = 567.8$  nm, designed to operate at 248 nm. It can produce gratings in PMMA-POFs with the Bragg wavelengths around 844 nm. To monitor the grating spectrum in transmission and in reflection, a super luminescent diode (Superlum SLD-371-HPI) and an optical spectrum analyzer (Yokogawa AQ637B) were used. An 850 nm 50:50 ratio SM-silica optical coupler was used for monitoring the reflection spectrum.

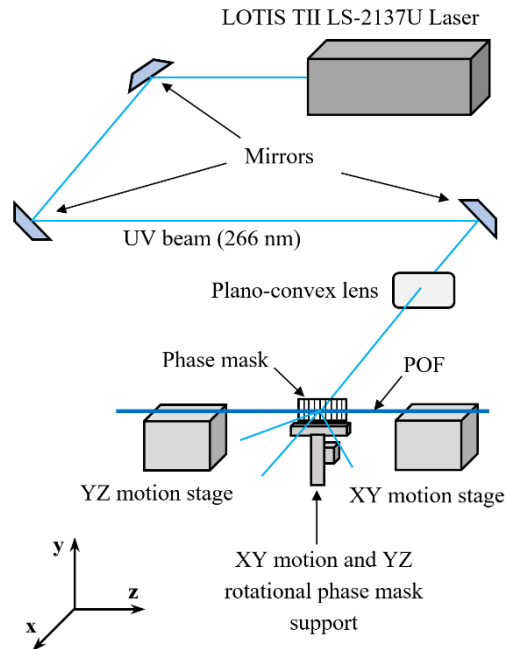


Fig. 1. Sketch of the experimental setup based on phase mask technique.

### 3. Results and discussion

The transmission and reflection spectra of the inscribed POFBG (with 8 mm in length) with a single 266 nm pulse is shown in Fig. 2. The Bragg wavelength is located at 840.460 nm, and shifted from 844 nm because the fiber was placed with some tension on the inscription setup [40]. Just after the illumination with a single laser pulse, the grating growth was almost instantaneous, reaching the saturation level in few seconds after the exposure. We believe the fast grating growth is due to the high concentration and uniform distribution of the dopant BDK in the core, since the saturation level of other POFBGs inscriptions using a single laser pulse [21] took several minutes. The reflective signal (green) has about 30 dB of reflective power and a Full Width at Half Maximum (FWHM) of 237 pm. The transmission rejection (red) is about 8 dB and the FWHM is 84 pm. Therefore, the grating reflectivity is approximately 84% and the maximum refractive index change in the core material is  $\Delta n = 0.5 \times 10^{-4}$ . By comparing these results to POFBGs in PMMA-mPOF doped with BDK inscribed with a single pulse from the KrF 248 nm laser [21,28], the reflectivity of the grating was lower, however, the pulse energy employed ( $72\mu\text{J}$ ) was also inferior (approximately by a factor of 87). When comparing to the results available regarding the production of POFBGs in the same mPOF [34], using a 400 nm femtosecond pulsed laser system, we achieved higher reflectivity in a much reduced inscription time.

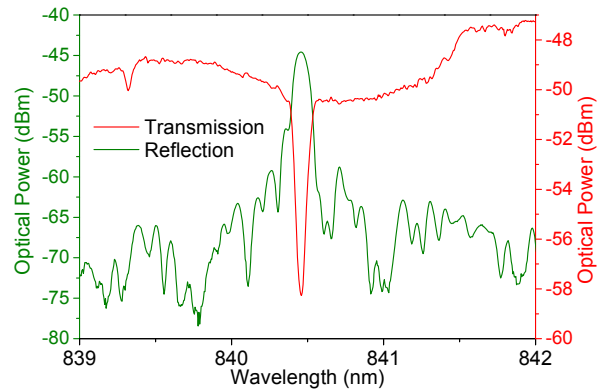


Fig. 2. Reflection/transmission spectra of the inscribed POFBG using a single pulse of 266 nm laser.

It is known that the necessity of keeping the laser and inscription setup stable for several minutes is critical to achieve stable gratings. Also, the reduction of the gratings inscription time can also improve the FBG stability [26]. In addition, the pre-annealing treatment made on the fibers can influence the grating stability. For this reason, the POFBGs transmission spectra were monitored for 40 days at room temperature (controlled environments conditions) to verify any instability on the grating strength, bandwidth and central wavelength. Figure 3 presents the results obtained for each POFBG in terms of grating strength, bandwidth and central wavelength, which were monitored over 40 days by measuring them every 2 days. Figures 3(a) and 3(b) show the gratings transmission spectra and bandwidth, respectively, whereas Fig. 3(c) presents the central wavelength of the POFBG. The results show a variation lower than 0.6 dB in the strength of the grating after 40 days. In addition, the bandwidth of the POFBG remains almost constant showing no significant change. For most sensing applications using FBGs, the change in the parameter to be monitored is related to the central wavelength variation, such stable wavelength (see Fig. 3(c)) enables the use of the presented setup for fast inscription of POFBGs in the monitoring of different parameters, in many different applications. It shall be noted that we inscribed more similar gratings and a very similar behavior was achieved.

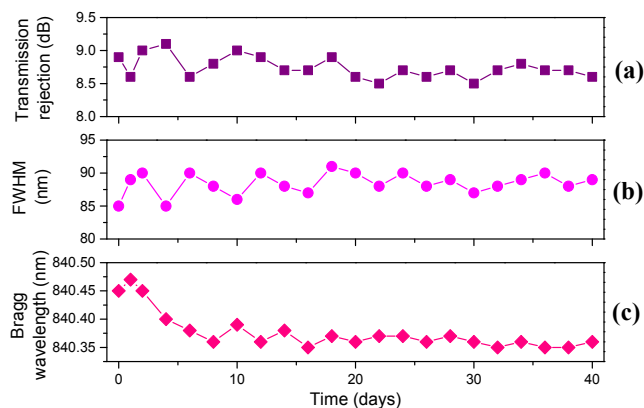


Fig. 3. Stability of BDK-doped POFBG after 40 days. (a) Gratings strength, (b) bandwidth and (c) central wavelength.

The temperature and strain response of the POFBG was studied to analyze the grating stability and sensing properties. Figure 4(a) shows the transmission spectra of the POFBG under different temperatures. The temperature was increased from 22 °C up to 52 °C, by steps of 5 °C. In each step, the temperature was kept constant over 20 minutes to ensure thermal stabilization and then the measurement was collected. Figure 4(b) shows the thermal tuning of the Bragg wavelength, and the obtained temperature sensitivity, after the linear fit, was  $-54.50 \pm 1.45$  pm/°C. From 22 °C up to 47 °C, the transmission rejection increased almost linearly with temperature, with a total variation of 2.13 dB.

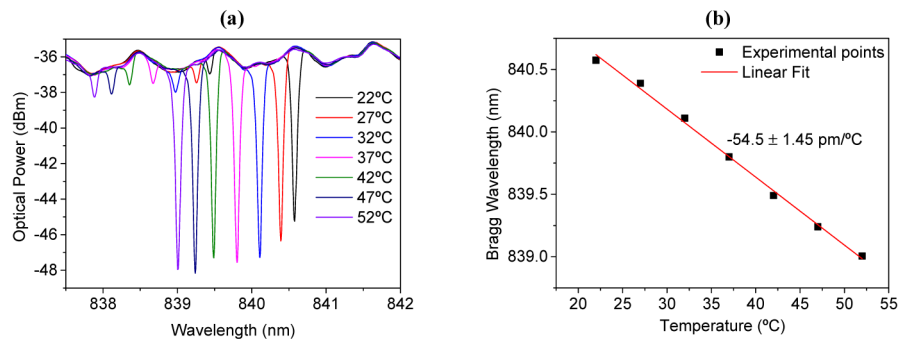


Fig. 4. (a) Transmission spectra of the POFBG at different temperatures; (b) Bragg wavelength tuning with increasing temperature.

The strain characterization was performed by fixing the fiber between a fixed and a manual translating stage, with 10  $\mu\text{m}$  resolution. The transmission spectra of the POFBG, when different percentages of strain are applied, are shown in Fig. 5(a). The fiber was stretched up to 1.26%, with 0.14% steps (5 min. to ensure stabilization), resulting in a total Bragg wavelength tuning of 8.9 nm. The displacement of the Bragg wavelength with increasing strain is presented in Fig. 5(b), and the obtained strain sensitivity was  $0.710 \pm 0.004$  pm/ $\mu\text{e}$ . Figure 5(c) shows the scattering of the measurement points around the fit line, from which the calculated standard deviation was found to be 48 pm. Improving precision in setting the fiber elongations can further decrease that result and the sensitivity error, which increases the measurement resolution. The transmission rejection during strain measurements had a nonlinear behavior and varied between  $-43.2$  dB and  $-44.7$  dB.



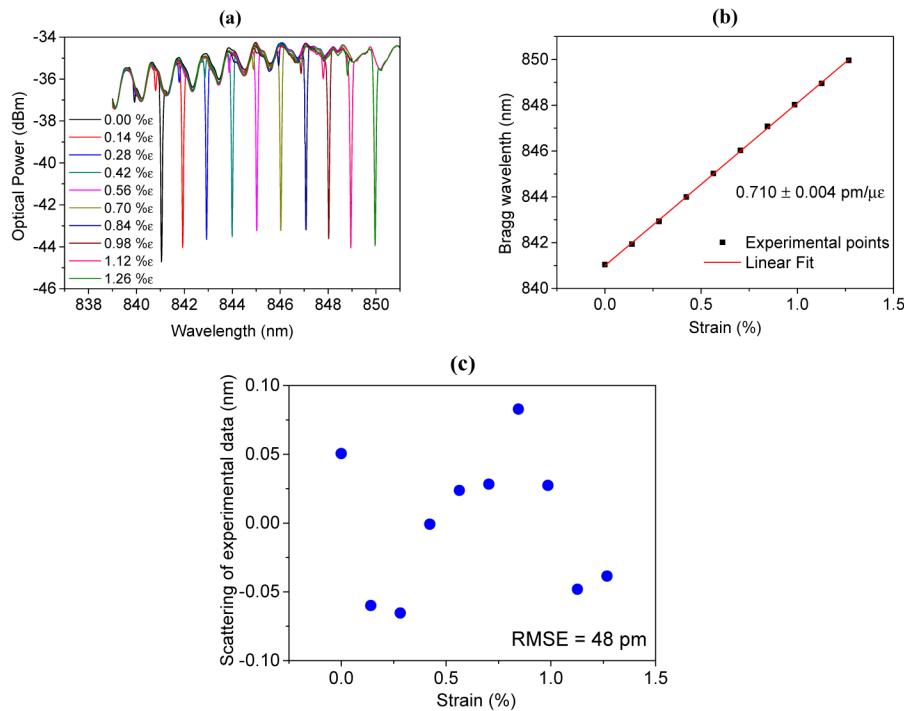


Fig. 5. (a) Transmission spectra of the POFBG at different strains; (b) Bragg wavelength tuning with increasing strain; (c) scattering of experimental points around the fit line with a Root Mean Square Error (RMSE) of 48 pm.

Cyclic testing was also performed to investigate any thermal and strain hysteresis during increasing and decreasing steps. Three full cycles were performed to compare the sensitivity range for increasing and decreasing response under different levels of strain and temperature. Table 1 summarizes the sensitivities obtained for each cycle and the associated hysteresis. All cycles show good approximations for increasing-decreasing sensitivities and a low level of hysteresis, i.e., the maximum difference in sensitivity between increasing and decreasing experiments.

Table 1. Sensitivity analysis for each cycle and hysteresis.

	Strain sensitivity		Strain sensitivity	
	Increasing (pm/ $\mu\epsilon$ )	Decreasing (pm/ $\mu\epsilon$ )	Increasing (pm/ $^{\circ}\text{C}$ )	Decreasing (pm/ $^{\circ}\text{C}$ )
Cycle 1	0.710	0.722	-54.5	-54.8
Cycle 2	0.725	0.719	-54.3	-53.9
Cycle 3	0.718	0.724	-54.7	-54.3
Maximum hysteresis		0.012		0.6

#### 4. Conclusions

In conclusion, we demonstrate for the first time a POFBG inscription in a BDk-doped PMMA-mPOF using a single low energy pulse from a Q-switched Nd:YAG laser system, operating at 266 nm. The grating exhibits more than 84% reflectivity, and a refractive index change of  $0.5 \times 10^{-4}$  in the core of the fiber. The POFBG stability after the inscription was analyzed by monitoring the grating strength, FWHM and central wavelength over 40 days, showing no significant changes in any of those parameters. Also, the strain and temperature sensitivities was studied and found to be  $0.710 \pm 0.004 \text{ pm}/\mu\epsilon$  and  $-54.50 \pm 1.45 \text{ pm}/^{\circ}\text{C}$ ,

respectively. The comparison of the POFBGs inscribed with the laser system presented in this work and with the KrF 248 nm laser system show a significant reduction in the pulse energy to obtain stable gratings using a single pulse. We believe the high concentration and the uniform distribution of the dopant contributed to the fast grating growth after the exposure. Nevertheless, the fiber reported in [41] and used in different works with the KrF 248 nm laser system [21,28,29], was tested with this laser (@266 nm) and we achieved Bragg gratings with identical spectral quality employing just one pulse (72  $\mu\text{J}$  –the lowest pulse energy to inscribe Bragg gratings in PMMA fiber). These results show the potential to reduce POFBG production costs, by employing cheaper laser systems (the laser system employed in this work is about 5 times cheaper when compared to the KrF 248 nm excimer laser system and the femtosecond laser system) and reducing the inscription time to a pulse width (in this case to 8 ns). In addition, the maintenance of the current laser system is much easier and cheaper. For example, it does not need a periodic supply of high-purity excimer gases as the KrF 248 nm laser system does. Furthermore, this report can bring new developments in different research groups around the world using alternative UV sources for fast fabrication of FBGs in different polymer materials.

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