Bragg grating writing in PMMA microstructured polymer optical fibers in less than 7 minutes

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Abstract: We demonstrate fiber Bragg grating (FBG) writing in PMMA microstructured Polymer Optical Fibers (mPOFs) using UV Phase Mask technique with writing times shorter than 10 min. The shortest writing time was 6 minutes and 50 seconds and the longest writing time was 8 min and 50 sec. The FBGs were written in a 125 µm PMMA mPOF having 3-rings of holes, the reflection peaks were centred at 632.6 nm and have a reflectivity as high as 26 dB. We also demonstrate how the writing dynamics depends on the intensity of the writing beam.

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1. Introduction

For the last three decades Fiber Bragg Grating (FBG) technology has been continuously developed and has matured enough to have its place among standard optical components in sensing [1], telecommunication and lasers [2]. FBGs are commercially produced in silica but in recent years a lot of research has been put into producing Bragg gratings in polymer optical fibers (POFs). As most polymers are intrinsically photosensitive, Bragg grating inscription in polymers is possible without doping. Several methods are used for writing Bragg grating in polymer fibers, such as point-by-point direct writing using a Ti:sapphire femtosecond laser [3], combination of the phase mask and ring interferometry [4, 5] and, the most commonly used, phase mask technique [6–9]. FBGs have been written both in step index polymers [4] and, in microstructured polymer optical fibers (mPOFs) [6]. Having FBGs in polymer fibers is a very promising technology due to several advantages polymers hold over silica. Some of these advantages are lower Young modulus, higher tensile strength and biological compatibility [10]; each of these properties open possibilities for various sensing applications. For example, silica fibers have a Young modulus of about 72 GPa [11] while an mPOF made of PMMA (polymethyl methacrylate) has a Young modulus around 2-3 GPa depending on the drawing conditions [12–15], which is about 30 times smaller than that of silica. The lower Young modulus is particulary advantageous when measuring large material stresses, bendings and strains under which silica fiber would normally break (applications such as sensing of airplane wings during the flight).

However, PMMA has a low melting temperature and a high water absorption which means that FBG sensors made of PMMA have a strong humidity dependence. Measures have to be taken to reduce sensitivity to humidity. This issue has been addressed by Yuan et al. where FBGs were inscribed in mPOF made of TOPAS (cyclic olefin copolymer) [16], a photosensitive [17], humidity insensitive polymer that can have a higher operating temperature [18]. Another downside commonly attributed to the plastic fibers is a low light transmission in comparison with silica fibers. However, for many sensing applications such as accelerometers or microphones [19] this does not pose a considerable drawback. FBG mPOF sensors are typically of short length, and limitations in transmission can be addressed by combining silica and polymer fibers [19]. But because of the high transmission losses at telecommunication wavelengths, there is a drive towards making FBG at visible wavelengths.

G. Statkiewicz-Barabach et al. [7] have demonstrated 1550 nm Bragg gratings with several higher order gratings, where one of the higher order gratings was centred at 659 nm. Carlos A.F. Marques et al. [20], have also demonstrated FBGs at visible wavelengths, they managed to write a FBG at around 600 nm by making 10 mm long gratings in a few moded mPOF. For sensitivity reasons single mode mPOFs are preferred.

Fabrication of Bragg gratings in mPOFs with the phase mask technique is a time consuming process. In mPOFs exposure times from 60 to 270 minutes have been reported [8, 9, 21], for up to 10 mm long gratings, while for the step index fibers times are shorter and typically amount to 45 to 100 minutes [5, 8, 9] with the lowest inscription time reported being approximately 20 minutes [20]. The writing time can be reduced by doping the fiber [22] but doped fibers are more difficult to fabricate, the transmission loss increases and they are less suitable for in-vivo biosensing. In this work we report on the fabrication of FBGs using the phase mask technique in mPOFs having a reflection peak strengths of up to 26 dB and written in less than 7 minutes. Short writing time is important for grating stability and is an important step towards (commercial) on-draw tower writing of FBG in mPOFs. The fabricated gratings have a reflection peak at 632.6 nm on average and are written into a 3-ring PMMA single mode mPOF fabricated at DTU Fotonik.

2. FBG writing setup

The technique we use for inscribing FBGs is the most commonly used phase mask writing technique. A 30 mW HeCd CW laser (IK5751I-G from Kimmon) operating at 325 nm is used for grating inscription. The laser light with a circular Gaussian beam profile and a diameter of approximately 3 mm, was directed through a series of 4 mirrors arriving at the focusing lens. The focusing lens is a plano-convex cylindrical lens (LJ4862-UV from Thorlabs) with a focal length of 25 mm, however the operational backfocal length was found to be 18.65 mm at 325 nm. The lens is focusing the beam through the phase mask down on to the fiber, which was lying about 100 μm below the phase mask. The focal line width was calculated to be about 4 μm. The phase mask has a size of 30 mm x 25 mm x 2 mm, a uniform pitch of 424.84 nm and was custom made by Ibsen Photonics, claiming less than 15% transmission in the 0th order, for writing of 650 nm FBGs using 325 nm laser light.
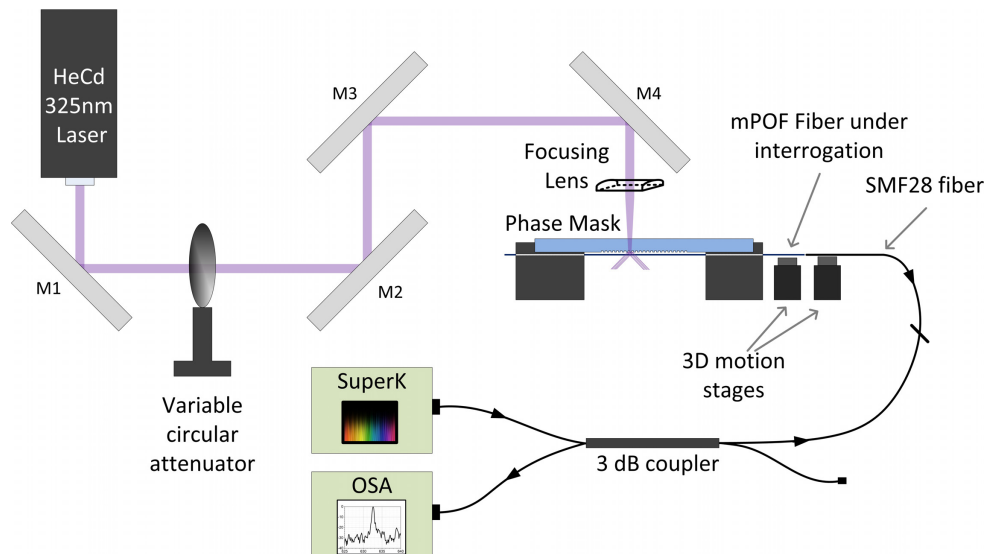

Fig. 1. Sketch of a writing and interrogation setup.

A sketch of the setup can be seen in Fig. 1. In order to find the optimal distance between the lens and the phase mask, a slide of fused silica glass with the same dimensions as the phase mask was obtained from Ibsen Photonics. The silica glass was used to create a mirror;

approximately 25 nm thick layer of Aluminum was deposited on one side of silica glass using e-beam deposition. The mirror was used to focus the beam precisely at the bottom of the silica glass, which was visible in the backreflection by matching the original and reflected beams on a pinhole paper attached to one of the mirrors. After removing the silica glass mirror and placing the phase mask back in the holder, the focus was shifted an additional approx. 175 µm further down, which is the optical distance between the phase mask and the core of the fiber.

In comparison with step-index fibers, mPOFs are suffering from long writing time due to their microstructured configuration, which scatters the light from the UV laser [23]. Due to this added scattering, it is necessary that the focus of the writing beam is well aligned with the core of the fiber.
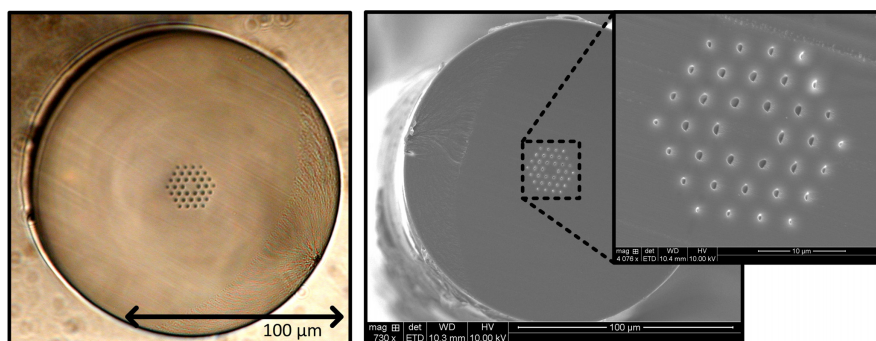

Fig. 2. Microscope image and Scanning Electron Microscope (SEM) image of the fiber facet.

The fiber used in this experiment is an mPOF, fabricated in-house at DTU Fotonik using a polymer draw tower. Commercially available 7 cm PMMA rods were obtained from Nordisk Plast A/S. The rods were machined down to a length of 10 cm and a diameter of 6 cm. The desired 3-ring hole structure was drilled into the preform. The preform was drawn down to canes with a diameter of approximately 5-6 mm. The canes were subsequently sleeved (stacked up inside extra tubes in order to increase their diameter) then drawn again, this time down to a fiber with a diameter of approx. 125 micron. A microscope image and Scanning Electron Microscope image of the resulting end facet is given in Fig. 2 which shows the cleave made by a fiber cleaver fabricated in-house [24] at 65° C temperatures of both blade and fiber holder. The final optical fiber has a hole size of 1 µm and the pitch (the hole to hole distance) of 3.75 µm. The hole to pitch ratio is 0.26 ensuring that the fiber is endlessly single mode [25]. The fiber has a propagation loss of around 10 dB/m at 630 nm (see Fig. 3). Note that the holes in the microscope image appear larger due to the diffraction limitations of the optical microscope. This effect has most likely caused overestimation of hole sizes in past fibers but, although the holes are smaller than previously reported fibers, the hole to pitch ratio is not particularly lower.

A SuperK white light source from NKT Photonics A/S was used to interrogate the mPOF. The output fiber was connected to a 650 nm 3dB coupler and, via a connected SMF28 fiber, the light was launched into the mPOF. Index matching oil was put in the space between the SMF28 and the interrogated mPOF to reduce reflections and thereby minimize the noise. The light reflected from the FBG was coupled back through the 3 dB coupler and finally to the optical spectrometer (Ocean Optics HR2000) or Optical Spectrum Analyzer (OSA, Ando AQ6315A). For fast monitoring of the FBG growth dynamics the optical spectrometer was used, while for accurate spectrum recording, the OSA was used.
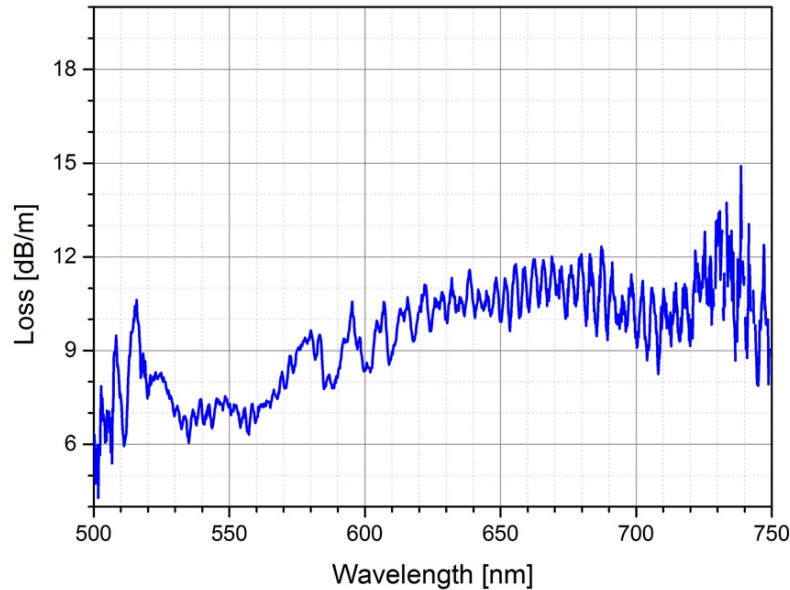
Fig. 3. Transmission loss of 3-ring PMMA fiber used in experiments.

3. Bragg grating inscription and results

To monitor the grating inscription, i.e. to track and record the peak growth, a LabView controlling software routine for the Ocean Optics Spectrometer was developed. As the spectrometer has a linear scale and a 12-bit analog to digital converter, the integration time had to be changed each time the signal was approaching the limit of 4096 counts. This means that in the output data, a proper scaling was made by scaling the different integration time slices to obtain a smooth curve. The resulting curves are presented in Fig. 4.

Last section of most of the curves seem noisy, as does the first section of the curve growth. This is due to the repositioning of the SMF28 fiber with respect to the mPOF. Repositioning had to be made in order to optimize the core coupling. At the beginning, as soon as the reflection peak was spotted, an optimization alignment was made. An additional realignment was made just after the laser writing was stopped in order to find the strongest peak reflection.

As the dynamic range of the Ocean Optics spectrometer is low, the final spectrum was taken with the Ando AQ6315A (OSA), in order to obtain a correct noise floor and peak strength. Since the relative growth observed with the Ocean Optics spectrometer was correct, the corresponding growth curves were scaled in whole to the final spectrum obtained by the OSA, the corresponding final spectra are shown in Fig. 5.

In Fig. 4 six grating growth curves are presented. Curves *a*, *b*, and *c* represent 3 fibers which had Bragg gratings written with maximum power from the laser, while the fibers *d*, *e* and *f* had gratings written with a circular attenuator inserted in the beam path, attenuating the laser light to approximately 72% of the initial power. In Fig. 5 the final reflection spectra are given normalized to 0 dB at the highest peak for easier comparison. All the gratings have a reflection peak centered at 632.6 nm. With our setup we were able to inscribe Bragg gratings in 125 μm PMMA fibers consistently in less than 10 minutes. The fastest writing time, the time between opening the shutter of the laser and reaching the saturation region (shown with arrows in the Fig. 4), is around 6 minutes and 50 sec, with a grating reflection strength of 26 dB (fiber *a*).
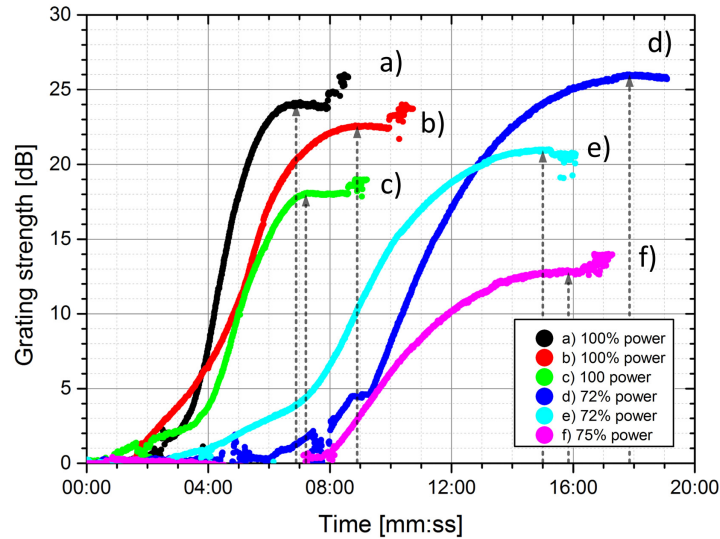
Fig. 4. Curves showing growth of the Bragg reflection with respect to time. FBGs *a*, *b* and *c* are written at full laser power while FBGs *d*, *e* and *f* are written at lower power. Arrows are showing the highest peak of the saturation region.
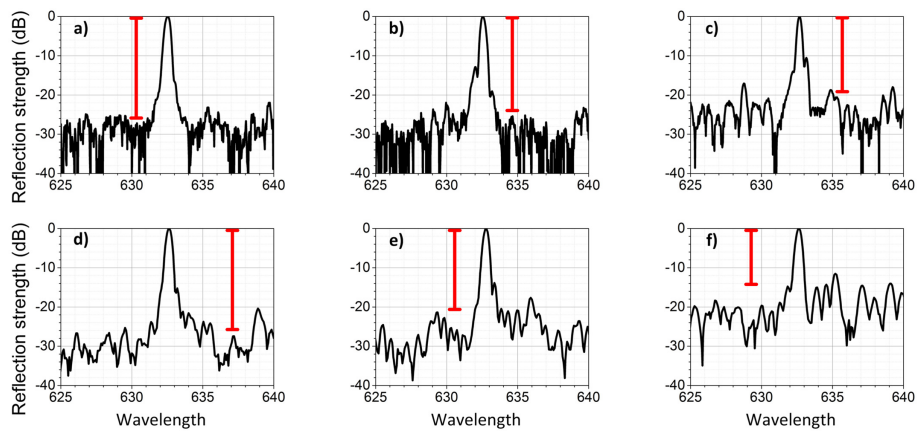

Fig. 5. Bandwidths of fibers written at full laser power (100% power, *a*, *b* and *c*) and fibers written at lower laser power (72% power, *d* and *e*, 75% power *f*), presented at Fig. 4.

While there does not seem to be a correlation between the grating reflection strength and the power, there is a strong dependence on power for the writing times and the rate of grating growth. Additionally, it was observed that with lower writing power, the threshold (the time when the grating peak is firstly observed) is shifted as well. That implies that some internal processes might be taking place in the fiber before the grating inscription actually starts. In each curve, it is noticeable that once the peak appears, the growth rate increases rapidly, especially in that initial period. Later on, at around half of the maximum reflectivity, the growth rate begins to slow down. As the grating approaches saturation the growth rate rapidly decreases.

Table 1. Comparison of growth rates and final quality of the reflection peaks for the 6 fibers investigated in Fig. 4.

	Growth Rate (10-90%)	Saturation Time (mm:ss)	FWHM	Grating strength
a)	7.9 dB/min	06:50	0.4 nm	26 dB
b)	3.99 dB/min	08:50	0.35 nm	24 dB
c)	3.7 dB/min	07:10	0.3 nm	19 dB
d)	3.18 dB/min	17:50	0.4 nm	26 dB
e)	2.47 dB/min	15:00	0.4 nm	21 dB
f)	2.1 dB/min	15:50	0.425 nm	15 dB

Regarding the quality of grating reflections, the results are summarized in Table 1. The fiber *a* has a clean noise floor, which is attributed to shorter exposure after the saturation region was reached. For some fibers, not presented here, a clear connection was observed between the writing time after the saturation was reached and the quality of the final reflection peak. Although the writing time is shortened because of the increased laser intensity, the gratings are not significantly stronger. Grating peaks are observed with various strengths: similar final spectra of around 20 dB are obtained by other research groups or by our group with different setup [5, 7, 8, 18, 20, 24].

There are two factors that are very important for the writing time, which are the intensity of the laser beam and the careful alignment to the core of the fiber. In the FBG writing setup used earlier by our group [8, 9, 15, 16, 18, 19, 24, 26] and by other groups [6] there was an additional cylindrical lens (at the position of the circular attenuator), which was expanding the beam in order for the illuminated region on the fiber (FBG) to be longer. That lens has now been removed, which effectively increased the laser intensity in the now smaller, 2-3 mm long, illuminated region. To estimate quantitatively the change in intensity entering the fiber, the laser beam size just above the fiber was measured both with and without the first lens. With the first lens, the beam reaching the fiber was about 15 mm long (part of the beam was blocked by the second lens holder), while without that first lens it is now 3 mm long. Additionally, the attenuation of the first lens was measured to be about 0.8 dB. Taking both effects into account, the light entering the fiber is 7-8 times more intense after removing the first lens. The second important factor is a precise alignment of the focus to the center (core) of the fiber. Here the lateral movement can easily be seen looking at the laser light reflected from the fiber [23], while the medial alignment is more difficult to achieve.

4. Conclusion

In this work we demonstrated a significant reduction in fiber Bragg grating writing times in undoped fiber. With our grating writing setup we were able to write a 26 dB grating in a single mode 3-ring PMMA mPOF in less than 7 minutes. The fastest writing time was 6 minutes and 50 seconds, which is about 10 times shorter than what was registered before for mPOF using UV phase mask technique. The gratings are centered at 632.6 nm and have a FWHM of 0.3-0.4 nm which, to our knowledge, is the lowest wavelength fundamental mode Bragg grating in mPOF. We have demonstrated a dependency between grating writing times and laser power showing that fast writing times require more intensity in the core. To our knowledge, this is the fastest FBG writing time as well as strongest FBG reported in mPOF using UV phase mask technique.