Continuous wave ultraviolet light-induced fiber Bragg gratings in few- and single-mode microstructured polymer optical fibers

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We report observations and measurements of the inscription of fiber Bragg gratings (FBGs) in two different types of microstructured polymer optical fiber: few-mode and an endlessly single mode. Contrary to the FBG inscription in silica microstructured fiber, where high-energy laser pulses are a prerequisite, we have successfully used a low-power cw laser source operating at 325 nm to produce 1 cm long gratings with a reflection peak at 1570 nm. Peak reflectivities of more than 10% have been observed. © 2005 Optical Society of America

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Over the past 15 years, fabrication techniques for fiber Bragg grating (FBG) inscription have advanced dramatically, facilitating the development of highly accurate and versatile FBG filter designs in a step-index single-mode silica fiber, with applications predominantly in telecommunications and optical fiber sensing.[1] In the past few years there has been growing interest in the potential that polymer optical fiber (POF) has within these fields; due to lower infrastructure costs, and that POF may be fabricated from a range of materials with different physical and chemical properties, POF is inherently biocompatible. The majority of the currently produced POF is based on polymethlymethacrylate (PMMA), a material that has been shown to be photoreactive.[2,3] Only recently has single-mode POF become available[4] and single-mode POF-based FBGs offer the prospect of significant advantages over silica-based devices for certain applications. For example, POF can withstand and measure much higher strains than are possible with silica fiber and possesses higher temperature sensitivity.[5] Continued POF development has focused on photonic crystal and microstructured designs, with considerable progress in the manufacture of microstructured POF (mPOF).[6] The geometry of this type of fiber provides it with radically different properties compared to a step-index fiber, such as an endlessly single-mode and air-guiding operation, or the ability to expose the electric field of the guided mode to substances contained within the holes. It is clearly attractive to be able to combine this new technology with grating-based devices, which is the motivation for the work reported here.

The microstructured geometry offers a particular challenge in terms of the grating inscription. For FBG production in step-index fibers, it is usual to focus the writing beam down into the fiber core; however, the presence of several rings of holes surrounding the core in the microstructured fiber scatter the incident beam, leading to a significant reduction in the optical intensity in the core region. Recent success in fabricating FBGs in a microstructured silica fiber with a small germanium-doped core[7] and in a pure silica microstructured fiber[8] by using a pulsed 193 nm laser, and inscription in undoped silica microstructured fiber by using a 267 nm femtosecond laser,[9] have provided confidence that this effect did not necessarily preclude grating inscription, but that high-energy pulses were always deemed necessary to compensate for the reduction in the optical intensity through hole-induced scattering.

This Letter reports for the first time, to our knowledge, on FBGs inscribed into few-mode and an endlessly single-mode mPOF, by using a low-power cw laser source.

The fiber used in this work was made from a PMMA primary preform of 70 mm diameter, into which the desired pattern of holes was drilled (Fig. 1).[6] The primary preform was drawn to a diameter of 12 mm to form the secondary preform that was itself drawn to the fiber directly. In mPOF fabrication the secondary preform is usually sleeved to increase its outer diameter. This step was omitted here to minimize the amount of material surrounding the structure and hence minimize UV absorption outside the core region.

The few-moded mPOF had an outside diameter of 160 μm and a core diameter of 13 μm; the core was surrounded by 60 air holes with diameters of 5.5 μm and a separation of 10 μm, which gave the ratio of hole diameter to spacing, d/Λ, as 0.55 (Fig. 1).

The ends of both mPOFs were cut using a cold sharp razor blade to create a flat end face. POF in general has significantly less mechanical rigidity

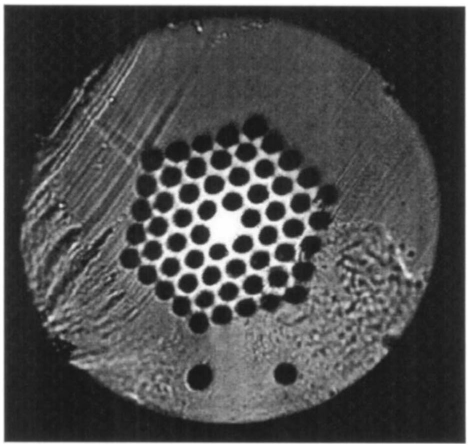

Fig. 1. Optical microscope image of the cross section of the few-mode mPOF.

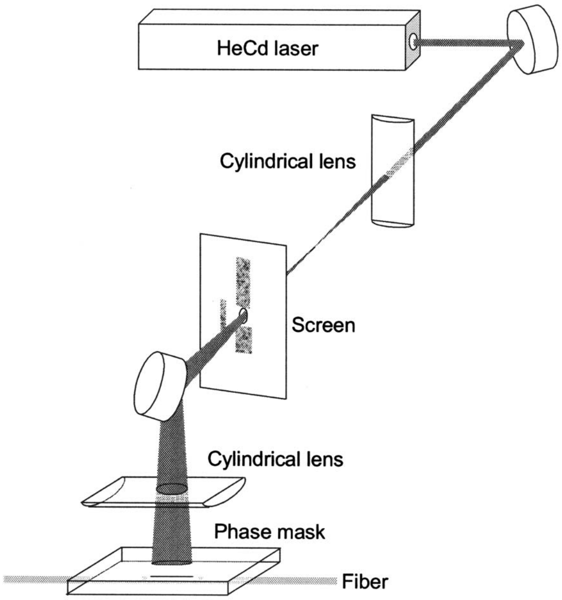

Fig. 2. Experimental arrangement.

compared with the glass fiber and so a special support was constructed. An 11.4 cm length of mPOF was mounted in v grooves, which were attached to two x, y, z translation stages, allowing for the adjustment of the fiber position. The v grooves were necessary to provide adequate mechanical support to the mPOF and to minimize the effects of air currents on the fiber position relative to the inscription laser beam. FBG inscription was undertaken using the standard phase mask technique utilizing a mask with a pitch of 1060.85 nm designed to produce a FBG in silica at $\sim$1536 nm. A cw helium–cadmium (He–Cd) laser with an output wavelength of 325 nm and a power of 30 mW was used to inscribe the FBGs. Two plano–convex cylindrical lenses with 10 cm focal lengths were incorporated in the system, one in the usual position before the phase mask, which served to focus the light down toward the core, and the other at a distance of 56.5 cm from the mPOF. The second lens was used to expand the 1.8 mm diameter laser beam to cover approximately 1 cm of the mPOF. See Fig. 2 for the experimental arrangement.

The orientation of the fiber geometry with respect to the incident laser beam proved to be critical for FBG fabrication in mPOF. Whereas in a step-index fiber the system alignment affects the quality of the grating, incorrect alignment of the mPOF during FBG inscription can completely prevent grating inscription; it is essential that the fiber is correctly oriented rotationally about its axis with respect to the incident beam. Inspection of the backreflections of the He–Cd beam from the mPOF revealed two different diffraction patterns as the fiber was rotated: one thin and bright, and the other broad and dull. It was found to be essential that the backreflection was thin and bright for inscription. Examples of the two patterns can be seen in Fig. 3. The successful bright diffraction pattern is likely to coincide with the laser beam being incident on the ΓM (flat side of the hexagon) axis of the photonic crystal structure because this orientation causes less light scattering.[10]

Moreover, successful inscription demanded careful control of the separation between the phase mask and the fiber. A separation of $\sim$80 μm worked well, whereas a distance of 20 μm also led to fringes being recorded within the holey region of the fiber; in this case, the reflection profile was irregular and highly dependent on launching conditions.

Having aligned the mPOF with the incident beam, light was coupled into the fiber to monitor grating growth. A single-mode fiber (SMF) 2×2 50:50 coupler designed to operate in the telecommunications C band was used so that the grating could be monitored in reflection. Backreflections were eliminated from one of the coupler arms, while the other arm had an angled pigtail spliced onto it, which was then aligned to the launch end of the mPOF (an index matching gel minimized any Fresnel reflections and improved coupling to the mPOF). Grating growth was monitored in reflection with illumination from an ASE light source (Thorlabs ASE-FL7002-C4, 5 mW output power, operating wavelength range of 1530–1610 nm) and an optical spectrum analyzer (OSA).

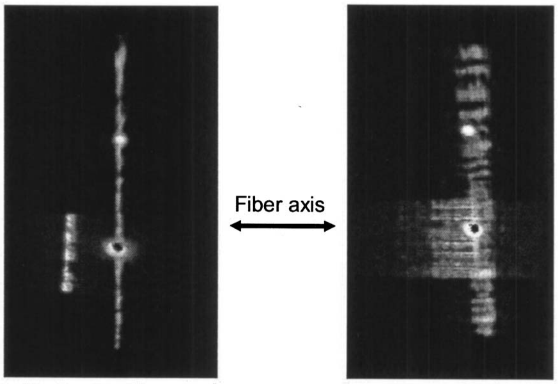

Fig. 3. Backscattered diffraction patterns of the He–Cd laser viewed by fluorescence; the pattern on the left was needed for successful inscription. Note that for clarity in the images, the fiber has been twisted slightly to shift the backscatter off the core region to the left of the main pattern; for correct alignment these would be superimposed. The orientation of the pattern is indicated on the screen in Fig. 2.

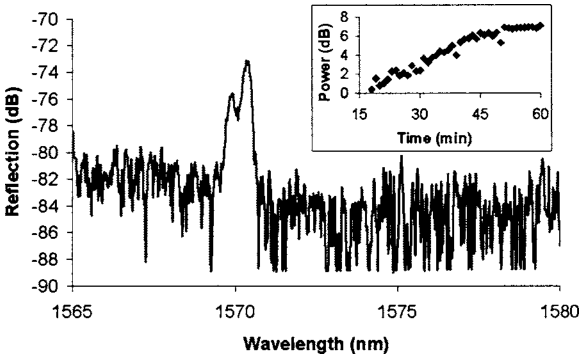

Fig. 4. Reflection profile of FBG fabricated in few-moded mPOF. Inset, growth of signal-to-noise ratio.

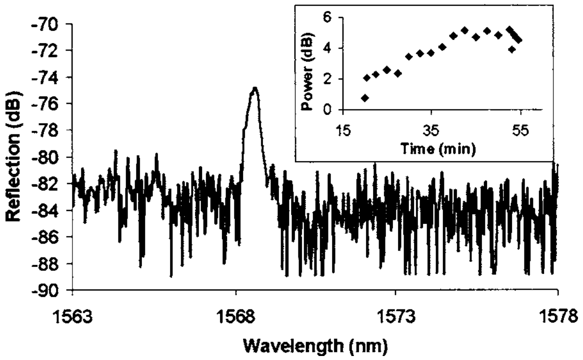

Fig. 5. Reflection profile of FBG fabricated in SM mPOF. Inset, growth of signal-to-noise ratio.

Inscription was initially attempted with the few-mode mPOF due to easier coupling into this fiber. Exposure lasted for 60 min at a room temperature of 29°C before saturation of the grating occurred. The resulting FBG had a Bragg wavelength of 1570 nm, a full width at half-maximum (FWHM) of 1 nm, a length of 1 cm, and a reflective power above the noise level of 7 dB. The grating profile (OSA bandwidth =0.2 nm) and the growth characteristics are shown in Fig. 4. Evidence for the few-mode structure of the reflectivity profile can be clearly seen.

The return signal comparable with the Fresnel reflection from the end of the fiber launching light into the POF in the absence of an index matching gel. The attenuation of the POF at the grating wavelength is ~72 dB/m; consequently, the 3 cm distance to the grating from the input face of the POF implies that the reflectivity of the grating will be at least 10%. The actual value should be higher since this calculation fails to take into account losses in coupling from the silica fiber to the POF. Possibly due to the high fiber attenuation at these wavelengths, it was not possible to observe the grating in transmission.

The second fiber investigated had a single-mode operation. The geometry of the holes was maintained but the diameters reduced to 2.7 μm with the separation changed to 8.8 μm, resulting in d/Λ being 0.31, leading to endlessly single-mode behavior. The inscription of the mPOF was then conducted by using exactly the same experimental conditions and alignment as previously described. The resulting FBG had a Bragg wavelength of 1569 nm, a FWHM of 0.5 nm, a length of 1 cm, and a reflective power above the noise level 2 dB less than that in the few-mode fiber. The slight difference in Bragg wavelengths between the two fiber types is most likely caused by a fractionally different strain being applied to the mPOF while mounting the fiber for fabrication. The grating profile (OSA bandwidth of 0.2 nm) and the growth characteristics are shown in Fig. 5.

We have demonstrated for the first time, to the authors' knowledge, the feasibility of inscribing FBGs in mPOF. We have initiated work to characterize their behavior, but clearly much still needs to be done. Our primary goals are to increase the grating strength, probably through the addition of dopants to the PMMA, and to characterize the long-term properties of the gratings, particularly at elevated temperatures. A move to shorter wavelengths, where the attenuation is much reduced, is also desirable.

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References

1. A. Othonos and K. Kalli, *Fiber Bragg Gratings, Fundamentals and Applications in Telecommunications and Sensing* (Artech House, 1999).
2. W. J. Tomlinson, I. P. Kaminow, E. A. Chandross, R. L. Fork, and W. T. Silfvast, Appl. Phys. Lett. **16**, 486 (1970).
3. M. J. Bowden, E. A. Chandross, and I. P. Kaminow, Appl. Opt. **13**, 112, (1974).
4. H. B. Liu, H. Y. Liu, G. D. Peng, and P. L. Chu, IEEE Photon. Technol. Lett. **16**, 159 (2004).
5. H. B. Liu, H. Y. Liu, G. D. Peng, and P. L. Chu, Opt. Commun. **219**, 139 (2003).
6. G. Barton, M. A. van Eijkelenborg, G. Henry, M. C. J. Large, and J. Zagari, Opt. Fiber Technol. **10**, 325 (2004).
7. B. J. Eggleton, P. S. Westbrook, R. S. Windeler, S. Spälter, and T. A. Strasser, Opt. Lett. **24**, 1460 (1999).
8. N. Groothoff, J. Canning, E. Buckley, K. Lyttikainen, and J. Zagari, Opt. Lett. **28**, 233 (2003).
9. L. B. Fu, G. D. Marshall, J. A. Bolger, P. Steinvurzel, E. C. Magi, M. J. Withford, and B. J. Eggleton, Electron. Lett. **41**, 638 (2005).
10. P. Domachuk, H. C. Nguyen, B. J. Eggleton, M. Straub and M. Gu, Appl. Phys. Lett. **85**, 1838 (2004).