Narrow Bandwidth 850-nm Fiber Bragg Gratings in Few-Mode Polymer Optical Fibers

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***Abstract*—We report on the inscription and characterization of narrow bandwidth fiber Bragg gratings (FBGs) with 850-nm resonance wavelength in polymer optical fibers (POFs). We use two fibers: an in-house fabricated microstructured POF (mPOF) with relative hole size of 0.5 and a commercial step-index POF, which supports six modes at 850 nm. The gratings have been written with the phase-mask technique and a 325-nm HeCd laser. The mPOF grating has a full-width at half-maximum (FWHM) bandwidth of 0.29 nm and the step-index POF has a bandwidth of 0.17 nm. For both fibers, the static tensile strain sensitivity is measured to be 0.71 pm/$\mu\varepsilon$ at 850 nm and 1.3 pm/$\mu\varepsilon$ at 1550 nm.**

***Index Terms*—Fiber Bragg grating (FBG), polymer optical fiber, fiber-optic sensors.**

I. Introduction

FIBER-OPTIC sensors based on Fiber Bragg Gratings (FBGs) have many important industrial applications [1], [2]. The fiber material of choice in industrial applications has so far been silica, because of its low loss and resistance to high temperatures. Polymer optical fiber (POF) FBGs have been used for strain and temperature measurements because of the low Young's modulus, high failure strain, and high thermal sensitivity of polymer compared to silica [3]–[8]. The POF FBGs reported until recently had a resonance wavelength around 1550 nm, primarily because of the availability of cheap telecommunications equipment at that wavelength. However, in contrast to silica fibers, POFs made of for example standard poly(methyl methacrylate) (PMMA) [9] and Topas [10], [11] have very high losses of more than 100 dB/m around 1550 nm. This makes it hard to work with POFs at the telecommunication wavelengths, unless using very short sections of fiber.

A considerable decrease in the material loss to about 2 dB/m can be achieved by working at a lower wavelength [7], [9]. In particular, the 2 dB/m target is possible at 850 nm at which CMOS (complementary metal-oxide-semiconductor) technology is available. For this reason there is currently a strong push in the sensor and interrogator community to develop devices at 850 nm. A 962 nm FBG has been written into a POF [12], but at this wavelength the loss of standard PMMA and Topas is still significant and the FBG suffered from a large zeroth-order component of the phase mask used in the writing process.

More importantly, it was recently reported that a 827 nm FBG could be written into a polymer fiber using a 30 mW 325 nm HeCd CW Laser and writing times around 2 hours through a phase-mask with period 557.20 nm [13]. The fiber was a multimode microstructured POF (mPOF) from Kiriama Pty Ltd, Sydney, Australia, with a large core diameter of 50 μm and 3 rings of holes. The loss was not quoted. The authors reported on prior problems with writing FBGs in both POFs and mPOFs, which they solved for the mPOF by adjusting the distance between the fiber and the phase-mask [13]. In the successful 827 nm writing experiment, the mPOF had a quite large core diameter. This makes it easier to write an FBG into the mPOF, which is otherwise very difficult due to the scattering of light at the air-polymer interface at all the holes [4]. However, the large core unfortunately makes the fiber heavily multimoded, which combined with a relatively short grating length of 1.8 mm, made the spectrum broad, with a full-width at half-maximum (FWHM) bandwidth of 2.45 nm.

For sensing applications narrow bandwidth FBGs and single-mode operation is important. This means that the core diameter of the mPOF is small and it is difficult to fabricate an FBG. Here we report the fabrication of narrow bandwidth 850 nm FBGs in both few-mode POFs (bandwidth 0.17 nm) and mPOFs (bandwidth 0.29 nm).

II. Grating Writing and Loss Measurements

The FBGs have been written using a phase-mask and a 30 mW 325 nm CW HeCd laser (IK5751 I-G, Kimmon) as in [13]. We expanded the beam to 1.2 cm with a cylindrical lens along the direction of the fiber axis and focused it in the orthogonal direction with a second cylindrical lens into the core. The pattern imprinted into the fiber was determined by the phase mask (Ibsen Photonics), placed just above the fiber, whose period of 572.4 nm was optimized for polymer fibers to give 850 nm gratings in the CMOS window.

We used two fibers. (1) a PMMA mPOF that we fabricated ourselves, with 3 rings of holes separated with a pitch of 6 μm and a hole size of 3 μm (see Fig. 1). The relative hole size of 0.5 means that the mPOF is few-mode at 850 nm [14]. (2) a commercially available PMMA step-index POF, which has a polystyrene doped PMMA core (MORPOF02, Paradigm Optics). The fiber has a quoted numerical aperture (NA) of 0.27 at 1300 nm and closer inspection shows that the core is not circular, but elliptical, with a diameter of 2 μm along the short axis and 6 μm along the long axis (see Fig. 1). The normalized frequency $V = (2\pi a)/(\lambda)\mathrm{NA}$, where a is the core radius, is then 2.606 at 1300 nm if considering an average core radius of 4 μm.

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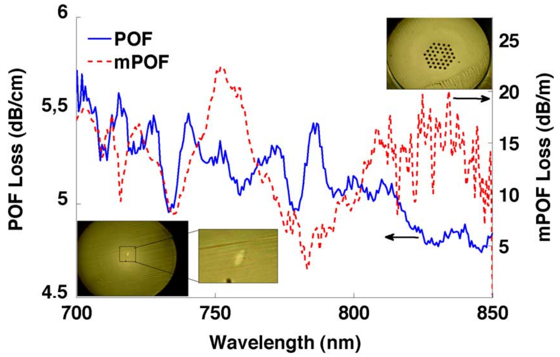

Fig. 1. Loss profile of the mPOF (red dashed line) and the step index POF (blue solid line) with insets showing the fiber end facets.

Scaling for 850 nm the V number becomes 3.98, which indicates that the fiber will support 6 modes at 850 nm. Few-mode POFs and mPOFs have been used successfully before for FBG inscription before, so we anticipate to obtain a reasonably clean reflection spectrum [4].

Before focusing on the FBG writing, we report in Fig. 1 the losses of the two fibers. The loss for the commercial POF has been given by the manufacturer to be 3 dB/cm at 1550 nm, 1 dB/cm at 1000 nm, and less than 0.2 dB/m at 650 nm. Our cutback measurement revealed that the loss was much higher than that. It was so high that we could not use pieces longer than 20 cm and had to settle for only 3 cuts in the cutback measurement. The small number of cuts and the fact that the fiber is multimode at 850 nm means that the loss spectrum has significant oscillations. Nevertheless, we can conclude that the fiber loss is above 100 dB/m even at short wavelength, which explains the fact that nobody were able to write good FBGs in this fiber so far.

The loss of the mPOF, as obtained by a cutback measurement with 14 cuts, is shown in Fig. 1. The mPOF is made from cheap PMMA from Vink with nonoptimal preform fabrication conditions. The measured 10 dB/m loss at 850 nm is thus significantly higher than the record mPOF loss of about 2 dB/m at 850 nm [7]. Nevertheless, 10 dB/m is more than an order of magnitude lower than the loss of the commercial POF. Further optimization in terms of cooling liquid used for preform drilling and proper washing and drying in clean atmosphere after drilling, are underway.

For the characterization of the FBG reflection spectrum we use an 850 nm circulator. The first arm of the circulator was connected to a SuperK Versa broadband source from NKT Photonics A/S. The broadband signal was then butt-coupled to the fiber from the second arm of the circulator. The reflection was collected and measured at the third arm of the circulator with an Optical Spectrum Analyzer (Ando AQ6317B).

The measured reflectance spectra, recorded with -18.5 dBm output power from the SuperK source, are shown in Fig. 2. The spectrum for the mPOF (POF) was recorded before saturation after a writing time of 185 min. (60 min.), where both FBGs show a normalized reflected power of about -40 dB, which includes coupling loss and fiber propagation loss. The longer writing time for the mPOF is due to the strong scattering of light at the holes, which significantly reduces the power reaching the core.

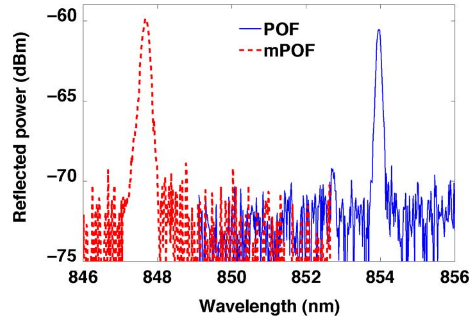

Fig. 2. Reflection spectrum of mPOF (red dashed line) and POF (blue full line) FBGs. The spectrum for the mPOF (POF) was recorded after a writing time of 185 min. (60 min.).

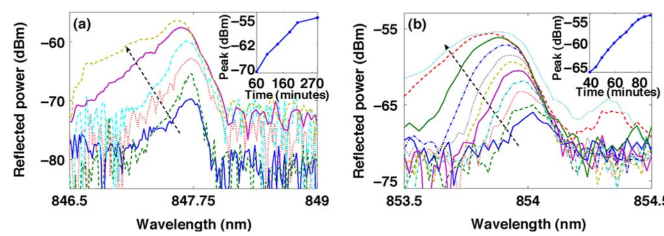

Fig. 3. FBG reflection spectra for increasing writing time for the mPOF (a) and POF (b). Inserts show the peak reflected power versus time.

The reflection spectrum of the mPOF (POF) has a central wavelength of 847.60 nm (853.96 nm) and a FWHM bandwidth of 0.29 nm (0.17 nm). The narrow line width is evidence to the fact that the fibers are few-moded. Both spectra were recorded during the writing process, where the fiber was given a small tension to keep it straight. After the writing, when the tension is released, the peak wavelength will blue shift a couple of nanometers. The noise level is 10 dB lower than the peak power, which means that the FBG resonance can be detected and tracked by conventional interrogators, such as the IMON from Ibsen Photonics.

The growth dynamics of the FBG writing process is shown in Fig. 3. It displays the typical scenario, in which the peak grows faster in the beginning and then saturates [15]. After 185 (60) minutes the spectrum of the mPOF (POF) starts to broaden more and more and side peaks start to appear. This means that the optimum writing time is around 185 min. for the mPOF and 60 min. for the POF. The saturation time, defined as the writing time after which the reflectance saturates, while the FWHM increases rapidly, is around 210 min. for the mPOF and 90 min. for the POF. During the initial rapid growth a standard blue shift of the peak is observed due to laser induced heating, which will disappear after the laser is turned off [6].

III. Strain Sensitivity Measurements

Here we perform strain measurements and check the measured sensitivities of 850 nm and 1550 nm FBGs against each other. The strain sensitivity experiments are particularly relevant due to the applications for which the 850 nm gratings are intended i.e., fiber-optic sensing of acceleration and sound.

The sensitivity of the FBG is defined as [2], [16]

$$\frac{\partial \lambda_B}{\partial \varepsilon} = C\lambda_B, \qquad C = \frac{2 - n_{\text{eff}}^2[P_{12} - \nu(P_{11} + P_{12})]}{2} \tag{1}$$

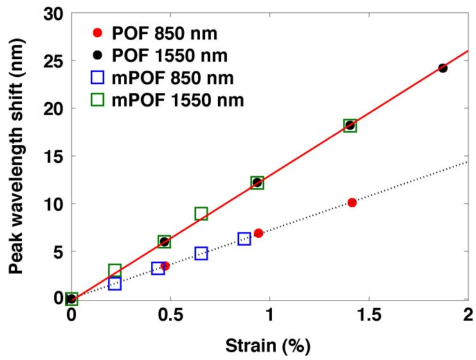

Fig. 4. Strain sensitivity of 1550 nm FBGs in POF (dots) and mPOF (squares), fitted to a straight solid line. Strain sensitivity of 850 nm FBGs in POF (dots) and mPOF (squares), fitted to a straight dashed line.

where $\lambda_B = 2n_{\rm eff}\Lambda$ is the Bragg wavelength, $n_{\rm eff}$ is the effective index of the fundamental core mode, and Λ is the grating period. The parameter C depends only on the fiber material, with $P_{i,j}$ being the Pockel's (piezo) coefficients of the stress-optic tensor and ν the Poisson's ratio. The change in C over the wavelength range 850–1550 nm can be neglected and thus (1) shows that the ratio between the sensitivity at 1550 nm and at 850 nm of a given fiber is approximately equal to the ratio of the resonance wavelengths, which is 1.82.

Fig. 4 shows the wavelength shift versus applied strain for both 850 nm and 1550 nm gratings in both mPOFs and POFs. Both 850 nm mPOF and POF FBGs respond linearly to the applied strain with an identical sensitivity of 0.71 pm/$\mu\varepsilon$. At 1550 nm both FBGs display a linear response with an identical sensitivity of 1.3 pm/$\mu\varepsilon$, which corresponds to an earlier measurement on this particular 1550 nm POF FBG [6]. The ratio of sensitivities is $1.3/0.71 = 1.83$, which is very close to the theoretically predicted value of 1.82.

We note that the sensitivity can be different from fiber to fiber depending on the material and on the thermal history of the fiber [6] e.g., 1.46 pm/$\mu\varepsilon$ was reported in [18] and 1.13 pm/$\mu\varepsilon$ was reported in [17] around 1550 nm, compared to the 1.3 pm/$\mu\varepsilon$ measured here and in [6]. Thus, even though both our fibers are made of PMMA, the fact that the POF is doped in the core, PMMA can vary from manufacturer to manufacturer, and the drawing conditions have been different, means that our mPOF and POF FBGs should not *a priori* have the same sensitivity. It is thus an interesting result that we find the same sensitivities of these two types of PMMA polymer optical fibers. Since our setup has been the same for the different measurements, this hints at that in fact also the different experimental setups play a role.

IV. Conclusion

In conclusion, we have reported the first narrow bandwidth FBG at 850 nm in two types of few-moded POFs. The 850 nm FBG in our own mPOF has a bandwidth of 0.29 nm, whereas the bandwidth of the FBG in a commercial step-index POF is 0.17 nm. We have measured their strain sensitivities to be identical 0.71 pm/$\mu\varepsilon$ at 850 nm and 1.3 pm/$\mu\varepsilon$ at 1550 nm.

The loss of the commercial PMMA step-index POF is too large for it to be relevant in sensing. However, with a loss of 10 dB/m at 850 nm and a bandwidth of 0.29 nm, the PMMA mPOF FBG is definitely a candidate for future strain sensing devices using CMOS technology, in particular when taking into account that the loss can be further reduced to 1 dB/m by improvement of the fabrication technology.

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