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Effects of pre-strain on the intrinsic pressure sensitivity of polymer optical fiber Bragg-gratings

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ABSTRACT

We experimentally demonstrate a scheme for improving the intrinsic pressure sensitivity of fiber Bragg-gratings (FBGs) inscribed in polymer optical fibers by applying pre-strain in order to suppress the pressure induced mechanical contraction of the fiber. This contraction would otherwise contribute to a blueshift of the Brag-wavelength, counteracting the dominant redshift caused by the stress-optic effect, which effectively reduces the pressure sensitivity of the FBG. By applying this technique we are able to improve the sensitivity of the FBG from 2.8 pm/bar to 7.3 pm/bar.

Keywords: Fiber Bragg-grating, polymer optical fiber, hydrostatic pressure sensing

1. INTRODUCTION

The interest in Fiber Bragg-gratings (FBGs) inscribed in polymer optical fibers (POFs) rather than conventional silica optical fibers has in the recent years increased, mainly due to the low Young's modulus and high thermal response of polymers compared to silica, potentially resulting in more sensitive sensors. Previous research includes POFBGs for strain[1,2], temperature[3,4] and humidity[5,6] sensing, but also investigations towards measuring hydrostatic pressure have been carried out[7–9]. These investigations show that, contrary to FBGs in silica fibers, the pressure response in POFBGs is positive, i.e. the Bragg-wavelength redshifts as the pressure load on the FBG increases.

1.1 Principle of hydrostatic pressure sensing using POFBGs

The principle of operation of an FBG can be described using the well-known Bragg-relation

$$\lambda_B = 2n_{eff}\Lambda,$$

where λ_B is the Bragg-wavelength, n_{eff} is the effective index of the fiber mode and Λ is the grating pitch. From this relation we can deduce an expression for the pressure response of the FBG

$$\frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial P} = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial P} + \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial P}, \tag{1}$$

where P is the pressure. The first term on the right hand side is related to the stress-optic effect, which increases the material refractive index and therefore the effective index of the fiber mode as the fiber material is compressed, resulting in a redshift of the Bragg-wavelength. The second term is due to mechanical contraction, which reduces the grating pitch, contributing to a blueshift of the Bragg-wavelegnth as the pressure is increased. In POFBGs the stress-optic effect is the dominating term resulting in positive pressure response of the grating. The blueshift originating in the contraction of the fiber, however, leads to a smaller pressure sensitivity of the FBG. In this work we present a scheme to enhance the pressure sensitivity of POFBGs by simply eliminating the contraction effect by applying a pre-strain on the FBG.

2. EXPERIMENTS AND RESULTS

2.1 FBG fabrication

The POF used in this study was a 150 µm outer diameter ZEONEX® single mode, microstructured polymer optical fiber (mPOF) fabricated in-house using the drill-and-draw technique, see Figure 1. The FBG was inscribed in the mPOF using the phase mask technique and a CW-laser at 325 nm at 5 mW output power. The pitch of the phase mask was 572.4 nm

(Ibsen Photonics A/S) resulting in a FBG reflection peak at 869 nm with a FWHM of 0.7 nm. After FBG inscription, the fiber was annealed at 120 °C for 24 hours in order to eliminate any residual stress originating from the fiber drawing process. This internal stress relaxation caused the Bragg-wavelength of the FBG to blueshift 37 nm to a final wavelength of 832 nm. The fiber containing the FBG was finally connectorized with an FC/APC connector and polished by a procedure similar to that previously described in the litterature[10], which provided robust and stable power coupling and low reflection noise compared to the more widely used method of butt-coupling.

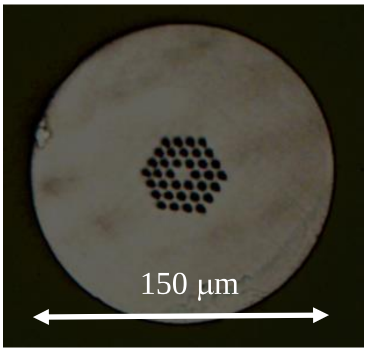

Figure 1. Microscope image of the optical fiber used in this work.

2.2 Strain and pressure characterization

The 600 – 900 nm part of a supercontinuum light source (SuperK Compact, NKT Photonics) was launched into the fiber through a 3 dB coupler and the reflected spectrum was measured using a CCD-spectrometer (Thorlabs CCS175) with a FWHM resolution of 0.6 nm connected to a PC. By applying a dynamic gate peak tracking algorithm[11], we were able to detect changes in the Bragg-wavelength with a sub-pixel resolution of 2 pm (determined as the standard deviation of λ_B measured for 100 samples with no external load on the FBG).

The strain response of the FBG was characterized by mounting the fiber on a translation stage with the end-point of the fiber fixed. As the stage was translated and strain was applied on the fiber, the shift in Bragg-wavelength was monitored, see Figure 2. In order to see if the fiber was properly annealed, the strain was increased and subsequently decreased in order to confirm that no significant hysteresis was present. The strain response of the FBG was found to be highly linear with a sensitivity of 0.733 ± 0.001 pm/με.

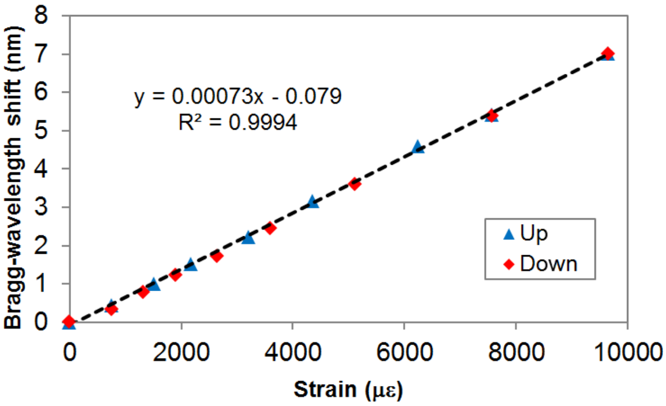

Figure 2. Strain response of the FBG for increasing and decreasing strain.

Next, we investigated the pressure response by using the setup shown in Figure 3a. The FBG was placed inside a custom build pressure chamber consisting of a hollow brass tube with an inner diameter of 5 mm filled with water, a hand screw to apply force on the water surface, a pressure gauge (Druck DPI 104, resolution 0.01 bar) and a demountable fiber port with a rubber seal. Due to the incompressible nature of water we were in this way able to rapidly increase the pressure in the system without affecting our measurements with temperature effects that would be otherwise present using a gas based setup. The holes of the fiber were left unsealed in order to avoid a collapse of the microstructure under high pressure.

First, a measurement was conducted with no pre-strain applied on the FBG. Secondly, a measurement with the FBG pre-strained on an aluminum plate using drops of UV-curing adhesive (NOA 76) to maintain a constant strain throughout the measurement was conducted. Based on the strain calibration curve in Figure 2, we estimated the level of applied pre-strain in this measurement to be 1100 με.

As seen in Figure 3b, there was a significant increase in pressure sensitivity by applying pre-strain on the FBG. By applying linear fits we have determined the sensitivity to be 2.8 ± 0.1 pm/bar for the FBG without pre-strain, and 7.3 ± 0.3 pm/bar for the FBG with 1100 με pre-strain applied. It should be noted, however, that the adhesive used to fix the fiber to the aluminum plate is also polymer-based and is to some degree compressible itself, which could result in additional strain applied on the FBG, leading to an additional redshift. Thus, in order to establish, whether or not compression of the adhesive has had any effect on the obtained results, we repeated the measurement three times with the FBG under a constant level of pre-strain (2500 με). Each time we reduced the distance between the fixing points by adding new drops of adhesive of similar size and shape. Pressure induced compression of these drops would then be expected to lead to an increasing amount of strain on the FBG and thus result in an increased sensitivity, as the distance between fixing points was decreased. As seen in Figure 4, however, no significant change in the sensitivity was observed in this way, from which we conclude, that the observed increase in hydrostatic pressure sensitivity by applying pre-strain to the POFBG can be attributed to the cancellation of the mechanical contraction alone.

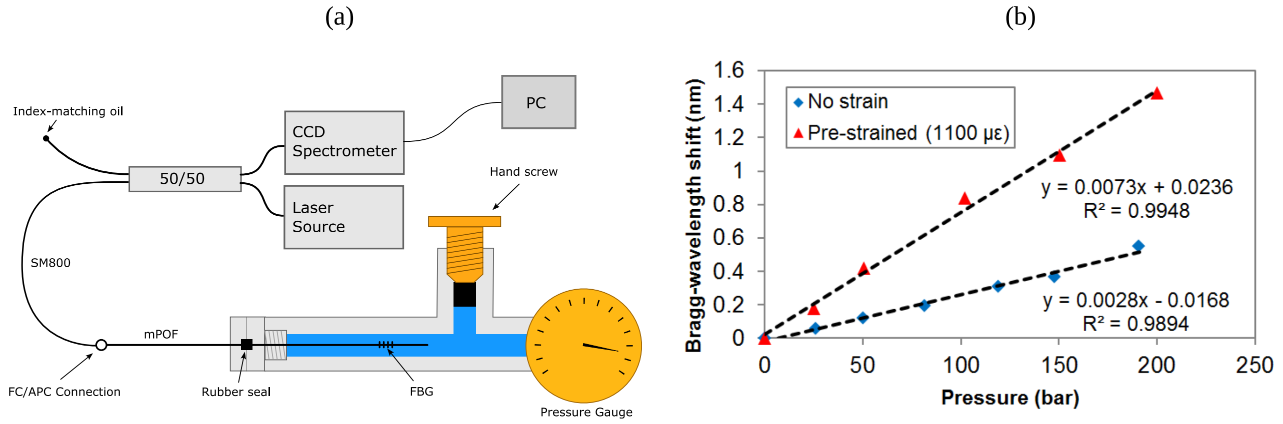

Figure 3. (a) Schematic diagram of the setup used to investigate the pressure response of the FBG. (b) Pressure response of the FBG without pre-strain and an applied pre-strain of 1100 με. A clear increase in the sensitivity is observed.

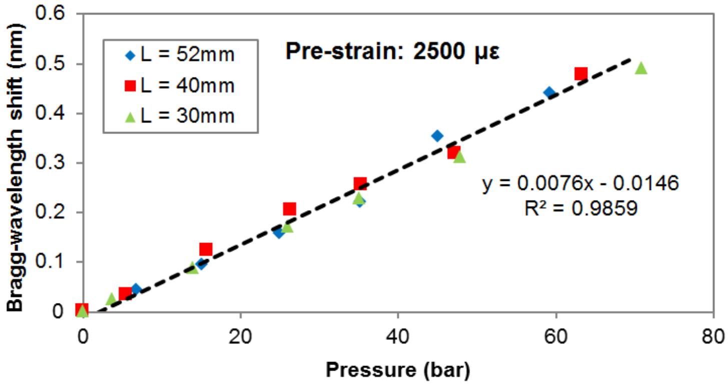

Figure 4. Pressure response of the FBG at a constant pre-strain for different distances L between fixing points. No significant change in the response is observed, suggesting that any strain induced by glue compression in the experiments is negligible. The dashed line is the linear fit of data corresponding to L = 52 mm.

3. CONCLUSION

We have presented the results from the initial investigations of the effect of pre-strain on the hydrostatic pressure sensitivity of an FBG inscribed in a microstructured polymer optical fiber. The sensitivity of the FBG with no applied strain has been found to be 2.8 ± 0.1 pm/bar. We have demonstrated that applying pre-strain of 1100 $\mu\varepsilon$ on the FBG results in an increased sensitivity of 7.3 ± 0.3 pm/bar. This effect can be attributed to the cancellation of the mechanical contraction of the fiber as the pressure is increased, which would otherwise counteract the dominating stress-optic effect.

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