Influence of mounting on the hysteresis of polymer fiber Bragg grating strain sensors

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Fiber Bragg grating sensors recorded in poly(methyl methacrylate) fiber often exhibit hysteresis in the response of Bragg wavelength to strain, particularly when exposed to high levels of strain. We show that, when such a fiber grating sensor is bonded directly to a substrate, the hysteresis is reduced by more than 12 times, compared to the case where the sensor is suspended freely between two supports. © 2013 Optical Society of America

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Polymer fiber Bragg grating (FBG) sensors are attracting interest due to their rather different material properties as compared to silica FBGs [1]. Polymers are flexible, nonbrittle, and clinically accepted [2]. They can survive higher strain than silica and they possess a much lower Young's modulus [3]. This is important when fiber sensors are used to monitor structures that are themselves rather compliant, as is the case, for example, with a tapestry [3]. In such situations, the use of silica fiber tends to locally reinforce the structure and reports strain much lower than the true background strain in the material.

As a viscoelastic material, the tensile properties of polymers are complicated; they display both hysteresis and a dependence on the timescales involved [4] and the magnitude of applied strain [5]. When a polymer optical fiber Bragg grating (POFBG) sensor is placed for several minutes under sufficient tension to cause a considerable elongation, a significant wavelength shift may remain when the tension is removed, which only gradually relaxes over time [6]. This is on the face of it a serious problem for practical applications of such strain sensors.

The application of pretension [7] to the POFBG or the annealing of the fiber [8] has been reported to reduce hysteresis in some situations. However, in this Letter we show that, for many practical applications, the hysteresis will actually be much lower than expected from existing published data. The point is that the experiments that have revealed the presence of hysteresis are usually conducted by fixing the fiber at two points on either side of the sensor, with one of these points capable of being moved using a translation stage. However, when grating sensors are applied to the monitoring of strain in a structure, they would normally either be glued to the structure directly [9] or possibly embedded in it [10].

In this work we compare the behavior of two identical sensors, where one is strained between two supports while the other is bonded directly to a cantilever. We show that the latter approach, which is much more characteristic of the way sensors would be applied in practice, displays hysteresis reduced more than 1 order of magnitude from the former.

Two identical FBGs were fabricated in few-moded microstructured polymer optical fiber (mPOF) fabricated from poly(methyl methacrylate) (PMMA) and obtained from Kiriama Pty Ltd. Most polymer fibers in use today are based on PMMA, although it should be noted that other materials may have advantages for sensing applications [11]. The core of the fiber is bounded by three rings of 5 μm holes spaced 5 μm apart. The few-moded fiber has a core diameter of 50 μm and an outer diameter of 150 μm. A helium–cadmium laser with a wavelength of 325 nm and a power output of 30 mW was used to inscribe the Bragg gratings in the mPOF. The laser beam was focused vertically downward using a 10 cm focal length cylindrical lens, through a 557.5 nm period phase mask, and onto the fiber. The mPOFs were laid in a v groove and taped down using polyimide tape to prevent them moving during inscription. The optimum inscription time for this fiber is between 40 and 60 min. The Bragg wavelengths of the inscribed gratings were in the region of 830 nm, the bandwidth (full width at half-maximum) was 0.3 nm, and the grating length was 2 mm, determined by the width of the UV laser beam. No thermal annealing of fiber or grating was carried out.

Inscription was monitored using an 830 nm 50/125 μm multimode 50:50 silica coupler (Thorlabs), an SLD light source (Superlum SLD371, 2 mW output power, bandwidth 50 nm), and an optical spectrum analyzer (OSA). A butt-coupled connection was made between the arm of the silica coupler and the mPOF using an fiber connector/angled physical contact (FC/APC) connector on the silica fiber. The end faces of the POF were cleaved using an 80°C hot cleave as described by Abdi *et al.* [12]. A small amount of polymer index matching gel was used in the coupling to reduce Fresnel reflections. Following grating inscription, the POFBG sensors were terminated with fiber connector/physical connector (FC/PC connectors [13].

The POFBGs were then connected via a bulkhead connector to a 50 μm core, multimode, step index 830 nm 50:50 silica coupler. The SLD light source and an OSA (Hewlett Packard 70004A) were connected to the other two ends of the silica coupler. The first sensing fiber was 12 cm long with the FBG 7.5 cm away from the connector, while the second was 13 cm long, and the FBG was 11.8 cm away from the connector.

The first FBG sensor was fixed using the UV-curing glue to two stages, as shown in Fig. 1. The distance between the two stages when the mPOF was suspended with no slack was 50 mm. The mPOF was strained to

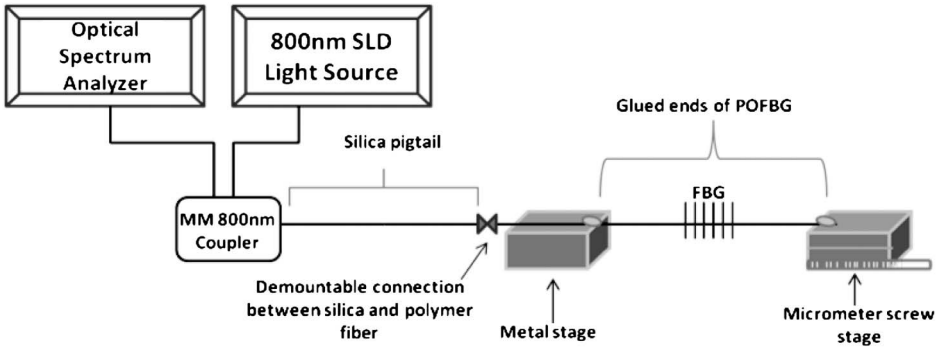

Fig. 1. Schematic diagram of the mPOF sensor suspended in free space.

2.75% of this distance, which is about 1.38 mm. The strain was manually increased up to this value and then decreased in steps of 0.05 mm at an interval of 30 s per reading. As the strain was increased and decreased, the reflection spectrum of the FBG from the OSA was captured on a computer using LabVIEW software to interface with the OSA. The Bragg wavelength of the spectrum at each strain state was calculated using the –3 dB averaging method [14]; the values obtained are shown in Fig. 2.

At a strain of 2.75%, a wavelength shift of 40.6 nm was observed, corresponding to a strain sensitivity of 1.3 pm/με. The initial Bragg wavelength of the FBG sensor before the strain was applied was 827.2 nm and the wavelength of the sensor when unstrained at the end of the experiment was 833.5 nm, which results in a wavelength difference of 6.3 nm, as may be seen in Fig. 2. At this point the fiber was observed to be hanging slack between the supports.

The second FBG sensor was attached using a UV-curable adhesive to a plastic (perspex) beam. The plastic beam had a total length of 30 cm; it was 3 cm wide and 0.6 cm thick. The beam was clamped to an optical bench so that 10 cm projected beyond the edge of the bench. The point at which the Bragg grating was inscribed on the polymer fiber was placed 2 cm beyond the bench edge. Approximately a 1.5 mm thickness of UV-curing glue was placed from 1 cm before to 1 cm after the FBG inscription point along the fiber and cured using the UV-curing lamp. A schematic diagram of the setup is shown in Fig. 3.

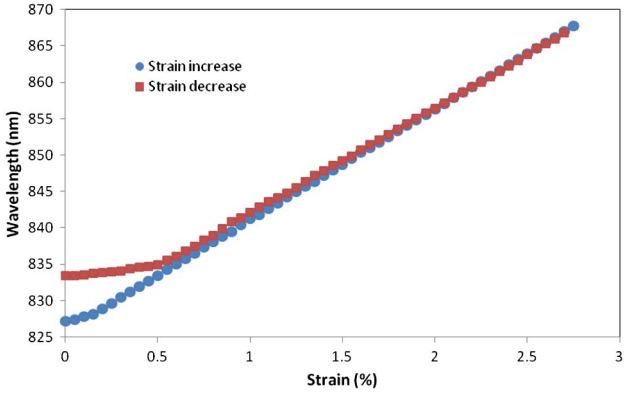

Fig. 2. Plot of the hysteresis at lower strain values in mPOFBG suspended in free air.

An incremental force was applied at the end of the beam to bend it downward and hence strain the FBG sensor at a rate of 0.06% per 30 s. At a strain of 2.75%, the force was then decreased at the same rate. The spectrum of the grating at each time interval was captured and the center wavelength calculated as before. The strain applied on the POF sensor was calculated using [15]

$$\text{Strain}(\varepsilon) = \frac{3Ddh}{2L3}, \tag{1}$$

where D is the distance of the glued POF grating from the free end of the beam, d is the displacement caused by the applied force on the beam, h is the thickness of the beam, and L is the length of the free end of the beam from the clamped point.

The plot of the results obtained is shown in Fig. 4. A wavelength shift of 40.9 nm was observed at a strain of 2.75%, which matches very closely the result of the previous experiment. The FBG sensor had an initial wavelength of 827.9 nm. After the application and removal of strain, the sensor had a wavelength of 828.4 nm, which shows a difference of 0.5 nm. This difference is more than 12 times smaller than the 6.3 nm obtained in the previous experiment, where the fiber was suspended in free space.

For both experiments, the wavelength differences between the increasing and decreasing strain readings at each strain point are plotted in Fig. 5. It can be seen that major hysteresis began at 0.6% strain in the free-space experiment, while the plastic beam experiment displayed rather more random but much smaller deviations. The uncertainty in the wavelength measurement was determined by stretching each sensor from 0% to 1.25% strain and measuring the wavelength on 10 separate occasions and then calculating the standard deviation. The results were 0.13 nm (free space) and 0.26 nm (plastic beam). These are relatively large compared to values typically observed with silica FBG sensors due to the few-moded nature of the polymer fiber used. The higher value for the grating on the beam may be due to the viscoelastic properties of the beam itself, disruption of the FBG reflection profile during gluing, or accuracy in the determination of the applied strain.

Figure 5 shows that hysteresis in polymer fiber is significantly reduced when the POFBG is bonded directly to a substrate as compared to when it is freely supported at both ends. In the former case, the substrate effectively forces the fiber back to somewhere close to its original

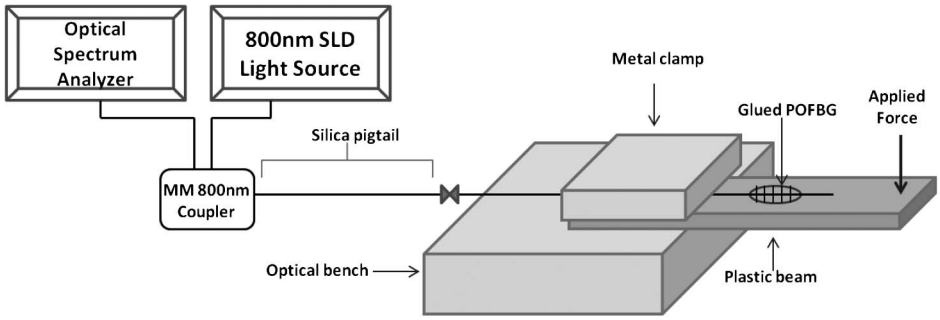

Fig. 3. Schematic diagram of mPOF sensor glued to plastic beam.

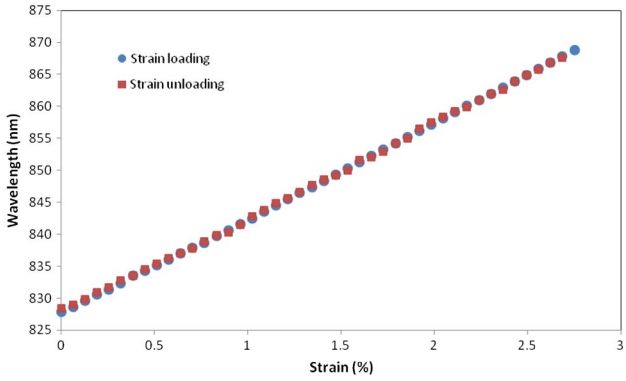

Fig. 4. Plot of considerably reduced hysteresis in mPOFBG when glued to a beam.

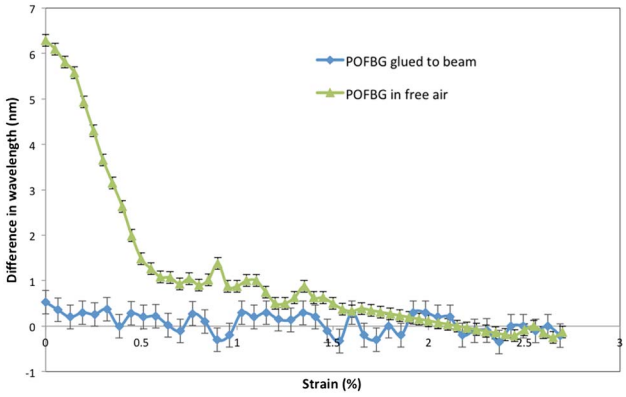

Fig. 5. Wavelength difference between strained and unstrained POF sensors.

length. This situation is likely to mirror how POFBG sensors would be used in practice and, hence, the viscoelastic nature of the POF is less of a problem in strain sensing applications than has previously been thought. Although the response obtained in Fig. 5 is not ideal, as there is some nonlinearity and a small amount of hysteresis at low strain, we believe both of these may be attributed at least to some degree to the plastic beam, which has its own viscoelastic properties.

In concluding, we note that the strain response of polymers is time dependent. Our experiments, which were conducted over tens of minutes, are representative of the timescales involved in quasi-static strain sensing where the problem of stress relaxation may be expected [4].

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