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Annealing effects on strain and stress sensitivity of polymer optical fibre based sensors

A. Pospori^{*a}, C. A. F. Marques^a, M. G. Zübel^a, D. Sáez-Rodríguez^b, K. Nielsen^c, O. Bang^c, D. J. Webb^a

^aAston Institute of Photonic Technologies, Aston University, Aston Triangle, Birmingham, B7 4ET, United Kingdom

^bOptical and Quantum Communications Group, ITEAM Research Institute, Universitat Politècnica de València, 46022 Valencia, Spain

^cDTU Fotonik, Department of Photonics Engineering, DK-2800 Kgs. Lyngby, Denmark

*a.posporis@aston.ac.uk; orcid.org/0000-0003-4866-1361

ABSTRACT

The annealing effects on strain and stress sensitivity of polymer optical fibre Bragg grating sensors after their photo-inscription are investigated. PMMA optical fibre based Bragg grating sensors are first photo-inscribed and then they were placed into hot water for annealing. Strain, stress and force sensitivity measurements are taken before and after annealing. Parameters such as annealing time and annealing temperature are investigated. The change of the fibre diameter due to water absorption and the annealing process is also considered. The results show that annealing the polymer optical fibre tends to increase the strain, stress and force sensitivity of the photo-inscribed sensor.

Keywords: POF, Bragg gratings, annealing, strain sensitivity, stress sensitivity, polymer fibre sensors

1. INTRODUCTION

Polymer optical fibre Bragg grating (POFBG) sensors have received attention recently because of their potentially enhanced performance in certain applications compared to their silica counterparts¹. Polymer optical fibres (POF) offer greater elasticity² and higher failure strain³. The lower Young's modulus of polymer materials^{2,4} renders POFBG sensors more sensitive to strain⁵, stress⁶, pressure⁷ and acoustic wave detection⁸. The large negative thermo-optic coefficient of polymer compared with the small positive thermo-optic coefficient of glass⁹⁻¹¹ can also offer to POFBG sensors enhanced sensitivity to temperature variations^{12,13}. Their biocompatibility¹⁴ can provide additional applications in the biomedical sector and the water absorption in some polymers such as PMMA can be used for humidity monitoring^{15,16}.

Some of the drawbacks of POFs are their high losses and their viscoelastic nature. The viscoelasticity can introduce hysteresis and creep effects when cyclic loading is applied to the fibre, which can influence the accuracy of the sensor reading. It has been demonstrated that these effects can be reduced by thermally anneal the fibres¹⁷. POFBG annealing was first used for multiplexing purposes^{7,18}, but then it was shown that annealing can also change the performances of the POF based sensors. Enhanced strain¹⁹ and humidity²⁰ sensitivity of POFBG sensors and longer temperature operational range²¹ has been reported. In this study, we investigate the annealing effects on strain and stress sensitivity of POFBG sensors. We report also a simple but well-controlled annealing process.

2. EXPERIMENTAL DETAILS

2.1 POFBG fabrication

Figure 1 illustrates the POFBG fabrication and interrogation setup. By using the phase mask technique, POFBGs with Bragg wavelength in the 850 nm region are photo-inscribed using a continuous-wave He-Cd laser (Kimmon IK3301R-G) with an output power of 30 mW and wavelength of 325 nm. Single-mode micro-structured PMMA optical fibre doped with benzyl dimethyl ketal²² is used. A super-luminescent diode (Superlum SLD-371) and an optical spectrum analyser (HP 86142A) were connected to the input arms of an 850 nm single-mode silica fibre coupler and the POF was connected to one of the output arms of the coupler using the butt-coupling method (Figure 1). This arrangement allowed for Bragg wavelength spectra monitoring in reflection. Various grating lengths are obtained (1.2 mm - 10 mm), but we

believe the grating length does not play any role in our experimental results because we monitor the wavelength shift and not the grating strength. After the photo-inscription, each POF was placed and glued into a FC/PC connector to facilitate monitoring of the Bragg wavelength.

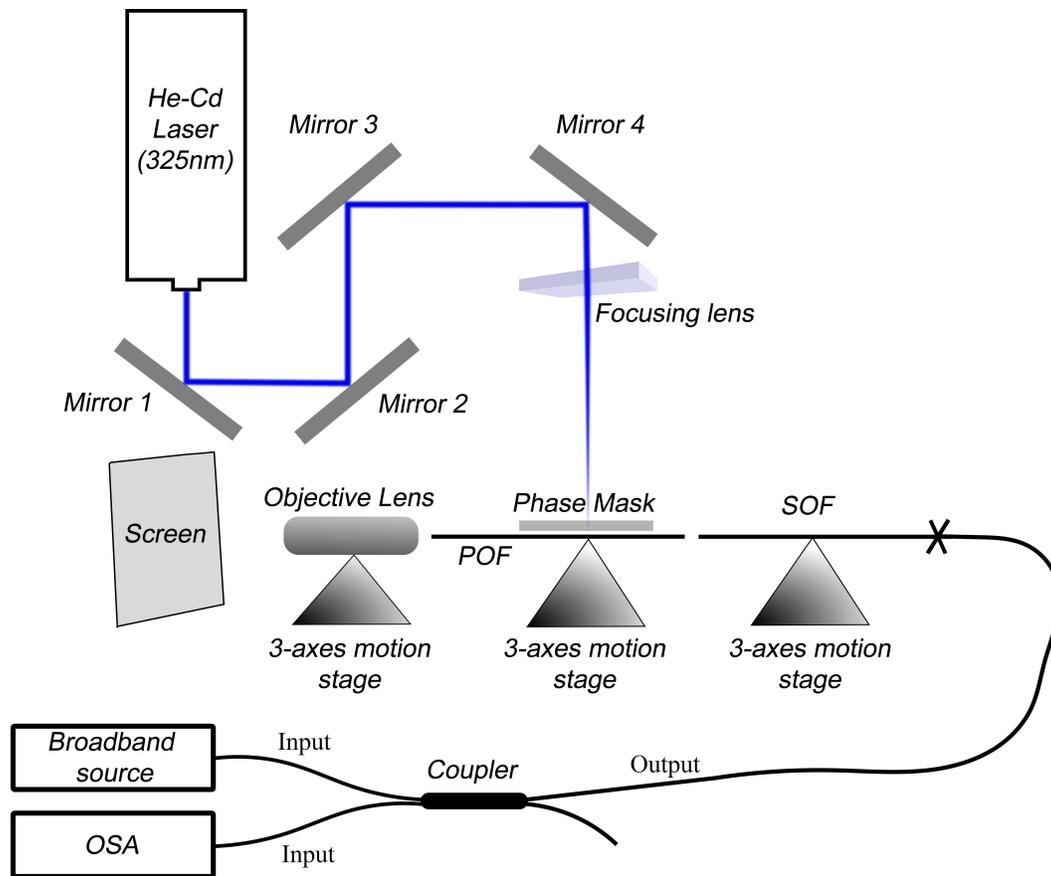


Figure 1: POFBG fabrication and interrogation setup

2.2 Characterisation of strain and stress sensitivity

The performance of the fabricated sensors is characterised before and after the annealing process. In order to measure their strain sensitivities, each sensor was attached between a movable stage and a fixed support by using magnetic fibre clamps. By moving one stage along the fibre axis, each POF was strained by 0.5%. The Bragg wavelength shift ($\Delta\lambda$) due to strain ($\epsilon = 0.005$) was monitored using the same interrogation method described above and the strain sensitivity for each device is calculated by $\Delta\lambda/\epsilon$. For the stress sensitivities measurements, each fibre was held perpendicular to the ground and a mass of a known value was added at the opposite end of the POF to stress the fibre. Stress (σ) can be calculated by

$$\sigma = \frac{F}{A} = \frac{mg}{\pi \left(\frac{d}{2}\right)^2}, \quad (1)$$

where F is the gravity force and A is the area where the force is applied. The gravity force can be found by considering the added mass m and the Earth's gravity acceleration value g which equals 9.8 m/s^2 . The area A can be found if the fibre

diameter d at the POFBG location is measured using an optical microscope. The stress sensitivity can be determined by $\Delta\lambda/\sigma$. Force sensitivity which is independent of the fibre diameter can be also calculated by $\Delta\lambda/F$.

2.3 Annealing process

Thermal annealing was only demonstrated previously by placing POFs in an oven or climatic chamber for extended periods of time (typically from several hours to several days)^{17-19, 23, 24}. In our case, POFs are annealed with a low cost and yet well-known procedure and for much shorter time (2 to 30 minutes). Fibres were placed in a cylindrical metallic tank with diameter of 127 mm and height of 22 mm filled with hot water. The water was heated using a hot plate under the metallic tank. The temperature of water was monitored by using a mercury thermometer (FISONS THL-290-050J). Two annealing temperatures 55 ± 2 °C and 60 ± 2 °C were investigated. The reason why hot water is used is because the equilibrium relative humidity value during annealing is a known parameter (100%) and controlling that parameter during annealing is important in order to have the same annealing conditions for all sensors. In addition, annealing in a high humidity environment has been shown to offer enhanced humidity sensitivity compared to lower humidity annealing²⁰ and this might be beneficial in our case. To ensure more accurate results, the POF's diameter was measured before and after annealing using an optical microscope in order to calculate the applied stress each time.

3. RESULTS AND DISCUSSION

Figure 2 depicts the wavelength shift of sensor 5 during the annealing process. The initial Bragg wavelength before the fibre is placed into hot water was 862.70 nm. After of 30 minutes annealing, just before the fibre is removed from the hot water, the Bragg wavelength was 821.88 nm. When the fibre was removed from hot water, the Bragg wavelength positive shifted by 1.19 nm due to the temperature change (60 ± 2 °C to room temperature). Therefore, the Bragg wavelength shifted from 862.70 nm to 823.07 nm indicating a total wavelength shift of 39.63 nm due to thermal annealing.

Table 1 lists the strain sensitivities of 9 POFBG sensors before and after the annealing process. Table 2 and Table 3 show the annealing effects on stress and force sensitivities respectively for the same sensors. Results show that in all cases the annealing enhanced the strain, stress and force sensitivities of the POFBG sensors. Different annealing times and temperatures were tried. However, higher annealing temperatures or longer annealing times do not clearly show an additional sensitivity enhancement and no conclusions can be drawn in this matter.

The initial sensitivity values are different for each sensor and our explanation is that each fibre has slightly different mechanical properties due to rapid fluctuations in fibre drawing conditions (drawing speed and temperature). The polymer molecule chains align with the fibre axis during the drawing process and when these stretched elastomers cool down, they create an internal stress in the fibre^{25, 26}. This internal stress results in less mobile molecular chains than in the bulk material, which affects the Young's modulus. Therefore, the fluctuations during the drawing condition can alter the elasticity along the fibre axis, potentially causing the significant variation in the initially measured sensitivities. These fluctuations can also be linked to fibre diameter variations (10% over lengths of a few centimeters in our case). Despite however the differences in the mechanical properties of each fibre, the sensitivities of the POFBG sensors were improved in all cases after the thermal annealing process. The reason for the improvement is likely because we exposed the material to temperatures above the β relaxation of PMMA²⁷, where the conformation of the polymer backbone chain can be reorganised and the stressed molecular chains can relax^{28, 29}. The molecular relaxation can increase the elasticity of the material and enhance the sensitivity of the POFBG sensors.

In order also to investigate the influence of the initial fibre water content on the annealing results, the following method was used. Before the annealing process, sensors 2, 8 and 9 were placed in a tank filled with water at room temperature for 44, 20 and 43 hours respectively and their sensitivities were compared with the other sensors. The high water content in the POFs before annealing did not provide any clear effects on the overall strain and stress sensitivity enhancement after annealing. Sensors 2, 8 and 9 were tested again one day after the initial assessment when they had achieved equilibrium with ambient conditions and no significant change in their measured sensitivities was observed.

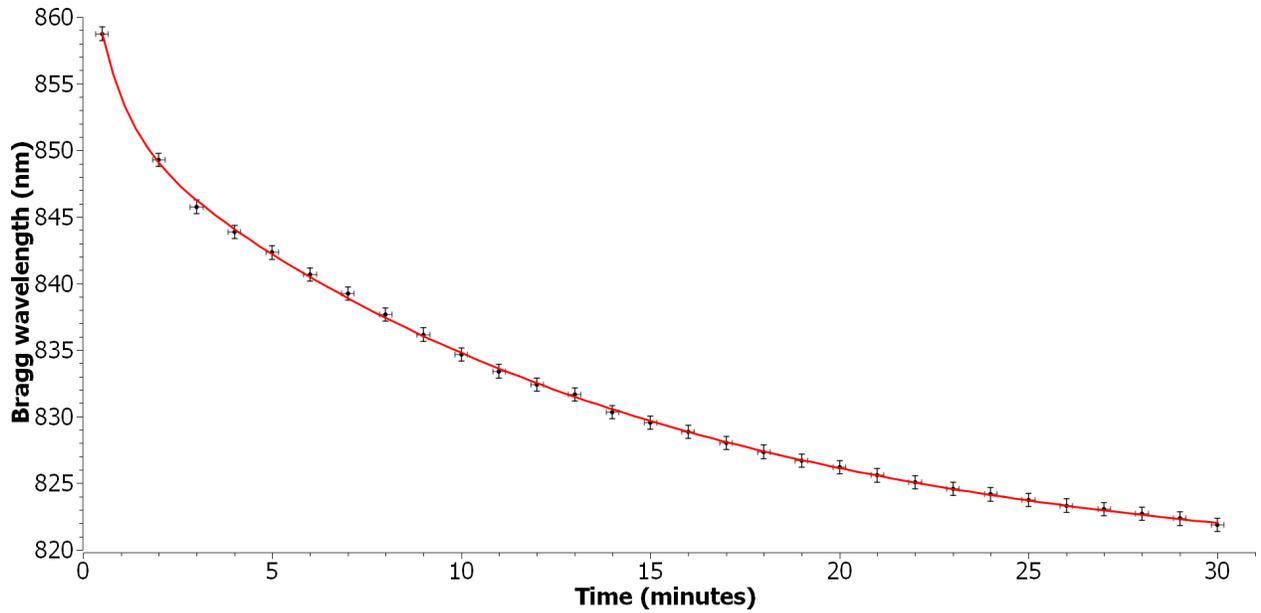


Figure 2: Wavelength shift of sensor 5 during the annealing process

Table 1: Strain sensitivities of POFBG sensors before and after thermal annealing

Sensor	Annealing time (minutes)	Annealing temperature ± 2 ($^{\circ}\text{C}$)	Strain sensitivity before annealing ($\mu\text{m}/\mu\epsilon$)	Strain sensitivity after annealing ($\mu\text{m}/\mu\epsilon$)	Sensitivity improvement after annealing
1	2	60	0.664	0.726	+9.3%
2	4	60	0.716	0.880	+23%
3	4	60	0.536	0.688	+28%
4	30	60	0.728	0.850	+17%
5	30	60	0.772	0.944	+22%
6	30	55	0.714	0.880	+23%
7	30	55	0.726	0.876	+21%
8	30	55	0.730	0.906	+24%
9	30	55	0.692	0.884	+23%

Table 2: Stress sensitivities of POFBG sensors before and after thermal annealing

Sensor	Annealing time (minutes)	Annealing temperature ± 2 ($^{\circ}\text{C}$)	Stress sensitivity before annealing (pm/kPa)	Stress sensitivity after annealing (pm/kPa)	Sensitivity improvement after annealing
1	2	60	0.137	0.217	+58%
2	4	60	0.180	0.260	+44%
3	4	60	0.147	0.201	+33%
4	30	60	0.196	0.258	+32%
5	30	60	0.173	0.202	+17%
6	30	55	0.184	0.220	+20%
7	30	55	0.178	0.205	+15%
8	30	55	0.182	0.221	+21%
9	30	55	0.194	0.231	+19%

Table 3: Force sensitivities of POFBG sensors before and after thermal annealing

Sensor	Annealing time (minutes)	Annealing temperature ± 2 ($^{\circ}\text{C}$)	Force sensitivity before annealing (pm/ μN)	Force sensitivity after annealing (pm/ μN)	Sensitivity improvement after annealing
1	2	60	0.0109	0.0137	+26%
2	4	60	0.0109	0.0143	+31%
3	4	60	0.0109	0.0137	+26%
4	30	60	0.0137	0.0179	+31%
5	30	60	0.0134	0.0146	+9%
6	30	55	0.0136	0.0165	+21%
7	30	55	0.0116	0.0133	+15%
8	30	55	0.0119	0.0142	+19%
9	30	55	0.0122	0.0145	+19%

4. CONCLUSION

Thermal annealing of POF was originally used by scientists for multiplexing purposes. Later, an annealing-induced sensitivity improvement in the POFBG sensors was noticed when they were used in strain, temperature and humidity monitoring applications. In the current work, POF annealing was shown to increase not only the strain, but also the stress and force sensitivities of the POFBG sensors. A low-cost, well-controlled annealing method is also presented where just hot water is enough for the annealing.

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