Sensitivity enhancement using annealed polymer optical fibre based sensors for pressure sensing applications

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ABSTRACT

Thermal annealing can be used to induce a permanent negative Bragg wavelength shift for polymer fibre grating sensors and it was originally used for multiplexing purposes. Recently, researchers showed that annealing can also provide additional benefits, such as strain and humidity sensitivity enhancement and augmented temperature operational range. The annealing process can change both the optical and mechanical properties of the fibre. In this paper, the annealing effects on the stress and force sensitivities of PMMA fibre Bragg grating sensors are investigated. The incentive for that investigation was an unexpected behaviour observed in an array of sensors which were used for liquid level monitoring. One sensor exhibited much lower pressure sensitivity and that was the only one that was not annealed. To further investigate the phenomenon, additional sensors were photo-inscribed and characterised with regard their stress and force sensitivities. Then, the fibres were annealed by placing them in hot water, controlling with that way the humidity factor. After annealing, stress and force sensitivities were measured again. The results show that the annealing can improve the stress and force sensitivity of the devices. This can provide better performing sensors for use in stress, force and pressure sensing applications.

Keywords: POF, Bragg gratings, annealing, force sensitivity, stress sensors, polymer fibres

1. INTRODUCTION

The recent high interest of the research community in polymer optical fibre Bragg grating (POFBG) sensors is due to the different mechanical and chemical properties of polymer optical fibre (POF) compared to silica[1]. Polymers are more flexible, they have higher failure strain[2] and greater elasticity[3]. These mechanical properties provide enhanced sensitivity or longer operational range to intrinsic polymer fibre sensors when they are used for strain[4], stress[5], pressure[6] and temperature[7, 8] monitoring, as well as for acoustic wave detection[9]. Polymers, as organic materials, can be chemically modified by adding other organic compounds to change their properties. In addition, they are biocompatible[10],which can lead to applications in the biomedical sector, and some polymers such as PMMA can absorb water, allowing them to be used for humidity detection applications[11, 12].

However, polymers are viscoelastic materials, which means that hysteresis effects can occur when cyclic loading is applied to POFBG sensors. POF thermal annealing can reduce hysteresis effects[13], and it can offer additional benefits, such as enhanced temperature and strain monitoring operational range[14, 15] and humidity sensitivity enhancement[16]. The annealing process has also been also used for POFBG multiplexing purposes[6, 17]. In this paper, it is shown that annealing POFBG sensors can also increase their sensitivity to force and stress and this is shown to impact on an application where an array of multiplexed POFBG pressure sensors is used for liquid level monitoring.

2. EXPERIMENTAL DETAILS AND RESULTS

For this study, a continuous-wave He-Cd laser (Kimmon IK3301R-G) with an output power of 30 mW at 325 nm and the phase mask technique have been used for the POFBG photo-inscription. All gratings were inscribed in a single-mode photosensitive PMMA fibre doped with benzyl dimethyl ketal[18]. Two phase masks of 557.5 nm and 580 nm pitch were used in these experiments. Therefore, using PMMA fibres with a refractive index of 1.487 at that region, gratings can be formed with Bragg wavelengths centred approximately at 829 nm and 862 nm, respectively. Bragg grating wavelengths

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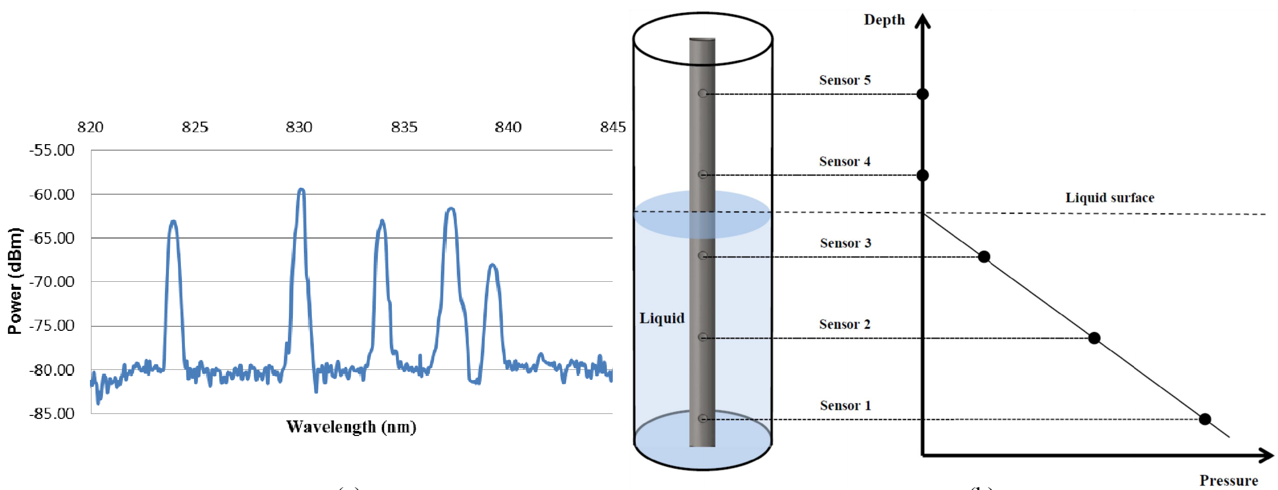
were monitored in reflection using a super-luminescent diode (Superlum SLD-371), an optical spectrum analyser (HP 86142A) and an 850 nm single-mode silica fibre coupler.

The motivation for our study of the effects of annealing on the force and stress sensitivity of POFBGs came from the development of a liquid level sensor incorporating 5 multiplexed POFBGs in a single 75 cm long fibre, spatially separated by 15 cm. Four of the five sensors were thermally annealed on a hot plate starting from 50 °C up to 70 °C in order to permanently blue shift their Bragg wavelength, resulting in a wavelength multiplexed sensor, the reflection spectrum of which is shown in Figure 1 (a). The five sensors were embedded in silicone rubber diaphragms and then they were clamped over holes in the side wall of a liquid container at different depths as illustrated in Figure 1 (b). The system performance was characterised by filling the container with liquid in steps of 2.5 cm, starting from the bottom and going to the top, which has height of 75 cm. By monitoring the Bragg wavelength shift following each step, the liquid level can be determine due to the different liquid pressure on each sensor[19]. Both increasing and decreasing liquid levels were investigated by performing cyclic tests.



(a) (b)

Figure 1: (a) Reflected spectra of POFBG array sensors (b) Array of pressure sensors for liquid level monitoring

Using tap water to fill the liquid container, the sensitivity of the POFBG sensors was found to be typically 98 pm/cm, see Table 1. Similar silica based sensors for water level monitoring have been reported with a sensitivity of 23 pm/cm[20] and the reason for the improved performance is the much lower elastic modulus of polymer fibre. Note however that sensor 5, which is the only one that had not been annealed, exhibits significantly less sensitivity compared to the annealed sensors. As such a discrepancy had also been observed in some other tests, we decided to investigate the role of annealing in more detail.

A set of 9 sensors was fabricated in the same fibre used for the level sensing experiment and these were characterized for force and stress sensitivity before and after thermal annealing. For each device, the diameter of the fibre was measured using an optical microscope. The fibre was then held perpendicular to the ground and a known weight added at the end of the fibre to stress the fibre whist the Bragg wavelength was monitored. In this way the stress and force sensitivities were determined. Then, the fibre was annealed in hot water and afterwards it was again characterised with the same method. The reason for using hot water is because it has already been demonstrated that annealing in a high humidity environment can offer humidity sensitivity enhancement[16].

Table 1: Depth sensitivity of POFBG sensors in liquid level monitoring system

Sensor	Annealed	Depth Sensitivity (pm/cm)
1	Yes	98.6 ± 0.3
2	Yes	98.1 ± 0.2
3	Yes	98.4 ± 0.6
4	Yes	97.6 ± 0.8
5	No	86.1 ± 2.6

The stress and force sensitivities of the 9 different POFBG sensors before and after thermal annealing are listed in Table 1. There is significant variation in the measured values for the different sensors, probably due to rapid fluctuations in drawing conditions (the fibre diameter was observed to vary by up to 10% over lengths of a few centimetres). In all cases however, the annealed sensors show significantly enhanced stress and force sensitivity compared to the same sensor before annealing.

Our explanation for this observation is as follows. The processing history of polymer fibre, such as the drawing conditions (drawing speed and temperature) plays an important role in the material properties. During the drawing process, highly oriented polymer sections are produced[21, 22] and the stretched elastomers that have cooled down will have less mobile chains than in the bulk material. This means that the material has lower elasticity and the fibre sensors are less sensitive to fibre stress. By thermally annealing the polymer fibres after they have been drawn, the stressed molecules can be relaxed and the material can become more elastic, which leads to sensitivity enhancement for the fibre based sensors.

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

Sensor	Annealing time (minutes)	Annealing temperature (°C) ± 2	Stress sensitivity before annealing (pm/kPa) ± 0.015	Stress sensitivity after annealing (pm/kPa) ± 0.015	Force sensitivity before annealing (pm/µN) ± 0.0005	Force sensitivity after annealing (pm/µN) ± 0.0005
1	2	60	0.137	0.217	0.0109	0.0137
2	4	60	0.180	0.260	0.0109	0.0143
3	4	60	0.147	0.201	0.0109	0.0137
4	30	60	0.196	0.258	0.0137	0.0179
5	30	60	0.173	0.202	0.0134	0.0146
6	30	55	0.184	0.220	0.0136	0.0165
7	30	55	0.178	0.205	0.0116	0.0133
8	30	55	0.182	0.221	0.0119	0.0142
9	30	55	0.194	0.231	0.0122	0.0145

3. CONCLUSION

It has previously been reported that annealing can increase the strain sensitivity of POFBG sensors. In the current work, several POFBG sensors were annealed in hot water and it has been shown that this annealing increases both the force and stress sensitivities of the sensors. It is clear that – as with silica fibre Bragg gratings - a proper annealing regime should be established before sensors are used in applications requiring optimised, long term, stable operation.

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