Development of flexible pressure sensing polymer foils based on embedded fibre Bragg grating sensors

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Abstract

This paper reports on the development of flexible polymer sensing foils based on embedded fibre Bragg grating (FBG) sensors. The foil consists of quasi-distributed sensing points with FBGs inscribed in highly birefringent photonic crystal fibres (PCF). A local pressure sensitivity of 9.08 pm/kPa and a pressure resolution of 0.11 kPa were achieved at sensing points.

Keywords: fibre Bragg grating, photonic crystal fibre, distributed sensing, polymer foil

1. Introduction

Fibre optical sensing technology has been gaining more and more attention owing to its inherent advantages including non-electric, lightweight, immunity to electromagnetic interference (EMI), environmental ruggedness. Additionally, the inscription of Bragg gratings in optical fibres has significantly enhanced the intrinsic sensing capability of optical fibres to external perturbations [1]. Furthermore, fibre Bragg gratings (FBGs) can also be embedded into materials to provide local strain or temperature sensing with high accuracy and resolution.

This paper presents the sensing principle and experimental results of photonic crystal fibre (PCF) Bragg gratings embedded in flexible polymer foils, towards the applications of external pressure mapping on irregular and/or moving surfaces in the fields such as robotics and medical devices.

2. Sensing principle

2.1. Fibre Bragg gratings

A fibre Bragg grating is a periodic or quasi-periodic variation of the refractive index of the fibre core in a short segment of an optical fibre, which leads to the reflection of a narrow band of the incident optical field and the transmission of all the rest, as shown in Fig. 1(a). The Bragg wavelength $\lambda_B$, which is the free space centre wavelength of back-reflected light from the Bragg grating, depends on the effective index of refraction of the core $n_{\text{eff}}$ and the periodicity of the grating $\Lambda$. Both $n_{\text{eff}}$ and $\Lambda$ are affected by changes in strain and temperature and cause the Bragg wavelength shifting, as shown in Fig. 1(b). The shift in the Bragg wavelength due to external perturbation is given by:

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Fig. 1. (a) Schematic diagram of a fibre Bragg grating structure and the spectral responses; (b) Bragg wavelength shifting due to the presence of strain or temperature change in fibre core

\[ \Delta \lambda_B = 2 \left( \Lambda \frac{\partial n_{\text{eff}}}{\partial \varepsilon} + n_{\text{eff}} \frac{\partial \Lambda}{\partial l} \right) \Delta \varepsilon + 2 \left( \Lambda \frac{\partial n_{\text{eff}}}{\partial T} + n_{\text{eff}} \frac{\partial \Lambda}{\partial T} \right) \Delta T \]

The first and second terms represent the strain and temperature effect respectively. As for many types of fibre optic sensors, FBGs are subject to both strain and temperature fields simultaneously. Therefore, measurement of the perturbation-induced wavelength-shift from a single FBG has the problem of discrimination between these two variables. In the case that two measurands are recorded, such as Bragg wavelengths \( \lambda_{B1} \) and \( \lambda_{B2} \), each shows dependence on strain and temperature changing as:

\[ \Delta \lambda_{Bi} = K_{\varepsilon i} \Delta \varepsilon + K_{T i} \Delta T \]

where \( K_{\varepsilon i} \) and \( K_{T i} \) are strain and temperature coefficients respectively. On condition that \( K_{\varepsilon 1}K_{T 2} \neq K_{T 1}K_{\varepsilon 2} \), the measurement can eliminate the cross-sensitivity and distinguish between strain and temperature responses, that is:

\[ \left( \begin{array}{c} \Delta T \\ \Delta \varepsilon \end{array} \right) = \frac{1}{K_{T 1}K_{\varepsilon 2} - K_{\varepsilon 1}K_{T 2}} \left( \begin{array}{cc} K_{\varepsilon 2} & -K_{\varepsilon 1} \\ -K_{T 2} & K_{T 1} \end{array} \right) \left( \begin{array}{c} \Delta \lambda_{B1} \\ \Delta \lambda_{B2} \end{array} \right) \]

2.2. FBGs in highly birefringent fibres

In single mode fibres (SMFs), due to the photoelasticity theory, when a transverse load is applied onto the fibre, the stress distribution in the fibre core results in a refractive index variation of the two orthogonal polarization directions, exhibiting stress-induced birefringence. This effect can cause the deformation of the reflected spectrum from the Bragg grating, such as the bifurcation and/or even distinct splitting of the Bragg peak [2]. Apparently, this behaviour degrades the functionality of FBG as a wavelength-encoded sensor. One way to diminish the negative effect of birefringence is to replace SMFs with polarization-maintaining fibres (PMFs), which have an intrinsic birefringence much higher than the stress-induced birefringence.

By introducing a highly asymmetric structure in the fibre, PCFs (also known as microstructured optical fibres, MOFs) have been demonstrated with birefringence levels on the order of \( 10^{-3} \) by manipulating the position, size or shape of the air holes [3]. FBGs in PCFs produce two Bragg wavelengths corresponding to the two orthogonal polarized modes, as shown in Fig. 2. The separation of the two Bragg peaks is related directly to the birefringence of PCF. With a high birefringence, the large peak separation allows the two Bragg peaks to shift from or towards each other in a relatively large wavelength range without the risk of overlapping. Fig. 3 shows the SEM picture of the cross section of PCFs employed in this work [4]. A Bragg peak separation of about 2 nm has been successfully achieved.

Another benefit is that the two Bragg wavelengths from a single FBG in PCF can be used as two measurands. According to Equation 3, as long as the two Bragg wavelengths respond to strain and temperature changing individually, and the condition \( K_{\varepsilon 1}K_{T 2} \neq K_{T 1}K_{\varepsilon 2} \) is satisfied, strain and temperature can also be discriminated.

3. Fabrication method

FBG sensors are embedded into flexible polymer foils so as to achieve a flexible skin sensitive to external pressure perturbation. In this work, (co)polymers based on composites of methyl methacrylate (MMA), butyl methacrylate (BuMA) and 2-ethylhexyl methacrylate (EHMA) were developed as the foil materials, with Young’s moduli ranging...
Fig. 2. Spectrum response of a single FBG inscribed in PCF

Fig. 3. SEM picture of the cross section of PCFs employed in this work

from 1.7 to 37.7 MPa. Those (co)polymers possess advantages such as tuneable flexibility, well-proved biocompatibility and chemical resemblance with the fibre coating. Furthermore, they can be produced by UV polymerization with full monomer conversion and high curing efficiency [5, 6].

Accordingly, dedicated UV-transparent moulds, composed of glass plates, silicone spacers and a metal frame, were realized to embed the fibres in a highly controllable and reliable manner. One example of the produced samples is shown in Fig. 4. It consists of one single winding PCF with 5 FBGs embedded in the middle layer of the foil, and the FBGs are aligned with a pitch of 10 mm.

Fig. 4. A sample of one single PCF with 5 FBGs embedded in polymer foil

Fig. 5. Schematic view of the setup for pressure sensitivity measurement

4. Experimental results and discussion

Pressure sensitivity experiments were carried out to evaluate the performance of the embedded FBG sensors. FBGs in PCF with the grating length of 5 mm were used and the full-width-at-half-maximum (FWHM) is smaller than 0.3 nm. The foil material was copolymer PMMA/EHMA with 20/80 mol% in composition with Young’s modulus of 5.6 MPa. A commercial FBG interrogator system FBG-Scan 700 with wavelength resolution of 1 pm was employed to track the Bragg wavelengths. The interrogator contains a built-in broadband light source with the wavelength range of 1525 – 1565 nm and performs spectral analysis by means of an InGaAs detector array and a spectrometer platform.

A schematic view of the setup is shown in Fig. 5. Pressure was applied with a ∅5 mm rounded-end pin mounted on a custom-made leaf spring. The leaf spring has a stiffness of about 4.6 N/mm in the linear operational range. The deflection of the spring was measured with a BENTLY 7200 series Proximitor® inductive sensor. Both loading and unloading procedures were performed by way of displacement at a rate of 1 mm/min. The whole procedure was assumed to be at constant temperature.
The two Bragg wavelengths shifted with respect to the changing of pressure applied directly upon the FBG, as shown in Fig. 6(a), and the peak separation is also plotted. With the maximum loading pressure about 85 kPa, the two Bragg wavelengths both shifted for about 780 pm. A relatively linear response and pressure sensitivity around 9.08 pm/kPa (0.908 pm/bar) was obtained, as shown in Fig. 6(b), leading to a pressure resolution calculated as 0.11 kPa. However, according to Fig. 6(a), there’s no evident relationship between the change of peak separation and pressure. This still requires further investigation and improvement.

5. Conclusions

By embedding FBGs in flexible methacrylate-based polymer, sensing foils with quasi-distributed sensing points were implemented. The negative effect of Bragg peak bifurcation and/or splitting due to stress-induced birefringence was minimized by using FBGs inscribed in PCFs. Pressure sensitivity of 9.08 pm/kPa at sensitive points was achieved, and an interrogator with wavelength resolution of 1 pm led to a pressure resolution of 0.11 kPa. No evident peak separation change with respect to pressure load was observed. Further study and improvement are conducted with the aim of pressure and temperature discrimination.

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