A pressure sensing sheet based on optical fibre technology

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Abstract

This paper presents a novel flexible sensing sheet, which is based on optical Fibre Bragg Grating (FBG) sensors and is capable of measuring distributed transverse loads. The device features an optical wavelength-encoded sensing signal, and it shows very promising results for pressure mapping applications. The prototype realized specifically consists of 15 FBGs, inscribed in highly-birefringent (hi-bi) Photonic Crystal Fibres (PCF) and embedded in a 2 mm thick polymer foil, which is cured by means of a customized UV polymerization procedure. The sensing elements (or taxels) are arranged over a sensing area of 30×50 mm\textsuperscript{2}, and distributed in a 3×5 matrix-like configuration; the spatial resolution is 10 mm. The taxels are first individually characterized and calibrated by conducting transverse pressure tests; a local pressure sensitivity of about 2.65 pm/kPa is registered. The sensor response to a transverse load applied over the sensing area is successively evaluated, and the results are here presented.

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1. Introduction

Optical fibre sensors, especially Fibre Bragg Grating (FBG) sensors, are widely applied in various sensing systems, owing to the prominent properties, like the absence of electrical signal in the sensor, immunity to Electromagnetic Interference (EMI) and environmental ruggedness [1, 2]. All these features have a major potential for medical and body contacting applications. In this work, FBGs inscribed in hi-bi PCFs, are embedded in a flexible polymer foil and used as sensing elements for the development of large area pressure mapping devices applicable in the rehabilitation and medical fields, such as posture detection, gait analysis and prosthetic design. Little work concerning this application of optical fibre sensors has been reported in the literature.

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2. The sensing elements

2.1. FBG sensing principle

A Fibre Bragg Grating is an in-line periodic variation of the refractive index of the fibre core in a short segment of an optical fibre. As shown in Fig. 1, it reflects a narrow band of the incident optical field and transmits all the rest. The wavelength, corresponding to the peak in the reflected spectrum, is referred to as the Bragg wavelength, $\lambda_B$; it is detectable with a FBG interrogating instrument, and is expressed by the following Bragg condition:

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

where $n_{\text{eff}}$ is the effective refractive index of the fibre core and $\Lambda$ is the grating period.

External perturbations, such as strain and temperature changes, affect both $n_{\text{eff}}$ and $\Lambda$, and eventually result in the shifting of Bragg wavelength in the optical spectrum. If the sensor works in a temperature constant environment, external loads leading to strain change in the FBG section, can be measured by monitoring the Bragg wavelength. When the temperature effect is taken into account, the problem of discrimination between strain and temperature arises. This is indeed a common issue for optical fibre sensors. Nevertheless, mechanical load sensing with low temperature dependence has been investigated for FBGs inscribed in modified hi-bi fibres [3].

2.2. FBGs inscribed in PCFs

In this work, FBG sensors inscribed in PCFs are chosen as the sensing elements. As a relatively new type of optical fibres with great design flexibility, PCFs have been demonstrated with exclusively high birefringence by manipulating the micro-structure inside the fibres. Moreover, FBGs inscribed in hi-bi fibres intrinsically yield two separated Bragg peaks in the reflected spectrum; this can avoid further peak bifurcation due to stress-induced birefringence during measurement, which causes problems for FBG instrumentation systems [4, 5]. Especially, since FBGs are mainly subject to transverse loads in this work, the mechanical stress anisotropy brings about stress-induced birefringence due to the photoelastic effect.

The PCFs employed in this work have a deliberately improved cross-sectional micro-structure as shown in Fig. 2 [6]. All FBG samples have a grating length of 5 mm and the full-width-at-half-maximum (FWHM) is smaller than 0.3 nm, to ensure peak determination accuracy and stability. Owing to the high birefringence of the PCFs, which is of the order of $10^{-3}$, a single FBG reflects two Bragg peaks with separation up to 1.5 nm. This large separation allows the two peaks to shift from or towards each other in a relatively large wavelength range without the risk of overlapping, which is also unfavourable to FBG interrogation.

Fig. 1. Schematic diagram of a FBG structure together with the incident, transmitted and reflected optical fields

Fig. 2. SEM image of the cross section of PCFs employed in this work
3. FBG-based pressure sensor prototype

3.1. Sensor prototype

As shown in Fig. 3, the sensor prototype consists of three PCFs, and each fibre contains five FBGs. They are embedded in the middle layer of a 2 mm thick polymer foil with a spatial resolution of 10 mm. That means each taxel has a size of 10×10 mm². The foil material is UV-curable copolymer PMMA/EHMA with 20/80 mol% in composition and it has a Young’s modulus of about 5.6 MPa, which has chemical affinity with the fibre coating to ensure reliable interfacial adhesion. Dedicated UV-transparent moulds, composed of glass plates, silicone spacers and a metal frame, were fabricated to produce the sensor prototype.

3.2. Sensor characterization

For the evaluation of the sensor performance, transverse pressure tests were firstly applied to the sensing elements. A schematic view of the experimental setup employed is depicted in Fig. 4. The pressure applied was in the range of 0 to about 600 kPa by using a Ø5 mm flat-end steel pin, which was mounted on a strain gauge type load cell. The Bragg peaks were detected using a commercial FBG interrogator, FBG-Scan 700 from FOS&S, with a built-in broadband light source. It performs peak detection based on a mean wavelength determination at -3 dB of the maximum peak power and it has a wavelength resolution of 1 pm. Fig. 5 shows the response of a single FBG sensor obtained during the pressure loading-unloading cycle. As can be seen, the two Bragg peaks shift simultaneously; the average pressure sensitivity registered is about 2.65 pm/kPa. The response also exhibits slight hysteresis, most likely because the host polymer behaves in a non-Hookean fashion.

The same FBG interrogator and an optical switch, with maximum 16 input channels and a switching frequency of 50 Hz, are employed to cyclically interrogate the status of all the FBG sensors under the application of loads distributed over the sensing area. The Bragg wavelengths are registered and processed in a LabVIEW program, according to the pressure sensitivity factors previously obtained; the results are finally interpolated in order to compute visualized images of the measured pressures. As an example, Fig. 6 illustrates the measured pressure map exerted by a 15×15 mm² square block of 1 kg, that is, a uniform pressure distribution of 43.5 kPa. As depicted, the maximum pressure sensed is around 41 kPa, while the non-uniformity in the measured pressure map is due to the post-processing technique used and to the fact that the applied pressure area and the taxel size are of the same order of magnitude.
Fig. 5. FBG response versus the applied pressure
Fig. 6. Image of the interpolated pressure map measured by the sensitive sheet

4. Conclusion

A flexible pressure sensing sheet was implemented by embedding distributed FBG sensors inscribed in PCFs, into a 2 mm thick polymer foil, and it was successively tested under the action of both concentrated and distributed loads. The device shows a local pressure sensitivity of about 2.65 pm/kPa and very promising performance when solving pressure mapping tasks. However, enhancements and additional issues still need to be considered in the future, such as evaluation of the temperature sensitivity and employment of alternative post-processing techniques.

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