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A polarisation maintaining fibre Bragg grating interrogation system for multi-axis strain sensing

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ABSTRACT

Fibre Bragg gratings (FBGs) written into polarisation maintaining (PM) fibres have been employed for multi-axis strain and temperature sensing. In this paper we report the development of a FBG interrogation system that is capable of detecting independently the two orthogonally polarised signals reflected from a PM FBG. The interrogation system imposes no limitation on the measurable strain range. This relaxes the requirements on the bandwidth of the grating spectrum, allowing the use of a shorter PM FBG (larger bandwidth) for sensing applications where a higher spatial resolution is required. In particular, this system is useful in the cases where the spectra of the reflected polarised signals are broadened or split, resulting from strain-induced structural changes of the PM fibre, or caused by the application of a non-uniform strain on the FBG.

KEY WORDS: Polarisation maintaining, fibre Bragg grating, interrogation system, multi-axis strain sensor.

1. INTRODUCTION

Optical fibre Bragg grating (FBG) sensors have many advantages for applications in process and health monitoring in composites and smart structures [1-3]. Applications of FBGs for axial strain and temperature sensing have been intensively investigated [2,3]. For structural applications however, it is often desirable to measure strain components transverse to the optical fibre in addition to the axial strain. In the fabrication of fibre-reinforced composites, for example, in order to minimise the warpage of the composites, the internal strain development in different dimensions needs to be measured during the curing process of the thermosetting polymers.

Several techniques have been reported for multi-axis strain sensing [4-6]. The technique using a combination of a FBG in single-mode fibre and an in-line fibre etalon [4] requires a separate demodulation system for each sensor type. As the two sensors are positioned sequentially they do not measure exactly the same strain, and the direction of transverse strain is not encoded in the spectral change of the FBG. Long-period fibre gratings (LPGs) have demonstrated high sensitivity to transverse strain [5]. Since LPGs are also very sensitive to other measurands such as temperature, bending and refractive index of the surrounding medium, it is a complex process to distinguish between transverse strain and other measurands for structural applications. FBGs written into polarisation maintaining (PM) fibre have been used as multi-axis strain sensors [1,7], and are promising candidates for simultaneous measurement of three strain components and temperature for structural monitoring applications.

The signal interrogation systems used with FBG sensors fabricated in single-mode fibres are also currently used for PM FBG multi-axis strain sensors [1,7]. Since the two orthogonally polarised optical signals reflected from PM FBGs are measured through the same channel and detector, they must be well separated in wavelength. The separation of Bragg wavelengths for the two polarisation eigenmodes is typically 0.5nm for a PM fibre with a beat length of 3.4mm at a wavelength of 1550nm. This separation is approximately twice the spectral bandwidth of either polarised mode reflected by the PM FBG. When a transverse strain is applied to a PM FBG, depending upon the fibre orientations relative to the applied load, the separation of the two Bragg wavelengths may reduce so that it becomes impossible to resolve the two peaks. Consequently, the measurable strain range is limited. Generally, when the spectra of the FBG

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from the two orthogonally polarised modes overlap substantially, the spectral changes in one polarised mode may affect both of the measured peak wavelengths. In practice, there are many factors which may make the spectrum of one or both of the two orthogonally polarised optical signals reflected from a PM FBG broaden or split into multiple peaks, including non-uniform strain, rotation of the principle axes of the PM fibre induced by strain or other measurands. Such spectral responses of a PM FBG are undesirable if the two orthogonal polarised signals reflected from the FBG are not detected separately.

In this paper we report the development of a FBG interrogation system that is capable of detecting independently the two orthogonally polarised signals reflected from a FBG fabricated in a PM fibre. As a demonstration of the feasibility of the interrogation system for multi-axis strain sensing, the transverse strain sensing characteristics of FBGs fabricated in bow-tie fibre are presented.

2. INTERROGATION SYSTEM

A schematic of the experimental arrangement used to measure the Bragg wavelengths of PM FBGs is shown in Figure 1. The output from a broad bandwidth superluminescent diode (SLD) with a PM fibre pigtail is coupled into the FBGs through a 2x2 PM fibre coupler. The reflected signals pass through a scanning PM fibre Fabry-Perot filter (PM FFP, Micron Optics), and are subsequently split into two orthogonal linear polarisation components using a fibre polarisation splitter (PS). The spectra of the two orthogonal polarised signals reflected from PM FBGs are recorded separately using two detectors, and processed in a computer using a LabView™ program via a data acquisition (DAQ) card.

The SLD has a central wavelength of 1560nm, and a 3dB bandwidth of 50nm. The power measured at the output from the fibre pigtail is 0.6mW. The finesse of the FFP is 895, and the free spectral range (FSR) is 5330GHz (≈42.7nm). All components in the interrogation system are connected using panda fibre and PM FC/PC connectors. The FFP-filter, PM fibre coupler and polarisation splitter are on a heat sink which is thermally stabilised at a temperature of 25 ^{o}C in order to minimise the effects of thermal fluctuations for these components. The connection between the SLD pigtail fibre and the input arm of the fibre coupler was aligned such that the output power from the slow- and fast- axes were approximately equal in each output arm of the coupler. For other connections, the slow-axis of the fibre was aligned with the FC/PC connector's key. The overall polarisation extinction ratio of the interrogation system was measured to be 15 ± 0.5dB.

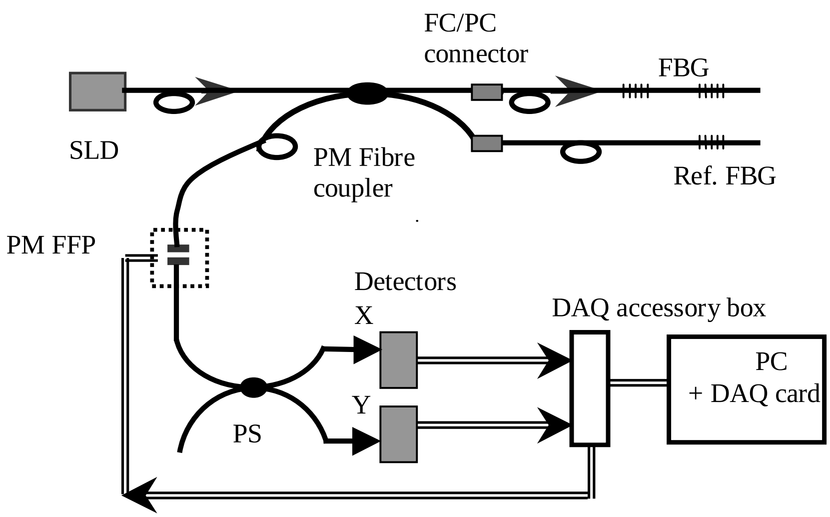

Figure 1 Schematic of the interrogation system.
SLD: superluminescent diode, PM FFP: a scanning PM fibre Fabry-Perot filter,
PS: fibre polarization splitter, X, Y: fast- and slow-axis mode polarized signals,
DAQ card: data acquisition card.

The scanning FFP filter is directly driven by an analogue signal provided by the DAQ card. The analogue signal is superimposed on a tuneable DC voltage, by which the central wavelength of the scanning spectrum can be tuned. The tuning voltage per FSR is 12 V. The acquisition of spectral data from the detectors is synchronised by the analogue signal. While it is simple to drive the scanning FFP filter using a DAQ card, there exist issues for further study in order to optimise the operation of the filter, including the non-linearity of the mechanical actuator (PZT) of the filter, wavelength drifts induced by thermal fluctuations and changes of DC voltage applied to the filter. In this work the wavelength measured by the interrogation system was calibrated using an ANDO optical spectral analyser and a Tunics-plus external-cavity tunable laser. The mode-hop-free single mode laser operating in the 1570nm band has a tuning rang of 100nm and wavelength accuracy of 0.05nm. All measurements of the wavelength were made relative to a thermally stabilised FBG at a temperature of 25^{o}C±0.5^{o}C. The reference FBG was written in single mode fibre with a Bragg wavelength of 1571nm.

3. PM FBG SENSORS

A schematic of the cross section of bow-tie fibre is shown in Figure 2. When a grating is formed in a PM fibre, the two orthogonal polarisation modes in the PM fibre will be reflected at different wavelengths since the effective refractive indices for the two modes are different as a result of the inherent birefringence of a PM fibre. The Bragg wavelength for a polarisation mode can be written as:

$$\lambda_i = 2 n_i \Lambda \qquad (\mathrm{i} = \mathrm{X}, \mathrm{Y}) \qquad (1)$$

Where n_i (i=X, Y) are the effective refractive indices of the two polarisation modes. For either polarisation mode in a PM FBG, the Bragg wavelength shift induced by application of an axial strain or a temperature change is generally similar to that for a FBG in a single-mode fibre. When a transverse load is applied to the PM fibre containing a FBG, however, the induced changes of n_i and λ_i are generally different for the two modes depending on the fibre orientation relative to the loading direction.

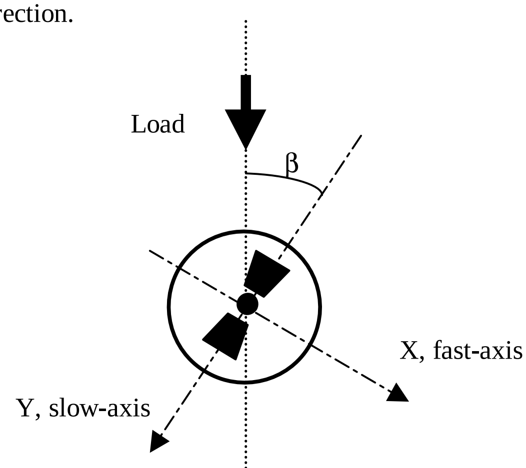

Figure 2 Schematic of the cross-section of a bow-tie PM fibre.

The PM fibre used in this study was Fibercore bow-tie fibre HB-1500. The fibre specifications from the manufacturer are summarised in Table 1. The FBGs, at nominal Bragg wavelengths of 1560nm, were written into the PM fibres using an injection seeded frequency-quadrupled Nd:YAG laser operating at a wavelength of 266nm. The two-beam interferometer technique was used to fabricate the FBGs. The grating length was 6mm.

Table 1 The fibre specifications of bow-tie fibre HB-1500

Cladding diameter (μm)	NA	Cut-off wavelength (nm)	Mode field diameter @1550nm (μm)	Core ellipticity	Beat length @633nm (mm)
125	0.17	1258	7.5	1.0 –1.4	1.3

4. TRANSVERSE STRAIN SENSING

The fixture used to apply a uniform transverse strain to a fibre section containing the FBG is shown in Figure 3. It was designed to minimise uncontrollable fibre rotation while applying a load to the fibres. The load applied to the fibres was detected using a FUTEK miniature load button with a capacity of 222N. The output voltage of the load button was recorded through the DAQ card simultaneously with the wavelength shifts of the gratings. When the values of measured load were averaged over a period of 20 seconds, the standard deviation was 0.7N.

The length of fibre section subject to the transverse load was 24mm. The support fibre and test fibre were the same type of PM fibre, and the buffer coating had been stripped from both fibres. The test fibre was held using two fibre rotators so that the dependence of load sensitivity on the fibre orientation relative to the load direction could be assessed. The resolution of the fibre rotators was 2^{o}. When the loading was in the direction of the slow-axis of the PM fibre, the fibre orientation was referred to as $\beta = 0^{o}$.

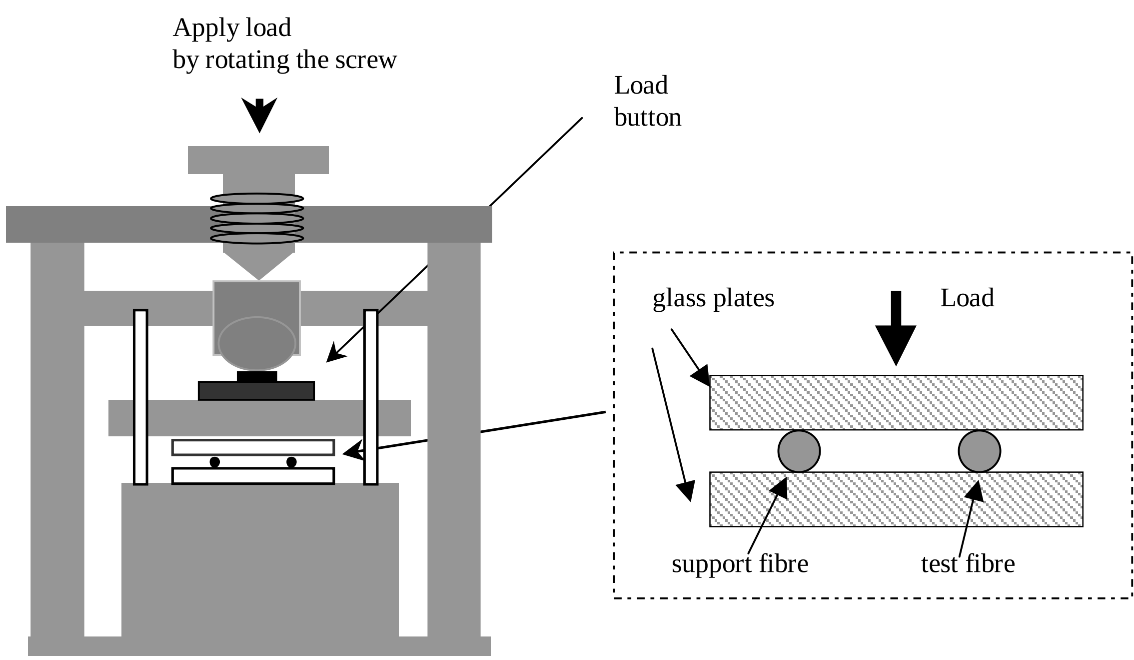

Figure 3 Schematic of the loading fixture used to apply a uniform transverse strain to a fibre section containing a PM FBG.

The reflection spectrum of the FBG is shown in Figure 4. The solid line is the spectrum of the fast-axis mode, and the dotted line is of the slow-axis mode. When there was no load applied to the grating (Figure 4 (a)), the Bragg wavelength separation for the two polarisation modes was 0.44±0.01nm, giving a beat length of 3.8mm at 1560nm. The weaker peaks at 1559.60nm and 1560.04nm in the reflection spectra of the fast- and slow-axis modes were from the reflection of a weaker grating. When a transverse load of 3.9N/mm was applied to the FBG with a fibre orientation of $\beta = 0^o$, i.e. the slow-axis being in the loading direction, the separation of the Bragg wavelengths for the two polarisation eigenmodes was 0.08nm. It would be difficult to measure the two peak wavelengths in this case if a standard FBG interrogation system was employed. In addition to the wavelength shift, a polarisation dependent loss was induced by the application of load. The peak reflection intensity of the fast-axis mode was much lower than that prior to applying the load.

When a transverse load of 3.9N/mm was applied to the FBG with a different fibre orientation ($\beta = 30^o$), a different spectral response was observed (Figure 4 (c)). A second peak appeared in the reflection spectrum of the fast-axis mode. While a non-uniform transverse load could result in such spectral change of the grating, the actual cause of this effect here may be the PM fibre structural changes induced by the uniform transverse loading. Such responses of a PM FBG to the transverse load are undesirable if the two orthogonal polarised signals reflected from the FBG are not detected separately. The fibre-orientation dependence of the spectral response will be useful in structural applications where strain directions need to be determined. In addition, this interrogation system will be capable of detecting non-uniform strain that broadens the reflection spectrum or forms multiple peaks for the individual polarisation modes.

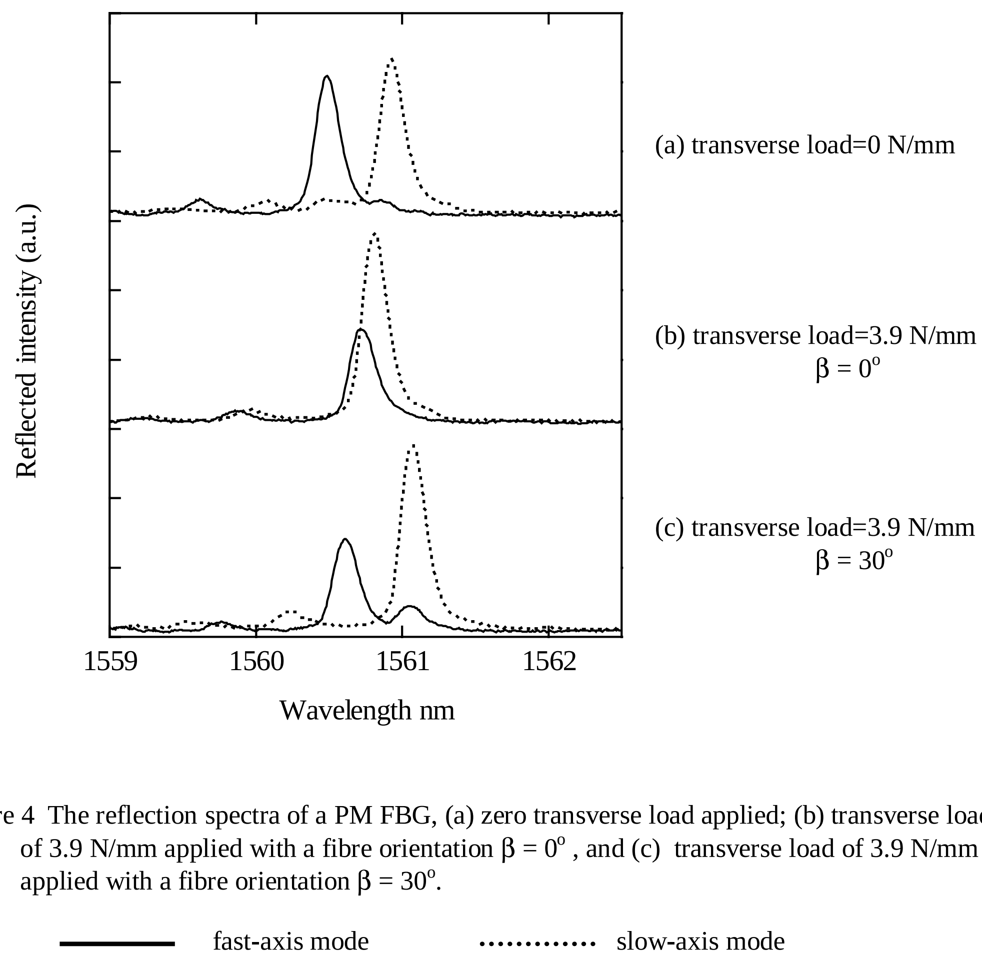

Figure 4 The reflection spectra of a PM FBG, (a) zero transverse load applied; (b) transverse load of 3.9 N/mm applied with a fibre orientation $\beta = 0^o$, and (c) transverse load of 3.9 N/mm applied with a fibre orientation $\beta = 30^o$.

The measured wavelength for the fast- and slow-axis modes in the PM FBG are plotted against transverse load with a fibre orientation of $\beta = 0^o$ in Figure 5. For a transverse load of up to 4.2N/mm, the PM FBG's response to transverse load was linear for the slow-axis mode. The solid line is a linear fit to the measured data. The transverse load sensitivity was -0.028±0.002 nm/(N/mm). For the fast-axis however, the response was non-linear. The dashed line is a second order polynomial fit to the data. As an indication of the load sensitivity of this mode with this fibre orientation, the slope of a linear fit to the measured data was 0.056±0.006 nm/(N/mm).

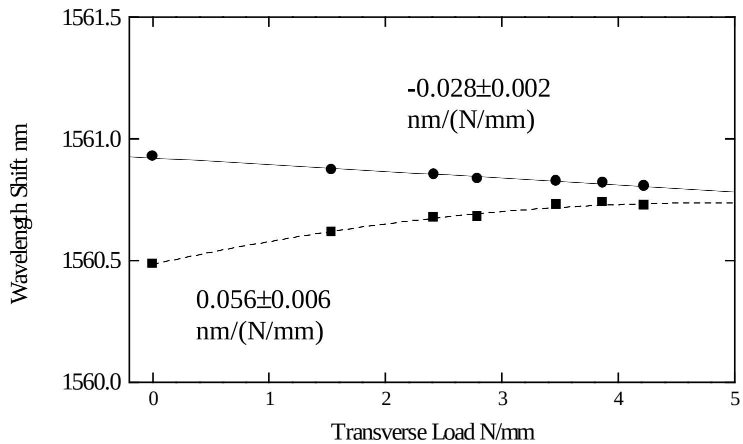

Figure 5 The Bragg wavelength versus transverse loading for the PM FBG with a fibre orientation of ß = 0°.

■ fast-axis mode, ● slow-axis mode

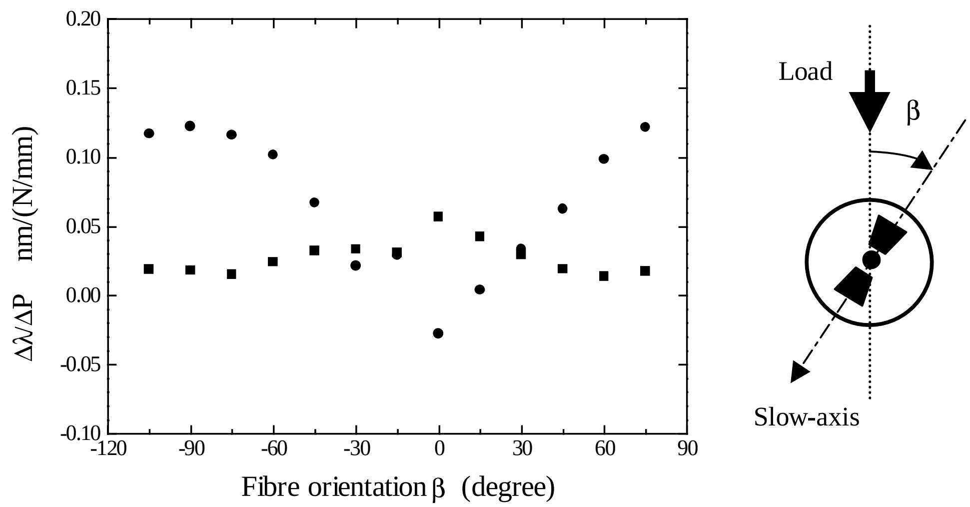

Figure 6 The transverse load sensitivities as a function of fibre orientations for the slow- and fast-axis modes for the PM FBG.

■ fast-axis mode, ● slow-axis mode

The transverse load sensitivities were measured for fibre orientations from -105° to 75° with a step of 15°. The measured transverse load sensitivities are plotted against the fibre orientation in Figure 6. The transverse load sensitivities were between 0.122 and -0.028 nm/(N/mm) for the slow-axis mode, while for the fast-axis mode they were between 0.056 and 0.016 nm/(N/mm). The amplitude of the load sensitivity variation along the fibre orientation for the slow-axis mode is approximately 3 times that for the fast-axis mode. When the load was applied in the direction of the fast-axis (β = -90°), the maximum value of load sensitivity for the slow-axis mode was measured. When the load was applied in the direction of the slow-axis (β= 0°), the minimum value of load sensitivity for the slow-axis mode and the maximum for the fast-axis mode were measured.

5. CONCLUSIONS

A novel signal interrogation system for PM FBG multi-axis strain sensors has been developed. It is capable of detecting independently the two orthogonally polarised signals reflected from a FBG fabricated in a PM fibre. It does not impose a limitation on the measurable strain range. This also relaxes the requirements on the bandwidth of the grating spectrum, allowing the use of a shorter FBG (larger bandwidth) for sensing applications where a higher spatial resolution is required. In particular, this system has unique capabilities in applications where the reflection spectrum of individual polarised signals reflected from a PM FBG is split or broadened, resulting from strain-induced structural changes of the PM fibre, or caused by applying a non-uniform strain to the FBG. The transverse strain sensing characteristics of FBGs written in bow-tie fibre have been investigated using the signal interrogation system.

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