Polarisation mode coupling of excessively tilted fibre Bragg gratings with directional transverse loading

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ABSTRACT

We report a distinctive polarisation mode coupling behaviour of tilted fibre Bragg gratings (TFBGs) with tilted angle exceeding 45°. The ex-45° TFBGs exhibit pronounced polarisation mode splitting resulted from grating structure asymmetry induced birefringence. We have studied and analysed the property of ex-45° TFBGs under transverse load applied to their equivalent fast- and slow-axis. The results show that the coupling between the orthogonally polarised modes takes place only when the load is applied to its fast-axis, giving a prominent directional loading response. This transverse load related polarisation property may be exploitable for implementation of optical fibre vector sensors capable of measuring the magnitude and orientation of the applied transverse load.

Keywords: transverse load, tilted fibre Bragg grating, vector sensor

1. INTRODUCTION

Optical fiber sensors capable of measuring transverse loads are useful for many industrial applications, for example, monitoring the strain distribution field in composite materials and structures[1,2] or used as all-fibre alternatives to load cells for engineering and processing requiring compact sensors for hazardous conditions. Transverse load measurement using fibre Bragg and long-period gratings made in low-bi and hi-bi, multi-core and conventional fibre have been reported[3,4,5,6]. The majority of these gratings exhibited a pronounced polarisation mode split effect resulted from the birefringence induced by the transverse loading. TFBGs with excessively tilted structures (> 45°) are capable of coupling light from the core mode to the forward-propagating cladding modes. Such gratings have also exhibited pronounced polarisation mode split characteristic and been reported for implementation of in-fibre twist sensors[7]. In this paper, we report a unique polarisation mode coupling property of ex-45° TFBGs under transverse load, which may be further explored for vector load sensors.

2. THEORY AND FABRICATION OF EX-45° TFBG

TFBGs are capable of coupling the light from forward-propagating core mode to backward-propagating, radiation and forward-propagating cladding modes when the tilt angle < 45°, = 45°and > 45°, respectively[8]. The strongest light coupling occurs at the wavelength determined by the phase match condition:

$$\lambda_{co-cl} = \left(n_{co} \pm n_{cl,m}\right) \cdot \frac{\Lambda}{\cos\theta} \tag{1}$$

where n_{co} and $n_{cl,m}$ are the effective mode refractive indices of fundamental core and *m*th cladding mode, Λ is the grating period and θ is the tilt angle of the structure. When the grating structure is excessively tilted, i.e > 45°, the fibre core becomes asymmetric, thus inducing a birefringence in the fibre. As experimentally observed, ex-45° TFBGs exhibit pronounced polarisation mode splitting[8], resulted from the structure asymmetry induced birefringence. Similar to a polarisation maintaining (PM) fibre, we may assign two orthogonal polarisation axes to the grating structure. As shown in Fig. 1(a), the direction perpendicular to the grating fringe plane may be regarded as the fast-axis and the direction in the plane as the slow-axis. The effective refractive index along the fast-axis and slow-axis can then be expressed as n_f and n_s and we have $n_f < n_s$.

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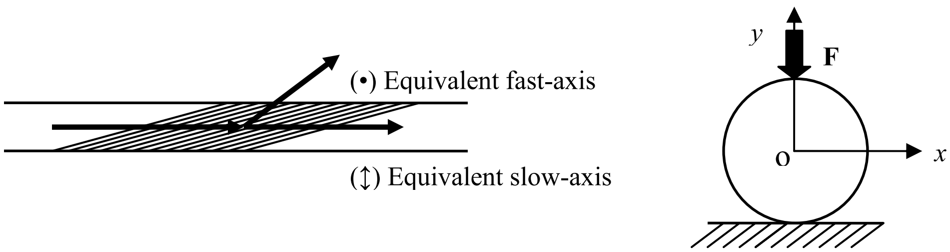


(a) (b)

Fig.1 (a) Schematic diagram of the ex-45° TFBG with two assigned orthogonal polarisation axes; (b) The cross section of the TFBG fibre in an assigned *x*-*y* coordinate system with transverse load applied along *y*-axis.

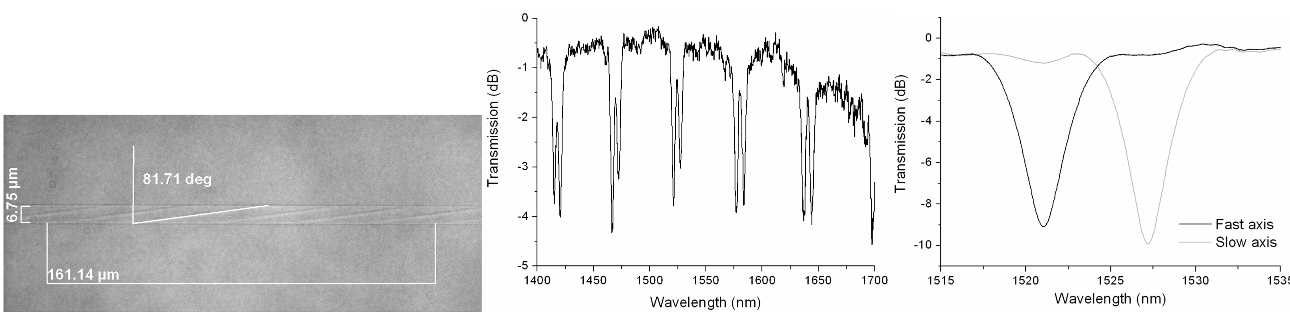
Considering a normal single mode fibre, when the transverse load is applied to *y*-axis as shown in Fig.1(b), for a given compressive force ***F***, the stresses in *x*- and *y*-direction are expressed in Hertz equations[9].

$$\sigma_x = \frac{2F}{\pi DL}, \qquad \sigma_y = -\frac{6F}{\pi DL} \tag{2}$$

where *D* is the fiber diameter, *F* is the applied force, and *L* is the length of the region under stress. It is noted that the horizontal normal stress σ_x is always positive or tensile in the whole cross section and the vertical normal stress σ_y is negative or compressive, which means $(\sigma_x - \sigma_y) > 0$. The refractive index changes in the cross section due to the photoelastic effect can be evaluated by[10]:

$$\Delta n = n_x - n_y = \left(n_{x0} - n_{y0}\right) + \left(C_1 - C_2\right)\left(\sigma_x - \sigma_y\right) \tag{3}$$

where C_1 and C_2 denote the stress-optical coefficients, and n_{x0} and n_{y0} are the effective refractive indices of the unstressed fiber and for silica glass, $(C_1 - C_2) > 0$ [11]. For an ex-45° TFBG, when the transverse load is applied along the slow-axis, we have $n_{x0} = n_f$ and $n_{y0} = n_s$. Thus, the first term in equation (3) will be negative resulting in a deduction in birefringence Δn, i.e. the grating structure is less PM-like. In this case, we may expect that the light coupling between the two orthogonally polarised modes is more easily facilitated under some perturbation. On the contrary, when the transverse load is applied to the fast-axis of the TFBG, we have $n_{x0} = n_s$ and $n_{y0} = n_f$ and the first term in equation (3) will be positive, resulting in increase in birefringence Δn. In this case, the ex-45° TFBG behaves more towards a PM fibre, preventing the light coupling between the two polarised modes.



(a) (b) (c)

Fig.2 (a) Image of the fringes of an 81°-TFBG taken under microscope; the tilt angle of the fringes is 81.71°. (b) The transmission spectrum of 81°-TFBG in the range from 1400nm to 1700nm. (c) The transmission spectra of one of the dual-peaks for two orthogonally polarised states.

In order to investigate the polarisation property of ex-45° TFBGs under transverse load, we UV-inscribed fibre Bragg gratings with tilted angles up to 81° in hydrogen loaded Corning SMF-28 fiber by phase mask method. The period of our special designed phase mask is 6.6μm. Fig. 2(a) shows the image of the tilted fringes of an 81°-TFBG under microscope. The tilted angle of the fringes is measured at 81.71°, which is in a good agreement with the design parameter.

We noticed that all the measured ex-45° TFBGs exhibited a polarisation mode-splitting feature. Fig. 2(b) depicts the transmission spectrum of an 81°-TFBG in the range from 1400nm to 1700nm, showing clearly a series dual-peak resonances, corresponding to the two sets of coupled cladding modes with orthogonal polarisation states. We then added a polariser and a polarisation controller before the TFBG to change the polarisation state of the probing light. When the light is switched to the fast- or slow-axis polarisation state, one of the dual peaks grows to its full strength ~8.6dB whereas the other almost disappears, as shown in Fig. 2(c). The separation between the paired peaks is about 6.16nm, giving an estimated combined fiber birefringence $\sim 2\times10^{-4}$.

3. IMPLETATION OF TRANSVERSE LOADING EXPERIMENT ON EX-45° TFBG

The transverse loading experiment was implemented by first laying the 81°-TFBG fiber and a dummy fiber of the same type between two flat surface aluminum plates, and then gradually increasing the load on the top. The schematic of the experiment is shown in Fig. 3(a) and (b). The light from a broadband source was launched into the one end of the grating fiber and the output was monitored from the other end by an optical spectrum analyser. A linear polariser and a polarisation controller were inserted between the broadband source and the TFBG to change the polarisation state of the probing light. Before the transverse load was applied, we set the polarisation state to fully excite the fast-axis mode on the shorter wavelength side by adjusting the polarisation controller. The grating length was 1.2 cm; and the loaded fiber length was 3.2 cm.

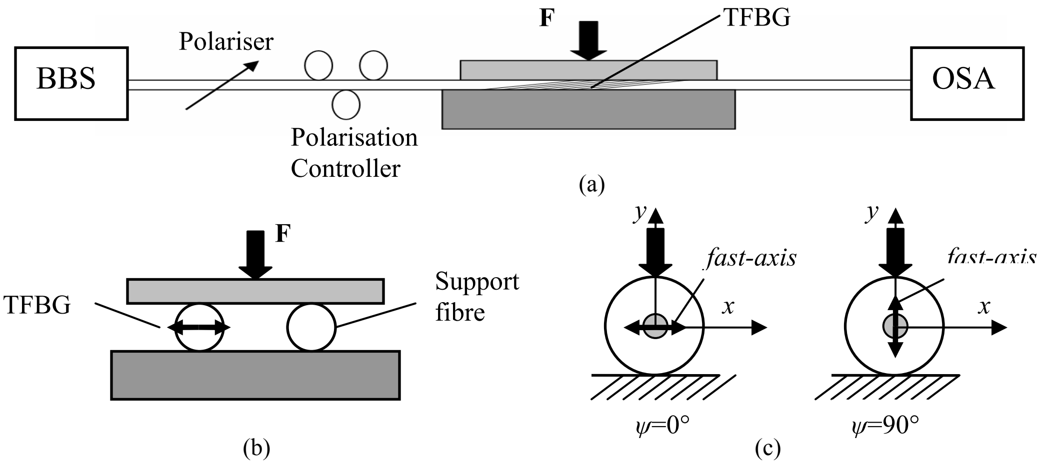


Fig.3 (a) and (b) The schematic diagrams of the transverse loading experiment system. (c) The cross section of the TFBG in an *x-y* coordinate system with transverse load applied along slow- and fast-axis; ψ is the angle between the fast-axis of the TFBG and *x* direction.

We applied the transverse load to the TFBG first to the slow-axis from 0 to 2.6kg (for two fibres) in an elevation step of 0.2kg, as shown $\psi = 0°$ in Fig. 3(c). The transmission spectrum for each applied load is plotted in Fig. 4(a). It is clear from Fig. 4(a) that with increasing load, the strength of fast-axis peak decreases but the slow-axis peak increases. Fig.4(b) depicts the transmission losses against applied load for both modes in linear scale, showing that the light was gradually coupled from the slow-axis to the fast-axis mode with the loading.

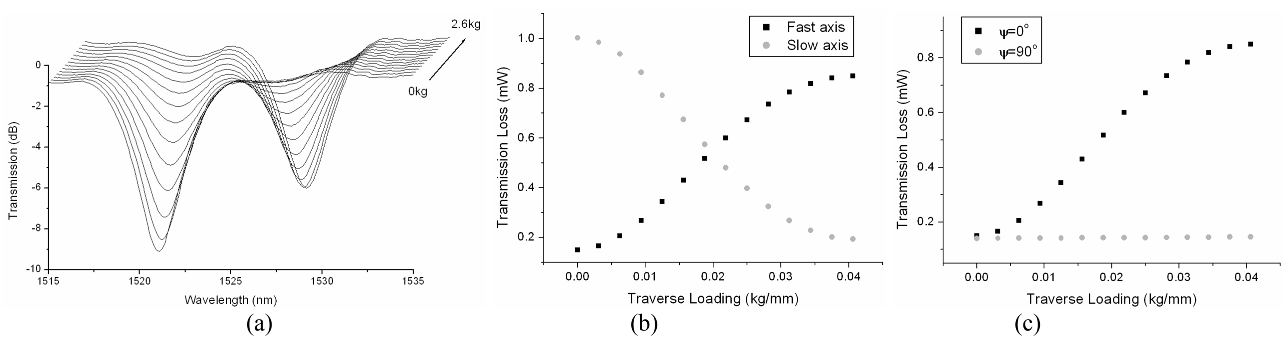


Fig. 4 (a) A waterfall plot of spectra evolution of 81°-TFBG with transverse load from 0kg/mm to 0.04kg/mm applied to the slow-axis. (b) Transmission losses of the two orthogonal polarisation modes plotted in linear scale with increasing load. (c) The transmission losses of the fast-axis mode with the load applied to fast- ($\psi = 90°$) and slow-axis ($\psi = 0°$).

We then repeated the loading experiment by applying the transverse load to the grating fast-axis (ψ = 90°) and did not observe any light coupling between the orthogonally polarised modes. This distinctive directional polarisation mode coupling behaviour agrees well with the theoretical explanation we give in section 2.

From an application point of view, the directional polarisation mode coupling behaviour exhibited by the ex-45° TFBGs may be explored for implementation of vector load sensors which have the ability monitoring not just the amplitude but also orientation of the load.

4. CONCLUSIONS

We have fabricated fibre Bragg grating devices with excessively tilted structures and experimentally observed pronounced polarisation mode splitting effect caused by the grating structure asymmetry induced birefringence. We further investigated the polarization property of such gratings under transverse load and found that TFBGs with excessively tilted structures exhibit a distinctive directional polarisation mode coupling behaviour under transverse load. When the load is applied to the equivalent slow-axis of the TFBG, the light will be coupled from the slow-axis mode to the fast-axis one, whereas no light coupling taking place when the load is applied to the fast-axis. This load direction related property may be explored for implementation of vector load sensors capable of measuring the magnitude and orientation of applied load.

REFERENCES

[1] K. S. C. Kuang, R. Kenny, M. P. Whelan, W. J. Cantwell and P. R. Chalker, "Embedded fibre Bragg grating sensors in advanced composite materials," *Compos. Sci. Technol.* **61**, 1379-1387 (2001).

[2] J. A. Guemes and J. M. Menéndez, "Response of Bragg grating fiber-optic sensors when embedded in composite laminates," *Compos. Sci. Technol.* **62**, 959-966 (2002).

[3] R. B. Wagreich, W. A. Atia, H. Singh and J. S. Sirkis, "Effects of diametric load on fibre Bragg gratings fabricated in low birefringent fibre," *Electro. Lett.* **32** (13), 1223-1224 (1996).

[4] I. Abe, H. J. Kalinowski, O. Frazão, J. L. Santos, R. N. Nogueira, and J. L. Pinto, "Superimposed Bragg gratings in high-birefringence fibre optics: three-parameter simultaneous measurements," *Meas. Sci. Technol.* **15,** 1453–1457 (2004).

[5] L. Zhang, Y. Liu, L. Everall, J. A. R. Williams, and I. Bennion, "Design and realization of long-period grating devices in conventional and high birefringence fibers and their novel applications as fiber-optic load sensors," *IEEE J. Sel. Top. Quantum Electron.* **5,** 1373–1378 (1999).

[6] M. Silva-López, W. N. MacPherson, C. Li, A. J. Moore, J. S. Barton, J. D. C. Jones, D. Zhao, L. Zhang and I. Bennion, "Transverse load and orientation measurement with multicore fiber Bragg gratings," *Appl. Opt.* 44 (32), 6890-6897, (2005).

[7] X. Chen, K. Zhou, L. Zhang, and I. Bennion, "In-fiber twist sensor based on a fiber Bragg grating with 81º tilted structure," *IEEE Photon.Technol. Lett.* **18** (24), 2596-2598, (2006).

[8] K. Zhou, L. Zhang, X. Chen and I. Bennion, "Low thermal sensitivity grating devices based on ex-45° tilting structure capable of forward-propagating cladding modes coupling," *J. Lightwave Technol.,* **24** (12), 5087-5094 (2006).

[9] R. A. Steinberg and T. G. Giallorenzi, "Performance limitation imposed on optical waveguide switches and modulator by polarization," *Appl. Opt.*, **15** (10), 2440-2453, (1976).

[10] R. Gafsi and M. A. El-Sherif, "Analysis of induced birefringence effects on fiber Bragg gratings," *Opt. Fiber Technol.* **6**, 299-323 (2000).

[11] N. Imoto, N. Yoshizawa, J. Sakai and H. Tsuchiya, "Birefringence in single-mode optical fiber due to elliptical core deformation and stress anisotropy," *Quantum Electron.*, **16** (11), 1267-1271, (1980).