Design Evaluation of DBR Fiber Laser Sensor for Directional Lateral Force Monitoring

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***Abstract*— This letter reports an analysis of the potential of distributed Bragg reflector (DBR) fiber laser sensor designed to monitor the force orientation information, and with the birefringence characteristics of optical fiber, enabling the measurement of a directional lateral force applied to the fiber. In system design, to interrogate birefringence variation of the sensor according to the change of applied force angles, a reference lasing signal was employed following the results of an analysis using heterodyning theory. Agreement between theoretical and experimental results was obtained for a constant lateral force loading from different directions corresponding to the variation of sensitivity in beat signals. The design created in this letter is based on fundamental principles and generic, thus suitable for use with any DBR fiber laser structure for vector sensor applications.**

***Index Terms*— Directional force, fiber laser sensor, birefringence, heterodyning.**

I. Introduction

FORCE and stress distribution can provide vital information in various applications, such as structural health monitoring and medical diagnostic analysis [1], [2]. Force and stress information can be obtained from light signal variation in either the strength or the orientation [3], [4]. Compared to electronic sensors, optic sensors have been paid more attentions in forces and stress measurement due to their unique advantage, such as harsh environment operating capability, immunity to EMI, and multiplexing capability [5]. Most of grating based and interferometric based optical sensors have poor performance to distinguish vector force or pressure [6], [7], however, polarization-sensitive optical fiber can provide directional information based on birefringence due to the anisotropic in optical fiber core.

Using polarimetric optical fiber technology to measure external force was first proposed by Xi *et al.* [8] and the relationship between the mode coupling coefficient in polarization-maintained fiber to evaluated external force from strength and orientation was studied by Makoto [9]. Due to fiber manufacturing technology progress, recently, using fiber sensor to study material mechanic deformation have been become more popular. For example, two different types of specialist polarization-maintaining side-hole(s) fibers for measurement of directional force was proposed by Karimi *et al.* [10] and a technology to interrogate the birefringence characteristics variation via a directional transverse applied force with a polarization maintaining fiber was demonstrated by Karimi *et al.* [11]. The directional information of force obtained from these research mainly include the two orthogonal polarimetric parameters change in polarization-sensitive optical fiber. But these existing polarization-sensitive optical fiber sensing technology are mostly based on the light power or wavelength measurement, which rely on the employment of high stability power meter or expensive wavelength measurement devices. Moreover in addition to sensors, the interrogation system has great effect on the measurement results.

In recent years, polarimetric heterodyning DBR fiber laser sensing technology has attracted considerable interest for the evaluation of lateral force [12], [13], due to it not only has advantages of polarization-sensitive fiber sensors, but also has a distinctive advantage of ease of interrogation in radio frequency (RF) domain. DBR fiber sensor with a single longitudinal mode output was first proposed and demonstrated by Tam and Guan et al., showing attractive sensing ability for lateral force [14], [15], axial strain, and acoustic pressure in our previous studies [16], [17]. However, the exsiting demodulation analysis method by directly beating two orthogonal polarimetric modes of DBR laser sensor weaken the directional measurement technological advantages of birefringence in fiber sensor.

To improve the orientation recognition ability, this letter demonstrates a novel demodulation method for DBR fiber laser sensor. The approach builds on a theoretical analysis of each orthogonal polarimetric mode change in DBR fiber laser as a function of the lateral force orientation, with this being followed up by an experimental verification based on the use of a reference lasing signal to interrogate two orthogonal polarimetric modes respectively change in DBR fiber laser sensor for estimation of the force orientation information.

II. Operating Principle

The DBR fiber laser sensor consisting of a pair of wavelength-matched Bragg gratings written in an

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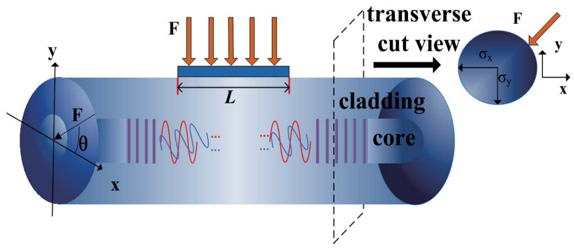

Fig. 1. The schematic of DBR fiber laser sensor when the cavity is subjected to lateral force. Here the cavity is composed by a pair of wavelength-matched FBGs, single resonant mode within the FBG transmission band can be obtained by shortening the cavity.

Er^{3+}-doped fiber, shown in Fig.1. It is obvious that the fiber is itself anisotropic and characterized by refractive index with different principal components along the x and y axes respectively, and two nearly degenerate orthogonal polarizations of LP_{01x} and LP_{01y} modes are given by:

$$\lambda_{x,y} = 2n_{x,y}\Lambda \tag{1}$$

where Λ is the grating pitch, n_x and n_y are the refractive index of each polarimetric mode. Assume a Cartesian coordinate system as shown in Fig.1, with x and y corresponding to the internal birefringent axes of the doped fiber. Also assume that lateral forces F compress the fiber at an angle θ with respect to the x axis over the region with length L. Using the stress σ_x,σ_y in case of plane force ($\sigma_z = 0$), we obtain the refractive-index changes in the fiber [18]:

for x-polarization,

$$\Delta n_x = -\frac{n_0^3}{2E}[C_1\sigma_x + C_2\sigma_y] \tag{2}$$

for y-polarization,

$$\Delta n_y = -\frac{n_0^3}{2E}[C_2\sigma_x + C_1\sigma_y] \tag{3}$$

where n_0 is the refractive index of the unstressed fiber, E is the Young's modulus of the optical fiber. $C_1 = (1+\nu)[(1-\nu)p_{11} - \nu p_{12}]$, $C_2 = (1+\nu)[(1-\nu)p_{12} - \nu p_{11}]$ are photoelastic constants, where ν is the Poisson coefficient, and p_{11}, p_{12} are photoelastic coefficients of the undisturbed optical fiber. $\sigma_x = (F/\pi r L)\cos^2\theta + (-3F/\pi r L)\sin^2\theta$,$\sigma_y = (F/\pi r L)\sin^2\theta + (-3F/\pi r L)\cos^2\theta$ are the stress components in the fiber core region due to the external force, where r is the fiber radius [9], [19].

In order to measure the absolute change of λ_x and λ_y under the directional lateral force respectively, a reference laser signal λ_z is induced, and beat signals can be expressed by:

$$\delta(\Delta\upsilon_{xz}) = \Delta\upsilon'_{xz} - \Delta\upsilon_{xz} \approx C\Delta n_x/n_0^2\lambda_0 \tag{4}$$

$$\delta(\Delta\upsilon_{yz}) = \Delta\upsilon'_{yz} - \Delta\upsilon_{yz} \approx C\Delta n_y/n_0^2\lambda_0 \tag{5}$$

and

$$\delta(\Delta\upsilon_{xy}) = \Delta\upsilon'_{xy} - \Delta\upsilon_{xy} \approx C(\Delta n_x - \Delta n_y)/n_0^2\lambda_0 \tag{6}$$

where c is the speed of light in vacuum, and λ_0 is the average lasing wavelength.

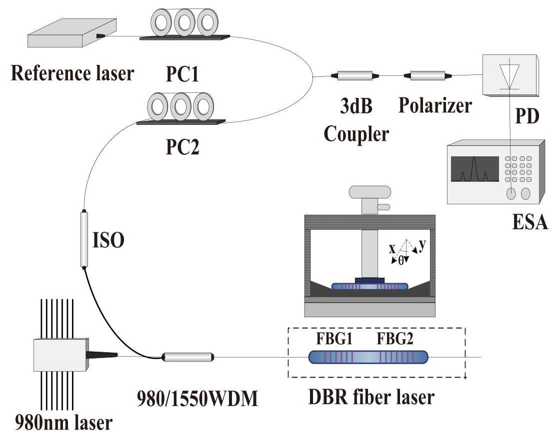

Fig. 2. Experimental setup for directional lateral force measurement.

III. Experiment and Results

Figure.2 is the schematic of directionality lateral force monitoring system, consisting of a DBR fiber laser sensor inscribed in a commercial Er^{3+}-doped fiber (OFS), which has a peak absorption of 20 dB/m at 1530 nm and a mode field diameter of about 5.2 μm. The FBGs were fabricated using phase-mask grating-writing technique with a 193 nm ArF excimer laser. The lengths of the two FBGs are 25 mm with a 30 dB reflectivity and 15 mm with a 22 dB reflectivity, separating by a nominal cavity length of 10 mm, thus the DBR fiber laser has a total length of 50 mm.

The DBR fiber laser sensor was pumped by a 980 nm laser diode (Bookham LC96X74) with an output power of 450 mW through a 980/1550 nm wavelength division multiplexer (WDM). The 1550.42 nm laser light with the continuous-wave saturation power -9 dBm emitted from the low reflectivity FBG end, and directed to the 1550 nm port of WDM. An optical isolator (ISO) was placed in front of the polarization controller (PC2) to reduce any unwanted reflection back to the fiber laser. A laser beam at wavelength of 1550 nm emitted from a tunable single frequency laser (DenseLight BF11), which served as a reference input signal. By adjusting the polarization controllers (PC1, PC2) and the polarizer which are used to obtain maximum extinction ratio among the lasing modes, and beat signals can be achieved at the Photodetector (PD, Thorlabs DET01CFC), which was connected to an electrical spectrum analyzer (ESA, Agilent Technologies E8247C).

Accordingly, the DBR laser sensor was fixed on a stage which can be rotated along the fiber's axis with various loading angles, and a silica plate was used to impose pressure on the DBR laser by loading weights. By rotating the optical fiber by axis, two polarization modes wavelengths of DBR laser shifted, and beat frequencies were variable with change of applied force angles according to Eq.(4) and Eq.(5).

Fig. 3 shows the beat frequency shifts (at around 66 MHz and 33 MHz) as a function of the lateral force applied to the fiber with different loading orientations. In this experiment, the force used was 0.0098N applied over a distance of 5mm. As can be seen from the graph, when the DBR fiber laser sensor was under initial state, its own

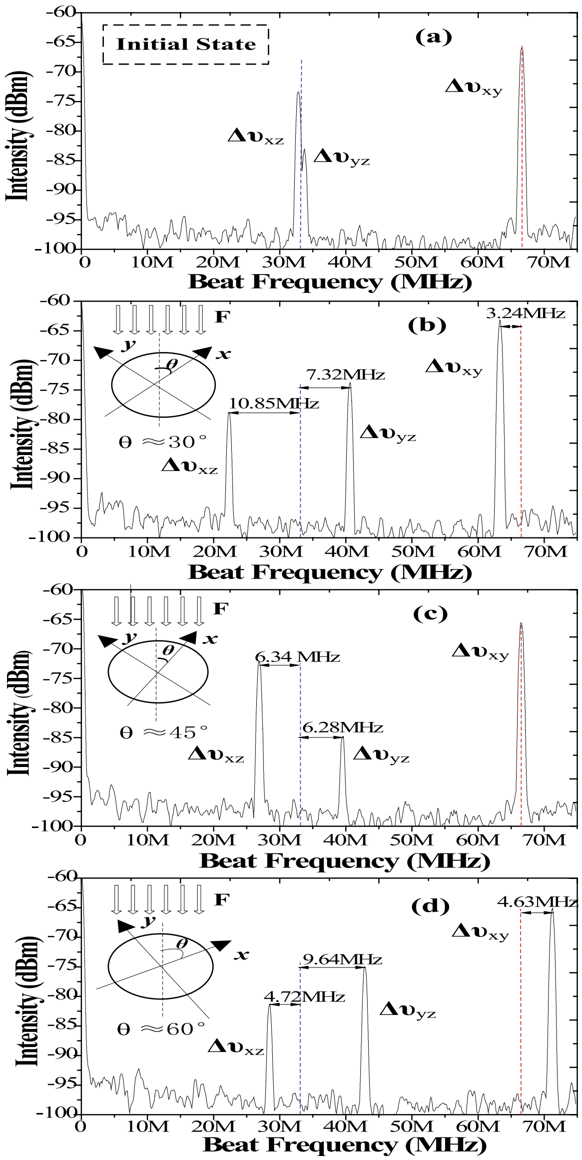

Fig. 3. Beat signals spectra against (a) no load, and loading weight at 0.0098N over a distance of 5mm with different angles at (b) $\theta \approx 30°$, (c) $\theta \approx 45°$, (d) $\theta \approx 60°$.

polarization beat frequency was $\Delta\upsilon_{xy} = 66.512$ MHz. To facilitate the measurement, we adjusted the reference laser wavelength to the central of two polarization modes of DBR laser sensor, so another two beat signals $\Delta\upsilon_{xz}$ and $\Delta\upsilon_{yz}$ was about 33.256 MHz (at half of $\Delta\upsilon_{xy}$), which was generated by DBR sensor and the referenced laser, shown in Fig.3(a).

Fig.3(b) shows the experimental results when the lateral force loaded at $\theta \approx 30°$, where the corresponding beat signals $\Delta\upsilon_{xz}$ decreased 10.85 MHz and $\Delta\upsilon_{yz}$ increased 7.32 MHz, which raised from the stress decomposition to principal polarization axes, the polarization wavelength of LP_{01x} shifted more than LP_{01y}, and beat signals $\Delta\upsilon_{xy}$ of DBR laser sensor decreased 3.24 MHz.

Fig.3(d) shows that the beat signals changed at $\theta \approx 60°$, where the polarization wavelength of LP_{01x} shifted less than LP_{01y}, the beat signals $\Delta\upsilon_{xz}$ decreased 4.72 MHz, $\Delta\upsilon_{yz}$ increased 9.64 MHz, and the $\Delta\upsilon_{xy}$ increased 4.63 MHz, respectively. Based on Fig.3, the DBR fiber laser sensor has shown a good ability to detect the lateral force orientation by beat frequency signals analysis.

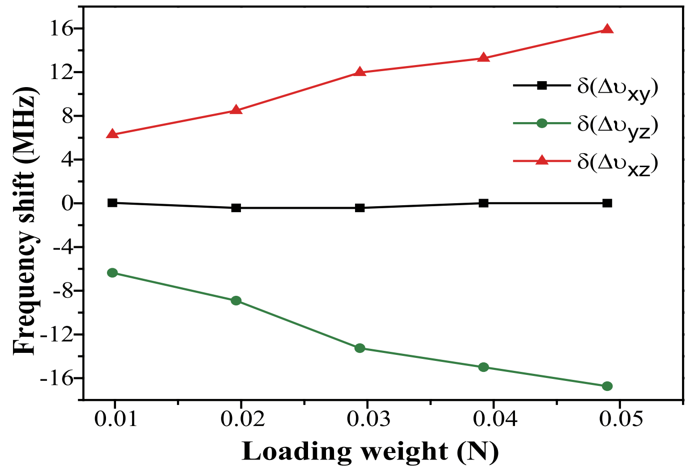

Fig. 4. Beat frequency shift against different loading weights at 45°.

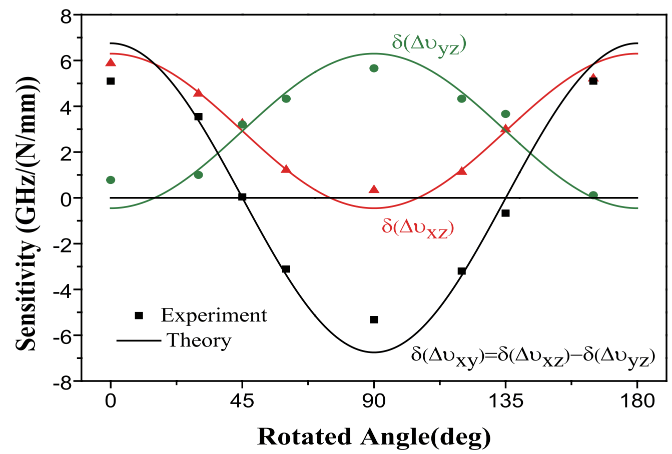

Fig. 5. Sensitivity as a function of rotational angle from 0° to 180° for DBR sensor. Points are obtained from the experimental work and the solid line results from the theoretical analysis.

Fig.3(c) confirms that at $\theta \approx 45°$, the beat signal $\Delta\upsilon_{xy}$ almost unchanged. It is because the force-induced index variation along the two orthogonal axes are almost the same, so the DBR laser sensors are insensitive to lateral force orientated at angles ($\theta = (2n+1)\pi/4$) via traditional polarimetric heterodyning method [14]. But by means of a reference lasing signal, the absolute values of two polarization sensing signals could be demodulated, and the corresponding beat signals $\Delta\upsilon_{xz}$ and $\Delta\upsilon_{yz}$ change with almost same proportion. Fig.4 shows the beat signals shift as a function of the force applied at $\theta \approx 45°$, where the applied force was increased in steps of 0.0098N, over the range from 0 to 0.05N.

The experimental results show that the DBR laser sensor with a constant load along different directions over the range from $\theta = 0°$ to 180° have demonstrated different sensitivities to lateral force, and these results obtained are summarized in Fig.5. This shows that the orientation of lateral force is associated with the proportion sensitivity testing (PST) of the corresponding beat signals change.

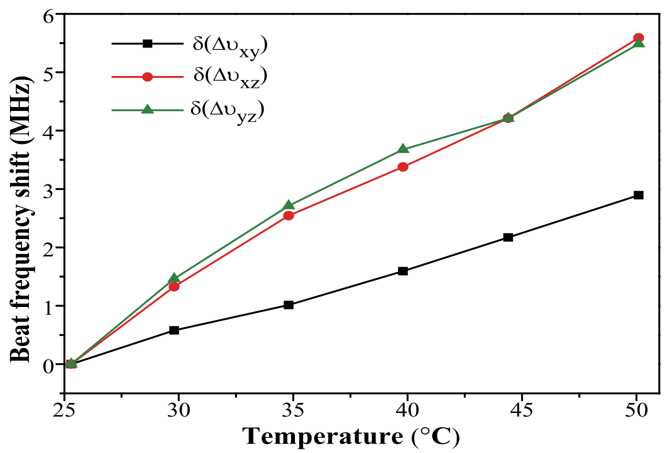

Fig. 6. Temperature response of the proposed directional lateral force DBR sensor.

The mismatch between the theory and experiments is expected to result from the assumption made in the theoretical analysis that there is a minimum contact surface area with the applied force and this is difficult to realize in practice.

The thermal stability of the DBR laser sensor was investigated by putting the sensing head into a tube oven. A thermocouple was placed near the sensing head for measurement of the temperature. The sensing head was kept unstrained. Figure.6 exhibits the measured beat frequency shifts as functions of temperature in the range from 25 °C to 50 °C in step of 5 °C. Note that the deviation elicited by temperature could be eliminated in several degrees. But measurement in large temperature difference, the margin of temperature error is wide especially to $\delta(\Delta \upsilon_{xz})$ and $\delta(\Delta \upsilon_{yz})$ that effect the directional discrimination. Some methods should be induced as possible to maintain thermal equilibrium during the measurement in this case.

We also investigated the beat frequency stability of the unstrained DBR laser sensor along time at room temperature(25 °C). During 24 hours testing, the beat-frequency fluctuation of $\delta(\Delta \upsilon_{xy})$ is less than 0.3 MHz, $\delta(\Delta \upsilon_{xz})$ and $\delta(\Delta \upsilon_{yz})$ is less than 0.5 MHz. Note that the fiber grating lasers also emits an amount of heat, and unexpected perturbations might appear in an acceptable range.

IV. Conclusion

We report an optical fiber sensing system for measuring directional lateral force, which has been developed and demonstrated using polarimetric DBR fiber laser sensors, in contrast to conventional polarization maintaining fiber sensors. The results exhibit that DBR fiber laser sensor has unique directional sensing abilities with heterodyning signals analysis corresponding to different lateral force directions. Moreover, the proposed method could be extended further in axial strain or hydrostatic pressure measurement applications which were regarded insensitive and hardly detected by DBR fiber laser sensors before [14]. Research is on-going to optimize the sensor systems designed for more precise orientation and positioning.

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