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Twist sensor based on axial strain insensitive distributed Bragg reflector fiber laser

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Abstract: A novel fiber-optic twist sensor based on a dual-polarization distributed Bragg reflector (DBR) fiber grating laser is proposed and experimentally demonstrated. By beating the signal between the two polarizations of the laser which operates at 1543.154nm, a signal of 30.78MHz in frequency domain is observed. The twist will change the fiber birefringence, and resulting in the beat frequency variation between the two polarization modes from the fiber laser. The result shows the beat frequency shifts as a Sinc function curve with the twist angle and both the measuring curve period and twist sensitivity depend on the twist length of the laser cavity. A high twist sensitivity of 6.68MHz/ rad has been obtained at the twist length of 17.5cm. Moreover, the sensor is insensitive to the environmental temperature, as well as strain along the fiber axis with ultralow beat frequency coefficients, making temperature and axial strain compensation unnecessary.

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1. Introduction

Measurements of torque or twist angle on bridges, buildings, trains or other structures plays very important role in modern smart structure monitoring. Fiber optic devices such as fiber Bragg gratings have been widely used to measure the twist rate due to their advantages including high sensitivity, compact size, immunity to electromagnetic interference [1, 2]. A considerable amount of twist sensor based on fiber gratings has been investigated. Joon Yong Cho reported an optical fiber twist sensor consisting of two mechanically induced long-period grating sections [3]. X. Chen demonstrated an in-fiber twist sensor based on a fiber Bragg grating with 81° tilted structure [4]. Peng Zu and Weiguo Chen fabricated the fiber twist sensor based on the Sagnac interferometer by use of photonic crystal fiber [5, 6]. However, most fiber grating sensors suffer from the cross sensitivity of the axial strain and temperature, and they also require expensive equipment for wavelength demodulation. Therefore, complicated schemes have to be introduced to compensate it.

Fiber Bragg grating lasers that operate in single longitude mode with dual polarization states have attracted considerable interest since they are relatively easy to fabricate [7, 8]. Their applications for sensing and microwave generation [9, 10] have been reported recently. For sensing applications, they convert the measurand into a change in the polarization mode beat frequency, offering advantages of easy interrogation, high signal-to-noise ratio, absolute encoding, and capability to multiplex a number of sensors on a single fiber through frequency-division-multiplexing technique. This sensing principle has been successfully demonstrated for measuring different parameters, such as: lateral force [11], displacement [12], bending [13], ultrasound [14] and current [15].

In this paper, we propose and demonstrate a novel axial strain insensitive fiber twist sensor based on the beat frequency signal measurement of a short cavity DBR fiber laser. The laser characteristics in both optical and frequency domain are investigated in details. Due to the fiber birefringence change caused by fiber twist, the beat frequency generated between two polarizations of the laser is sensitive to the variation of twist angle. By monitoring the periodical beat frequency response, the twist angle could be deduced. Meanwhile, the beat frequency response at different twist length is discussed as well, which indicates the capability for multi-point sensing applications.

2. Principle

The DBR fiber laser sensor is composed of two wavelength matched Bragg gratings written in an active fiber with appropriate separation. When the cavity length reduces to several centimeters, single-frequency lasing can be easily achieved by carefully optimizing the cavity parameters. Due to the fiber birefringence, the laser always operates in two orthogonal polarization states, and when the laser output is monitored by a photodetector (PD), the two polarization modes will generate a beat signal in the radio frequency domain. The beat frequency is given as [14]:

$$\Delta \nu = \frac{Bc}{n_{\text{eff}} \lambda_0}$$  \hspace{1cm} (1)
where \( c \) is the light speed in vacuum, \( \lambda_0 \) is the laser wavelength; \( n_{\text{eff}} \) and \( B \) are the average refractive index and birefringence of the optical fiber, respectively.

In a practical optical fiber there is an intrinsic linear birefringence due to the deviations from a circular shape of its core. When the twist is applied onto the fiber, a circular birefringence is induced according to the shear strain. So the total birefringence will be distinguished in three situations according to the magnitude of the twist rate [16]. In the case of small twist, the linear birefringence is dominant and for medium twist the shear strain in the twisted fiber gives rise to a circular birefringence with a proportional to the twist, while for strong twist, the total birefringence is dominated by the induced circular birefringence. In the experiment, due to the low birefringence of the EDF which is about \( 10^{-7} \), the twist applied onto the cavity could be considered as a strong twist.

By fixing one end of the fiber and twisting the other end, the retardance (\( \Delta \Phi \)) caused by the strong twist between the two orthogonal guided polarization modes can be expressed as a function of twist rate \( \omega \) and twist length \( z \) [17]:

\[
\Delta \Phi = 2 \sin^{-1} \left( \frac{\rho}{\sqrt{1+\rho^2}} \sin \gamma z \right)
\]  

where:

\[
\rho = \frac{\Delta \beta}{2(\omega-\alpha)}
\]

\[
\gamma = \frac{1}{2} \sqrt{\Delta \beta^2 + 4(\omega-\alpha)^2}
\]

where \( \Delta \beta \) refers to the intrinsic propagation constant retardance between the two polarizations. For the twist fiber, \( \alpha \) is the optical rotation which can be described as:

\[
\alpha = g \omega
\]

The coefficient of proportionality \( g \) is found experimentally to be 0.08 [16]. And for strong twist, the evolution is dominated by the induced circular birefringence. So the Eq. (2) can be simplified as:

\[
\Delta \Phi = \Delta \beta \frac{\sin[(\omega-\alpha)z]}{\omega-\alpha}
\]

Consequently, the birefringence cause by the twist can be described as:

\[
\Delta B = B \frac{\sin[(\omega-\alpha)z]}{\omega-\alpha}
\]

where \( B \) is the original birefringence of the fiber.

According to Eq. (5) and (6), the birefringence is dependent on both the fiber twist \( \omega \) and the length of the effective twist length \( z \). For twist sensor based on fiber laser, \( z \) stands for the effective length of the laser cavity. So when the laser cavity is subjected to the twist, the fiber birefringence will be changed periodically as a Sinc function, as well as the beat frequency. In this case, it could be useful for twist sensing applications.

3. Sensor structure and experiment research

The schematic diagram of the proposed DBR fiber laser is shown in Fig. 1. The laser is fabricated by inscribing a pair of Bragg wavelength matched uniform FBGs into a short length of erbium doped fiber directly. The Er-doped fiber has peak absorption of 6.0dB/m at 1530 nm. The two FBGs are written by the phase mask scanning technique with a 244nm frequency-doubled argon laser. The fiber laser consists of two 10mm long reflectivity grating,
and 10 mm grating spacing. The transmission spectrum depth and bandwidth of the FBG1 are 23dB and 0.2nm, while the other one has a transmission spectrum depth of more than 25dB, which could be estimated through the fabrication process. Therefore, the effective length of the cavity is calculated to be about 13mm [18]. The twist length in Fig. 1 refers to the distance from fiber holder to the middle of the cavity.

The laser is pumped by a 980nm laser diode (LD) with a highest output of 600mW through a 980/1550nm wavelength division multiplexer (WDM). The backward output is split into two parts, one is monitored by an optical spectrum analyzer (OSA) with a resolution of 0.02nm, and the other is injected into a photodetector (PD) through a polarization controller (PC) and a polarizer. The beat frequency signal is observed by an electrical spectrum analyzer (ESA). By adjusting the PC and the polarizer, the beating signal intensity of the two orthogonal polarization modes could be maximized at the PD.

Figure 2 (a) shows the output spectrum of the short cavity DBR fiber laser measured by OSA. The laser operates in a single longitudinal mode around 1543.154nm with a side mode suppression ratio of nearly 50dB.

Then we investigate the response of the laser in frequency domain. A 23cm length of fiber with the laser cavity positioned in the middle was fixed by a fiber holder on one side and a fiber...
rotator with an engraved dial on the other end. In order to eliminate any bending effects, we applied small axial strain to the fiber to keep it straight. As shown in Fig. 2(b), when there is no twist induced into the cavity, the frequency observed is only 30.78MHz, corresponding to an original fiber birefringence which is $2.3 \times 10^{-7}$. The 3dB linewidth of the beat signal is about 10kHz and the frequency drift got is about 50kHz.

In order to obtain the twist response of the sensor, the frequency spectra were recorded by increasing the twist angle from 0° to 600° with an interval of 20°. The relationship between the beat frequency and the twist angle is shown in Fig. 3. It is obvious that the beat frequency changes periodically with the twist angle as a Sinc function.

Moreover, the measuring sensitivity is investigated by changing the position of the laser cavity. The Fig. 3 (a) (b) (c) and (d) displays the variation curves between the laser beat frequency and the twist angle with different twist lengths. In each one of Fig. 3, there is a certain region that beat frequency varies almost linearly with the twist, which could simplify the measurement in practical applications. The effect of the twist length on the response sensitivity in the linear area of the laser is different. In Fig. 3 (a), when the twist length is 5.5cm, the sensitivity in the linear fitting region from 240° to 380° is 3.42MHz/rad. In Fig. 3 (b) and (c), the sensitivity increases to 4.67MHz/rad and 6.09MHz/rad in the linear region from 60° to 160° and 20° to 100°, respectively. While it goes to 6.68MHz/rad from 40° to 120° as the twist length increases to 17.5cm. This linear measuring range is determined by the period, but it could be enhanced by fitting the curve with proper linear coefficient in other regions. The linear fitting region reveals the capability of achieving high sensitivity in terms of presetting the fiber twist in this area in advance.

Meanwhile, the fitting curve period varies with the twist length as well. Figure 4 depicts the relationship between the twist length and the period of the measuring curve. The period varies almost linearly with the twist length, which could be used for multi-point twist monitor by
cascading several cavities along a single fiber. The correlative coefficient of the experiment result is 0.9426, indicating the maximum twist length deviation is 1.67cm when it is used for precise positioning. The error in Fig. 4 is caused by the twist length uncertainty. Since the physical length of laser cavity is 3cm, the exact space between fiber holder and laser cavity position is uncertain. In the experiment, we define the twist length as the distance from fiber holder to the middle of the cavity. This could be suppressed by further reducing the cavity length in terms of employing high gain coefficient EDF.

In order to investigate the axial strain cross-sensitivity of the sensor, one end of the DBR fiber laser was fixed, whereas the other was stretched by using a manual translation stage. Strain was calculated from the elongation of the stretched fiber divided by the original length. During the strain response measurement, the environmental temperature was kept stable.

Figure 5 represents the wavelength shift and beat signal frequency response to applied strain in the range of 0 to 1200 µε, which are observed by OSA and ESA, respectively. It can be seen that the laser wavelength increases linearly with the axis strain with the coefficient of 1.09pm/µε. However, the beat frequency almost keeps stable, with the coefficient of only 81Hz/µε, indicating that the beat signal is nearly independent with the axial strain. This characteristic could be very useful for practical applications since the axial strain effect can be ignored in comparison to the beat frequency shift. The reason is when the fiber birefringence is low, the axial strain effects applied onto the two polarizations are nearly the same, resulting in the synchronous wavelength drift in these two polarizations. Similarly, it could be deduced that the sensor will also be insensitive to the temperature fluctuation.
The temperature response of the laser cavity is shown in Fig. 6. As the temperature increases from 10°C to 90°C, the lasing wavelength varies with a coefficient of 11.69pm/°C, while the beat frequency decreases almost linearly with a coefficient of only −36.17kHz/°C, which could be considered as a relatively small thermal response since the frequency fluctuation of the laser is about 50kHz.

![Wavelength and polarization beat frequency variation as a function of temperature.](image)

Fig. 6. Wavelength and polarization beat frequency variation as a function of temperature.

4. Conclusion

We investigate the characteristics of the twist sensor based on a dual-polarization DBR fiber laser. The laser operates in two orthogonal polarization modes and by beating the signal between the two polarizations, a signal of 30.78MHz in frequency domain is obtained. The experimental frequency response shows that the beat signal changes as Sinc function with the twist angle, which is well agreed with the theoretical analysis. Both the sensitivity and measuring curve period depend on the twist length. A high twist sensitivity of 6.68MHz/rad has been obtained at the twist length of 17.5cm. The sensor shows good performance of independent to the axial strain variation with an ultralow coefficient of 81Hz/µε, and is also insensitive to the temperature fluctuation with a coefficient of −36.17kHz/°C. The sensor reveals the advantages of small dimension, and relatively easy to fabricate. Meanwhile, it exhibits the capability of multiplexing several cavities along a single fiber to achieve multi-point sensing due to its compact structure and low lasing threshold. In addition, the low beat frequency obtained in the experiment makes the demodulation easier with low-speed and inexpensive electronic devices.

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