A novel distributed spun fiber twist sensor based on frequency-scanning φ-OTDR

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Abstract: A novel distributed twist sensor utilizing frequency-scanning φ-OTDR in a spun fiber is theoretically analyzed and experimentally demonstrated by tracking the fiber twist induced frequency shift of correlation peak, enabling distributed quantitative twist measurement. © 2022 The Author(s)

1. Introduction

Twist sensing has drawn significant interest in various applications, including structural health monitoring [1], and 3-D shape sensing [2], etc. So far, various optical fiber twist sensors have been investigated, which can be categorized into two types, including the fiber grating-based and the interferometer-based twist sensors. The fiber grating-based twist sensors are constructed by diverse fiber gratings, such as the long period gratings, fiber Bragg gratings, tilted FBGs and the phase-shifted FBG, etc. [3-5]. Another type known as the optical fiber interferometer-based twist sensors are fabricated by various fiber interferometers, including the Sagnac interferometers, multi-modes interferometers and Mach-Zehnder interferometers [6,7]. These two types of twist sensors, however, can only be used to measure twist at a single spot, but not be able to achieve distributed twist sensing, which severely restricts their applications. Recently, a distributed twist sensor utilizing the OFDR technology in a helical multicore fiber was reported, in which directional twist measurement was demonstrated with a linear sensitivity of 1.9 pm/(rad/m) and a spatial resolution of 9.4 mm [8]. This work reveals that the usage of distributed sensing technique and specialty optical fiber might be a good way to overcome the shortcoming of the conventional fiber grating-based and interferometer-based point sensors, and enables fully distributed twist sensing.

In this work, a novel distributed twist sensor utilizing frequency-scanning φ-OTDR in a spun fiber is developed. Owing to the helical stress zone structure of the spun fiber, it is sensitive to twist. In addition, the frequency-scanning φ-OTDR is well-known for its ultra-high sensitivity and measurement resolution, which can be used to measure the fiber twist effect by retrieving the frequency shift in the correlation spectrum between two measurements. For proof of concept, distributed twist sensing over a 136 m spun fiber with a 1 m spatial resolution was demonstrated, and the measured frequency shift shows a quadratic fitting dependence on the twist angle. The proposed novel sensor is very promising for high-sensitivity distributed twist measurement.

2. Principle and simulation

Frequency-scanning φ-OTDR launches pump pulses with different frequencies in sequence into the sensing fiber. External disturbance, such as stress or temperature change, applied on the fiber will lead to a change in the effective refractive index of light, the phase differences between the scattering points in the sensing fiber will vary accordingly. A laser frequency shift can be utilized to compensate for the phase difference since it is related to both the frequency of the optic pulse and the effective refractive index in the fiber. This is done by calculating the correlation between two measurements, as a result the disturbance can be retrieved from the frequency shift of the corresponding Rayleigh backscattering spectrum with respect to the reference spectrum without external disturbance.

As shown in Fig.1(a), due to the helical structure of the stress region of the spun fiber, fiber twist will give rise to deformation of the fiber geometry from its initial circular cross section to an elliptical one, as a result the strain induced by fiber twist will cause a significant change in the effective refractive index of light. The impact of fiber twist induced deformation on the property of transmitting light has been investigated by simulation using finite element method. A circle stress region and a deformed elliptical one with an eccentricity of 0.5 (e=0.5) have been used for simulation, which corresponds to the cases without and with twist applied. Fig.1(b) shows the simulated mode field distribution for the two cases, respectively. The result indicates that the transmitting light still remains single-mode property, however the effective refractive index is changed with an order of 10^{-5}. This reveals that fiber twist will cause the variation of local optical property, and this disturbance can be measured using frequency-scanning φ-OTDR. The adopted algorithm to measure the frequency shift of Rayleigh backscattering spectrum is the correlation peak detection method, which can be expressed as

$$R_{12}(f,z)=\frac{\sum_{i=1}^{N}\left(I_1(\nu_i,z)-\bar{I}_1(z)\right)\left(I_2(\nu_i+f,z)-\bar{I}_2(z)\right)}{\sqrt{\left(\sum_{i=1}^{N}\left(I_1(\nu_i,z)-\bar{I}_1(z)\right)^2\right)\left(\sum_{i=1}^{N}\left(I_2(\nu_i+f,z)-\bar{I}_2(z)\right)^2\right)}} \tag{1}$$

Where N is the frequency scanning number, $\bar{I}_1(z)$ and $\bar{I}_2(z)$ are the average powers at all frequencies at fiber length z for the two measurements. If no environmental perturbation occurs between the two measurements, the cross-correlation peak will be at $f=0$, otherwise the correlation peak will appear at $f=\Delta\nu$, and $\Delta\nu$ is the frequency shift of the Rayleigh backscattering spectrum required to be measured.

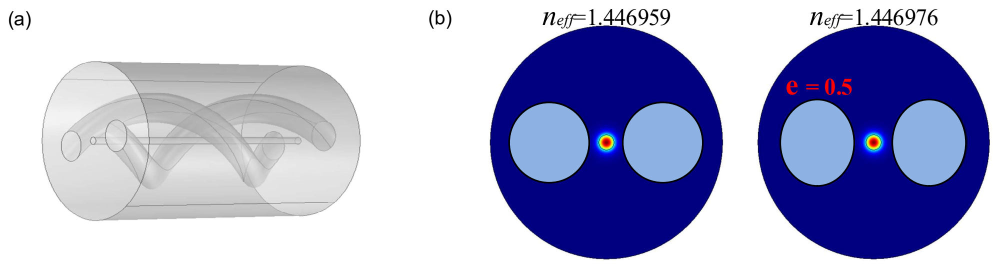

Fig. 1: (a) Single period of the spun PMF; (b) the simulated mode field distribution before and after twist.

3. Experiment setup and results

The experiment setup is shown in Fig.2. A frequency-stabilized coherent laser with a narrow linewidth of 100Hz operating at 1550nm is used as the light source. The continuous light output from light source firstly passes through an electro-optic modulator with a bandwidth of 20 GHz, which is controlled by a microwave signal source to generate carrier-suppressed double-sideband modulation and then one of the sidebands is filtered by a fiber grating filter with a bandwidth of 6 GHz. Then the filtered sideband is chopped into optical pulses through a semiconductor optical amplifier with high extinction ratio, which is modulated by an electrical pulse signal generated by the AWG. The pulse width used in the experiment is 10 ns, corresponding to a spatial resolution of 1 m. The optical probe pulses are then amplified by an erbium-doped fiber amplifier, which is followed by a band-pass filter to remove the amplified spontaneous emission noise. Finally, the pump pulse light is launched into the fiber under test with a length of 136 m through a circulator, of which the fiber segment between 132 m and 133 m is applied with different twist angles utilizing a fiber rotator. At the receiver side, a photodetector with a bandwidth of 500 MHz is used to convert the optical signal into an electrical signal, which is then collected by an oscilloscope with a sampling rate of 5 GS/s.

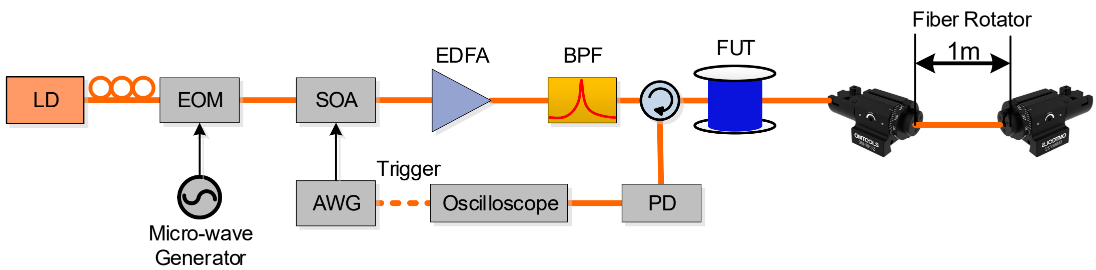

Fig. 2: Experiment setup. EOM: electric-optic modulator; SOA: semiconductor optical amplifier; AWG: arbitrary waveform generator; EDFA: erbium-doped fiber amplifier; BPF: band-pass filter; FUT: fiber under test; PD: photodetector.

The twist is applied to the sensing fiber to investigate the response of the proposed system. The Rayleigh backscattering traces of pump pulses with different frequencies are collected, which are then used to calculate the correlation with the reference traces without twist applied. Fig. 3(a) shows a typical cross-correlation spectrum, where a 5° twist was applied to the 1 m fiber segment. It is observed that fiber twist causes an apparent frequency shift in the correlation spectrum, while the correlation peak of the other fiber segments remains at $f=0$. For the sake of observation, the measured spectrums of Rayleigh backscattering with and without twist applied at the location of 132 m are shown in Fig. 3(b). It turns out that the spectrum waveforms are quite similar, but just with some frequency shift, which is caused by fiber twist. The frequency shift is determined by cross-correlation, as shown in Fig. 3(c).

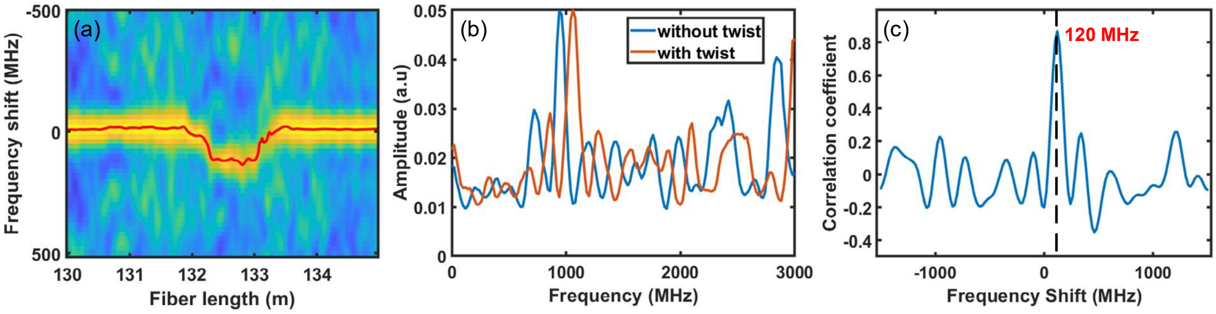

Fig. 3: (a) The cross-correlation spectrum; (b) the frequency spectra at 132 m; (c) the cross-correlation curve of trace.

In order to investigate the dependence of frequency shift on the twist angle, different twist has been applied to the sensing fiber from 0° to 25° in turn with an interval of 5°, and the measured frequency shift under different twist angles are shown in Fig.4(a). In addition, a dashed line which is the mean value of each frequency shift trace between the 132m and 133m fiber segment has also been plotted in Fig.4(a) for reference. It can be seen that the frequency shift increases with the increment of twist angle. The average values of the frequency shifts in Fig.4(a) as a function of twist angle are plotted in Fig.4(b). It is observed that the frequency shift shows a nonlinear dependence on the twist angle, therefore the experimental data is fitted with a quadratic function. The fitting curve has a R-square coefficient of 0.9923 and a RMSE of 50.34MHz. It is seen that the slope of the fitting curve increases as the twist angle enlarges, this indicates that the proposed sensor has higher sensitivity for larger twist angle. It is important to note that the dynamic range of the system can be improved by increasing the frequency scanning range of modulated pulses.

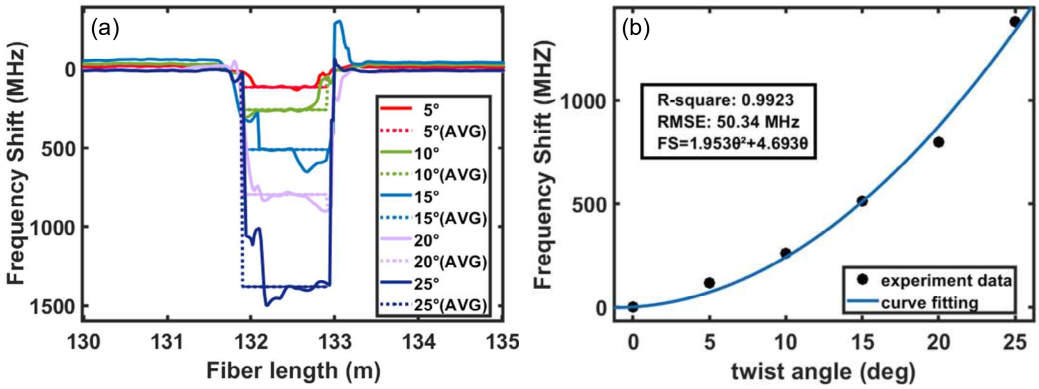

Fig. 4: (a) The measured frequency shift at different twist angles; (b) the frequency shift variation with twist angles.

4. Conclusions

In this work, we propose a novel high-sensitivity distributed twist sensor utilizing the frequency-scanning φ-OTDR with a spun fiber. The proposed sensing system is very promising for quantitative distributed twist detection in industrial applications, e.g. 3-D shape sensing, structural health monitoring, etc.

Acknowledgements

National Key Research and Development Program of China (2021YFB2800902); National Natural Science Foundation of China (61931010, 62105111); Fundamental Research Funds for the Central Universities (HUST: 2021XXJS026); Hubei Province Key Research and Development Program (2021BAA008).

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