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Strain-independent fiber torsion and displacement sensor based on acoustically-induced fiber grating

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ABSTRACT

We present a strain-independent torsion and displacement fiber sensor using acoustically-induced fiber grating (AIFG) in dual-mode fiber (DMF). By tuning the radio frequency of driving signal, LP_{01} and LP_{11} modes generated by the AIFG can be exploited to measure the dynamic displacement and torsion variations, respectively. Both the twist angle and the twist direction can be monitored via image detection facility at the end of DMF. Between torsion angles of $-80°$ and $80°$, the highest twist sensitivity reaches 15 pixel/°. The average displacement sensitivity is 5 pixel/μm within the recorded two-dimensional movement of 100um × 80um. The stable property of sensor is verified when the strain is varied from 100 με to 1500 με.

1. Introduction

Torsion and displacement, as two physical parameters characterizing the internal injury state of the structure, have become two of the most important mechanical parameters for architecture health monitoring. The most common fiber torsion sensors are implemented by monitoring the wavelength shift in optical spectrum analyzer, such as fiber gratings [1,2], fiber interferometers [3], polarimeters [4,5], and photonic crystal fibers (PCFs) [6]. The inherent symmetry of these fiber sensors makes them only measure the rotation angle, but hard to indicate the direction and the dynamic trace of rotation. Displacement sensing has been demonstrated in optical fibers using several different mechanisms, including fiber interferometers [7,8], fiber gratings [9,10] and optical time domain reflectometer (OTDR) [11]. The sensitivity of the aforementioned fiber sensors is limited by the spectral resolution for the spectrum measurement. The required equipment of spectrum measurement such as optical spectrum analyzer (OSA) increases the cost of fiber sensor system. Meanwhile, the grating and interferometric sensors have the cross sensitivities from the axial strain and temperature. Additionally, different mechanical parameters interact with each other in same sensor. The complex signal interrogation can separate different physics parameters, which needs high-resolution optical spectrum analysis. Special PCFs and tilted fiber Bragg grating [12,13] provide an alternative to mitigate cross sensitivities, however most fabrications of these structures are relatively complex and costly.

Recently, another method to sense environment variation is proposed based on image detection of fiber mode including interference [14] and mode coupling [15]. Mechanical parameter monitoring based on fiber mode imaging benefits from its very low sensitivity to temperature [14,15]. For this type of fiber sensor, the charge coupled device (CCD) or power meter is applied as a detector, which reduce the cost of sensing devices. How to make the sense image easily to be processed or identified is a common problem. The mode converters at specific wavelength couple the fundamental mode to the higher-order modes, such as long-period gratings [16], photonic lantern [15] and photonic crystal fiber [17]. Acoustically-induced fiber grating (AIFG) [18–21] has sparkled another way to control the excitation of the higher-order modes, as it can be used as the tunable mode converter by tuning the amplitude and frequency of driving signal at different wavelength.

In this letter, we present an all fiber sensor based on acoustically-induced fiber grating in the dual-mode fiber (DMF). By tuning the radio frequency of driving signal, LP_{01} and LP_{11} modes generated by the AIFG can be exploited to measure the displacement and torsion variations, respectively. Without the complex device such as fiber interferometers and PCFs, the simple structure built by mode converter and CCD can track the dynamic variations. The AIFG as a mode converter at specific wavelength do not participate in sensing. The system without gratings and interferometers is insensitive to strain along the transmission direction. Based on image processing, the dynamic variation of spatial beam

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detected by CCD can be easily tracked and quantified. Hence, both the twist angle and the twist direction could be monitored via image detection at the end of DMF. Using traditional fiber sensors based on OSA, it is hard to monitor the variation of direction in movement, especially in multi-direction movement like fold motion. Compared to optical spectral detection, CCD has high sensitivity and fast response at specific wavelength, thus the optical power detection is easy to implement with low input power and high detection speed. On the other hand, the two-dimensional displacement and torsion will not interact with each other, because the circular symmetry of the LP_{01} mode and noncircular symmetry of the LP_{11} mode can be well separated. Our image detection algorithm, compare with traditional image recognition based on feature learning, is simpler and faster because that we do not need to use image segmentation and learning technic. The image detection, instead of the spectrum measurement, enables the receiver to be developed as a contactless system and the whole structure has the potential to be rebuilt by cheap devices that work in visible wavelengths.

2. Sensor structure and experimental setup

The experimental setup for the fiber torsion and displacement sensor is sketched in Fig. 1. The Fabry-Perot laser diode (FPLD, HP 8164a) is used as the light source of 0.5 mW at $\lambda = 1568$ nm. The output beam is coupled into a single-mode fiber (SMF, Corning SMF-28), and then the SMF is directly fused with a dual-mode fiber (DMF). Due to axial symmetry of the excitation fields, only axially symmetric fundamental mode of the DMF is excited. The core diameter of the home-made DMF is 12.3 μm, which is deliberately designed to be larger than that of SMF. The DMF has a refractive index difference between core and cladding of $\Delta = 0.54\%$ and a cladding radius of $r_{cl} = 55$ μm. The piezoelectric transducer (PZT) is attached to a cone acoustic transducer and its other side sticks on a steel plate as a mount. The diameter of the DMF for forming the AIFG is etched down to 41 μm by the hydrofluoric acid to achieve the resonance wavelength within a proper range and enhance the overlap between optical modes and acoustic modes. The etched DMF is rigidly attached to the tip of the horn-like acoustic transducer by adhesive. During the encapsulation process, optical photosensitive adhesive rapid solidification method is used under ultraviolet light. The AIFG generated in the DMF can selectively convert the input fundamental mode to LP_{11} modes by adjusting the frequency of the RF (RIGOL DG1022U and YOKOGAWA AQ6375). We notice that the AIFG works only as a mode converter and will not involve in sensing physical parameters. With the twist and displacement from the rotator and the motion stage, the fiber modes profiles keep rotating and moving in x-y plane, respectively. The output beam is collimated using a 20× micro-objective (MO). Subsequently, the CCD (Xenics Xeva) records the spatial distribution of power and transfers it to image processing facility (IPF). The IPF calculates the torsion angle from the data variation of LP_{11} mode and gets two-dimensional displacement from the data variation of LP_{01} mode.

PZT receives sinusoidal signals from the RF source and generates the acoustic wave. Then the acoustic wave is amplified at the tip of the horn-like acoustic transducer and propagates along the etched DMF. The dynamic micro-bend grating is formed via the periodic modulation of the refractive index, which is produced with a period of thousands of micrometers in the fiber core. This refractive index modulation would induce coupling between the core fundamental mode (LP_{01}) and the co-propagation modes (LP_{11}) when the phase matching condition [18,19]

$$\beta_1 - \beta_2 = \frac{2\pi}{\Lambda} \tag{1}$$

is satisfied, where $\beta_1 = 2\pi n_{eff}^{01}/\lambda$ is propagation constants of the LP_{01} mode, $\beta_2 = 2\pi n_{eff}^{11}/\lambda$ is propagation constants of the LP_{11} mode, $\Lambda = \sqrt{\pi r_{cl} C_{ext}/f}$ is the grating periodicity, n_{eff}^{01} and n_{eff}^{11} are the effective index of LP_{01} mode and LP_{11} mode, λ is the light wavelength, r_{cl} is the radius of fiber cladding, $C_{ext} = 5760$ m/s is the velocity of the acoustic wave in silica, and f is the frequency of the acoustic wave. The fundamental mode can be selectively converted to LP_{11} mode at a specific wavelength by adjusting the RF frequency based on the phase matching condition in DMF. The coupling coefficient between the LP_{01} mode and the LP_{11} mode of AIFG can be expressed as [19,20]

$$K = \frac{\pi}{\lambda}\sqrt{\frac{\varepsilon_0}{\mu_0}}n_0 \int \psi_1(x,y)\psi_2(x,y)\Delta n(x,y)dxdy \tag{2}$$

where n_0 is the core refractive index of fiber, $\Delta n(x, y)$ is the refractive index modulation caused by the acoustic wave mode, $\psi_1(x, y)$ and $\psi_2(x, y)$ are the field distribution of the LP_{01} mode and the LP_{11} mode. Without the perturbation of index, the different mode would not couple with each other. The permittivity perturbation caused by the acoustic wave on the cross section of the etched fiber is antisymmetric and can be expressed as [18,21]

$$\Delta n(x,y) = (1+\chi)\kappa^2 u_0 x \tag{3}$$

where $\chi = -0.22$ is the photoelastic coefficient of fiber, K and u_0 are the wavevector and the amplitude of acoustic flexural wave, respectively. As a tunable mode converter, the AIFG excites higher modes and input them to the sensor head. Our aim is to make the optical modes switch between LP_{01} mode and the LP_{11} mode at the center wavelength of FPLD, so we build an individual test platform to

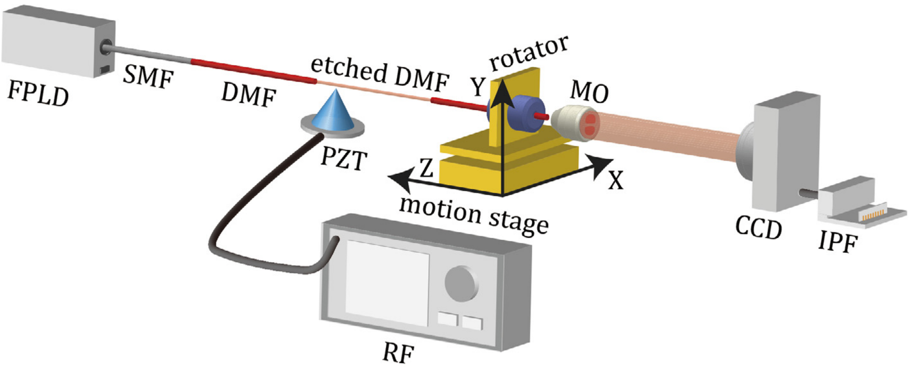

Fig. 1. Experimental setup for fiber torsion and displacement sensor. FPLD, Fabry-Perot laser diode; SMF, single mode fiber; DMF, dual mode fiber; PZT, piezoelectric transducer; RF, radio frequency; MO, micro-objective; CCD, charge coupled device; IPF, image processing facility.

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