High Sensitive Directional Torsion Sensor Based on the Helical Long-Period Grating Inscribed in Seven-Core Fiber

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***Abstract*—We demonstrated the fabrication of a helical long-period fiber grating (HLPG) on seven-core fiber (SCF) by CO_2 laser. With the help of a homemade eccentric welding platform, the high-quality grating spectra in seven cores are measured. Due to the addition of the helix structure, the gratings of different cores show high torsional sensitivity of -0.53 nm/(rad/m) and have the direction of torsion. The SCF-HLPGs have a potential application in the field of torsion sensing.**

Keywords—helical long-period grating, seven-core fiber, torsion sensing.

I. Introduction

With the rapid development of science and technology, multi-core optical fiber (MCF) technology has received extensive attention in the field of optical fiber communication and sensing. Based on multi-core optical fiber space-division multiplexing technology, it has become an important solution to solve the crisis of optical fiber communication capacity. On the other hand, with its characteristics that multiple cores can be transmitted independently under the same cladding, multi-core optical fiber has attracted more and more research in the field of sensing[1-2].

As an important parameter for detecting stress and internal conditions, torsion has important application value in the field of engineering instruments and meter testing. The ability to discern the direction of torsion is also important when testing the instrument. Among them, according to its sensing structure, the fiber torsion sensor can be divided into two types: fiber grating type [3] and fiber interference type [4]. Long-period fiber gratings have been widely used in torsional sensing due to their advantages of flexible preparation, high writing efficiency, and high sensitivity. In recent years, because multi-core optical fibers can provide multiple independent parallel channels, researchers have gradually applied long-period fiber gratings to multi-core optical fibers, making various types of multi-core fiber long-period gratings for torsional sensing. In 2017, Shen[5] et al. developed a grating writing technology combining CO_2 laser heating and torsion, which engraved spiral long-period fiber gratings in 19 fiber cores distributed in hexagons at one time. The experimental results show that the maximum torsional sensitivity is -0.2 nm/(rad/m).In 2018, Zhang[6] et al. proposed to introduce helical long-period grating (HLPG) into MCF by CO_2 laser splicing system to achieve directional torsion and temperature identification. The experimental results show that directional torsion measurement from -

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17.094 rad/m to 15.669 rad/m with a sensitivity of ~0.118 nm/(rad/m).In 2022, Peng[7] et al. proposed HLPG in four-core fiber, thanks to the special spatial distribution of the cores, the maximum torsional sensitivity is -0.289 nm/(rad/m).

In this paper, We propose a high-sensitivity torsional sensor, based on carbon dioxide laser engraving technology and fiber rotation and displacement system to prepare helical long-period gratings on seven-core fibers (SCF), and compare the response of center and outer cores to torsion. The maximum torsion sensitivity of the sensor is as high as -0.63 nm/(rad/m) for ultra-low curvature values ranging from -36nm/(rad/m) to 36nm/(rad/m). The proposed SCF-HLPG has a promising perspective on the torsion sensing fields.

II. Experimental Results and Discussions

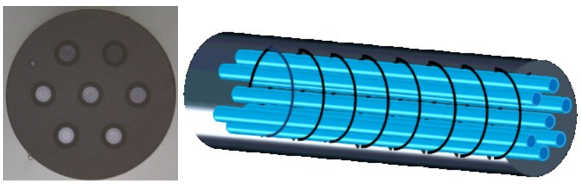

Fig. 1. (a) Microscope image of the SCF cross-section. (b) Schematic diagram of SCF-HLPG.

Figure 1(a) shows a cross-sectional view of the MCF used in the experiment. It has seven cores, and the cladding diameter, core diameter, and distance between cores are 150 μm, 8.8 μm, and 42 μm, respectively. The schematic diagram of the structure of the seven-core fiber helical grating is shown in Fig. 1(b).

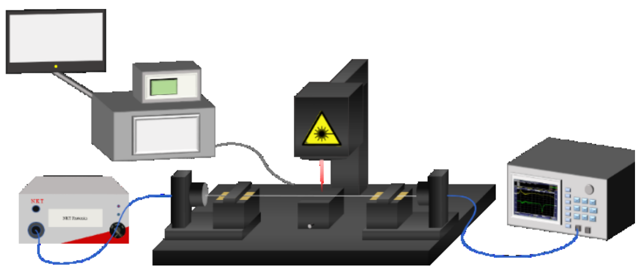

Fig. 2. Schematic diagram of SCF-HLPG fabrication experiment setup.

Figure 2 is a schematic diagram of the SCF-HLPG preparation and spectral measurement system, The writing system consists of a CO_2-laser (CO_2-H10, Han's laser) with a 3D dynamic focusing galvanometer and a 3D displacement stage with a fiber fixture. The average output power of a CO2 laser is about 0.6 W and the pulse frequency is 5 kHz. compared with the conventional LPFG engraving and measurement, the seven-core optical fiber HLPG preparation system adds an optical fiber rotary stepper motor and an optical fiber displacement stepper motor, one end of the optical fiber is fixed on the rotary stepper motor, and the other end is horizontally placed in the optical fiber slot of the platform and can rotate freely. The transmission spectra of the prepared gratings were monitored online using a supercontinuum broadband light source (BBS, SuperK, NKT Photonics) and a spectrometer (OSA, AQ6375, Yokogawa).

In the grating writing process, the period and length of the grating are controlled by the rotary stepper motor and the displacement stepper motor, and the writing efficiency of the grating is determined by the modulation time of the laser. and their accuracy were 0.01 degree/s and 100 μm/s, respectively. The grating period can be calculated by [8]

$$\Lambda = \frac{360°v}{\omega} \tag{1}$$

where Λ and v are the grating periods and the moving speed of the displacement stepper motor, respectively. ω is the rotation speed of the rotary stepper motor.

We prepared several sets of HLPGs with different periods, ranging from 368 μm-376 μm. The transmission spectra of the core at the center of different periods are shown in Fig. 3(a). The five resonant dips with the wavelength of 1384, 1427, 1486, and 1575 nm, and the transmission contrast of -15.02, -16.44, -17.42, and -18.82 dB, respectively. To observe the transmission spectrum on different cores, we selected a grating with a period of 368μm and used a homemade multicore fiber eccentric alignment platform to observe the projection spectrum on the high-quality intermediate core and the outer core respectively, as shown in Fig. 3(b).

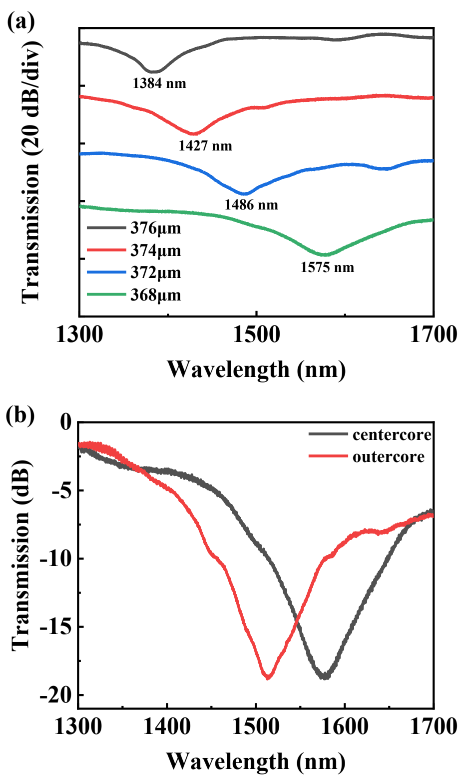

Fig. 3. (a) Transmission spectra of LPGs in the center cores of MCF with different grating pitches from 368 μm to 376 μm. (b) Transmission spectrum of the center and outer cores with a period of 470μm.

Fig. 4. Schematic diagram of the torsion measurement experimental setup.

Figure 4 shows a schematic diagram of the SCF-HLPFG torsion sensing device, using a spectral detection method combining a broadband light source and a spectrometer. In torsional sensing experiments, one end of the grating is fixed and the other end is fixed to a rotatable fixture. The torsion rate acting on the fiber can be expressed as:

$$T = 2\pi\theta/360°L \tag{2}$$

where L is the spacing of two fixed points and θ is the angle of rotation of the fiber. In the experiment, L is set to 17.5 cm.

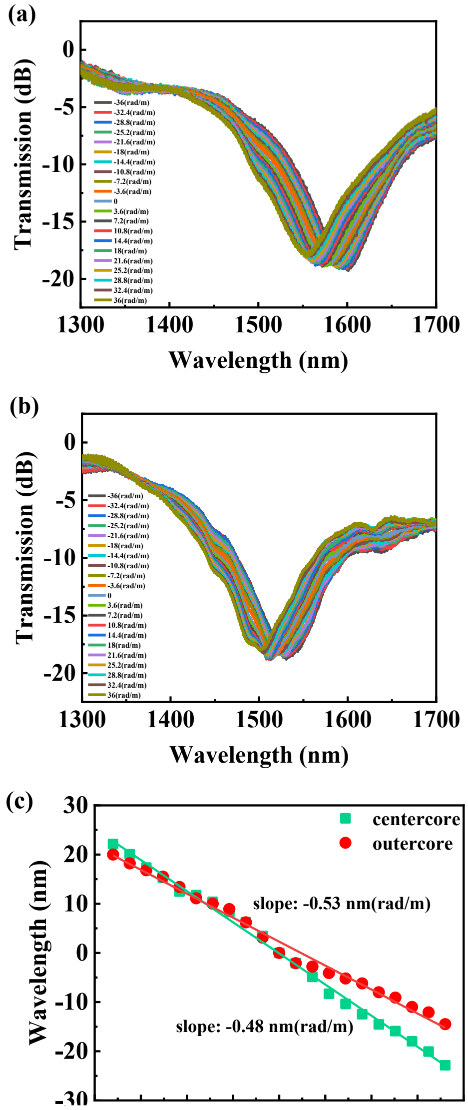

Fig. 5. Transmission spectra of SCF-HLPGs in the center core (a) and outer core (b) vary with the twist rate increasing from -36 to 36 rad/m. (c) The variation of the resonant wavelength with the twist rate increases.

We selected the SCF-HLPFG with a period of 470μm for torsional sensing experiments with a torsion range of 0 to ±36 rad/m in steps of 3.6 rad/m. We specify that the direction of the grating helix is counterclockwise. Figure 5(a) and 4(b) plots the transmission spectra of the center and outer core gratings vary with different torsion rates. As can be seen, the two HLPGs show directional torsion responses. When torsion is counterclockwise, the resonance dip is redshifted with an increase in the torsional rate, and when torsional is clockwise, the resonance dip is blueshifted with an increase in the torsional rate. with the twist rate changing from −36 rad/m to 36 rad/m, the resonance dip shifts to the shorter wavelength, and the transmission spectra were recorded with a step of 3.6 rad/m. The maximum wavelength offsets of the two gratings are 22 and 20 nm respectively. Figure 5(c) shows the torsion characteristics of the center core and outer core gratings of SCF-HLPG, the torsion sensitivities are -0.53 nm/(rad/m) and -0.48 nm/(rad/m), respectively. which is much higher than the sensitivity of SMF-HLPG.

III. Conclusion

In conclusion. We, successfully used a CO_2 laser to engrave the helical structure in the multicore fiber and used the self-made multicore fiber eccentric alignment platform to obtain high-quality grating transmission spectra in the center and outer cores. The torsional response of the center core HLPG and the outer core HLPG were studied, and the two HLPGs showed high sensitivity to torsion, -0.63 nm/(rad/m) and -0.48 nm/(rad/m)respectively, and could identify the direction of torsion, so the sensor has great potential in the field of torsion sensing.

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