Vector Bending Sensor Based on Long-Period Gratings in Linearly Arranged Three-Core Fiber

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***Abstract*—In this paper, a vector bending sensor based on long-period gratings (LPGs) in three-core fiber (TCF) is proposed. The three cores of TCF are linearly arranged, and the middle core is distributed in the center. LPGs with a period of 465 μm and period number of 35 were prepared by arc-discharge method. Due to the special spatial distribution of the cores in TCF, the proposed TCF-LPGs can realize vector bending measurement. The directional bending sensing characteristics of TCF-LPGs with curvature range from 0.2490 m^{-1} to 0.8731 m^{-1} are demonstrated. The bending responses in different directions all show good linearity, and the bending sensitivities are obviously different, which show the sine function behavior with bending directions from -180° to 180°. And the maximum of bending sensitivity is -8.83 nm/m^{-1}, obtained at 0°. Therefore, the fiber structure has potential application prospects in the field of vector bending measurement.**

Keywords—multicore fiber; long-period gratings; vector bending sensor

I. Introduction

Vector bending measurement plays an important role in mechanical engineering and structural health monitoring such as, mechanical bending angles measurement [1], human posture detection [2][3], bridge and road construction, structural deformation [4] marine environment [5] and robots [6]. Generally, the key components for vector bending measurement includes mechanical [7], electrical [8] and optical fiber sensors [9]-[14] have been proposed. Among them, optical fiber sensors are widely concerned because they offer advantages over other sensors such as small size, resistance to electromagnetic interference, corrosion resistance, high sensitivity and low maintenance costs.

In recent years, multicore fiber (MCF) has provided a flexible and configurable platform for vector bending sensing applications [15]. Because MCF has unique fiber structure with multiple cores in a single fiber cladding, which can construct a variety of functional fiber devices as well as the application for vector bending detection [16]. The special spatial distributions of fiber cores in MCFs allow them to respond not only to the magnitude of the bend but also to the bending direction. Various types of grating structures have been introduced into MCF, including fiber Bragg gratings (FBGs), tilted FBGs and long-period gratings (LPGs). Yang et al. [17] proposed a directional bending sensor based on FBGs selectively written in one core of dual-core few-mode fiber, which reflected the ability of directional bending sensing and achieved a maximum bend sensitivity of -37.41 pm/m^{-1}. Mao et al. [18] demonstrated a vector bending sensor based on dual-core hollow eccentric fiber with FBGs, presenting the ability to simultaneously measure the bending curvature in three directions (0°, 90° and 180°) in the curvature range from 0 to 4.759 m^{-1}, and its curvature sensitivity could be 33 pm/m^{-1}. Apart from FBGs in MCF, LPGs in MCF is also potential in the field of vector bending measurement. Wang et al. [19]proposed a two-dimensional bending sensor on triangle arrangement three-core fiber (TCF), where two LPGs with different periods were written in two external cores and the central core, showing a maximum bending sensitivity of 3.234 nm/m^{-1}. Besides, Barrera et al. [20] demonstrated a bending sensor based on three different LPGs inscribed in seven-core fiber using a selective inscription technique, which can distinguish bending directions from 0º to 360º in curvature range from 0 m^{-1} to 1.77 m^{-1}. It can be seen that, the LPGs-based MCF bending sensors outperform the FBGs-based MCF bending sensors, due to the higher bending sensitivity and the ability to distinguish multiple bending directions. However, the proposed MCF-LPGs should be fabricated with high precision and the limitation of uncertain efficiency in each fiber core in MCF do affect sensitivity.

In this paper, we fabricated LPGs in linearly arranged TCF, using arc-discharge method, for the implementation of a complete vector bending sensor. The bending sensing properties of TCF-LPGs were studied experimentally. Under a certain curvature, the bending responses to different directions are different. The bending sensitives in all selective directions from -180° to 180° show good linearity. And the bending sensitivities exhibit a sine function with the bending direction increasing from -180° to 180°. Moreover, the maximum bending sensitivity of -8.83 nm/m^{-1} could be obtained 0°. The proposed TCF-LPGs would be potential in the field of vector bending sensing measurement.

This work is jointly sponsored by National Natural Science Foundation of China (62005157), Shanghai Sailing Program (20YF1416800), and "Chenguang Program" supported by Shanghai Education Development Foundation and Shanghai Municipal Education Commission.

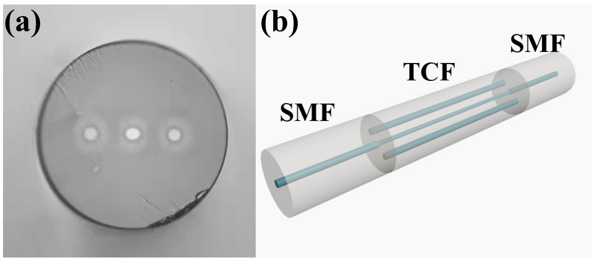

Fig. 1. (a) Microscope image of the TCF cross-section. (b) The schematic diagram of the connection between TCF and SMF.

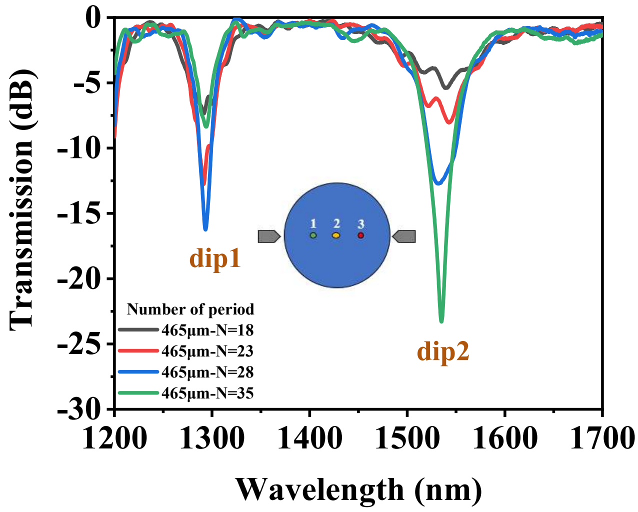

Fig. 2. The transmission spectra of preparation process, and the inset is the discharge position of the electrode on the TCF.

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. *TCF-LPGs Fabrication*

Figure 1(a) shows the microscope image of the TCF cross-section. Three cores of TCF are linearly arranged, and the middle core is distributed in the center. The central core is an elliptical core and the others are circular cores. The diameters of the major and minor axes of the elliptical core are 9 μm and 7 μm, respectively. The diameters of the cladding and two outer cores are 125 μm and 7 μm, respectively. The distance between the cores is 28.2 μm. The structure of our proposed bending sensor is formed by two ends of TCF fused with the SMF, respectively. The schematic diagram of the connection between TCF and SMF is shown in Fig. 1(b).

In the experiment, the arc-discharge method was used to fabricate LPGs in TCF. The experimental device setup for preparing LPGs consisted of an arc-discharge device (FITEL, S179), an one-dimensional displacement platform with a precision of 10 μm and the fiber optic fixture. The broadband light source (BBS, SC-5, YSL) and optical spectral analyzer (OSA, ANDO, AQ6317B) were used to monitor the transmission spectrum during the grating fabrication. During the experiment, one end of the fiber was fixed on a one-dimensional displacement platform, and the other end was attached with a weight to keep the fiber straight. In the gratings preparation experiment, the fiber was controlled by a one-dimensional platform to move a certain distance, which is a grating period. For each movement, the fusion splicer is discharged once. The purpose of the whole process is to generate a series of disturbances inside the fiber, resulting in changes in the axial refractive index of the fiber.

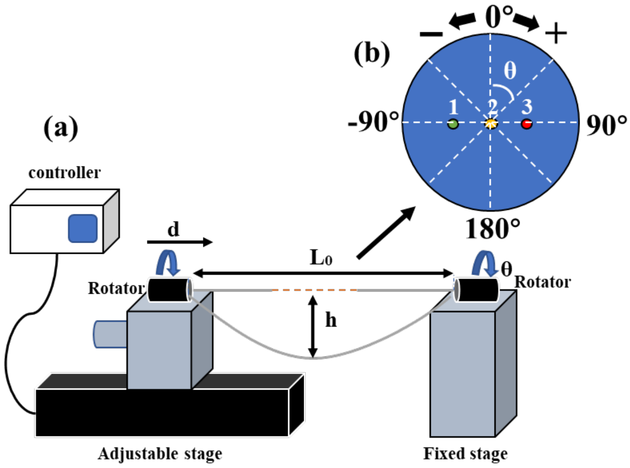

Fig. 3. (a) Schematics diagram of experimental setup for vector bending sensing measurement. (b) Bending direction with respect to the vertical line connecting the axis of three cores.

In the fabrication process of TCF-LPGs, the electrode additional discharge intensity was 91 bits, the additional discharge time was 170 ms, and the general discharge was 85 bits. The insertion in Fig.2 shows the position of the electrode discharge on the TCF. LPGs with the grating period of 465 μm and period of 35 were fabricated. The transmission spectra of the preparation process are shown in Fig. 2. It can be obtained that as the period number increases, the contrast of two resonant dips (dip 1 and 2) increases. The contrast of two resonant dips are -8.37dB and -23.3 dB, at 1293.7 nm and 1535.1 nm, respectively.

B. *Vector bending sensing measurement*

The bending characteristics of the proposed TCF-LPGs were further investigated. Figure 3(a) depicts the schematic diagram of experimental setup for vector bending sensing measurement. In the experiment, the TCF-LPGs structure was placed between two fiber rotators with a distance of 30 cm, where the position of LPGs was located in the middle. Curvature and bending direction were controlled by moving a one-dimensional displacement platform and rotating two optical fiber rotators simultaneously, respectively. The applied curvature could be expressed as

$$C = \frac{2h}{h^2 + (\frac{L_0 - d}{2})^2}$$

where h is the vertical height of the top position of the fiber bend. L_0 is the initial distance between two fiber rotators, d is the distance traveled by the one-dimensional displacement. For the vector bending sensing measurement, We define the position of 0 ° as perpendicular to the direction of the arc discharge, which is marked in Fig. 3(b). Two arrows define clockwise rotation as positive direction and counterclockwise rotation as negative direction, respectively. Thus, the selective bending directions in our experiment are range from -180° to 180° with a step of 30°, as shown in Fig. 4. The bend direction angle θ was defined as the included angle between the bending plane and the vertical line connecting the axis of three cores. In the case of θ equals 0° , the bending direction of TCF-LPGs is perpendicular to the axis of the three-core connection. And the direction of 180° which is also the -180°, is the directly opposite to the direction 0°.

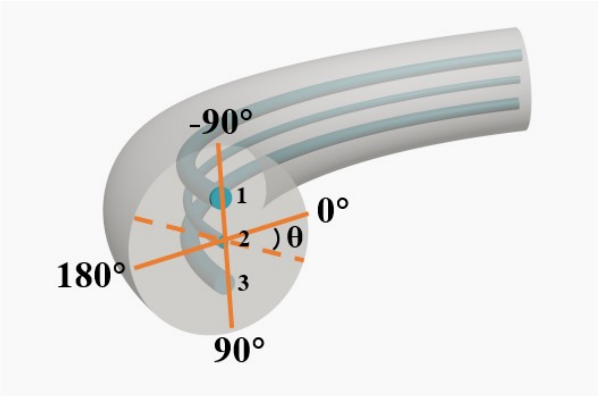

Fig. 4. Bend direction angle θ is the included angle between the fiber bend plane and the vertical line connecting the axis of three cores.

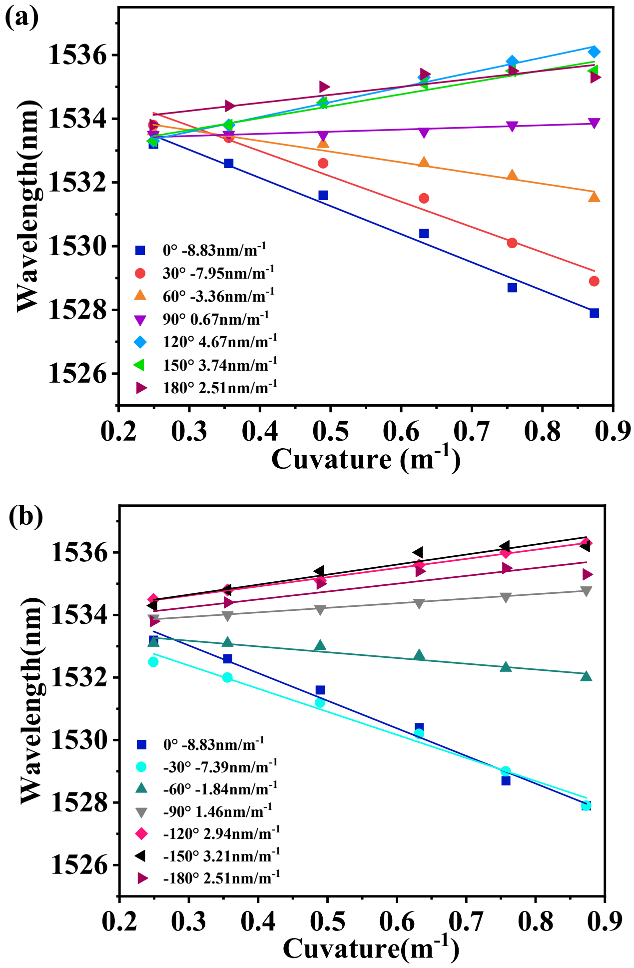

Fig .5. The dependence of wavelength on curvature variations in (a) positive and (b) negative directions.

Figure 5(a) and 5(b) show the dependence of wavelength on curvature variations in positive and negative directions, respectively. With the curvature increases from 0.2490 m^{-1} to 0.8731 m^{-1}, the resonant wavelength shifts either towards longer or shorter wavelength at different bending directions. It is obvious that all the bending properties show good linear responses and the bending sensitivities are obviously different. The bend sensitivity is negative with a blue shift in the resonant wavelength in case of θ between -60° and 60°, while the bend sensitivity is positive with a red shift in the resonant wavelength in the case of θ between 90° and 180° or θ between -180° and -90°.

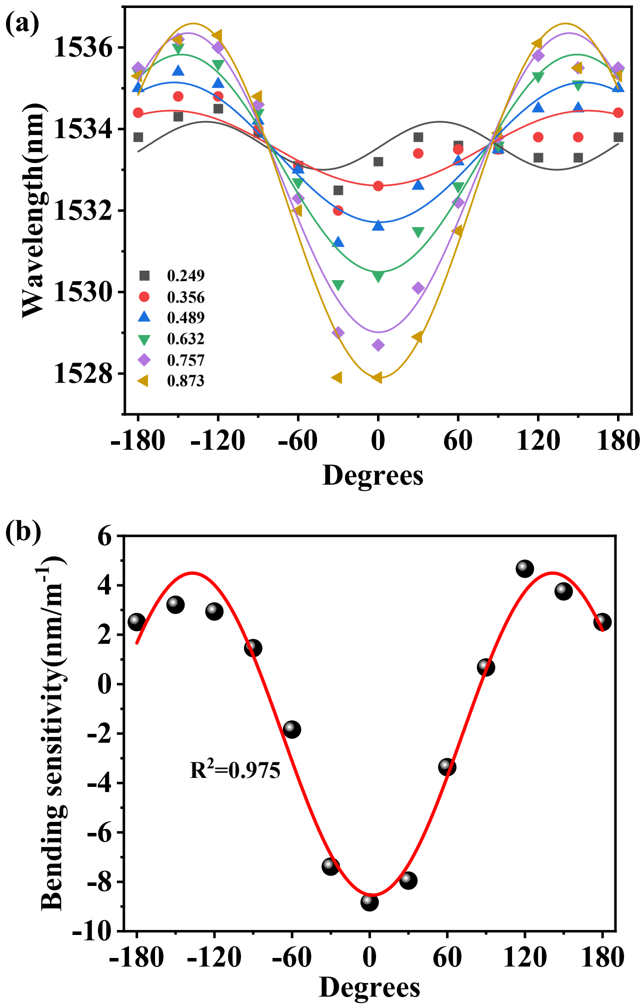

Fig .6. (a) The fitting curve of the resonant wavelength and the corresponding curvature with the direction angle. (b) Relationship between curvature sensitivity and experimental bending orientation angle.

The dependence of resonant wavelength on bending direction is shown in Fig. 6(a). It can be seen that the responses of the resonance wavelengths to the bending curvature is different in different bending directions. At certain curvature, the relationship between resonant wavelength and bending direction is in good agreement with the sine function. And with the curvature increases, the amplitude of sine function increases. According to the results of linear fitting in Fig. 5, the relationship between bending sensitivity and direction is plotted in Fig. 6(b). It is obvious that they present a good sine relationship, the fitting degree reaches 0.975. When θ equals 0°, the bending direction of TCF-LPGs is perpendicular to the axis of the three-core connection, and the maximum bending sensitivity of -8.83 nm/m^{-1} is obtained. When θ equals 90°, the bending direction of TCF-LPGs coincides with the axis of the three-core connection, and the minimum bending sensitivity of 0.67 nm/m^{-1} is obtained. Therefore, the TCF-LPGs exhibits the capability of directional bend sensing. And the fiber structure has potential application prospects in the field of vector bending sensing measurement.

III. Conclusion

In conclusion, a vector bending sensor based on LPGs in linearly arranged TCF has been experimentally demonstrated. The bending sensing characteristics of the TCF-LPGs in curvature range from 0.2490 m^{-1} to 0.8731 m^{-1} at different directions were investigated. The bending responses in different directions all show good linearity, and the bending sensitivities are obviously different. The bend sensitivity is negative with a blue shift in the resonant wavelength in case of θ between -60° and 60°, while the bend sensitivity is positive with a red shift in the resonant wavelength in the case of θ between 90° and 180° or θ between -180° and -90°. The bending sensitivity reaches a maximum of -8.83 nm/m^{-1} at θ equals 0° and a minimum of 0.67 nm/m^{-1} at θ equals 90°. Therefore, TCF-LPGs have directional bending sensing ability. The fiber structure has potential application prospects in the field of vector bending sensing measurement.

ACKNOWLEDGMENT

This work is jointly sponsored by National Natural Science Foundation of China (62005157), Shanghai Sailing Program (20YF1416800), and "Chenguang Program" supported by Shanghai Education Development Foundation and Shanghai Municipal Education Commission.

REFERENCES

[1] C.K.Y. Leung, K.T. Wan, D. Inaudi, et al., "Optical fiber sensors for civil engineering applications," Mater Struct., vol. 48, pp. 871-906, Nov. 2015.

[2] L. Li, R. He, M.S. Soares, et al., "Embedded FBG-based sensor for joint movement monitoring," IEEE Sens. J., vol. 21, no. 23, pp. 26793-26798, Dec. 2021.

[3] C. Majidi, R. Kramer, R.J. Wood, "A non-differential elastomer curvature sensor for softer-than-skin electronics," Smart Mater. Struct., vol. 20, no. 10, pp. 105017, Aug. 2011.

[4] Zheng S, Shan B, Ghandehari M, et al. "Sensitivity characterization of cladding modes in long-period gratings photonic crystal fiber for structural health monitoring, " Measurement, 2015, 72: 43-51.

[5] R. Min, Z. Liu, L. Pereira, et al., "Optical fiber sensing for marine environment and marine structural health monitoring: a review," Opt. Laser Technol., vol. 140, pp. 107082, Aug. 2021.

[6] L. Xiong, G. Jiang, Y. Guo, et al., "A three-dimensional fiber bragg grating force sensor for robot". IEEE Sens. J., vol. 18, no. 9, pp. 3632-3639, Mar. 2018.

[7] Saleh R, Barth M, Eberhardt W, et al. "Bending setups for reliability investigation of flexible electronics. Micromachines, " vol. 12, no.1, pp. 78. Jan, 2021.

[8] F. Xue, J. Hu, S. X. Wang and J. He, "Electric Field Sensor Based on Piezoelectric Bending Effect for Wide Range Measurement, " in IEEE Transactions on Industrial Electronics, vol. 62, no. 9, pp. 5730-5737, Sept. 2015.

[9] Z. Li, X. Yang, H. Zhu and F. Chiavaioli, "Sensing Performance of Fiber-Optic Combs Tuned by Nanometric Films: New Insights and Limits, " IEEE Sensors Journal, vol. 21, no. 12, pp. 13305-13315, 15 June15, 2021.

[10] F. Chiavaioli, P. Zubiate, I. D. Villar,et al, "Femtomolar detection by nanocoated fiber label-free biosensors, " ACS Sens. 2018, vol. 3, no.5, 936–943, May 2018.

[11] Z. Li, X. Yang, H. Zhu and F. Chiavaioli, "Sensing Performance of Fiber-Optic Combs Tuned by Nanometric Films: New Insights and Limits, " IEEE Sensors Journal, vol. 21, no. 12, pp. 13305-13315, 15 June15, 2021.

[12] Y. Qian, Y. Zhao, Q. Wu, and Y. Yang, "Review of salinity measurement technology based on optical fiber sensor," Sensors and Actuators B: Chemical, vol. 260, pp. 86–105, May 2018.

[13] Y.M. Raji, H.S. Lin, S.A. Ibrahim, M.R. Mokhtar, Z. Yusoff, "Intensity-modulated abrupt tapered fiber mach-zehnder interferometer for the simultaneous sensing of temperature and curvature," Opt. Laser Technol., vol. 86, pp. 8-13, Dec. 2016.

[14] L.A. Herrera-Piad, I. Hernández-Romano, D.A. May-Arrioja, et al., "Sensitivity enhancement of curvature fiber sensor based on polymer-coated capillary hollow-core fiber," Sensors, vol. 20, no. 13, pp. 3763, Jul. 2020.

[15] Herrera-Piad L A, Hernández-Romano I, May-Arrioja D A, et al., "Sensitivity enhancement of curvature fiber sensor based on polymer-coated capillary hollow-core fiber," Sensors, vol.13, pp.3763, Jul5,2020.

[16] S. Dong, B. Dong, C. Yu, and Y. Guo, "High Sensitivity Optical Fiber Curvature Sensor Based on Cascaded Fiber Interferometer, " Journal of Lightwave Technology, vol. 36, no. 4, pp. 1125-1130, 2018/02/15 2018.

[17] K Yang, J He, C Liao, et al., "Femtosecond laser inscription of fiber Bragg grating in twin-core few-mode fiber for directional bend sensing," J. Light. Technol., vol. 35, no. 21, pp. 4670-4676, Nov. 2017.

[18] G Mao, T Yuan, C Guan, et al., "Fiber Bragg grating sensors in hollow single-and two-core eccentric fibers," Opt Express., Jan. 2017, vol. 25, no. 1, pp. 144-150, Jan 2017.

[19] S Wang, W Zhang, L Chen, et al., "Two-dimensional microbend sensor based on long-period fiber gratings in an isosceles triangle arrangement three-core fiber," Opt Lett., vol. 42, no. 23, pp. 4938-4941, Dec. 2017.

[20] D Barrera, J Madrigal, S Salesl, "Long period gratings in multicore optical fibers for directional curvature sensor implementation," J. Light. Technol., vol. 36, no. 4, pp. 1063-1068, Feb. 2018.