Highly Sensitive Two-Axis Bending Sensor Based on Arc-Induced Long Period Fiber Grating in Dual Side-Hole Fiber

Volume 10, Number 1, February 2018

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DOI: 10.1109/JPHOT.2017.2781733
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Abstract: A highly sensitive two-axis bending sensor based on long period fiber grating (LPFG) in a dual side-hole fiber (DSHF) is presented and experimentally investigated. The LPFG is fabricated by periodically collapsing a piece of DSF with automatic arc discharge technology. The existence of the two air holes in the DSF makes the cladding modes, regardless of the polarization state, concentrate in the area perpendicular to the connection of the two holes. Such a feature leads to quite different bending responses at the directions perpendicular and parallel to the connection of the air holes, which makes the DSF-based LPFG suitable for two-axis bending measurement. The bending sensitivity of the LPFG are 21.03 nm/m \(^{-1}\) and 15.77 dB/m \(^{-1}\) at the orthogonal directions, respectively. Besides, compared with the general arc-induced LPFGs in solid fibers, the size of the DSF-based LPFG is effectively reduced because the periodic air hole collapse in the DSF causes a large geometric deformation of the fiber core and increases coupling coefficient between the core and cladding modes. The sensing characteristics of strain, polarization, surrounding refractive index, and temperature are also investigated in our experiment.

Index Terms: Two-axis bending, dual side hole, long period fiber grating, arc discharge technology.

1. Introduction

The detection of bending has played an important part in many fields, including robotics, astronautics, structural monitoring, and automotive industry. Due to the advantages of small size, high sensitivity and better stability, optical fiber sensors have a unique superiority for measuring curvature [1]–[4]. In some specific applications, the recognition of bending direction was one of the key parameter selections. Various types of fiber structures have been developed for directional bending measurement, such as Mach-Zehnder interferometers, Fabry-Perot interferometers, fiber Bragg gratings (FBGs), long period fiber gratings (LPFGs) and so on [5]–[10]. Most of the structures have...
a very good effect on one-dimensional bending detection due to their axial asymmetrical structure. However, the one-dimensional curvature sensors have an intrinsic defect that is insensitive to the direction perpendicular to the most sensitive plane. To solve the problem, some sensors have been fabricated for two-dimensional bending measurement, including cascaded fiber gratings and interferometers [11]–[18]. For the former, most of them need at least two sensing elements, such as cascaded two LPFGs and two FBGs [11]–[14], or FBGs in twin-core few-mode fiber [15]. For the later [16]–[18], they could realize the vector bending by one sensing element, however their interference signals have multiple resonance peaks whose sensitivities are quite different. Moreover, the reproducibility of the interferometer-based sensor is not good.

In this paper, we propose a highly sensitive two-axis bending sensor based on a LPFG inscribed in a dual side hole fiber (DSHF). The LPFG was fabricated by periodically collapsing a DSHF with automatic arc discharge technology. Similar kinds of LPFGs based on single-mode or photonic crystal fibers (PCF) with holly structures have been developed for the measurement of curvature [19]–[23]. They includes LPFGs written in PCF by using femtosecond laser irradiation [19] or arc discharge [20], [21], a LPFG inscribed in a six side-hole fiber with UV-exposure [22], and a LPFG written in a DSHF with CO\textsubscript{2} laser [23]. Although these LPFGs have their own characteristics such as large curvature range, sensitive to axial rotation or insensitive to temperature, they can only realize one-dimensional bending detection, or even cannot identify the direction of bending.

Different from the existed LPFGs based on holly-structured fibers, the proposed LPFG in the present work revealed quite different spectrum responses to two orthogonal bending directions, and therefore it can realize two-axis bending measurement. At the bending direction perpendicular to the connection line of the two air holes, the wavelength of the resonant dip of the LPFG shifts with the increase of curvature, while at the bending direction parallel to the connection line, the depth of the resonant dip varies with the curvature variation. Such a phenomenon has not been reported in previous work on LPFGs to the best of our knowledge. The DSHF-based LPFG cannot only realize two-axis bending measurement with just one LPFG, but also has an ultra-high sensitivity and a simple fabrication method. Besides, compared with the general arc-induced LPFGs in solid fibers [3], [24]–[26], the size of the DSHF-based LPFG is effectively reduced because the periodic air hole collapse in the DSHF causes a large geometric deformation of the fiber core and increases coupling coefficient between the core and cladding modes.

2. Experimental Details
The proposed sensing structure based on the LPFG in DSHF is schematically shown in Fig. 1(a). It is composed of a fraction of periodically collapsed DSHF with a length of \(\sim 1.5\) cm and two pieces
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Fig. 2. (a) The experimental setup and (b) the interference signal for measuring the birefringence of the DSHF.

Fig. 3. Transmission spectra evolution of the LPFG in DSHF with the grating pitch of 500 μm while periods vary from 4 to 27.

of SMF. As shown in Fig. 1(b), the DSHF which is a home-made fiber consists of an elliptical core, two large air holes on both sides of the core and a conventional cladding. The major and minor axes of the elliptical core are about 11.4 μm and 8.7 μm, respectively. The diameters of the two air holes and cladding are 40 μm and 125 μm, respectively. The SMF here is a conventional one, whose diameters of the core and cladding are 8.5 μm and 125 μm, respectively. The photographs of the collapsed DSHF obtained from the view of 0° and 90° are presented in Fig. 1(c) and (d), respectively.

In order to know more about the material in our work, we experimentally measure the birefringence of the DSHF. The schematic diagram of the setup is shown in Fig. 2(a), and the interference signal formed by a Sagnac loop based on a 3 dB coupler is shown in Fig. 2(b). The mean birefringence of the DSHF are about 1.8 × 10^{-5} around 1340 nm and 2.6 × 10^{-5} around 1570 nm, respectively.

The DSHF-based LPFG was fabricated only by using a polarization maintaining fiber fusion splicer (Fujikura FSM-100P+). The fabrication process of the LPFG sensing head was as follows. First, a short piece of DSHF was fusion spliced in between two SMFs with a general splice program. The discharge duration and discharge current of the splice program were set to be 1004 ms and 10 mA, respectively. Then the DSHF was periodically discharged and collapsed with a fixed pitch by using a specially designed collapsing and moving program [27]. The program consisted of three main steps, and SWEEP motor was employed to drive the corresponding transmission stages in the Z direction. Step one: The fiber was moved along its longitudinal axis via the SWEEP motor.
with a pre-set grating pitch. In the present work, the pitch was set as 500 $\mu$m. Step two, the arc discharge time and duration were respectively set to 1020 ms and 14.9 mA. Under such discharge parameters, the air holes of the DSHF could be partly collapsed and the transmission loss of the core mode was kept small enough. Step three: turn back to step one. Thus, the program executed periodical point-to-point discharge and a high-quality LPFG in DSHF were produced with a period number of 27. The transmission spectra evolutions of the DSHF-based LPFG are shown in Fig. 3.

3. Experiments and Discussion

The sensing characteristics of the proposed structure, including directional bending, polarization, strain, surrounding refractive index (SRI) and temperature are investigated experimentally. Except the temperature measurement, all the experiments mentioned above are investigated at room temperature of 26 °C.

3.1 Bending Characteristics

The experimental setup used to carry out the directional bending measurement is shown in Fig. 4. The LPFG inscribed in DSHF was put in the V-grooves of the fiber holder, covered by a metal sheet simultaneously. A 2 g mass was hung on the SMF for keeping the DSHF-based LPFG close to the metal sheet during the bending process. A pair of rotatable clamps on the adjusting frames, with a division value of 5°, were used here for changing the bending direction. A 1550 nm super luminescent diode (SLD) was used to inject light into the sensing structure, and an optical spectrum analyzer (OSA) was used to detect the signal. As for measuring the directional bending and states of polarization, the resolution of OSA was set to 0.1 nm. As for measuring the strain, temperature, and SRI, we used the OSA for data collection with a resolution of 0.02 nm. At last, the sensing head was bent by pressing the metal sheet with a precise micrometer screw. Thus, the exact curvature of the LPFG can be calculated by

$$ C = \frac{2h}{h^2 + (0.5z)^2} $$

(1)

where $h$ and $z$ are the bending displacement of the metal sheet and the length of the fiber holder, respectively.

The bending characteristics of the DSHF-based LPFG was tested in the curvature range of 0 m$^{-1}$ to 2.8 m$^{-1}$ at different bending directions. The spectral responses at the directions of 0° and 90° are shown in Fig. 5(a) and (b), respectively. From the figures we can see that, at the bending direction of 0° the resonant wavelength of the LPFG suffered a blue shift with the increase of curvature, while at the direction of 90° the resonant wavelength did not change except for a wavelength hop. The phenomena can be explained as follows. The core mode couples with the cladding modes at a specific resonance wavelength $\lambda$

$$ \lambda = \left( n_{\text{eff,co}} - n_{\text{eff,cl}}^m \right) \Lambda $$

(2)
where $n_{\text{eff, co}}$ and $n_{\text{eff, cl}}^m$ are effective refractive indexes (ERIs) of the core and cladding modes, respectively. $\Lambda$ is the pitch of the LPFG. The two air holes in the DSHF break the circularly symmetrical structure of the fiber. In the asymmetric fiber, the cladding modes of the DSHF, whether the x-polarized or the y-polarized, distribute in the area that is perpendicular to the connection of the air holes. As a result, when the bending direction is perpendicular to the connection of the air holes (0°), $n_{\text{eff, cl}}^m$ raised with the increase of the curvature while $n_{\text{eff, co}}$ was nearly unchanged. Therefore, the resonant wavelength shifted with the curvature variation. When the bending direction parallel to the connection of the air holes (90°), both $n_{\text{eff, co}}$ and $n_{\text{eff, cl}}^m$ remain unchanged because that they all are at the neutral plane of the bending, which result in the unshifted resonant wavelength. From Fig. 5(a) we can also see that the peak attenuation decreased from 0 m$^{-1}$ to 1.8 m$^{-1}$ and then increased from 1.8 m$^{-1}$ to 2.8 m$^{-1}$ at bending direction of 0°. The reason for this phenomenon, as in the case of the mode hop in Fig. 5(b), is due to the changes in the coupling coefficients between the core mode and different cladding modes. That is to say, when the proposed sensor was curved, the coupling coefficient of the core mode to one cladding mode decreased and that to another cladding mode increased. As a result, the coupled energy of the core mode was gradually transmitted from the original cladding mode to its adjacent mode.

The wavelength shift and the depth variation of the resonant peak versus curvature at the bending direction of 0° is presented in Fig. 6(a). From the figure, the resonant wavelength decreased with the increase of the curvature and the bending sensitivity expressed in wavelength shift is 21.03 nm/m$^{-1}$. The depth variation of the resonant peak versus curvature at the bending direction of 90° is presented in Fig. 6(b). The black squares and the red circles present the depth variations of the resonant peaks at the wavelength of 1557.4 nm and 1612.8 nm, respectively. We find the difference between the two peaks versus curvature has a good linear relationship (blue solid line), corresponding to a sensitivity of 15.77 dB/m$^{-1}$. Because of the symmetrical structure, the situation at direction of 180° and 270° are similar to that of 0° and 90°, respectively.

The sensitivities of directional bending are much higher than those reported LPFG-based sensors, which is mainly caused by the collapse of side holes enlarging the geometric deformation of the fiber core. And for the unique phenomenon of the orthogonal bending, it could be used as a high-quality two-axis bending sensor.

### 3.2 Polarization Characteristics

In order to find out the effect of the birefringence of the DSHF on the characteristics of the LPFG, we experimentally measured the transmission spectrum of the proposed LPFG at
Fig. 6. (a) The relationships between the resonant wavelength and curvature (red), between the peak attenuation and curvature (blue) at 0°, and (b) the relationships between the peak attenuation and curvature (black: at wavelength of 1557.4 nm, red: at wavelength of 1612.8 nm) and differences between two peaks versus curvature (blue) at 90°.

Fig. 7. Transmission spectra evolution of the arc-induced LPFG in DSHF with polarization state from 0° to 90°.

different polarization states. We supplemented to a 4-axis polarization scrambler module and a manual-operated polarizer at the input side of the LPFG to get different directions of linearly polarized light beam. The LPFG was kept straight. Fig. 7 shows the transmission spectra evolution of the arc-induced LPFG in DSHF when the polarization state changed from 0° to 90°. The resonant wavelength shifted from 1554.6 nm to 1553.7 nm, and the peak attenuation changed from −34.97 dB to −40.37 dB, respectively. The largest wavelength variation presenting a difference between the birefringence of the core mode and the resonant cladding mode is 0.9 nm, which corresponds to \((n_{cx}^0 - n_{cy}^0) - (n_{clm}^{zm} - n_{clm}^{zm}) = 1.8 \times 10^{-6}\). The small wavelength difference also indicates that the two resonant peaks in Fig. 5 corresponds to two different cladding modes rather than two polarization states of one cladding mode.

3.3 Strain Characteristics

The tensile strain testing of the sensor was performed by utilizing the adjusting frame shown in Fig. 4. Fig. 8(a) and (b) show the spectral responses of the arc-induced LPFG in DSHF under different strain, and the corresponding linear approximation, respectively. It could be seen that the
resonant wavelength had a red shift and the peak attenuation increased as the axial strain increased from 0 με to 530 με, which was mainly caused by the elasto-optic effect. The strain sensitivities of the proposed structure are 3.2 pm/με and −0.0123 dB/με, respectively. The larger strain sensitivity is caused by the dual side holes, which decrease the cross sectional area of the fiber. Therefore, such kind of sensing structure could also be used as a highly sensitive strain sensor.

3.4 Surrounding Refractive Index Characteristics

The transmission characteristics of the arc-induced LPFG in SRI in the range from 1.3676 to 1.3414 with a division value of 0.003 were experimentally investigated. The SRI solution was configured by salt in the laboratory. From Fig. 9(a) and (b), the resonant wavelength had a blue shift and the SRI sensitivity was −60.19 nm/RIU. That is because the SRI sensitivity arises from the dependence of the ERI of the cladding modes on the external medium refractive index.

Fig. 8. (a) Spectral responses of the arc-induced LPFG in DSHF under different strain, and (b) the relationships between the resonant wavelength and strain (red), between the peak attenuation and curvature (blue).

Fig. 9. (a) Spectral responses of the arc-induced LPFG in DSHF under different SRI, and (b) the relationships between the resonant wavelength and SRI.
3.5 Temperature Characteristics

For temperature characteristics, the sensing structure was put into a temperature controller, whose temperature range was set from 30 °C to 100 °C in our experiments. The spectral responses of the arc-induced LPFG in DSHF under different temperature and the corresponding linear fit are shown in Fig. 10(a) and (b), respectively. The resonant wavelength had a red shift with the increase of the temperature, and the measured temperature sensitivity was 76.9 pm/°C, which is similar to those of general LPFGs.

4. Conclusion

In conclusion, we experimentally investigated a highly sensitive two-axis bending sensor based on a LPFG in the DSHF. The LPFG is fabricated only by the automatic arc discharge technology. Because of the very different responses for directional bending, it can be used as a highly sensitive two-axis bending sensor, with sensitivities of 21.03 nm/m−1 and 15.77 dB/m−1 at the orthogonal directions, respectively. Other sensing characteristics including polarization, strain, temperature, and SRI were also measured experimentally. The sensitivities of the strain, temperature and SRI are 3.2 pm/με, 76.9 pm/°C, and −60.19 nm/RIU, respectively.

References