Simultaneous measurement of torsion, strain and temperature using a side-leakage photonic crystal fiber loop mirror

Xin Wang¹, Shuqin Lou^{1*}, Xinzhi Sheng², Sheng Liang²

Abstract: A fiber optic sensor for simultaneous measurement of multi-parameter is proposed. The fiber sensor is realized by a fiber loop mirror based on a piece of homemade side-leakage photonic crystal fiber. Affected by the group birefringence of the side-leakage photonic crystal fiber, which induced by the elliptical germanium-doped core and the linear side-leakage defect, the fiber loop mirror has different wavelength responses to torsion, strain and temperature at different interference fringe valleys. By monitoring the wavelength shifts of three selected valleys in the transmission spectrum, simultaneous measurement of torsion, strain and temperature is achieved. The maximal sensitivities to torsion, strain and temperature are 151.14 pm/°, 1 pm/με and 71 pm/°C, respectively.

Key words: fiber sensor, photonic crystal fiber, side-leakage

1. Introduction

Over the last decades, fiber optic sensors have attracted considerable attention and been widely used in many fields with the advantages of compact size, high sensitivity, fast response and wide dynamic range[1]. In the early years, fiber optic sensor usually employs a simple structure with

long period grating[2], Bragg grating [3]or fiber interferometer[4, 5]. Through measuring the change of intensity or wavelength shift, fiber optic sensor can realize the measurement of strain, temperature, pressure, refractive index and other quantities.

With further research, many novel structures have been demonstrated, such as cascaded structure[6, 7], core-offset structure[8], taper structure[9], fiber loop mirror with a section of special fiber[10], etc. Among above structures, a fiber loop mirror (FLM) or Sagnac interferometer is a very attractive method for use in optical fiber sensing due to its remarkable advantages, such as low cost, great flexibility and good stability[11]. Compared with fiber Bragg grating sensors, fiber loop mirror based sensors are proved to have higher sensitivity[12], nevertheless, they usually show cross-sensitivity to temperature and strain, which is a drawback for the development of temperature-insensitive strain sensor. From another perspective, several authors take advantage of the cross-sensitivity to realize simultaneous measurement of temperature and strain. For instance, in 2007, Sun *et al.* reported a fiber sensor that contains two types of high-birefringence fibers in a Sagnac fiber loop mirror[13]. By monitoring the different responses of the two sections of high-birefringence fibers, the proposed fiber sensor was capable of measuring temperature and strain simultaneously. In 2008, Frazão *et al.* presented a method to tune the sensitivity of the sensor in a highly birefringent erbium-doped fiber loop mirror when it is pumped[14]. With this method, simultaneous measurement of strain and temperature was achieved. In 2009, Han *et al.* presented a polarization-maintaining photonic crystal fiber (PM-PCF) based Sagnac fiber loop mirror incorporating an erbium-doped fiber[15], it is possible to simultaneously measure temperature and strain by monitoring the variation of transmission peak power and peak wavelength, respectively. Recently, Wang *et al.* proposed a novel simultaneous

method for strain and temperature measurement[12], the sensing head was composed of a fiber loop mirror and a section of fiber Bragg grating made of a polarization maintaining fiber.

According to the reports, fiber loop mirror based sensors are mainly focused on dual-parameter measurement. As multi-parameter measurement is generating great interest, we present a novel fiber loop mirror sensor using a side-leakage photonic crystal fiber (SLPCF) for multi-parameter measurement. The sensor is experimentally demonstrated to be sensitive to torsion, temperature and strain. The maximal sensitivities to torsion, strain and temperature are $151.14 \text{ pm}/^\circ$, $1 \text{ pm}/\mu\epsilon$ and $71 \text{ pm}/^\circ\text{C}$, respectively.

2. Principle and experimental setup

Figure 1(a) illustrates the micrograph image of the homemade SLPCF. An elliptical germanium-doped core in the fiber center is adopted to introduce the fiber birefringence, meanwhile, a linear side-leakage defect is symmetrically introduced by missing rows of air holes on both sides of the core to improve the fiber birefringence. The cladding diameter of the fiber is about $125 \mu\text{m}$. The elliptical germanium-doped core diameters are $4 \mu\text{m}$ (horizontal) and $2.88 \mu\text{m}$ (vertical). The refractive index difference between the germanium-doped and undoped region is about 0.32%. The average hole diameter and the pitch of air holes are about $5.48 \mu\text{m}$ and $8.06 \mu\text{m}$, respectively.

Fig.1. Micrograph image of the homemade SLPCF(a) and mode field distribution of LP_{01} mode (b) and LP_{11} mode(c)

To investigate the modal characteristics of our homemade SLPCF, we adopt the finite element method to simulate the fiber properties. The fiber geometry was obtained by extracting cross-section micrograph image of the SLPCF sample. As shown in Fig.1(b) and (c), simulation results indicate that the SLPCF supports LP_{01} mode and LP_{11} mode. However, because of the leakage of linear defect and absorption of the polymer coating, the second order modes (LP_{11}) is highly lossy and cannot be guided effectively in the coated SLPCF. Fig.2 shows the transmission spectrum of a 70.4 cm-long SLPCF, which was obtained by splicing the SLPCF ends with two sections of single mode fibers (SMF, Corning SMF-28). It can be found that there is no significant modal interference in the transmission spectrum, demonstrating that the second order modes are very weak in the SLPCF, which is in accordance with the theoretical analysis.

Fig.2 Transmission spectrum of a 70.4 cm-long SLPCF.

Figure 3 shows the schematic configuration of the experimental setup. The configuration consists of a supercontinuum light source (SuperK compact, Koheras A/S), a side-leakage photonic crystal fiber loop mirror (SLPCFLM), and an optical spectrum analyzer (OSA, Yokogawa AQ6375) with a resolution of 0.05 nm. The fiber loop mirror is formed by a 3dB coupler, a 70.4cm-long coated SLPCF (represented by blue line) and a polarization controller. Because of the air holes collapse during the splice and the mode field mismatch between the SLPCF and SMF, the insertion loss of the SLPCF is about 6 dB. With the 3dB coupler, the input light can be split into two counter-propagating waves. The phase difference is accumulated due to different velocities of the waves in SLPCF. When the two waves recombine at the 3 dB coupler, the interference effect would be observed by the OSA. Figure 4 shows the obtained transmission spectrum of the fiber loop mirror. The wavelength spacing between the adjacent valleys is given by $S=\lambda^2/GL$ [16], where λ is the average wavelength, G and L are group birefringence and the length of SLPCF, respectively. It can be observed from Fig.4 that the fringe spacing is not very uniform, it is mainly attributed to effects of the elliptical germanium-

doped core and the linear side-leakage defect on the chromatic dispersion characteristics of the group birefringence in SLPCF.

Fig.3 The schematic configuration of the experimental setup

Fig.4 Transmission spectrum of the SLPCFLM. V1, V2 and V3 denote three valleys at the wavelengths of 1491.23 nm, 1549.95 nm and 1607.38 nm, respectively

When the physical parameters (torsion, strain or temperature) applied to the SLPCF are changed, the group birefringence of the fiber or the fiber length can be altered, leading to change of the phase difference, and thus resulting in wavelength shifts of the valleys or peaks in the output spectrum. Due to the chromatic dispersion characteristics of the group birefringence in

SLPCF, the proposed sensor would have different wavelength responses to the physical parameters at different interference fringe valleys. Therefore, it provides the potential for simultaneous measurement of the multiple physical parameters. When the torsion, strain and temperature are applied to the SLPCF, the sum wavelength shifts of the valleys depended on changes in these parameters can be expressed as[16]

$$\Delta\lambda_i = K_{\tau i}\Delta\tau + K_{\varepsilon i}\Delta\varepsilon + K_{T i}\Delta T \quad (i = 1, 2, 3) \quad (1)$$

The above equation can be also written in the following matrix :

$$\begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \\ \Delta\lambda_3 \end{bmatrix} = \begin{bmatrix} K_{\tau 1} & K_{\varepsilon 1} & K_{T 1} \\ K_{\tau 2} & K_{\varepsilon 2} & K_{T 2} \\ K_{\tau 3} & K_{\varepsilon 3} & K_{T 3} \end{bmatrix} \begin{bmatrix} \Delta\tau \\ \Delta\varepsilon \\ \Delta T \end{bmatrix} \quad (2)$$

Where $\Delta\tau$, $\Delta\varepsilon$, and ΔT are the torsion angle, strain and temperature variations, respectively. $\Delta\lambda_i$ ($i=1, 2, 3$) are the wavelength shifts of the selected valleys at V1, V2 and V3, which denote the three valleys around the wavelengths of 1491.23 nm, 1549.95 nm and 1607.38 nm, respectively. K_{τ} , K_{ε} and K_T are the torsion, strain and temperature sensitivities, respectively. By monitoring the wavelength shifts of the three selected valleys in the transmission spectrum of the SLPCFLM sensor, variations of the torsion, strain and temperature can be achieved.

3. Experimental results and discussions

In the experiments, as shown in Fig.3, a section of SLPCF is fixed at two fiber holders placed on an optical table with an initial separation. One of the two holders is fixed, and the other one is translational and rotatable. The length of the sensing fiber between the two fiber holders is about 20.5 cm. All the measurements are performed with the coated SLPCF.

The torsion can be applied to one fiber end by tuning the rotatable stage at a constant temperature (room temperature). The torsion angle is varied over the range of 0° to 180° in the clockwise (CW) and the anticlockwise (ACW) directions, respectively. When the torsion is applied to the fiber, it would bring a circular birefringence α , $\alpha = g\tau$, where g is the photo-elastic coefficient, and τ is the torsion vector[17]. The combination effects of the torsion-induced circular birefringence and the intrinsic birefringence in SLPCF will generate an elliptical birefringence, thus changing the phase difference of the two counter-propagating waves. The elliptical birefringence is proportional to the torsion angle, and its rotary direction is determined by the torsion direction. When the fiber is twisted clockwise, the elliptical birefringence is right-rotary, whereas it is left-rotary when the fiber is twisted anticlockwise. The different torsion directions would result in the different rotary elliptical birefringence, thus causing an opposite change of the phase difference. Therefore, shifts of the transmission spectrum towards longer or shorter wavelength depend on the torsion direction. The experimental results are shown in Fig. 5. It can be found that the valleys shift towards shorter wavelengths when the fiber is twisted in clockwise direction, whereas the opposite process occurs when the fiber is twisted in anticlockwise direction. The torsion sensitivities are 151.14 pm/°, 150.08 pm/° and 141.4 pm/° at the three valleys V1, V2 and V3, respectively. The torsion resolution is about 0.34°, which is limited by the resolution of OSA. The achieved torsion sensitivities are much higher than that of the previous reports which use the ultra-long period fiber grating[17] and Sagnac interferometer with polarization-maintaining side-hole fiber[18]. In addition, even though the torsion sensitivities in this paper is lower than that in our previous work[11], but the linearity of the wavelength shifts is improved.

Fig.5 Transmission spectra under different torsion angles(a), wavelength shifts of the valleys versus torsion angle(b), where the circles and the solid lines represent the experimental data and linear fitting data, respectively.

In addition to the high sensitivity of torsion, we also investigate the strain response of the SLPCFLM. When the SLPCF is subjected to strain, the fiber length would be increased by ΔL and the strain can be represented by $\varepsilon = \Delta L / L$. The wavelength shift caused by strain can be expressed by $\Delta \lambda_s = \lambda(1 + p_e)\varepsilon$, where λ is the wavelength in vacuum, p_e is the effective coefficient for the strain-induced birefringence change corresponding to the photoelastic constant of the birefringence. Figure 6 shows the transmission spectra of SLPCFLM under different strains and the response of wavelength shift to strain. The wavelength shifts have good linear relationships with the applied strain. The transmission spectrum has a red shift with an increase of the applied strain, and it has a larger shift at the longer wavelength. The strain sensitivities of the three valleys are 0.789 pm/ $\mu\varepsilon$ at V1, 0.959 pm/ $\mu\varepsilon$ at V2 and 1 pm/ $\mu\varepsilon$ at V3 with an average resolution

of $55.236 \mu\epsilon$. The sensitivity is higher at the longer wavelength indicating that the group birefringence of SLPCF increases with an increase of strain.

Fig.6 Transmission spectra under different strains(a), wavelength shifts of the valleys with respect to strain(b), where the circles and the solid lines represent the experimental data and linear fitting data, respectively.

At last, the response of temperature of the SLPCFLM is also investigated. The sensing head is placed in an oven with temperature control range from 12°C to 40°C . As shown in Fig. 7, the valleys shift to the longer wavelengths along with the increase of temperature. This can be explained that the germanium-doped glass and the pure silica both have positive thermal expansion coefficients, especially Ge-doped glass has a larger thermo-optic coefficient than that of pure silica. As a result, the SLPCF have a positive temperature dependence of the group birefringence which makes all the valleys shift to the longer wavelengths with the increase of temperature. The wavelength shifts have good linear relationships with temperature. The

temperature sensitivities are 71 pm/ °C, 62.7 pm/ °C and 58.54 pm/ °C at the valleys of V1, V2, and V3 with an average resolution of 0.8°C, which are close to our previous work[11].

Fig.7 Transmission spectra under different temperatures(a), wavelength shifts of the valleys with respect to temperature(b).

Experimental results show that the three valleys are linearly shifted with torsion, strain and temperature over the measurement ranges, separately, which makes it possible to realize simultaneous measurement of three physical parameters by a matrix. Substituting the sensitivities coefficients of the three physical parameters into Eq. (2), the sensitivity matrix for simultaneous measurement of torsion, strain and temperature can be deduced as

$$\begin{bmatrix} \Delta\tau \\ \Delta\epsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} -0.0659 & 0.2491 & -0.1869 \\ 0.8042 & -11.9654 & 11.8403 \\ 0.1454 & -0.3974 & 0.2664 \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \\ \Delta\lambda_3 \end{bmatrix} \quad (3)$$

Where, the units of $\Delta\tau$, $\Delta\epsilon$, ΔT and $\Delta\lambda$ are angular degree (°), microstrain ($\mu\epsilon$), degree centigrade (°C) and picometer (pm), respectively. $\Delta\lambda_1$, $\Delta\lambda_2$ and $\Delta\lambda_3$ are the wavelength shifts of the three

valleys at 1491.23 nm (V1), 1549.95 nm (V2) and 1607.38 nm (V3). With this sensitivity matrix, the proposed SLPCFLM is capable of measuring the variations of torsion, strain and temperature by simultaneously monitoring the wavelength shifts of the three selected valleys in the transmission spectrum.

4. Conclusion

We experimentally demonstrated a novel side-leakage photonic crystal fiber loop mirror for simultaneous measurement of torsion, strain and temperature. The fiber birefringence in SLPCF is induced by the elliptical germanium-doped core and the symmetrical linear side-leakage defect. The proposed sensor has different wavelength response to each physical parameter at the different valleys. The valleys shift towards shorter wavelengths when the fiber is twisted in clockwise direction, whereas the opposite process occurs when the fiber is twisted in anticlockwise direction. The valleys shift to longer wavelengths with increase in the strain or temperature. By monitoring the wavelength shifts of the three selected valleys in the transmission spectrum, simultaneous measurement of torsion, strain and temperature can be achieved with a low-cost and simple structure.

Acknowledgement

This work is supported by the National Science foundation of China Grant No. 61475016,

References

- 1 Leung, C. K., Wan, K. T., Inaudi, D., Bao, X., Habel, W., Zhou, Z., Ou, J., Ghandehari, M., Wu, H. C. Imai, M. Review: Optical fiber sensors for civil engineering applications. *Materials and Structures* **48**, 871-906 (2015).
- 2 Wang, Y., Rao, Y., Ran, Z., Zhu, T., Zeng, X. Bend-insensitive long-period fiber grating sensors. *Optics & Lasers in Engineering* **41**, 233-239 (2004).

- 3 Tian, X. G., Tao, X. M. Torsion measurement using fiber Bragg grating sensors. *Experimental Mechanics* **41**, 248-253 (2001).
- 4 Jianghai, W., Guanghui, W., Ying, C., Qizhen, S., Ruibing, L., Perry Ping, S., Deming, L. Refractive index sensor using microfiber-based Mach-Zehnder interferometer. *Optics Letters* **37**, 67-69 (2012).
- 5 Wang, T., Wang, M. Fabry-Pérot fiber sensor for simultaneous measurement of refractive index and temperature based on an In-Fiber Ellipsoidal Cavity. *IEEE Photonics Technology Letters*, **24**, 1733-1736 (2012).
- 6 Juan Hu, D. J., Lim, J. L., Jiang, M., Wang, Y., Luan, F., Ping Shum, P., Wei, H., Tong, W. Long period grating cascaded to photonic crystal fiber modal interferometer for simultaneous measurement of temperature and refractive index. *Optics letters* **37**, 2283-2285 (2012).
- 7 Cao, Y., Liu, H., Tong, Z., Yuan, S., Su, J. Simultaneous measurement of temperature and refractive index based on a Mach-Zehnder interferometer cascaded with a fiber Bragg grating. *Optics Communications* **342**, 180-183 (2015).
- 8 Cao, Y., Liu, H., Tong, Z., Yuan, S., Su, J. Simultaneous measurement of temperature and refractive index based on a core-offset Mach-Zehnder interferometer cascaded with a long-period fiber grating. *Optics Communications* **11**, 69-72 (2015).
- 9 Li, J., Zhang, W., Gao, S., Geng, P., Xue, X., Bai, Z., Liang, H. Long-period fiber grating cascaded to an S fiber taper for simultaneous measurement of temperature and refractive index. *IEEE Photonics Technology Letters*, **25**, 888-891 (2013).
- 10 Pérez-Herrera, R. A., André, R. M., Silva, S. F., Becker, M., Schuster, K., Kobelke, J., Lopez-Amo, M., Santos, J. L., Frazão, O. Simultaneous measurement of strain and temperature based on clover microstructured fiber loop mirror. *Measurement* **65**, 50-53 (2015).
- 11 Chen, W., Lou, S., Wang, L., Zou, H., Lu, W., Jian, S. Highly Sensitive Torsion Sensor Based on Sagnac Interferometer Using Side-Leakage Photonic Crystal Fiber. *IEEE Photonics Technology Letters* **23**, 1639-1641 (2011).
- 12 Wang, Q., Xia, J., Zhao, Y., Liu, X., Wang, P., Zhang, Y.-n., Sang, C., Wang, L. Simultaneous measurement of strain and temperature with polarization maintaining fiber Bragg grating loop mirror. *Instrumentation Science & Technology* **42**, 298-307 (2014).
- 13 Sun, G., Moon, D. S., Chung, Y. Simultaneous Temperature and Strain Measurement Using Two Types of High-Birefringence Fibers in Sagnac Loop Mirror. *IEEE Photonics Technology Letters* **19**, 2027-2029 (2007).
- 14 Frazao, O., Egypto, D., Aragao-Bittencourt, L., Giraldi, M. T. M., R. Marques, M. B. Strain and Temperature Discrimination Using High-Birefringence Erbium-Doped Fiber Loop Mirror With High Pump Power Laser. *IEEE Photonics Technology Letters* **20**, 1033 - 1035 (2008).
- 15 Han, Y. G., Chung, Y., Sang, B. L. Discrimination of strain and temperature based on a polarization-maintaining photonic crystal fiber incorporating an erbium-doped fiber. *Optics Communications* **282**, 2161-2164 (2009).
- 16 Frazão, O., Silva, S., Baptista, J., Santos, J., Statkiewicz-Barabach, G., Urbanczyk, W., Wojcik, J. Simultaneous measurement of multiparameters using a Sagnac interferometer with polarization maintaining side-hole fiber. *Applied Optics* **47**, 4841-4848 (2008).

- 17 Silva, S. F. O., Frazao, O., Santos, J. L., Araujo, F. M.Ferreira, L. A. Discrimination of Temperature, Strain, and Transverse Load by Using Fiber Bragg Gratings in a Twisted Configuration. *IEEE Sensors Journal* **6**, 1609-1613 (2006).
- 18 Mo, Q. J., Zhu, T.Rao, Y. J. Highly sensitive fiber-optic torsion sensor based on an ultra-long-period fiber grating. *Optics Communications* **266**, 187-190 (2006).