Gas Sensing with A Highly Birefringent Microfiber Photonic Microcell

Wa Jin[1,2], Xuejing Liu[3] and Wei Jin[2]

[1]Department of photoelectron, College of information science and engineering, Yanshan University, Qin Huangdao, China
[2]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[3]College of Instrumentation and Optoelectronic Engineering, Beihang Univerisity, Beijing, China

*jinwa@ysu.edu.cn

ABSTRACT

We report the fabrication of in-line photonic microcells (PMCs) by encapsulating tapered highly birefringent microfibers (Hi-Bi MFs) inside glass tubes. The encapsulation isolates Hi-Bi MFs from external environment and makes them more suitable for real-world applications. Gas sensing is realized by fabricating micro-channel on the PMC for ingress/egress. A fiber Sagnac loop interferometer (SLI) incorporating a Hi-Bi microfiber PMC demonstrated a gas pressure sensitivity of 599 pm/bar, and RI sensitivity of 2024 nm per refractive index unit (nm/RIU) in gaseous environment .

Keywords: *Gas sensor, highly birefringent microfibers, photonic microcell, pressure, refractive index*

1. INTRODUCTION

Recently, there have been growing research activities in the fabrication, characterization and application of micro/nano optical fibers [1, 2]. Various micro/nano fiber devices such as evanescent wave couplers and sensors, coiled resonators, interferometers and filters [3-5] have been reported. These micro/nano fibers may find novel applications in wavelength-scale light transmission, processing and interconnection, which would be useful for photonic integration, computing, and nano-scale sensing. A highly birefringent (Hi-Bi) Sagnac loop interferometer (SLI) in which two orthogonal polarization modes exhibit different responses to temperature, strain, and refractive index [6,7] has been studied for potential sensor applications [8, 9] and shown to have a number of advantages including simple design and flexibility, great stability and lower cost.

In this paper, we report the use of a highly birefringent microfiber photonic microcell based SLI for high sensitivity gas pressure and refractive index measurement. The Hi-Bi MFs are fabricated by tapering a processed conventional single mode fiber (SMF) and the photonic microcells (PMC) are fabricated by encapsulate the Hi-Bi MFs into a capillary tube. By incorporating an encapsulated highly birefringent (Hi-Bi) microfiber PMC into a fiber-optic Sagnac loop interferometer (SLI), we demonstrated gas refractive index (RI) sensors achieved RI sensitivity of 2024 nm per RI unit (RIU) and gas pressure sensors with coefficient of 599 pm/bar.

2. EXPERIMENTAL SETUP

The Hi-Bi MF in this paper was taper-drawn from a commercial SMF-28 fiber.The fiber was firstly “cut” by use of a femtosecond IR laser to remove parts of the cladding on both sides of the fiber, and the cut region was then tapered down to a MF with an approximately elliptical shape. The detailed process for fabricating Hi-Bi MF tapers has been described in a previous paper [10]. The uniform length of the Hi-Bi microfiber we used here is ~ 1 cm and the diameter of the major axis is ~2.8 μm.

The Hi-Bi MF was encapsulated into a capillary tube to fabricate the PMC. The MFs are kept straight and suspended along the center area of a capillary tube while their SMF pigtails are glued to the two ends of the capillary. Side holes are drilled on the capillary wall and act as ingress/egress channels for sample gases. The encapsulation does not change the optical property of the MF but the capillary tube protects the MF from external disturbance and contamination. The PMCs of such made are robust and stable, and can be easily integrated into standard fiber-optic circuits with low loss, making the MF-based devices more practical for real-world applications. .

By splicing the Hi-Bi MF photonic microcell into a Sagnac interferometer system, gas pressure and refractive index are measured. Fig. 1 (a) shows the SLI system which includes a polarization controller (PC) and a 50:50 SMF coupler. Ignoring the insertion loss of the 3-dB coupler and the attenuation of the SMF taper in the loop, the transmission spectrum of the SLI is described by [11]

$$T = [1 - \cos(\varphi)]/2 \qquad (1)$$

where $\varphi = 2\pi LB/\lambda$ is the phase difference, L and B are the total length and the birefringence of the Hi-Bi microfiber respectively. The obtained Hi-Bi microfiber was inserted in a capillary tube with the length and inner diameter of 5 cm and 900 µm, respectively, which is sealed by AB glue on both sides. The transmission spectra of a SLI containing the above mentioned Hi-Bi microfiber is shown in Fig. 1 (b)

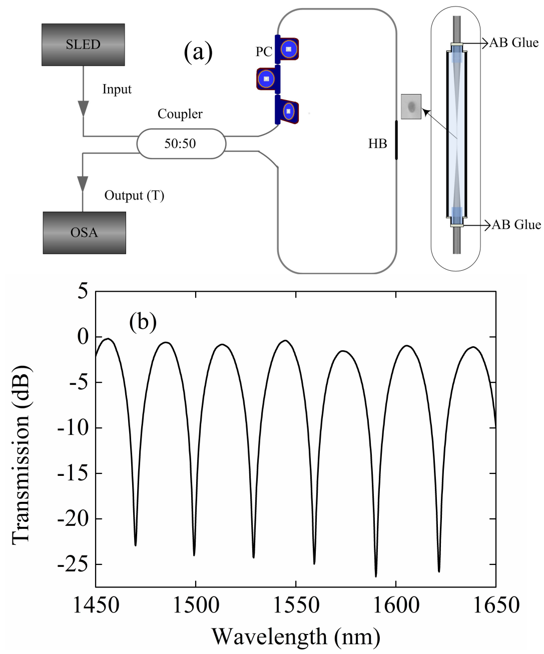

Fig.1 (a) Experimental setup for sensing measurement. Insert: Schematic diagram of the PMC with a Hi-Bi microfiber. (b) Transmission spectrum of the SLI with the Hi-Bi microfiber PMC

3. ERIMENTAL RESULTS

The Hi-Bi MF photonic microcell was placed inside a gas chamber shown in Fig. 2(a). The inlet and outlet of the chamber were kept open to make sure that the pressure in the chamber is stable and at atmospheric pressure. Standard hydrogen and nitrogen gases were mixed with different proportions by varying the flow rate of the gases, which were controlled by two digital mass flow controllers (MFCs). The gas mixture was then guided into the gas chamber within which the encapsulated microfiber sample is placed. For a small gas chamber, the gas concentration within the gas chamber and the capillary reaches steady state within seconds, and the refractive index of the gas mixture may be calculated by using [12]

$$n_m = v_{H_2} n_{H_2} + v_{N_2} n_{N_2} \qquad (1)$$

where n_m is the refractive index of the gas mixture, and n_i and v_i are respectively the refractive indexes and the fraction of the gas component *i* (*i*=H_2 or N_2).

The experimental process is as follows: firstly, the hydrogen gas was switched off and the nitrogen gas with a flow rate of 150 sccm (standard cubic centimeter per minute) was continually injected into the chamber, the spectrum was recorded when it became stable, which means that the nitrogen gas had completely filled the chamber; the flow rate of hydrogen gas was then set to 50, 150 and 450 sccm, the evolution of spectrums were recorded; the flow of nitrogen gas was set to 0 sccm and only the hydrogen gas was injected into the chamber, the spectrum was recorded when the chamber was fully filled with hydrogen. The five recorded spectrums correspond respectively to (v_i , v_i) = (1,0), (3/4,1/4), (1/2, 1/2), (1/4, 3/4) and (0,1). Figure 2 (b) shows the dip wavelength around 1558 nm as a function of RI of the gas mixture, and the detailed spectrums for the five gas mixtures are shown in the inset of Fig. 2(b). The dip wavelength shifts to the longer wavelength with increasing refractive index and the slope coefficient or sensitivity is 2024 nm/RIU.

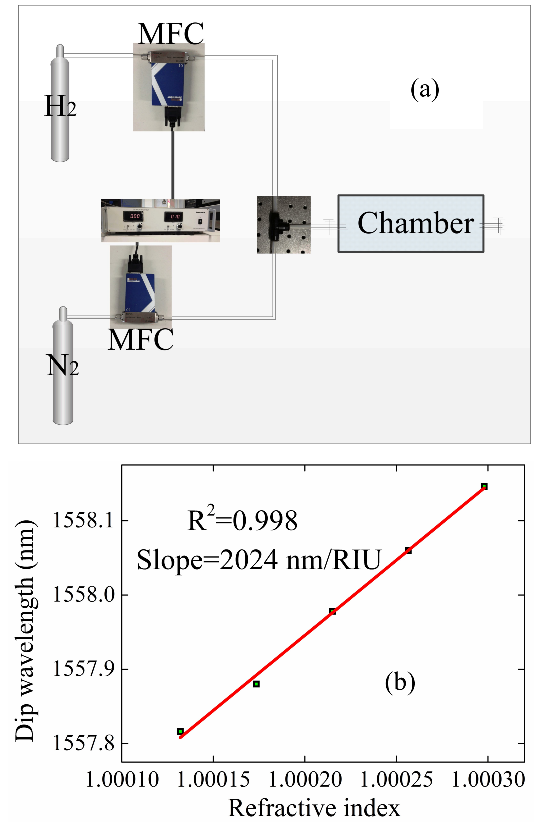

Fig. 2(a) Setup for producing gas mixtures with different refractive indexes. MFC: mass flow controller. (b) Dip wavelength as a function of refractive index. Inset: spectrums for five different gas mixtures.

The PMC can also be used as a sensor to measure gas pressure. For the purpose of applying different gas pressure into the capillary tube, one of the two holes on the capillary wall was sealed when the capillary filled with pure nitrogen and a three port tube as shown in the inset in Fig. 3 was used to change the (nitrogen) gas pressure inside the capillary. The gas pressure inside the capillary was ramped up or down by a gas pump, the experiments were carried out at room temperature (~25℃). The gas pressure change resulted in a change in the RI surrounding the Hi-Bi microfiber, which altered the phase difference between the two orthogonal polarization states. The dip wavelength as a function of gas pressure is shown in Fig. 6, and the pressure sensitivity is 599 pm/bar and is much higher than that of other optical fiber devices [13,14], which demonstrates that the PMCs could be used as a gas chamber to exploit sensing applications.

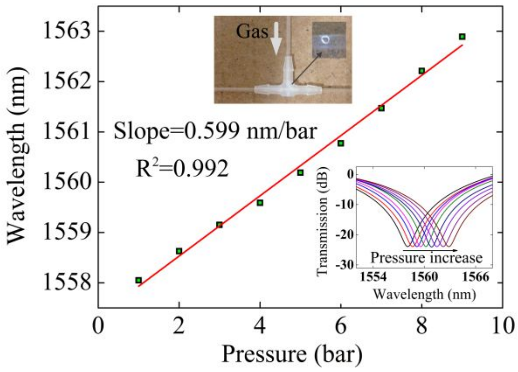

Fig. 3 Dip wavelength around 1558 nm (at room temperature) as a function of gas pressure from 1 to 9 bar.

4. CONCLUSION

In summary, with an encapsulated Hi-Bi microfiber PMC spliced into a Sagnac loop interferometer, we demonstrated gas pressure and RI sensors with pressure sensitivity of 599 pm/bar and RI sensitivity of 2024 nm/RIU at RI ≈ 1. Compared with the previous gas chamber, the designed capillary tubes are more simple and effective for the encapsulation to be as gas sensing cells. Based on this, the PMCs could be explored to more gas sensing applications.

5. ACKNOWLEGEMENT

This work is supported by the National Natural Science Foundation of China (Grant No. 61205068, 61475133), project supported by the Provincial Natural Science Foundation of Hebei (Grant No. F2016203392); project supported by the Provincial College and University Natural Science Foundation of Hebei (Grant No. QN2016078); project supported by the Science and Technology Project of Qin Huangdao City (Grant No. 201601B050).

REFERENCES

[1] L. M. Tong, R. R. Gattass, J. B. Ashcom, S. L. He, J. Y. Lou, M. Y. Shen, I. Maxwell, and E. Mazur, "Subwavelength-diameter silica wires for low-loss optical wave guiding," Nature 426, 816-819 (2003).

[2] P. Pal and W. H. Knox, "Low loss fusion splicing of micron scale silica fibers," Opt. Express 16(15): 11568-11573 (2008).

[3] X. S. Jiang, L. M. Tong, G. Vienne, X. Guo, A. Tsao, Q. Yang, and D. R. Yang, "Demonstration of optical microfiber knot resonators," Applied Physics Letters 88(22): 223501-223501-3 (2006).

[4] S. S. Wang, Z. F. Hu, Y. H. Li, and L. M. Tong, "All-fiber Fabry-Perot resonators based on microfiber Sagnac loop mirrors," Optics Letters 34(3): 253-255 (2009).

[5] Y. Chen, Z. Ma, Q. Yang, and L. M. Tong, "Compact optical short-pass filters based on microfibers," Optics Letters 33(21): 2565-2567 (2008).

[6] O. Frazao, B.V. Marques, P. Jorge, J.M. Baptista, and 1.L. Santos, "High birefringence D-type fiber loop mirror used as refractometer," Sensor and Actuators B: Chemical 135: 108-111 (2008).

[7] C .L. Zhao, 1.R. Zhao, W. Jin, 1. Ju, L. Cheng, and X.G. Huang, "Simultaneous strain and temperature measurement using a highly birefringence fiber loop mirror and a long-period grating written in a photonic crystal fiber," Optics Communication 282(20): 4077-4080 (2009).

[8] M. Campbell, G. Zheng, A. S. Holmes-Smith, and P. A. Wallace, "A frequency-modulated continuous wave birefringent fibre-optic strain sensor based on a Sagnac ring configuration," Meas. Sci. Technol. 70(2): 141-143 (1999).

[9] E. De La Rosa, L. A. Zenteno, A. N. Starodumov, and D. Monzon, "All-fiber absolute temperature sensor using an unbalanced high-birefringence Sagnac loop," Opt. Lett. 22(7): 481–483 (1997).

[10] H. Xuan, J. Ju, and W. Jin, "Highly birefringent optical microfibers," Optics Express 18(4). 3828-3839 (2010).

[11] Y. X. Jin, C. C. Chan, Y. F. Zhang, X. Y. Dong, "Temperature sensor based on a pressure-induced birefringent single-mode fiber loop mirror," Measurement science and technology 21(6): 065204-065208 (2010).

[12] Sibel GEACAI, Irina NIŢĂ, Olga IULIAN, Elis GEACAI, "Refractive indices for biodiesel mixtures," U.P.B. Sci. Bull., Series B 74(4): 149-160 (2012).

[13] D.-W. Duan, Y.-J. Rao, and T. Zhu, "High sensitivity gas refractometer based on all-fiber open-cavity Fabry–Perot interferometer formed by large lateral offset splicing," J. Opt. Soc. Am. B 29(5): 912-915 (2012).

[14] Z. Liu, C. Wu, M.-L. V. Tse, C. Lu, and H.-Y. Tam, "Ultrahigh birefringence index-guiding photonic crystal fiber and its application for pressure and temperature discrimination," Opt. Lett. 38(9): 1385-1387 (2013).