Optical Fiber Flowmeter Using Silver-coated FBG Cascaded by Waist-enlarged Bitaper

Xinhuai Wang, Xinyong Dong, and Yan Zhou
Institute of Optoelectronic Technology, China Jiliang University, Hangzhou 310018, China

Abstract— A novel hot-wire flowmeter based on a silver-coated optical fiber Bragg grating (FBG) cascaded by waist-enlarged bitaper is proposed and experimentally demonstrated. The silver coating deposited on the surface of the FBG absorbs light of a pump laser, which is coupled into the fiber cladding by the specially-fabricated fiber waist-enlarged bitaper, to generate heat. Thus, the temperature of the FBG increases to a certain level, while air flow cools down the FBG by taking heat away. Bragg wavelength of the FBG changes with velocity of air flow according to a certain relationship. Experimental results show that a large measurement range up to 13.7 m/s is realized.

1. INTRODUCTION

Flow measurement is important for many applications in chemical engineering, in the energy and aerospace industries, and in medical equipment technology. Many approaches including differential pressure measurement, ultrasonic measurement, vortex shedding measurement and heat transfer have been proposed and employed for mass flow measurement [1–3]. Optical fiber anemometers have attracted many interests because of their advantages such as electrically passive operation, immunity to electromagnetic interference, high sensitivity, integrated structure, and the capability of remote sensing [4, 5]. In recent years, optical fiber Bragg grating (FBG) based hot-wire anemometers have been proposed by coating the FBG's surface with a metal film and heating with a high power pump laser [6–8]. To couple the laser light from the core to the cladding area of the FBG is very important in these anemometers because the metal coating can only absorb the laser light propagating in the fiber cladding area. Various coupling devices have been proposed including multimode fibers [6], no-core fibers [7] long-period fiber gratings [8], core-offset fusion splice [9] and so on.

In this paper, we propose an optical fiber hot-wire flowmeter based on a specially-fabricated fiber bitaper collaborating with a silver-coated FBG. The bitaper with an enlarged waist diameter shows high and stable coupling efficiency so that most of the pump laser power is coupled from the fiber core to the fiber cladding and absorbed by the silver coating film. That helps to improve the sensitivity by providing a relatively larger initial wavelength shift of the FBG. Furthermore, it has enhanced mechanical strength than a normal fiber so that high airflow velocity measurement is expected.

2. SENSOR FABRICATION AND PRINCIPLE

The proposed optical fiber flowmeter is schematically presented in Fig. 1. It consists of a waist-enlarged fiber bitaper and a FBG coated with a silver film. The bitaper couples laser light into the fiber cladding to heat the silver layer. Its coupling efficiency mainly depends on the length and the shape of the bitaper. The FBG is used to monitor the ambient temperature change influenced by heating from the silver absorption and airflow around. Note that the distance between the fiber grating and the bitaper should be as short as possible because there is high loss when the light propagates in the fiber cladding.

The FBG was manufactured by using a phase mask method in a hydrogen-loaded single-mode fiber (SMF-28). The achieved 4-mm-long FBG has reflectivity of 98% at the Bragg wavelength of 1549.36 nm and 3-dB bandwidth of 0.32 nm. The silver film was deposited on the surface of the FBG by the vacuum evaporating method and its thickness is ~ 120 nm, limited by the used deposition system. To prevent silver from being oxidized, a quartz film with thickness of 100 nm was then deposited over the silver film.

A waist-enlarged fiber bitaper was then fabricated 1-mm long prior to the FBG by using a fusion splicer (Fujikura FSM-60s) under the manual splicing mode, where we used a much larger overlap distance of 100 μm, instead of the commonly used setting of 10 μm, to make a waist-enlarged optical fiber bitaper [10, 11]. Given fixed fusion splicer parameter settings and good fiber tip conditions, repeatability of bitaper fabrication is achievable. The inset of Fig. 1 shows a micrograph view of

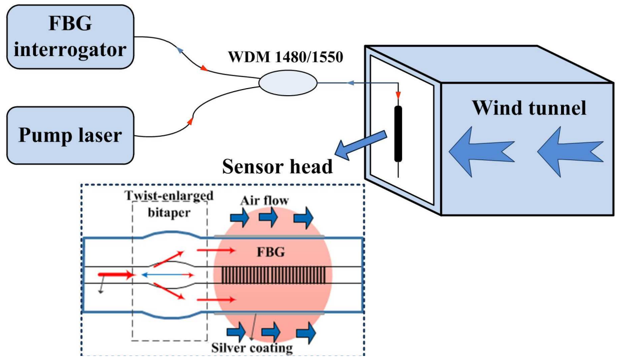

Figure 1: Schematic diagram of the proposed optical fiber flowmeter.

the formed bitaper. Its maximal diameter was increased from 125 μm to 145 μm. Its insertion loss is ~ 10 dB, which means $\sim 90\%$ of the input light can be coupled into the cladding of the fiber by the bitaper.

The silver film absorbs this part of pump laser power and generates heat, which increases temperature of the FBG. Bragg wavelength of the FBG is then shifted to a longer wavelength. When air flows by, part of the heat will be taken away and the temperature will be reduced by an amount depending on the air flow velocity, leading to a blue-shift for the Bragg wavelength of the FBG. Flow measurement is then realized by monitoring wavelength shift of the FBG. Based on the theory of hot-wire flowmeter [12], one can write the heat loss as a function of the air flow velocity as

$$P\varphi a_{\mathrm{Ag}} = \left[T_{(v)} - T_e\right]\left(A + B\sqrt{v}\right) \tag{1}$$

where $T_{(v)}$ is the temperature of the flowmeter at airflow velocity of v, T_e is the temperature of the environment, A and B are empirical calibration constant, and v is the air flow velocity. Assuming there is equilibrium between the heat generation and loss, the following relationship can be achieved. P is the input laser power, φ is the coupling coefficient of waist-enlarged fiber bitaper, a_{Ag} is the absorption coefficient of the silver film to pump laser. Bragg wavelength of the FBG changing with temperature of the flowmeter can be described as

$$\lambda - \lambda_0 = k(T_{(v)} - T_e)\lambda_0 \tag{2}$$

where k is the FBG's temperature coefficient of sensitivity, λ_0 is the wavelength of the FBG without laser heating. The relationship between Bragg wavelength of the FBG and the airflow velocity thus can be given as

$$\lambda = \lambda_0\left(1 + \frac{kP\varphi a_{\mathrm{Ag}}}{A + B\sqrt{v}}\right) \tag{3}$$

Based on this equation, the airflow velocity can be determined from the measured wavelength shift of the FBG.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental setup is shown in Fig. 2. The pump laser with output power of 340 mW at 1480 nm was utilized to heat the sensor head through a 1480/1550 nm WDM coupler. A wind tunnel with cross-sectional dimension of 60 cm × 60 cm was used to provide stable airflows. A FBG interrogator with wavelength resolution of 1 pm and scanning frequency of 500 Hz was used to monitor Bragg wavelength shift of the FBG.

Figure 2(a) presents spectral response of the FBG before and after the pump laser was turned on. It shows that the laser heating leads to the FBG a large Bragg wavelength shift of 1.19 nm. This pump laser-induced wavelength shift is just double that of our previous reported FBG flowmeter assisted by a core offset fusion splice. So the coupling efficiency is improved significantly by using the waist-enlarged bitaper. Considering temperature sensitivity of the FBG, 10.9 pm/°C, which was achieved from real testing, we can figure out that temperature of the optical fiber flowmeter would be about 109°C higher than the room temperature when the pump laser is turned on. A high initial temperature increment is obviously helpful to increase the measurement range.

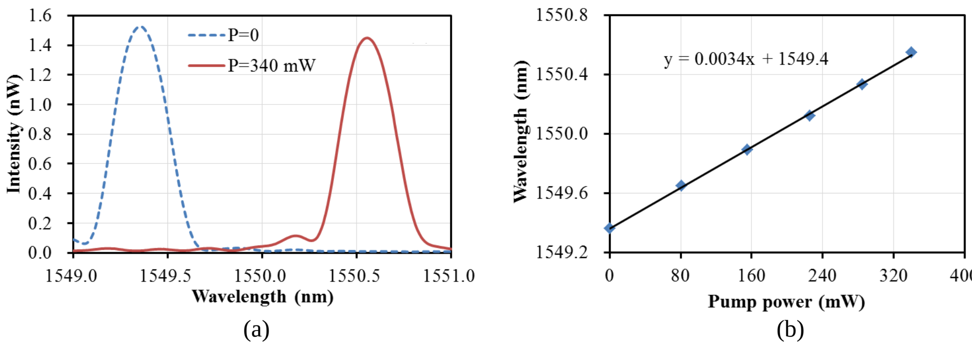

Figure 2: (a) Reflection spectra of the FBG flowmeter with and without laser heating. (b) Bragg wavelength of the FBG against power of the pump laser.

It is also noticed that reflectivity of the FBG with pump laser heating was reduced slightly by $\sim 5\%$ due to a minor chirp effect caused by a nonuniform temperature distribution along the length of the FBG. Due to continuous absorption by the sliver layer, power of the pump laser and the heating effect were reducing slowly along the FBG. This is the reason why the FBG was slightly chirped and its reflectivity was reduced. However, the influence to Bragg wavelength measurement of the FBG is totally negligible because the change of reflectivity is so small. Fig. 2(b) shows the measured Bragg wavelength of the FBG as a function of the laser power. It can be seen that the wavelength shift is proportional to the power of the laser with a slope of 3.4 pm/mW.

Airflow measurement was carried out at a fixed temperature of 20°C to avoid any possible influences caused by the environmental temperature variations. The pump laser was set at the maximum output power of 340 mW in order to achieve an as large as possible initial temperature Bragg wavelength shift of the FBG sensor. The airflow velocity in the wind tunnel was changed in a wide range from 0 to 13.7 m/s. Fig. 3 shows the reflection spectra of the flowmeter under different air flow velocities. Obviously, the Bragg wavelength shifts gradually to shorter wavelengths with the increment of the airflow velocity. It agrees well with the theoretical analysis. The total wavelength shift is 1.0 nm when the airflow velocity was changed from 0 to 13.7 m/s. It is also noticed that with increase of the airflow velocity, reflectivity of the FBG returns slightly to the original one. It is because the nonuniform temperature-induced chirp effect of the FBG is relieved gradually with the decrease of temperature.

Figure 4 shows the measured wavelength of the flowmeter as a function of the airflow velocity. It is obviously shown that the Bragg wavelength of the FBG was reduced more quickly with airflow velocity when the velocity was lower. By data fitting based on Eq. (3), we achieved a very close fitting curve, as shown in Fig. 4. The R-squared value is 0.9986. Eq. (3) is then rewritten as

$$\lambda = \frac{0.91}{0.76 + \sqrt{v}} + 1549.36 \tag{4}$$

It should be noticed that Eq. (4) is correct only under specific conditions aforementioned for our sensor and measurement setup. Any change of individual factors, including but not limited to power

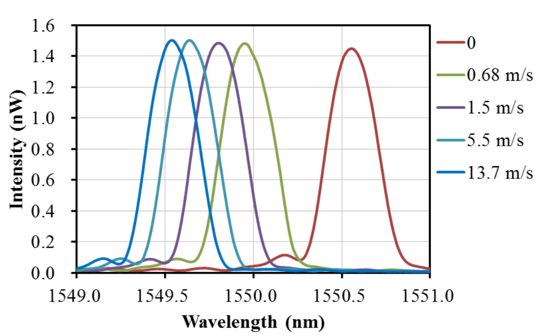

Figure 3: Reflection spectra of the flowmeter under various airflow velocities.

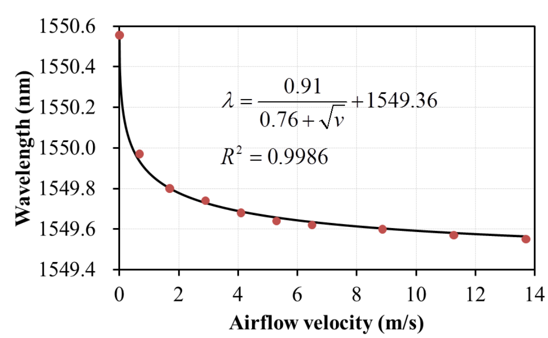

Figure 4: Resonant wavelength versus applied airflow velocity.

of the pump laser, coupling coefficient of the bitaper and environmental (or airflow) temperature, may introduce changes to the equations. It can be seen in Fig. 4, the response is close to linear when the airflow velocity is between 1.7 and 5.3 m/s. The sensitivity is ~ 47.2 pm/(m/s). Based on the wavelength resolution of 1 pm of the FBG interrogator we used, the corresponding resolution for airflow velocity measurement is up to 0.021 m/s.

4. CONCLUSION

An optical fiber thermal flowmeter has been demonstrated by using a silver-coated FBG assisted by a waist-enlarged fiber bitaper. Except for the enhanced mechanical strength than a normal fiber, the bitaper showed high and stable coupling efficiency so that most of the pump laser power was coupled from the fiber core to the fiber cladding and absorbed by the silver coating film. That helps to improve the sensitivity by providing a relatively larger initial wavelength shift of the FBG. High sensitivity of 47.2 pm/(m/s) and high resolution of 0.021 m/s have been achieved for the airflow velocity measurement.

ACKNOWLEDGMENT

This work was supported in part by the National Basic Research Program of China (973 Program) under Grant 2010CB327804, in part by the National Natural Science Foundation under Grant 61203205, and in part by the National Natural Science Foundation of Zhejiang Province, China, under Grant Z13F050003.

REFERENCES

1. Cha, J. E., Y. C. Ahn, and M. H. Kim, "Flow measurement with an electromagnetic flowmeter in two-phase bubbly and slug flow regimes," *Flow Meas. Instrum.*, Vol. 12, No. 5, 329–339, 2002.
2. Venugopal, A., A. Agrawal, and S. V. Prabhu, "Review on vortex flowmeter-designer perspective," *Sens. Actuators A, Phys.*, Vol. 170, Nos. 1/2, 8–23, Nov. 2011.
3. Oda, S., M. Anzai, S. Uematsu, and K. Watanabe, "A silicon microma- chined flow sensor using thermopiles for heat transfer measurements," *IEEE Trans. Instrum. Meas.*, Vol. 52, No. 4, 1155–1159, Aug. 2003.
4. Jewart, C., B. McMillen, S. K. Cho, and K. P. Chen, "X-probe flow using self-powered active fiber Bragg gratings," *Sens. Actuators A, Phys.*, Vol. 127, No. 1, 63–68, Feb. 2006.
5. Lien, V. and F. Vollmer, "Microfluidic flow rate detection based on integrated optical fiber cantilever," *Lab Chip*, Vol. 7, No. 10, 1352–1356, Oct. 2007.
6. Cashdollar, L. J. and K. P. Chen, "Fiber bragg grating flow sensors powered by in-fiber light," *IEEE Sensors J.*, Vol. 5, No. 6, 1327–1331, Dec. 2005.
7. Wang, X., X. Dong, Y. Zhou, K. Ni, J. Cheng, and Z. Chen, "Hot-wire flowmeter based on silver-coated fiber bragg grating assisted by No-core fiber," *IEEE Photon. Technol. Lett.*, Vol. 25, No. 24 2458–2461, Dec. 2013.
8. Caldas, P., P. A. S. Jorge, G. Rego, O. Frazão, J. L. Santos, L. A. Ferreira, and F. Araújo, "Fiber optic hot-wire flowmeter based on a metallic coated hybrid long period grating/fiber Bragg grating structure," *Applied Optics*, Vol. 50, No. 17, 2738–2743, Jun. 2011.
9. Dong, X., Y. Zhou, W. Zhou, J. Cheng, and Z. Su, "Compact flowmeter using silver-coated fiber bragg grating," *IEEE Photonics Journal*, Vol. 4, No. 5, 1381–1386, Oct. 2012.
10. Meng, Q. Q., X. Y. Dong, Y. Zhou, K. Ni, Z. M. Chen, C. L. Zhao, and S. Z. Jin, "Simultaneous measurement of curvature and temperature with fiber taper-based MZI containing fiber Bragg grating," *Journal of Electromagnetic Waves and Applications*, Vol. 26, No. 17–18, 2438–2444, Dec. 2012.
11. Ni, K., X. Dong, C. Chan, T. Li, L. Hu, and W. Qian, "Miniature refractometer based on Mach-Zehnder interferometer with waist-enlarged fusion bitaper," *Optics Communications*, Vol. 292, 84–86, 2012.
12. Bruun, H. H., *Hot-Wire Anemometry: Principles and Signal Analysis*, Oxford University Press, 1995.
13. Gao, S., A. P. Zhang, H.-Y. Tam, L. H. Cho, and C. Lu, "All-optical fiber flowmeter based on laser heated fiber Bragg gratings," *Optics Express*, Vol. 19, No. 11, 10124–30, May 2011.