Hot-wire Anemometer Based on Frosted Fiber Bragg Grating Coated with Silver Film

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Abstract. Hot-wire anemometer is proposed based on a frosted fiber Bragg grating (FBG) coated with silver film assisted by a coupler of lumbar-enlarged optical fiber taper. The silver film adhered to the surface of frosted FBG absorbs pumping light, which is coupled into the fiber cladding by the lumbar-enlarged taper to generate heat. A strong diffuse reflection occurs on the surface of frosted FBG, which increases absorption of light by silver film. Center wavelength of frosted FBG changes with velocity of airflow according to a relationship. Experimental results reveal that sensitivity is 5.3 pm/mW and the measurement range from 0 to 20.36 m/s.

1. Introduction

Flow measurement is a vital parameter in all kinds of territory such as chemical engineering, physical detection, automobile manufacturing, medical equipment in various applications technology and so on[1, 2]. Optical fiber anemometers have caused extensive concern due to the superiority such as simple, sensitivity, strong to electromagnetic interference, long-distance detecting, low power consumption, electrically passive operation and integrated structures[3-5]. Flow sensors are mainly based on microelectronic and mechanical system technology, some of them are based on optical fiber device[5, 6]. However, they also have limitations such as corrosive environment, temperatures extremes and radiation environment under the relatively harsh working environment.

In view of the above deficiencies, thermal anemometry stands out and is used commonly in air flow measurement. In the late years, hot-wire anemometers optical sensor based on fiber Bragg grating (FBG) has been proposed as a new research focus[7-10]. It is realized that anemometer contains a pump laser, FBG coated with metal film and an optical coupler, which couples the pumping light from fiber core into cladding. The metal film absorbs the pump laser from cladding, temperature of metal film rises, which drifts the Bragg wavelength of FBG.

In this paper, we propose an optical fiber hot-wire anemometer based on a lumbar-enlarged optical fiber coupler combining with a frosted FBG. The coupler possesses not only high but also stable coupling efficiency so that most power of the pumping light can be coupled from fiber core into cladding. Fiber Bragg grating is ground by a grinder, silver film is adhered to the FBG. A strong diffuse reflection occurs on the surface of frosted FBG, and the silver film absorbs more light and obtain a higher initial temperature. When air flows through anemometer, the temperature of anemometer drops and the Bragg wavelength drifts.
2. Sensor Fabrication and Principle

The proposed optical fiber anemometer is schematically presented in Fig. 1, which consists of a lumbar-enlarged optical fiber taper and frosted FBG with silver film coated. The taper, with a maximal diameter of 145 μm, can couple pump laser light from fiber core into cladding. The silver film absorbs energy of the pump laser and heats the FBG. The FBG was written in a hydrogen-loaded single-mode fiber (Corning SMF-28) with a scanning 244-nm UV laser beam through the phase-mask method. Bragg wavelength was 1555.088 nm and 3-dB bandwidth of 0.2082 nm with a reflectivity of 98%. It should be noted that the taper was proximate to the FBG, because there was a high loss when the light propagates in the cladding. It was 3 mm in our sensor.

A lumbar-enlarged optical fiber taper was fabricated 1 mm long by using a fusion splicer (Fujikura FSM-60s) under the auto-splicing mode with a much larger overlap distance of 150 μm and a large discharge time of 1500 ms. The core diameter of SMF was 8 μm, cladding diameter was 125 μm, cladding refractive index was 1.45. The inset of Fig. 1 shows a micrograph view of the coupler and frosted FBG. The diameter of the fiber transforms to 145 μm from 125 μm. Insertion loss was ~11 dB, which meant ~92% of incident light was coupled into cladding by the taper.

The FBG was ground by the grinder in order to keep the cladding rough, which makes the silver absorb more light transmitted in the cladding. The illustration of Fig. 1 demonstrates a micrograph view of frosted FBG. After that, silver film was adhered to the surface of the FBG through vacuum evaporating method with a thickness of ~120 nm. To prevent oxidation, a quartz film with thickness of ~100 nm was deposited on the silver.

Fig. 2. Experimental system.

The silver film absorbs power of pumping light in order to generate heat, which makes temperature of the FBG rise. Result that a red shift of center wavelength of the FBG. When wind passes, part of heat is taken away, which makes the resonant wavelength of the FBG transfer to short wavelength. A dynamic thermal equilibrium based on the pumping light power and airflow velocity can be achieved.

The hot-wire anemometer is an instrument for measuring the velocity of flow by monitoring wavelength shift of the FBG based on the solution of the heat convection equation (King’S equation). When the airflow rate is greater than 0.5 m/s, forced convection plays a major role, free convection can
be ignored. By monitoring and analyzing wavelength shift of the FBG, flow measurement can be achieved. The heat transfer of convective heat transfer is calculated by Newton cooling formula:

\[ Q = h(t_w - t_f) = h\Delta t \]  \hspace{1cm} (1)

When heat exchange area is \( S \),

\[ Q_S = S h(t_w - t_f) = Sh\Delta t \]  \hspace{1cm} (2)

here, \( \Delta t \) is average temperature difference of heat exchange area, \( h \) is convective heat transfer coefficient of surface, \( A \) and \( B \) are empirical calibration constant, \( \nu \) is airflow rate.

Based on previous research,

\[ Q_S = P\phi a = (A + B\sqrt{\nu})\Delta t \]  \hspace{1cm} (3)

here, \( P \) is input energy, \( \phi \) is coupling coefficient of lumbar-enlarged fiber, \( a \) is absorption coefficient of the silver film to pump laser.

\[ \lambda - \lambda_0 = kP\Delta t\lambda_0 \]  \hspace{1cm} (4)

here, \( k \) is the FBG’s temperature coefficient of sensitivity, \( \lambda_0 \) is the initial wavelength of the FBG. The relevance between Bragg wavelength of the FBG and the airflow rate can be showed as\[11-13\]

\[ \lambda = \lambda_0(1 + \frac{kP\phi a}{A + B\sqrt{\nu}}) \]  \hspace{1cm} (5)

3. Experimental Results and Discussions

The experimental device is presented in Fig. 2. A wind tunnel was used to provide stable airflows, whose caliber was 60 cm \( \times \) 60 cm. In experimenting, the airflow rate is varied from 0 to 20.36 m/s. The output laser power of the pump laser turned to 264 mW at 1480 nm in order to heat the anemometer through a 1480/1550 nm WDM coupler. The output wavelength of broadband source (BBS) range from 1550 nm to 1565 nm. An optical spectral analyzer (OSA) with precision of 20 pm interrogated Bragg wavelength of the FBG.

Fig. 3 (a) presents the reflection spectra of FBG anemometer with and without rough before and after laser pumping. It shows that unfrosted FBG has a center wavelength shift of 0.908 nm while frosted FBG has a red shift of 1.404 nm, due to pump laser heating. It also can be noticed that, compared with unfrosted FBG, the reflection spectral of the frosted FBG with and without pumping light has a distinguishable deformation, the reflectivity reduces slightly and the reflection profile changes. On the condition of continuous absorption by the sliver film, power of the pumping lighting and temperature are reducing gradually along the FBG, which is called chirp effect. Reduction in reflectivity of the FBG will intensify if the pump power increase furthery. However, there is no obvious effect on measurements. Fig. 3 (b) revels wavelength shift of frosted FBG and unfrosted FBG against power of the pumping light. The wavelength shift is linear, the slope of frosted FBG anemometer is 5.3 pm/mW, which is 1.5 times as high as unfrosted FBG anemometer, which means frosted FBG absorbed more light of cladding than unfrosted one indeed.

Fig. 3 (a) Reflection spectra of FBG anemometer before and after friction with and without laser pumping. (b) Wavelength shift of FBG before and after friction against power of the pumping light.

The measurement of airflow rate was handled based on the fixed pump laser power of 264 mW. Airflow measurement was developed on the condition of a fixed temperature of 25°C in case of the
influences of environmental temperature. The airflow rate in the wind tunnel range from 0 to 20.36 m/s. Fig. 4 takes on the reflection spectra of frosted FBG anemometer under different airflow rate. It can be noticed that, center wavelength diverts gradually to short wave length with the increase of the airflow velocity. It is also should be observed that with increase of the airflow velocity, the reflectivity is enlarged step-by-step and the spectral profile return to the start state. The reason why is that the chirping effect was eliminated gradually along when the sensor was cooled down by airflow. This wavelength shifts induced by the laser pumping is more than double than previous FBG anemometer coated with silver film and combined by a core-offset fusion splice, even if the pump laser power in this experiment is 76 mW lower[13]. Thus the absorption efficiency of silver film is improved significantly because of frosted FBG.

Fig. 4 Reflection spectra of frosted FBG anemometer under various airflow velocities.

From the demonstration of Fig. 5, it should be noted that reflectivity of the FBG returns slightly to the start one with increase of the airflow rate. However, as the sensor is poor, which is hard to stand a stronger airflow. Under condition of 10.9 pm/℃ temperature sensitivity, we can calculate that the FBG is 83℃. The temperature of airflow at the rate of 20.36 m/s is 6 degrees lower than the frosted FBG anemometer.

Bring data into Eq. (4), a fitting curve with R-squared value of 0.998 can be achieved, as reveled in Fig. 5. Eq. 4 can be written as the following expression:

\[ y = \frac{0.49}{0.35 + \sqrt{x}} + 1555.08 \]  \hspace{1cm} (5)

Based on the above formula, airflow rate is worked out from the measured center wavelength of the FBG sensor. The variant can be written as:

\[ v = (\frac{0.49}{1-1555.08} - 0.35)^2 \]  \hspace{1cm} (6)

 Noticed that Eq. (5) and Eq. (6) are workable only under aforementioned conditions and measurement process. Any variation of single condition, including but not limited to coupling coefficient of the lumbar-enlarged fiber taper, power of the pumping light, environmental (or airflow) temperature and initial center wavelength of the FBG, may change parameter of the equations.

Fig. 5 Resonant wavelength versus applied airflow velocity.

It can be seen that the airflow velocity is almost invariable and the response becomes smaller and smaller when airflow rate is over 6 m/s in the demonstration of Fig. 5. What can't be ignored is that center wavelength of the FBG declines more quickly under a greater airflow rate. The sensitivity and resolution of FBG anemometer under different airflow velocity can be obtained from the analysis of Fig.
5, as shown in Table 1.

Table 1. The sensitivity and resolution of FBG anemometer under different airflow velocity.

| Airflow velocity(m/s) | 0.873 | 2.384 | 3.794 | 5.127 |
|------------------------|-------|-------|-------|-------|
| Resolution(pm/m/s)    |       |       |       |       |
| Unfrosted              | 398.06| 38.39 | 17.59 | 10.65 |
| Frosted                | 738.95| 24.25 | 10.13 | 5.78  |

It can be clearly seen that the sensitivity of unfrosted FBG anemometer is up to 398.06 pm/(m/s) and the resolution can reach 0.05 m/s, when the airflow rate is lower than 6m/s. The response is almost linear when the airflow rate is between 1.0 m/s and 6.0 m/s, the sensitivity and the resolution is ~54.83 pm/(m/s) and 0.36 m/s, respectively. The highest sensitivity of frosted FBG anemometer is 738.95 pm/(m/s), the resolution is 0.027 m/s. The corresponding temperature change, under condition that temperature sensitivity of the FBG is 10.9 pm/°C, is ~128°C. The sensor is still 3°C higher than the airflow rate of 20.36 m/s.

4. Summary

A hot-wire anemometer is proposed based on a frosted fiber Bragg grating (FBG) coated with silver film assisted by a lumbar-enlarged optical fiber taper. A 1480 nm pumping light with a maximum output power of 264 mW was operated to heat the FBG through the optical fiber taper coupler. The sensitivity of the FBG anemometer without rough is up to 398.06 pm/(m/s) and the resolution can reach 0.05 m/s. When airflow velocity is between 1.0 m/s and 6.0 m/s, the sensitivity and the resolution are ~54.83 pm/(m/s) and 0.36 m/s respectively. The highest sensitivity of frosted FBG anemometer is 738.95 pm/(m/s), the resolution is 0.027 m/s. Frosted FBG anemometer increases the absorption of light conveyed in the cladding, which effectively improves the sensitivity. The optical fiber anemometer is dominant with the superiority of cost, manufacture, physical strength, structure, which enjoys good potential in all kinds of applications.

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