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Magnetic field sensor based on reflection spectrum measurement of fiber Bragg grating

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ABSTRACT

A novel magnetic field sensor by using an optical fiber Bragg grating (FBG) cascaded by a cleaved optical fiber end, which is face surrounded with magnetic fluid (MF), is experimentally demonstrated. Through Fresnel reflection (FR) of the fiber end face, side mode suppression ratio (SMSR) of reflection spectrum of the FBG is tuned by refractive index (RI) of the MF, which is sensitivity to the external magnetic field. As a result, magnetic field measurement is successfully achieved. Compared with previously reported methods based on FR of a fiber end only, it eliminates the influence of power level fluctuation of the optical source and therefore improves the measurement accuracy and stability. Furthermore, temperature can be measured simultaneously by monitoring wavelength shift of the FBG.

Keywords: Fiber-optic sensor, fiber Bragg grating, magnetic intensity, Fresnel reflection, side mode suppression ratio

1. INTRODUCTION

Magnetic fluid (MF) is a kind of colloidal system that dispersing nanoparticles in a suitable liquid carrier. It exhibits remarkable magneto-optical properties like tunable refractive index (RI), birefringence and so on. By using typical multimode interferometer with tunable RI of MF, many kinds of optic fiber sensor have been realized [1-3]. It has been reported that an optical fiber Sagnac interferometer based on MF by Zu *et al.*[4]. They also infiltrated MF into air holes of photonic bandgap fiber to tune the bandgap and to measure magnetic field [5]. MF has also be employed to collaborate with different fiber gratings, such as long-period fiber gratings [6, 7], cladding-etched fiber Bragg gratings (FBG) [8] and tilted-fiber Bragg gratings (TFBG) [9, 10] to realized magnetic field measurements or to achieve magnetic field-tunable devices. As we know, RI of MF is sensitive to not only the magnetic field intensity, but also the temperature variation [11]. To compensate the temperature effect, one can immerse a reference fiber into the same MF without applying magnetic field [12]. Intensity-modulation of magnetic field intensity and temperature has been also achieved by using MF-based TFBG and chirped-fiber Bragg grating presently [13]. However, these kinds of sensors mentioned above are made use of particular kinds of fiber or with special processes. It may induce more complex fabrication or operation in practical applications.

In this work, a novel magnetic sensor operated in reflection mode is experimentally demonstrated based on a normal FBG cascading with a cleaved fiber end surrounded with MF. Through Fresnel reflection (FR) of the fiber end face, side mode suppression ratio (SMSR) of reflection spectrum of the FBG is tuned by RI of the MF, which is sensitivity to the external magnetic field. Compared with previously reported method based on FR of a fiber end only [7, 11], it eliminates the influence of power level fluctuation of the optical source and therefore improves the measurement accuracy and stability. Furthermore, temperature can be measured simultaneously by monitoring wavelength shift of the FBG.

2. EXPERIMENTAL SETUP AND PRINCIPLE

Fig.1 illustrates schematic diagram of the experimental setup. Three ports of circulator were connected to a broadband source (BBS), the proposed sensor and an optical spectrum analyzer (OSA: Yokogawa, AQ6370B), relatively. The magnetic field intensity was tuned by changing the distance from the sensor to permanent magnet and measured in real-time by a gauss meter [3]. Reflection spectra were monitored by using OSA. The detail of the proposed sensor is shown

in the top right-corner of Fig.1. The sensor configuration is formed by a normal FBG cascading a cleaved fiber end face surrounded with MF. The FBG has a Bragg wavelength of 1549.87 nm at 28°C, reflectivity of 14.48 dB and 3-dB bandwidth of 0.2 nm. The fiber length between FBG and end face is longer than 2 m, because it must be longer than the coherence length of light source [14]. After being cleaved, the end face was sent into the center of a MF-filled capillary tube with inner diameter of ~500 μm and length of 3 cm and then sealed by epoxy resin. The MF we used (EMG 607, Ferrotec Inc.) is a kind of stable water based ferro-fluid. The average diameter of the magnetic nanoparticles, Fe_3O_4 , is ~10 nm, and volume concentration is ~1.8%.

Given the FR at the cleaved fiber end face, SMSR will vary with RI of MF. As analyzed in [14, 15], Fresnel reflectivity R_F at cleaved end face of an optical fiber can be expressed by

$$R_F = \left(\frac{n_f - n_m}{n_f + n_m} \right)^2 \quad (1)$$

where n_f , RI of fiber core, can be known from the datasheet of single mode fiber manufacturer, and n_m , RI of MF, is related to magnetic field intensity which follows Langevin function [16]. Within the bandwidth of BBS, the dependence of n_f and n_m on wavelength can be nearly ignored. Hence, SMSR of FBG is given by

$$\text{SMSR} = 10 \lg \left[\frac{R_{\text{FBG}}(\lambda_B)}{R_F} \right] \quad (2)$$

where $R_{\text{FBG}}(\lambda_B)$ is FBG reflectivity[11, 14, 15]. With Eq. (1) and (2), by detecting the value of SMSR, magnetic field intensity can be obtained, which corresponds to the unique RI of MF.

Fig.1. Schematic diagram of the experimental setup.

Fig.2. Reflection spectra of the FBG under air and various magnetic field intensities.

For temperature measurement, the Bragg wavelength of FBG changed due to thermal expansion and thermo-optic effects of optical fiber, but it barely tuned by magnetic field changes. Therefore, temperature can be measured simultaneously by monitoring wavelength shift of FBG.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The SMSR of FBG in the proposed sensor was increased significantly as compared with that in air before coated, as demonstrated in Fig.2. It is also observed that SMSR of FBG increases gradually with the enhancement of magnetic field intensity. The trends agrees well with the aforesaid sensor deposited by different RI of liquid as illustrated in [17]. Thus, RI of MF increases gradually on the condition of enhancing magnetic field intensity. In addition, it is notable that noise becomes stronger at the bottom of reflection spectra when magnetic fields intensity increases. It may be caused by out of flatness of the end face, which is perhaps attached to the nanoparticles, Fe_3O_4 . Moreover, it has been also reported absorption and scattering of metal nanoparticles is an influenced factor to spectra [18, 19]. Moreover, from the data recorded, the Bragg wavelength was 1549.87 nm steadily under the OSA resolution of 0.02nm, which is nearly insensitivity to the different magnetic field intensities.

Fig.3. Relationship between SMSR of FBG and magnetic field intensity.

Fig.4. Relationship between Bragg wavelength and temperature and stability test of the proposed sensor under different temperatures.

In order to study the relationship between SMSR of FBG and magnetic field intensity exactly, we averaged the data of reflection spectra without Bragg wavelength to eliminate noise mentioned previously, and then figure out SMSR of FBG as analyzed in [14, 15]. The relationship between SMSR of FBG and magnetic field intensity is shown in Fig.3. Within a range to 50 Gauss, SMSR of FBG nonlinearly increased from 27.96 dB to 33.02 dB. The data for ascending and descending order fit well and the maximum deviation is ± 0.10 dB (at 20 Gauss). With the influence of power level fluctuation of the optical source, reflection spectra will drift entirely all the time. Thanks to the relative SMSR of FBG, the proposed sensor has a capacity of improving the accuracy and stability in magnetic field intensity measurement.

To test temperature response of the proposed sensor, we put it in a water-bathed tank, changed temperature from 10 to 60°C with no external magnetic field, and recorded the shift of Bragg wavelength with OSA. Fig.4 shows the relationship between Bragg wavelength and temperature. The data fit well to the quadratic function $y = 0.0084x + 1549.6$ with fitting degree of 0.9958. The sensitivity of 9.4 pm/°C is achieved. It is also indicated that SMSR of FBG was approximately stable, and the maximum floating rate is 1.7% (at 40°C) in Fig. 4, when the temperature increased. The deviation of wavelength shift is mainly caused by the instable thermal distribution of bathed water. The wavelength shift of the FBG is only tuned by temperature variation. Therefore, temperature can be measured at the same time.

4. CONCLUSION

We have experimentally demonstrated a novel FBG-based magnetic field fiber sensor by cascading a cleaved end face surrounded with MF. Through FR of the fiber end face, SMSR of reflection spectrum of the FBG is tuned by RI of the MF, which is sensitivity to the external magnetic field. As a result, the magnetic field measurement is successfully achieved within a range up to 50 Gauss and maximum deviation of ± 0.10 dB. The method we used eliminates the influence of power level fluctuation of the optical source and therefore improves the measurement accuracy and stability. Furthermore, temperature can be measured simultaneously by monitoring wavelength shift of the FBG with the sensitivity of $9.4 \text{ pm}/^\circ\text{C}$.

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