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Intensity-modulated magnetic field sensor based on magnetic fluid and optical fiber gratings

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An intensity-modulated magnetic field sensor based on magnetic fluid and optical fiber gratings is proposed and experimentally demonstrated. The sensor is formed by a tilted-fiber Bragg grating (TFBG) coated by magnetic fluid (MF) and cascaded by a chirped-fiber Bragg grating (CFBG). Transmission of the TFBG is modulated by refractive index of the MF, which is sensitive to external magnetic field. The CFBG is well designed to reflect a broadband of light spectrally located at the cladding mode resonances region of the TFBG. Therefore, reflected optical power is modulated twice by the magnetic field and measurement is realized in reflection manner. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4828562>]

Optical fiber magnetic field sensors have attracted a lot of research attentions due to their many advantages including safety in hazardous environments, immunity to electromagnetic interference, high sensitivity, high response frequency, and small size.^{1,2} Recently, magnetic fluid (MF), as an attractive nano-material with magneto-optical effects including Faraday effect, tunable refractive index, field dependent transmission and birefringence,^{3,4} was intensively investigated in magnetic field measurement.⁵⁻⁹ By taking advantage of the field dependent birefringence of MF, Zu *et al.* reported an optical fiber Sagnac interferometer based magneto-optical fiber sensor.⁵ The same group of researchers infiltrated MF into air holes in the cladding of a short length index-guided photonic crystal fiber to convert it into a photonic bandgap fiber with a tunable band gap and measured magnetic field by monitoring the bandgap wavelength.⁶ Based on the tunable refractive index of MF, Gao *et al.* presented a magnetic field sensor through measuring intensity of the transmission light in MF-filled photonic crystal fiber.⁷ Optical fiber gratings based magnetic field sensors or tunable filters were also reported by surrounding them with MFs.⁸⁻¹² Various fiber gratings have been used, including long-period fiber gratings,⁸ cladding-etched fiber Bragg gratings,⁹ and tilted-fiber Bragg gratings (TFBGs).^{11,12} Childs *et al.* reported a two-TFBG-based cavity structure with MF coating, but the ghost mode-based resonance adds to the difficulty of fabrication.¹¹ Lin *et al.* reported a two dimensional magnetic field vector sensor by measuring transmission loss of a TFBG, which is modulated by birefringence of MF.¹² However, most of the reported MF-based optical fiber magnetic field sensors are based on wavelength or spectral measurement that increases the cost of the measurement system because of the expensive signal demodulator despite its self-referencing capability. And the measurement is usually

based on transmission operation mode that causes inconvenience in practical applications.

In this work, an intensity-modulated magnetic field sensor operated in reflection mode is proposed and demonstrated based on a MF-coated TFBG cascaded by a chirped-fiber Bragg grating (CFBG). Transmission of the TFBG is modulated by refractive index of the MF, which is sensitive to external magnetic field. The CFBG is well designed to reflect a broadband of light spectrally located at the cladding mode resonances region of the TFBG. The reflected optical power is modulated twice by the magnetic field through the MF-coated-TFBG. Magnetic field strength measurement is therefore realized. The achieved magnetic field sensor is intensity-modulated and working in reflection mode, thus possesses advantages of low cost and easy operation.

The gratings were manufactured by using phase mask method in a hydrogen-loaded Germanium-doped single-mode fiber with a frequency-doubled Argon laser emitting at 244 nm. The TFBG, achieved with a uniform phase mask of 1083 nm period, is 10-mm long with a tilt angle of 6°. The Bragg mode resonance of the TFBG locates at 1578 nm with transmission loss of ~0.5 dB while cladding mode resonances locate between 1500 and 1576 nm with maximum transmission loss of ~25 dB at ~1540 nm. The CFBG is 18-mm long, with reflectivity of 9.5 dB in a broad and well-designed reflection band of ~36 nm (1528–1564 nm), which covers most of the cladding mode resonance region of the TFBG. Figures 1(a) and 1(b) show the measured optical spectra of the TFBG and the CFBG, respectively. After the TFBG was cascaded by the CFBG, the reflection spectrum was measured and shown in Fig. 1(c). The reflected optical power of the Bragg mode resonance of the TFBG can be neglected as its power is much lower than the CFBG.

The MF used in this experiment, EMG605 from Ferrotec, is a water-based ferrofluid fabricated by using the chemical coprecipitation technique. It is a black-brown translucent liquid with refractive index of ~1.40. The nominal

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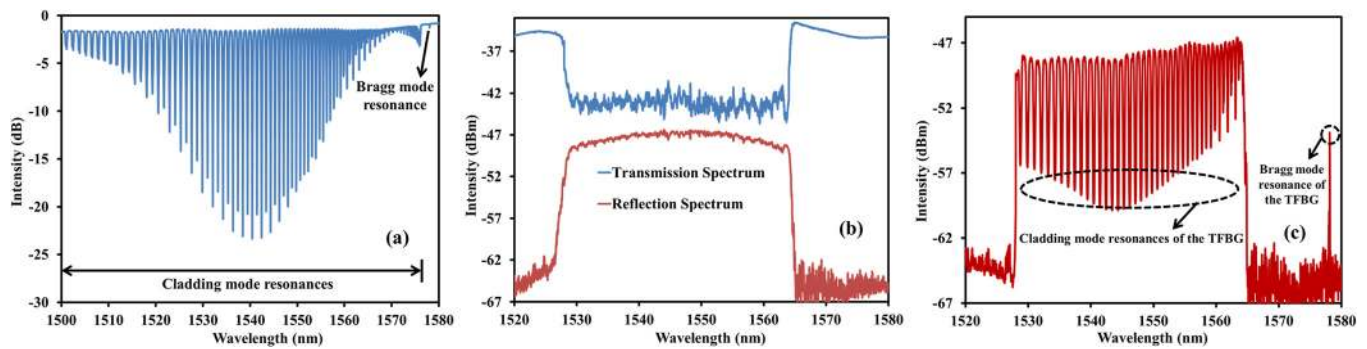


FIG. 1. (a) Transmission spectrum of the TFBG; (b) Transmission and reflection spectra of the CFBG; (c) Reflection spectrum of the CFBG-cascaded TFBG.

diameter of the nanoparticles, Fe_3O_4 , is 10 nm. The magnetic susceptibility and saturation magnetization are 2.96 G and 220 G, respectively. When an external magnetic field is applied, the structural pattern state of MF is changed from random homogenous to field dependent structural pattern. The nanoparticles in MF agglomerate and further form chains and magnetic columns along the direction of magnetic field. Consequently, dielectric constant of the MF will increase with the external magnetic field, and so does its refractive index.³

The TFBG has tilted grating planes related to the perpendicular of the fiber axis. It cannot only couple the light from forward propagating core mode to backward propagating core mode as normal FBGs do but also couple the forward propagating core mode to backward propagating cladding modes.^{13,14} What is more, the mode coupling ratio for the later one is dependent on the refractive index of the surrounding material.^{15–17} When surrounding refractive index reaches or exceeds effective refractive index of a cladding mode of the TFBG, this mode is no longer guided and the coupling now occurs with a continuum of radiation modes. Spectrally, this behavior is marked by a smoothing of the cladding mode resonances and reduction of the transmitted optical power.¹⁷ This forms the basic principle of magnetic field sensor because the MF's refractive index changes with external magnetic field strength.

By cascading the CFBG to the TFBG, the MF-modulated optical signal will be reflected and pass through

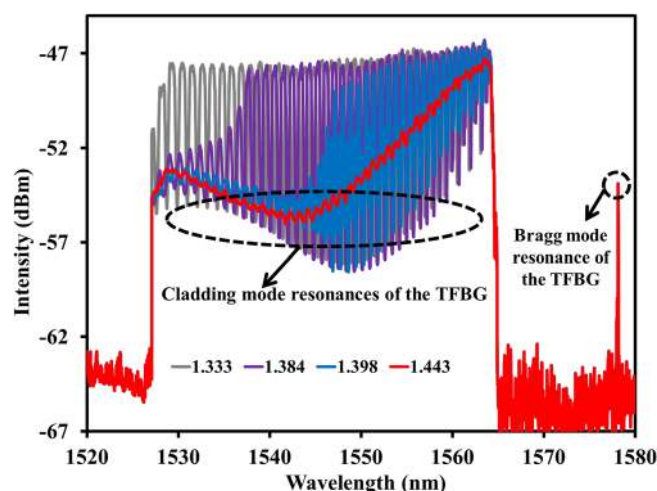


FIG. 2. Reflection spectrum evolution of the CFBG-cascaded TFBG with surrounding refractive index.

the TFBG again that enhances the modulation effect of the MF and hence improves the sensitivity. In addition, the operation mode of the magnetic field sensor is changed from transmission to reflection, which makes the lead-in and lead-out optical fiber the same one, providing obvious convenience in practical measurements.

To testify feasibility of the proposed sensor head, we measured its response to refractive index by using glycerin-water solutions with different concentrations. Figure 2 shows the measured reflection spectra of CFBG-cascaded TFBG to surrounding refractive index. It can be seen that the cladding mode resonances disappear and convert to radiation mode gradually from the high order (or short wavelength) side as expected. When the refractive index is changed from 1.333 to 1.443, all the cladding mode resonances in the reflection band are disappeared and optical power of the reflected signal is decreased significantly.

The experimental setup for magnetic field measurement with the proposed magnetic field sensor is shown in Fig. 3. A variable magnetic field was generated by an electromagnet (EM4-HVA, LakeShore) and calibrated by a gaussmeter (Model 425, LakeShore). The magnet has two poles of 10 cm diameter, and the air gap between the two poles was fixed at 15 cm in the experiment. The TFBG was fixed in a capillary tube filled with MF and placed in the center of the uniform field zone. The transverse Hall probe of the gaussmeter was fixed near the sensor head. The magnetic field was applied perpendicularly to the fiber axis. Light from a broadband light source (BBS) was launched into the sensor through an optical fiber circulator. The reflected light is guided into an optical spectrum analyzer (OSA) or an optical power meter (OPM).

The magnetic field strength was increased from 0 to 160 G. Figure 4 shows the measured reflection spectrum evolution of the CFBG-cascaded TFBG sensor with magnetic field. It is

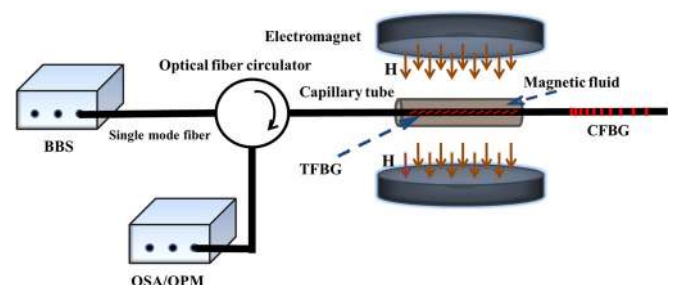


FIG. 3. Experimental setup for magnetic field measurement.

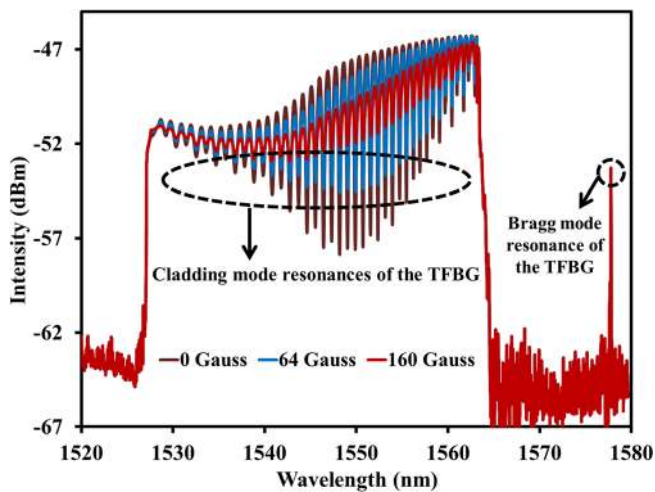


FIG. 4. Reflection spectrum evolution of the sensor with magnetic field strength.

observed that the high-order cladding mode resonances of the TFBG in the short wavelength side are already weakened even when there is no magnetic field applied. That is because of the relatively high initial refractive index of the MF (~ 1.40). With increase of the magnetic field strength, all cladding mode resonances of the TFBG are attenuated gradually with a reduced extinction ratio. The trend agrees well with that of the refractive index measurement result, but the detailed manner of evolution in reflection spectrum with magnetic field is slightly different. There is no clear “cut-off” wavelength observed related to the surrounding refractive index and the low order cladding mode resonances in the long wavelength side are attenuated simultaneously.

The slightly different evolution in spectrum may be attributed to the existence of Fe_3O_4 nanoparticles in the MF. It was reported that absorption and scattering of metal nanoparticles can change transmission spectrum of TFBG by introducing additional losses.^{18,19} The Fe_3O_4 nanoparticles and the magnetic chains/columns formed under magnetic field make the cladding modes of the TFBG lossy through evanescent field.¹² The so-caused loss or attenuation can be described with imaginary part of complex refractive index of the MF. A calculated attenuation up to 17 dB is reported for imaginary part of refractive index of $\sim 2.9 \times 10^{-4}$ for a copper nanoparticle-deposited TFBG.¹⁹

Figure 5 shows the measured reflected optical power against magnetic field strength. It can be seen that the reflected optical power decreases rapidly and linearly with magnetic field strength for low strengths less than 80 G. It decreases less rapidly and nonlinearly for intermediate strengths and tends to saturate at ~ 140 G. The data fit well to quadratic function $y = 0.0007x^2 - 0.2002x + 54.929$ with fitting degree of 0.9965. And in the linear response, range sensitivity of 147 nW/G is achieved.

The sensor performance can be improved by using a light source with higher output power and using MF with better matched refractive index to the TFBG and larger response to magnetic field. However, fluctuation in the power of the light source or change in the transmission loss of the signal may reduce the measurement accuracy. Fortunately, that can be compensated by separately monitoring the power of the

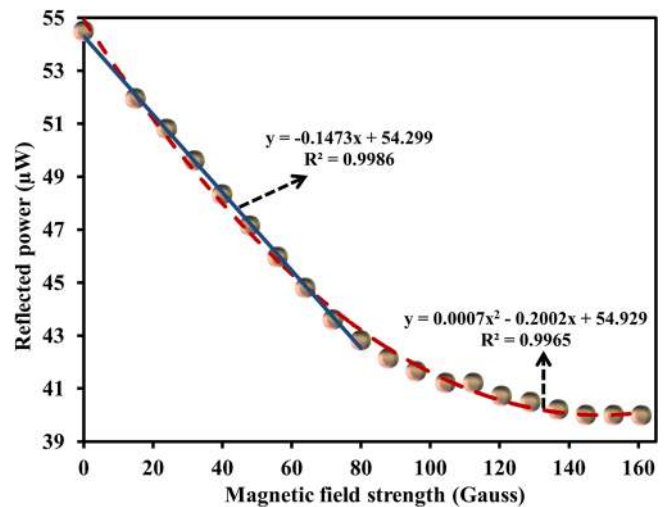


FIG. 5. Measured reflected optical power against magnetic field strength.

Bragg mode reflection, which does not change with the external magnetic field as shown in Fig. 4. The response of the TFBG is known to also depend on polarization state of the input light. Polarized light source should therefore be avoided in the sensing system as the reflected power may change if the polarization state of the input changes due to environmental factors. In our case, this can be neglected because the light source output has nearly no polarization dependence.

Temperature variation may also reduce measurement accuracy by inducing wavelength shift of the TFBG spectrum and by changing refractive index of the MF slightly.^{13,20} One possible situation is that source of the large magnetic field generates heat and changes the temperature. During our measurement, no obvious resonant wavelength shift was found, as shown in Fig. 4, because even the maximum magnetic field strength is not high. Therefore, we believe that the external magnetic field generated heat in a very low level that can be neglected. Even through, if the sensor works under environment of variable temperature, additional temperature compensation would be required because of the temperature-induced change in refractive index of the MF.

In summary, an intensity-modulated magnetic field sensor is reported based on a MF-coated-TFBG cascaded by a well-designed CFBG with its reflection band covers most of the cladding mode resonances region of the TFBG. The reflected optical power is modulated twice by the magnetic field through the MF-coated-TFBG. Intensity-modulated magnetic field measurement in a reflection manner has been realized with sensitivity up to 147 nW/G and measurement range of 140 G. It possesses advantages of robustness, low cost, and ease of fabrication and operation in practical applications.

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