Magnetostrictive composite material-based polarimetric heterodyning fiber-grating laser miniature magnetic field sensor

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A novel fiber-optic magnetic field sensor is demonstrated based on a dual-polarization fiber-grating laser, which is embedded in an epoxy resin-bonded magnetostrictive composite material with doped Terfenol-D particles. A simple structure is designed to convert the magnetic field-induced strain to transversal stress, which is applied to the fiber laser to produce beat note frequency changes for measurement purposes. The response of the proposed sensor is measured, and shows quite a good directivity and linearity with a sensitivity of 10.5 Hz/μT to the magnetic field. It also shows a large measurable range up to about 0.3 T.

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Fiber-optic sensors for magnetic fields have been subject to considerable research efforts for their advantages, which include a large bandwidth, compact size, lightweight, and immunity to electromagnetic interference. Many mechanisms can be used to implement fiber-optic magnetic field sensors, such as those based on the Faraday effect, magnetic force, and so on[1–4], among which magnetostrictive material-based implementations are very popular. However, bulk magnetostrictive materials are normally fragile and show a limited upper working frequency, due to the strong eddy current at high frequencies. For example, monolithic Terfenol-D is a well-known giant magnetostrictive material. It shows high-performance magneto mechanical properties for quasi-static (<10 Hz) and low frequency (<10 kHz) applications, and has found wide applications in sonar and actuator devices since the 1980s. However, for operations above a few kilohertz, eddy-current losses show up and limit its application significantly. Moreover, Terfenol-D is quite brittle, thus rendering it difficult to use in machining and device fabrication. Therefore, to overcome these shortcomings, magnetostrictive composite materials are proposed to improve performance[5–7]. Basically, a magnetostrictive composite material can be fabricated by incorporating Terfenol-D particles into a passive polymer matrix to form magnetostrictive particulate composites[8,9]. The insulating polymer layers between the Terfenol-D particles significantly increase the resistivity of the composite material, and hence reduce the eddy-current losses for high-frequency applications. The polymer-based magnetostrictive composites are also much less brittle due to the improved elastic modulus of the matrix, which makes magnetostrictive composite materials easy for machining and reshaping. Therefore, magnetostrictive composite materials have been attracting much attention and are being used in more and more applications in recent years[10,11].

To implement a fiber-optic magnetic sensor based on magnetostrictive composite materials, the change in the composite materials due to the applied magnetic field should be translated onto a light wave for sensing. Normally, this can be done by implementing an interferometer, such as the popular homodyning schemes in various applications[12–14]. Heterodyning schemes can also be used, such as those schemes based on heterodyning fiber-grating lasers[1,3,15–17], which have demonstrated high sensitivity and a wide dynamic range in many applications. A unique feature of the heterodyning fiber-grating laser is that it produces two lasing modes with orthogonal polarizations that can beat on a photo detector after a polarizer to generate a radio-frequency beat signal that has a frequency equal to the frequency difference between the two lasing modes. The beat signal changes its frequency according to the birefringence variation of the laser cavity[18]. Due to the huge frequency of the light wave, a beat-frequency variation of a megahertz order can result, due to an extremely weak birefringence variation of 10^{-8} in the laser cavity. Therefore, the sensors based on the heterodyning fiber-grating laser can be very sensitive, with a considerable compact package, and permit a much easier and simpler signal extraction by electronic signal processing.

Because the heterodyning fiber-grating laser is sensitive to transversal stress, in this Letter, we demonstrate a novel miniature fiber-optic magnetic field sensor by embedding a heterodyning fiber-grating laser into an epoxy resin-bonded magnetostrictive composite material with Terfenol-D particles incorporated. When a transversal magnetic field is applied, the magnetic field induces a strain in the magnetostrictive composite material. A mechanical structure is designed to convert this strain to transversal stress, which is applied to the embedded heterodyning fiber laser to change the beat note frequency. By discriminating this beat note frequency change, the strength of the applied magnetic field can be measured. The response of the proposed sensor is measured, and shows quite a good directivity, with a sensitivity of 10.5 Hz/μT to the magnetic field and a large measurable range up to about 0.3 T.

A 193 nm excimer laser is employed to inscribe a dual-polarization distributed Bragg reflector (DBR) fiber laser on an Er-doped fiber (Fibercore M-12) with grating lengths of 6.5 and 5.5 mm respectively, and a grating spacing of 5 mm. At 979 nm, the Er-doped fiber exhibits an absorption coefficient of 11.3 dB/m. The laser output of the fiber grating is at 1557.1 nm and is in single-longitude mode with two polarized states in orthogonal polarizations. Due to the birefringence inherent inside the laser cavity, the frequencies of the two orthogonally polarized states are different. Therefore, by photo detecting the laser output, a beat signal occurs. Its frequency $\Delta\nu$ is expressed by

$$\Delta\nu = \frac{c}{n_0\lambda_0}B, \tag{1}$$

where B is the birefringence of the laser cavity, n_0 is the average refractive index, λ_0 is the wavelength of the laser, and c is the light speed in vacuum. The fiber laser generates a beat note at around 847 MHz after photo detection. Paralleled by a dummy fiber, the fiber laser is then attached to the inner bottom of a rectangular glass groove with dimensions of 5 cm × 1 cm × 1 cm and covered by a glass slide with dimensions of 7 mm × 7 mm.

Among the various magnetostrictive materials, Terfenol-D shows the highest magnetostriction. We then prepare the magnetostrictive composite material by mixing the Terfenol-D particles with E44 epoxy resin and 650 polyamide curing agent according to a volume ratio of 1:10:10. The diameters of the Terfenol-D particles are not uniform, but range from 30 to 500 μm. The mixture with the Terfenol-D particles is then poured into a rectangular glass groove with the fabricated DBR fiber laser inside. The mixture is cured in a stationary magnetic field of 200 Gs to align the Terfenol-D particles along the magnetic field. The mixture is cured for 8 h before it is ready for measurement.

Figure 1 shows the fabricated fiber-optic magnetic field sensor, which is in a miniature package that is about 5 cm long. The sensor is then put inside a magnetic field that is generated between two electromagnets for measurements, as shown in Fig. 2. The schematic diagram of the experimental setup is also shown in Fig. 2. The fiber-optic magnetic field sensor is put perpendicular to magnetic field. When a transversal magnetic field was applied to the sensor, the magnetic field induced a strain inside the magnetostrictive composite material, due to the magnetostrictive effect. Because the fiber laser is covered by a glass slide, the strain due to the magnetic field is then converted to a lateral force, which is then applied to the fiber laser. It has been shown that a lateral force results in a linear birefringence change inside the laser cavity, according to Ref. [15]

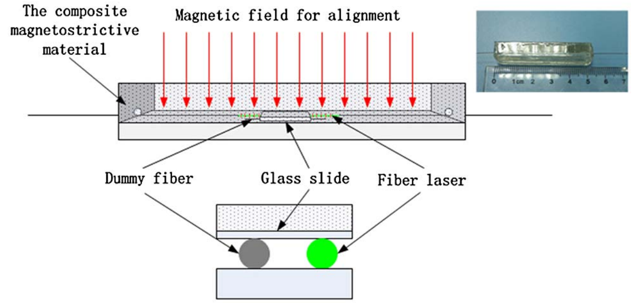

Fig. 1. The fabricated fiber-optic magnetic field sensor created by embedding a heterodyning fiber laser into an epoxy resin-bonded magnetostrictive composite material with Terfenol-D particles incorporated.

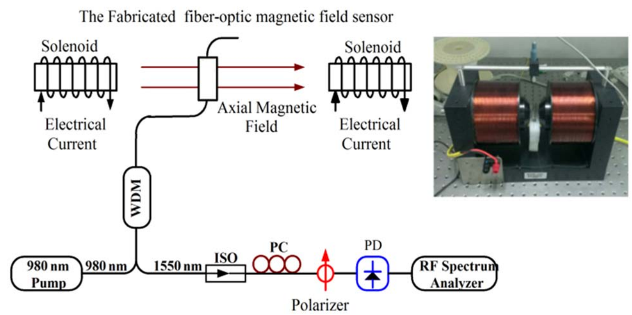

Fig. 2. The experimental setup for the magnetic field measurement. ISO: isolator; WDM: wavelength division multiplexer; PC: polarization controller; PD: photo detector.

$$B_f = \frac{2n_0^3(p_{11}-p_{12})(1+\nu_p)\cos(2\phi)}{\pi r E}f, \tag{2}$$

where f is linear force per unit length, ϕ is the angle between the direction of the applied force and the fast axis, r is the fiber radius, and p_{11} and p_{12} denote the strain-optical tensor components of the silica fiber material with E, the Young's modulus, and ν_p, the Poisson's ratio of the silica fiber. With Eq. (1) and (2), the beat frequency resulting from the applied lateral force is expressed by[15]

$$\Delta\nu_f = \frac{2cn_0^2(p_{11}-p_{12})(1+\nu_p)\cos(2\phi)}{\pi r\lambda_0 E}f. \tag{3}$$

Equation (3) shows that the beat frequency linearly changes with the magnetic field-induced lateral force. Because the magnetostriction is linear with the magnetic field, the magnetic field-induced beat frequency changes with the magnetic field in a linear relationship. Equation (3) also shows that the sensitivity of the sensor to the magnetic field is maximized when the magnetostriction-induced lateral force is applied along one of the fiber polarization axes[3]. Therefore, during the sensor fabrication, we have identified the slow and fast axes of the fiber laser, so as to attach the laser to the rectangular groove along one axis to maximize the sensitivity.

Figure 3 shows the measurement of the frequency shift for a magnetic field of 3600 Gs. The beat note frequency is continuously monitored. Before the magnetic field is applied, the beat note frequency is around 847 MHz. After the magnetic field is applied, the beat note frequency jumps to a higher frequency. A frequency transition of about 3.6 MHz is clearly identified by measuring the beat note frequency change before and after the magnetic field is applied. Therefore, the 3600 Gs magnetic field induces a beat frequency change of about 3.6 MHz.

The response of the heterodyning fiber laser to the magnetic field is then measured. The magnetic field is varied from −3600 to 3600 Gs in a step of 300 Gs. For each value of the magnetic field, the response of the fiber laser is measured as the beat note frequency difference of the fiber laser before and after the magnetic field is applied, as illustrated in Fig. 3. Figure 4 shows the measured beat

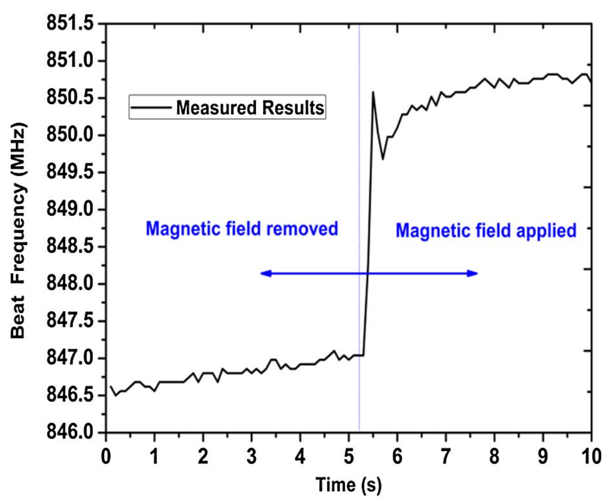

Fig. 3. Measured beat frequency when a 3600 Gs magnetic field is applied to the fabricated fiber-optic magnetic field sensor.

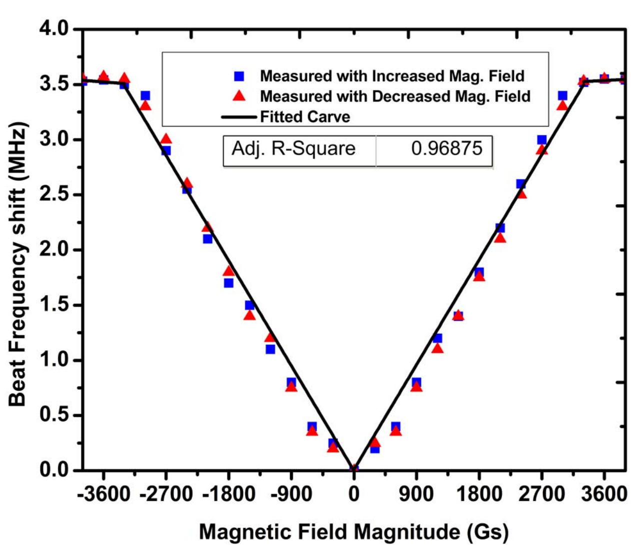

Fig. 4. The measure beat frequency shift of the fiber laser for various applied magnetic field magnitudes. A fitted curve for the measured results is also plotted as the solid line.

frequency shift of the fiber laser for various applied magnetic field magnitudes. A good linearity of the beat frequency response to the magnetic field is observed. The solid curve in the figure is the linear fit of the measured data, which shows a sensitivity of about 10.5 Hz/μT with an adjusted R-squared value of about 0.97. The measurements are taken in two sequences, with one in the increased magnetic field, and the other in the decreased magnetic field. Both measurement sequences produce almost the same results at the same magnetic field magnitude. This finding shows that the magnetic hysteresis of the magnetostrictive composite material is insignificant, and the proposed fiber-optic magnetic field sensor has quite a good repeatability.

Another observation is that the measured beat note frequency tends to be saturated for magnetic field magnitudes greater than 3300 Gs. This is due to the saturation of the magnetostriction in a large magnetic field. Therefore, the proposed fiber-optic magnetic field sensor is able to measure quite a large magnetic field up to 0.3 T.

It should be noted that the magnetostrictive composite material should be enclosed in a container with adequate stiffness. A soft container will expand and contract together with the magnetostrictive composite material, and hence the magnetic field-induced strain will not be able to be applied to the fiber laser effectively, thus lowering the sensitivity and degrading the repeatability. Therefore, a rectangular glass groove is used to hold magnetostrictive composite material in the experiment. The stiffness of the composite material is also important for the sensing performance, which is determined by the ratio between the Terfenol-D particles, the epoxy resin, and the curing agent. Several ratios have been tested, and the ratio used in this paper is the best one for our experiment.

Directivity is also an inherent property of magnetostriction. During the preparation of the magnetostrictive composite material, a stationary magnetic field of 200 Gs is applied to the composite material to align the Terfenol-D particles along the stationary magnetic field. Therefore, if the measured magnetic field is in line with the stationary magnetic field used for the alignment of the Terfenol-D particles, the proposed fiber-optic magnetic field sensor shows the maximum response. Otherwise, the response will be diminished according to the angle between the measured magnetic field and the alignment magnetic field, which can be given as

$$\Delta\nu_{\mathrm{dir}} = \Delta\nu_{\mathrm{max}} \cdot \cos\theta, \tag{4}$$

where $\Delta\nu_{\mathrm{dir}}$ is the beat note frequency change due to the measured magnetic field, $\Delta\nu_{\mathrm{max}}$ is the beat note frequency change if the measured magnetic field is in line with the aligned magnetic field, and θ is the angle between the measured magnetic field and the aligned magnetic field.

During the preparation of the magnetostrictive composite material, the aligned magnetic field is applied perpendicularly to the sensor. For the results shown in Figs. 3 and 4, the measured magnetic fields are also

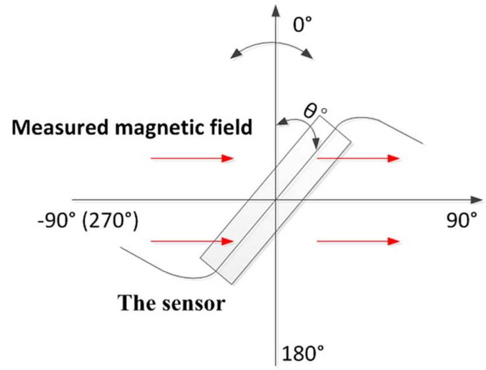

Fig. 5. The setup to measure the directivity of the proposed fiber-optic magnetic field sensor. The direction of the measured magnetic field is fixed, but the direction of the sensor is rotated to different angles.

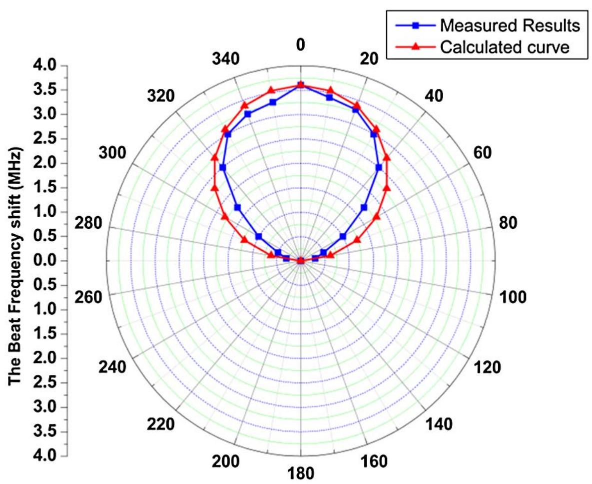

Fig. 6. The beat frequency shift of the fiber laser for various angles between the sensor and magnetic field direction with a 3600 Gs magnetic field applied. A calculated curve is also plotted as the solid line.

perpendicular to the sensor. It is then necessary to measure the directivity of the proposed fiber-optic magnetic field sensor, which can be done by applying the measured magnetic field to the sensor at different angles, as shown in Fig. 5. In the experiments, the direction of the measured magnetic field is fixed, but the sensor is arranged at different angles in the magnetic field, as shown in Fig. 5. The angle of 0° denotes that the measured magnetic field is in line with the aligned magnetic field.

The angle is varied from −90° to 90° in a step of 10°. Figure 6 shows the measured and the calculated results according to Eq. (4) for a measured magnetic field of 3600 Gs. The measured results match well with the calculated results, and the directivity of the proposed fiber-optic magnetic field sensor is clearly observed with the maximum response at the direction of the aligned magnetic field.

In conclusion, we demonstrate a novel fiber-optic magnetic field sensor by embedding a heterodyning fiber-grating laser into an epoxy resin-bonded magnetostrictive composite material with Terfenol-D particles incorporated. Within a miniature package with dimensions of 5 cm × 1 cm × 1 cm, the fiber-optic sensor demonstrates a good linearity with a sensitivity of about 10.5 Hz/μT and a maximum measurable magnetic field of about 0.3 T. The sensor also shows good directivity with the maximum response in the direction of the aligned magnetic field.

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