

Ampere force based magnetic field sensor using dual-polarization fiber laser

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Abstract: A magnetic field sensor is proposed by placing a dual-polarization fiber grating laser under a copper wire. With a perpendicular magnetic field applied, an electrical current flowing through the copper wire can generate Ampere force to squeeze the fiber grating laser, resulting in the birefringence change inside the laser cavity and hence the change of the beat note frequency. When an alternating current is injected into the copper wire, the magnetic field induced beat note frequency change can be discriminated from environment disturbances. A novel fiber-optic magnetic field sensor is therefore demonstrated with high sensitivity and inherent immunity to disturbances.

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1. Introduction

Fiber-optic magnetic field sensors have been actively studied over years because of the advantages over their electronic counterparts in immunity to electromagnetic interference, light weight, compact size and large bandwidth. Many mechanisms have been explored,

including Faraday effect, magnetostrictive effect, magnetic force, Lorentzian force, etc [1–4]. Among them, Faraday effect based schemes can measure magnetic fields directly. However, because the Verdet constant of silica fibers is quite small [5], their sensitivities are fairly low. Therefore, magneto-optic crystals are frequently employed to enhance the sensitivity [6]. Schemes based on other mechanisms normally measure magnetic fields indirectly and need external transducers which usually enhance their sensitivities. However, such external transducers may also result in some disadvantages. For example, magnetic materials, such as magnets and magnetostrictive materials are quite popular in various indirect magnetic field sensing schemes [2, 3, 7]. However, the inherent magnetic saturation and hysteresis of magnetic materials may greatly reduce the dynamic range and cause inaccurate measurement.

Various configurations of fiber-optic magnetic field sensors have been proposed, such as those based on optical fibers with interferometric detection [8, 9] and fiber Bragg gratings with wavelength interrogation [10, 11]. Dual-polarization fiber grating laser based sensors have been attracting many attentions these years [12, 13]. The two orthogonally polarized lasing modes generate a radio-frequency (RF) beat signal after a polarizer. The frequency of the beat signal changes according to the variation of the birefringence inside the laser cavity. An extremely weak cavity birefringence change of 10^{-8} can result in a beat-frequency variation of megahertz order. Therefore, dual-polarization fiber grating laser based sensors exhibit high sensitivities and much easier and simpler signal extraction by electronic signal-processing.

Immunity to environment disturbances is always a big concern for fiber-optic sensors because the refractive index of silica fiber can be easily changed by temperature variation, bending and other environment disturbances which interfere with the measurands and make the measurements unreliable. Normally, some passive methods, such as disturbance insensitive packages, external references and compensations [14], have to be adopted to protect the measurands from disturbances. However, such passive methods are not sufficient as their reliability in long-term is very likely problematic. Methods with inherent immunity to environment disturbances are highly desired.

In this paper, we propose a novel magnetic field sensor based on dual-polarization fiber grating lasers and magnetic field induced Ampere force. The Ampere force is generated by an electric current in a perpendicular magnetic field, which presses the dual-polarization fiber grating laser to shift the beat signal frequency. We demonstrate when an alternating electric current is employed, the proposed scheme can discriminate the magnetic field from environment disturbance very well, showing an inherent ability of anti-disturbance.

2. Principle

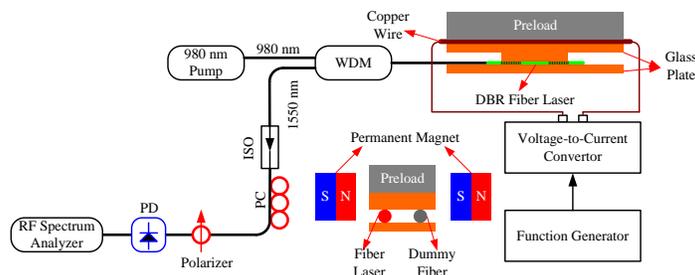


Fig. 1. Schematic and experiment setup for magnetic field sensor based on a dual-polarization fiber grating laser and magnetic field induced Ampere force. ISO: Isolator; WDM: Wavelength division multiplexer; PC: Polarization controller. PD: Photodetector.

The schematic diagram of the proposed magnetic field sensor is shown in Fig. 1. A dual-polarization fiber grating laser is placed under a copper wire to sense the Ampere force generated by the electric current flowing through the copper wire. The fiber grating laser operates in single longitude mode with two orthogonally polarized states. The inherent

birefringence inside the laser cavity results in a frequency difference between the two orthogonally polarized states, which generates a beat signal by photodetecting the laser output with the beat frequency $\Delta\nu$ given by

$$\Delta\nu = \frac{c}{n_0\lambda_0} B \quad (1)$$

where c is the light speed in vacuum, λ_0 is the laser wavelength, n_0 and B are the average refractive index and the birefringence of the optical fiber, respectively. With a transversal force applied to the laser cavity, a linear birefringence is induced and expressed by [15]

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

where p_{11} and p_{12} are the components of strain-optical tensor of the fiber material, ν_p is Poisson's ratio, f denotes linear force per unit length, r is the fiber radius, θ is the angle of the applied force with respect to the fast axis and E is the Young's modulus of the silica fiber. Therefore, with Eq. (1), the beat frequency change due to the applied lateral force is given by

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

which suggests a linear relationship between the beat frequency change and the lateral force.

It is well known that an electrical current in a perpendicular magnetic field generates a lateral force F_H named Ampere force as expressed by

$$F_H = H \cdot I \cdot L_H \quad (4)$$

where H is the magnetic field, I is the electric current and L_H is the length of the electric current experiencing the magnetic field. If all the force is applied onto the laser cavity, the Ampere force per unit length is

$$f_H = H \cdot I \cdot L_H / L_C \quad (5)$$

where L_C is the laser cavity length. With Eq. (3) and (5), the perpendicular magnetic field induced beat frequency change can be presented as

$$\Delta\nu_H = \frac{2cn_0^2(p_{11} - p_{12})(1 + \nu_p)\cos(2\theta)}{\pi r \lambda_0 E} \cdot \frac{L_H}{L_C} \cdot H \cdot I \quad (6)$$

It then shows that the magnetic field induced beat frequency is linearly related to the magnetic field and the electric current with the sensitivity maximized when the Ampere force is applied along one of the fiber polarization axes.

Environment disturbances can also induce linear birefringence into the laser cavity. Normally, these environment disturbances manifest as some low frequency perturbations. If the electric current is a direct current, the magnetic field induces a stationary birefringence which is difficult to be discriminated from the birefringence by disturbances. However, the proposed scheme permits injecting an alternating electric current into the copper wire. If a sinusoid alternating current with a frequency of ω_{ac} and amplitude of A is injected, the beat frequency is then given by

$$\Delta\nu = \frac{c}{n_0\lambda_0}(B_I + B_D) + \frac{2cn_0^2(p_{11} - p_{12})(1 + \nu_p)\cos(2\theta)}{\pi r\lambda_0 E} \cdot \frac{L_H}{L_C} \cdot H \cdot A \cdot \cos(\omega_{ac}t) \quad (7)$$

where B_I is the inherent birefringence of the fiber and B_D is the disturbances induced birefringence. The magnetic field induce frequency change is then moved to a band centered at ω_{ac} . The frequency change due to environment disturbances remains in low frequency band as the disturbances are magnetic field and electric current independent. Therefore, the disturbances can be greatly suppressed by bandpass filtering, providing a quiet detection of the magnetic field. The proposed scheme hence shows an inherent capability to combat environment disturbances.

3. Experiment and Results

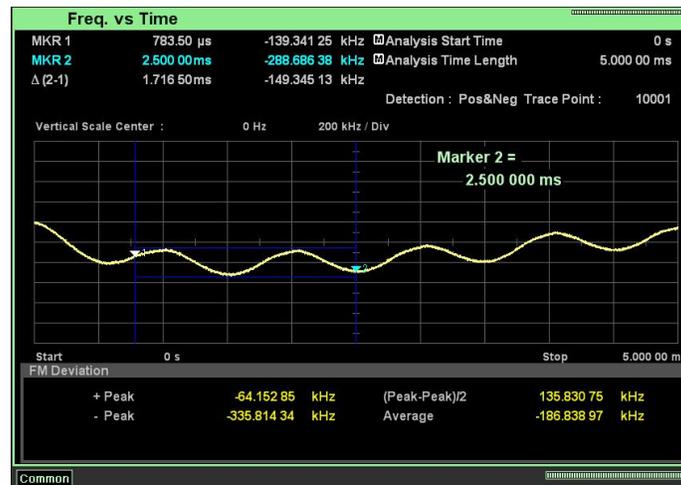


Fig. 2. The measured waveform for the beat signal frequency variation versus time with an alternating current of 160 mA amplitude at 1 kHz and a magnetic field strength of 197 G.

The experiment setup is shown in Fig. 1. The proposed fiber-optic magnetic field sensor was put in a perpendicular magnetic field generated by two permanent magnets with their spacing varied to tune the magnetic field magnitude. The fiber grating laser was a dual-polarization distributed Bragg reflector (DBR) fiber laser inscribed on an Er-doped fiber (Fibercore M-12) with grating lengths of 7.5 mm and 5.5 mm, respectively, and a grating spacing of 6 mm. The absorption coefficient is 11.3 dB/m at 979 nm. The Ampere force was generated by an alternating electric current in a copper wire and controlled by a function generator through a voltage-to-current convertor. The copper wire was glued to a big glass plate of 760 × 250 mm. To ensure the Ampere force was completely exerted onto the fiber grating laser, the big glass plate was also glued to another small glass plate of 180 × 250 mm placed on the fiber grating laser and a dummy fiber arranged parallel to the laser. The fiber grating laser was supported by another glass plate and positioned with the fiber polarization axis aligned to the force direction to maximize the response sensitivity. The output of the fiber grating laser was photodetected after a polarizer to generate an RF signal for monitoring by an RF spectrum analyzer. To ensure the fiber grating laser was firmly squeezed by the glass plates, a preload of 200 g was placed on the big glass plate, which also provided a bias force to shift the original beat frequency of about 390 MHz to about 630 MHz. The measured waveform for the beat signal frequency variation versus time is shown in Fig. 2. The magnetic field magnitude is 197 G and the electrical current injecting into the copper wire was alternating at 1 kHz with amplitude of 160 mA. A 1 kHz sinusoid waveform is clearly observed, showing that the beat frequency of the fiber grating laser was varying at 1 kHz due to the Ampere

force applied by the alternating current. It is also observed that the average beat frequency was slowly drifting due to environment disturbances, such as vibration and air flow [16]. However, the amplitude and the frequency of the beat frequency variation do not change with these environment disturbances. By detecting the amplitude at 1 kHz, the Ampere force and hence the magnetic field can be measured and the environment disturbances can be significantly suppressed, which can be effectively achieved, for example, by correlating the beat frequency variation with the alternating current signal driving the copper wire.

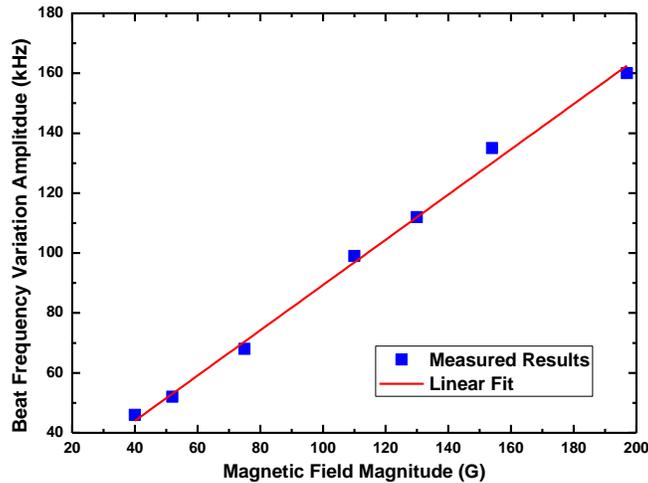


Fig. 3. The beat frequency variation amplitude for various magnetic field magnitude. The current was alternating at 1 kHz with amplitude of 240 mA.

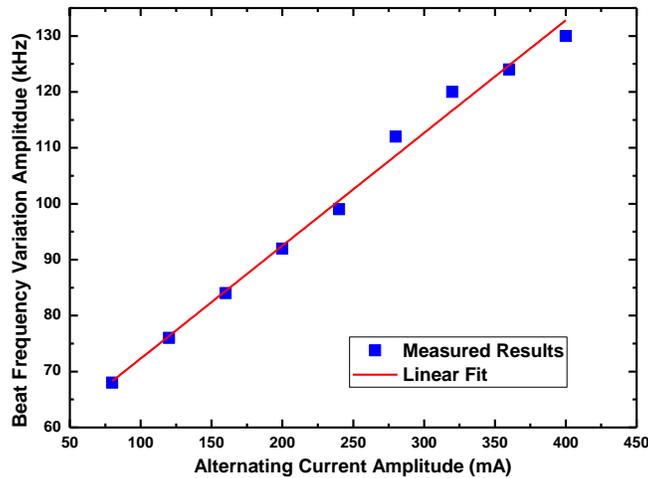


Fig. 4. The beat frequency variation amplitude at 1 kHz for various alternating current amplitude and a magnetic field magnitude of 110 G.

Figure 3 shows the measured beat frequency variation amplitude at 1 kHz for different magnetic field magnitude with alternating current amplitude of 240 mA. Figure 4 shows the measured beat frequency variation amplitude at a magnetic field magnitude of 110 G for various amplitude of alternating current at 1 kHz. The results confirm that the beat frequency variation amplitude is linearly related to the magnetic field magnitude and the alternating current amplitude as already shown by Eq. (7). Moreover, the results suggest that the

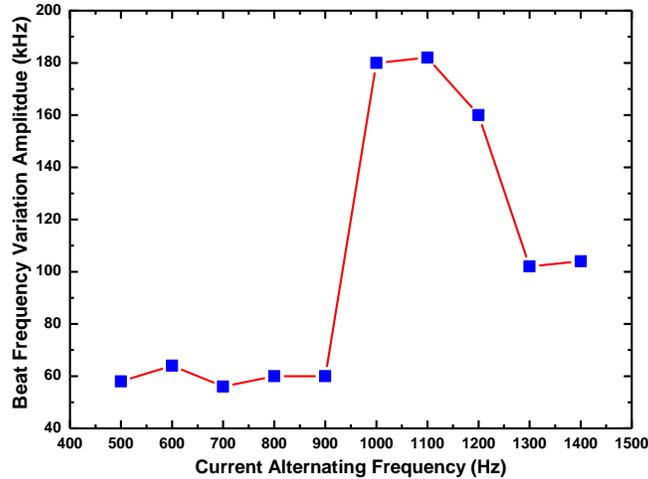


Fig. 5. The measured beat frequency variation amplitude at various current alternating frequency. The amplitude of the alternating current is 320 mA and the magnetic field magnitude is 197 G.

sensitivity of the proposed sensor can be easily tuned by varying the alternating current amplitude, which will be enhanced at larger alternating current amplitude provided the power dissipation is tolerable.

As the proposed sensor translates a magnetic field to Ampere force, the mechanical structure has great impact on the response of the sensor. For the structure employed in the experiments, the measured response in a 197 G magnetic field for alternating current of 320 mA amplitude at different frequencies is shown in Fig. 5. The structure appears more sensitive at frequency between 1 kHz and 1.3 kHz which should be a resonance peak of the structure. Normally, environment disturbances seldom appear in such high frequency band. Therefore, it is possible to greatly improve the sensitivity by a proper mechanical structure deliberately designed to maximize its response in a particular frequency band at which the alternating current is operating and very few environment disturbances are present. Moreover, a bandpass filter with extremely narrow passband can be implemented by correlating the detected frequency variation with the driving signal of the alternating current to significantly suppress noises. A performance much better than those of wavelength discrimination based schemes is therefore very promising. A minimal detectable magnetic field of much less than 1 G should be very likely with a proper design of the electronic signal processing, which makes the proposed sensor potentially suitable for applications needing weak magnetic field detection, such as navigation, spatial and geophysical research.

4. Conclusion

A novel fiber-optic magnetic field sensor is proposed and demonstrated based on magnetic field induced Ampere force and dual-polarization fiber grating laser. The magnetic field induced Ampere force is generated by an alternating current inside a copper wire and is applied to the dual-polarization fiber grating laser to change its beat frequency for magnetic field measurement. The proposed sensor shows an inherent capability to combat environment disturbances by performing the measurement in a quiet high frequency band. The experiment results validate the theoretical analysis and demonstrate a novel fiber-optic magnetic field sensor with high sensitivity and good performance.

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