Sensitivity enhancement of Faraday effect based heterodyning fiber laser magnetic field sensor by lowering linear birefringence

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Abstract: In this paper, we demonstrate that the sensitivity of Faraday effect based heterodyning fiber laser sensors for magnetic field can be effectively enhanced by lowering the intrinsic linear birefringence inside the fiber laser cavity. Well explained by theoretical analysis and confirmed by birefringence tuning through transversal force, it shows that the sensitivity to magnetic field intensity is inversely proportional to the linear birefringence. A CO2-laser treatment is therefore proposed to tune the intra-cavity linear birefringence. With CO2-laser treatment, the intra-cavity linear birefringence can be lowered permanently to effectively enhance the sensitivity of a heterodyning fiber laser sensor to magnetic field.

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1. Introduction

Fiber-optic magnetic field sensors are more attractive than their electronic counterparts in immunity to electromagnetic interference, light weight, compact size and large bandwidth and therefore have been actively explored over years [1–4]. Although many mechanisms can be employed to implement fiber-optic magnetic field sensors, such as magnetostrictive effect, magnetic force, Lorentzian force, etc, Faraday effect based schemes are frequently preferred for many applications as they measure magnetic fields directly without external transducers. However, because the Verdet constant of silica fibers is quite small [5], their sensitivities are generally fairly low. Therefore, very long sensing fiber or magneto-optic crystals have to be employed usually to enhance the sensitivities [6], which results in some disadvantages such as unreliability due to environment disturbances.

Dual-polarization fiber grating laser based sensors have been attracting many attentions these years [7–9]. Recently, we have proposed a novel miniature fiber-optic magnetic field sensor based on a dual-polarization fiber grating laser less than 20 mm [1]. The dual-polarization fiber grating laser produces two orthogonally polarized lasing modes to generate a radio-frequency (RF) beat signal after a polarizer with the beat frequency proportional to the intra-cavity birefringence. A magnetic field parallel to the laser can induce a circular birefringence into the laser cavity through Faraday effect, which combines with the intra-cavity intrinsic linear birefringence to form an elliptical birefringence. The magnetic field can therefore be sensed through measuring the beat frequency resulted by the elliptical birefringence. A distinct advantage of the sensor is that the sensitivity is irrelevant to fiber laser length, which then permits miniaturizing the size of fiber-optic magnetic field sensors by use of short-cavity fiber lasers. However, the sensitivity of the proposed prototype is still fairly low for practical applications, which therefore need to be enhanced further.

In this paper, we demonstrate that the sensitivity of a Faraday effect based heterodyning fiber laser magnetic field sensor can be effectively enhance by lowering the intra-cavity intrinsic linear birefringence. A theoretical explanation is given, which is verified by experiments. CO₂-laser heat treatment of fiber laser is also experimentally demonstrated as a practical technique to lower the birefringence and enhance the sensitivity.

2. Principle

It has been shown that the beat frequency generated by the two orthogonally polarized laser outputs of a dual-polarization fiber grating laser is given by [7]

\[ \Delta v = \frac{c}{n_0 \lambda_0} B \]  

(1)

where \( c \) is the light speed in vacuum, \( \lambda_0 \) is the laser wavelength, \( n_0 \) and \( B \) are the average refractive index and the birefringence of the optical fiber, respectively. Normally an intrinsic linear birefringence \( \beta \) (rad/m) is presented in a fiber laser cavity, resulting in two eigenpolarization modes of linear polarization. When a magnetic field parallel to the fiber laser cavity is applied, a uniform circular birefringence \( \alpha \) (rad/m) is induced into the cavity through Faraday effect. The resultant birefringence of the combination of the linear and the circular birefringence is an elliptical birefringence \( \Omega \) (rad/m) with its magnitude given by [10]

\[ \Omega = \sqrt{\alpha^2 + \beta^2} \]  

(2)

The circular birefringence induced by a magnetic field is written as [11]

\[ \alpha = 2VH \]  

(3)

where \( H \) is the magnetic field and \( V \) is the Verdet constant. When \( \alpha \ll \beta \), the beat frequency is then simply related to the magnetic field by
\[ \Delta v = \frac{c}{2\pi n_0} \beta + \frac{c}{\pi n_0 \beta} (VH)^2 \]  

(4)

Therefore, when the circular birefringence is far less than the intra-cavity intrinsic linear birefringence, the beat frequency is simply increased from its intrinsic beat frequency by an amount proportional to the intensity of the magnetic field. It also shows that the beat frequency increment due to the magnetic field is inversely proportional to the intra-cavity intrinsic linear birefringence. Therefore, a lower intra-cavity intrinsic linear birefringence can result in a higher sensitivity to magnetic field.

The most straightforward method to lower linear birefringence may be to apply a transversal force to the laser cavity although the induced birefringence is not permanent and an external transducer is required. Permanent birefringence modification can also be induced by ultraviolet post-processing [12]. However, the capability of birefringence tuning in this way is somewhat limited. Heat treatment by use of a CO₂-laser is a more powerful method to permanently change birefringence because the CO₂-laser irradiation can induce a significant refractive index change and/or deformation of fiber geometry in silica fibers. With CO₂-laser treatment, large birefringence tuning could be realized and has been demonstrated to enhance the capability of multiplexing for heterodyning fiber laser sensors [13].

3. Linear birefringence tuning

Dual-polarization fiber grating lasers were fabricated by inscribing pairs of wavelength-matched Bragg gratings in an Er-doped fiber (Fibercore, M-12) by use of a 193 nm excimer laser and phase masks with grating lengths of 7.5 and 5.5 mm, respectively, and a grating spacing of 6 mm. The absorption of the Er-doped fiber is 11.3 dB/m at 979 nm.

To continuously tune the linear birefringence, a setup as shown in Fig. 1(a) was employed to tune the linear birefringence by transversal force. The fiber grating laser for test was supported by a glass plate and positioned with the fiber polarization axis aligned to the force direction. A dummy fiber was placed near and parallel to the fiber grating laser. Another glass plate was then placed on the dummy fiber and the fiber grating laser to support a load. Different weights of load resulted in different levels of transversal force to tune the intra-cavity intrinsic linear birefringence, which manifested as different beat frequencies of the fiber grating laser at its free state of no magnetic field.

To permanently change the intra-cavity birefringence, heat treatment of the fiber grating laser by use of a CO₂-laser was introduced. Figure 1(b) shows the experiment setup. The CO₂-laser emitted pulses at a repetition rate of 3 kHz with the laser beam focused to a spot of about 100 \( \mu \)m in diameter by a ZnSe lens. The fiber grating laser cavity was fixed at the focal plane before the CO₂-laser treatment. The CO₂-laser beam transversely scanned across the fiber (along y axis) by a computer-controlled galvanometric mirror with a longitudinal step (along z axis) of 40 \( \mu \)m. As a result, a continuous index modification can be formed between the two Bragg gratings since the moving step was much smaller than the diameter of the laser spot. The length of the laser-irradiated region was 4 mm. The output energy and the scanning...
speed were 5 W and 150 mm/s, respectively. The scanning speed was quite high to avoid geometrical deformation of the treated fiber laser. The CO2-laser treatment process can be repeated for a number of cycles to induce required beat-frequency shift.

During the CO2-laser scanning process, the silica fiber absorbed the 10.6 μm light and released a great deal of heat. The silica fiber softened and then rapidly cooled down to room temperature [14]. As a result, the volume of the material expanded and its refractive index decreased. The induced index decrease has been characterized by measuring the change in phase difference by composing a Fabry-Perot interferometer [15]. Note that the index modification is non-uniform over the fiber cross section due to the laser side irradiation, which has been verified by observing the near-field profile of the coupled LP1n modes at the resonance wavelengths for long period gratings fabricated by CO2-laser side irradiation [16, 17]. Generally speaking, the part facing the incident direction of the CO2-laser experiences a larger index reduction. The index gradient can be enhanced by repeating the scanning cycles and optimizing the irradiation parameters, e.g., the scanning speed and the laser output energy. Therefore, due to the induced non-uniform index distribution, an additional birefringence can be introduced into the fiber laser cavity to make the output beat frequency tuning possible. The operation to tune the beat frequency by CO2-laser treatment has been detailed in [13]. Basically, the beat frequency can be tune to higher or lower frequencies depending on the CO2-laser irradiation direction and dosage.

4. Experiment results

![Experiment setup for magnetic field sensing by a dual-polarization fiber grating laser through Faraday effect. ISO: Isolator; WDM: Wavelength division multiplexer; PC: Polarization controller. PD: Photodetector.](image)

The experiment setup for magnetic field sensing is shown in Fig. 2. A magnetic field was generated by the electric current injecting into two solenoids. A dual-polarization fiber grating laser was placed in the magnetic field with the laser cavity parallel to the magnetic field. A conventional magnetic field meter was placed near the dual-polarization fiber grating laser to measure the magnitude of the magnetic field applied to the fiber grating laser. The fiber grating laser operates in single-longitudinal mode with two orthogonally polarized laser outputs according to the intra-cavity birefringence. The two orthogonally polarized outputs mixed on a photodetector to generate an RF beat note with its frequency equal to the frequency difference between the two laser outputs, which was then monitored by an RF spectrum analyzer. The method to measure the beat frequency shift due to magnetic field has been shown in [1]. Basically, the beat frequency was continuously monitored. A magnetic field was applied to the laser cavity at the beginning of the measurement. After a while, the magnetic field was removed and the fiber laser restored to its free state, resulting in an abrupt beat frequency transition. According to the theoretical analysis, the magnetic field induced beat frequency can then be measured by subtracting the beat frequency with the magnetic field applied by the beat frequency without the magnetic field.
The intra-cavity intrinsic linear birefringence was tuned by applying a transversal force to a dual-polarization fiber grating laser lasing at 1529.79 nm at first. Without magnetic field and load, the beat frequency is around 395 MHz. The magnetic field induced frequency shifts for various beat frequencies of free state were then measured for a magnetic field of 4500 G, which is shown in Fig. 3. About 20 times sensitivity enhancement has been achieved by tuning the beat frequency of free state from 395 MHz to 19 MHz. A curve of theoretical calculations according to inverse proportion is also plotted with Verdet constant of 0.5 rad/T/m obtained by the measurement at 395 MHz. An inverse proportion relation of the magnetic field induced frequency shifts to the beat frequencies of free state is clearly identified, which confirms the theoretical analysis and indicate that the sensitivity to magnetic field can be enhanced by lowering the intra-cavity intrinsic linear birefringence. In the limit of the linear birefringence tuned to 0, the beat frequency will be linearly dependent on the magnetic field [1], reaching a maximum sensitivity of 3.25 kHz/G in theory for the fiber laser.
used in this experiment. Although the linear birefringence is critical to the sensitivity, the disturbances to the linear birefringence, such as those caused by temperature variations, should not impose significant impact on the sensitivity because the disturbances are normally much smaller than the linear birefringence, making the inverse proportional coefficient determined mainly by the linear birefringence.

Another dual-polarization fiber grating laser lasing at 1551.4 nm was then processed by CO2-laser treatment for demonstration. The beat note is at around 396 MHz, which is shown as the solid curve in Fig. 4. The other curves in Fig. 4 illustrate the resulted spectrum of the beat notes after CO2-laser treatment of the fiber grating laser which was tune to a higher beat frequency at around 625 MHz and two lower frequencies at around 237 MHz and around 51 MHz, respectively. The sensitivities of the dual-polarization fiber grating laser to magnetic field after tuning to those beat frequencies were then measured in a magnetic field of 4500 G and shown in Fig. 3. A theoretical curve of inverse proportion is also plotted with Verdet constant of 0.56 rad/T/m obtained by the measurement at 396 MHz, which matches the experiment results very well. Another observation is that the CO2-laser treatment does not change Verdet constant since all measurements follow the inverse proportion exactly. Therefore, the CO2-laser treatment exhibits the same effect as transversal force to modify the linear birefringence of the fiber grating laser, which effectively tunes the sensitivity according to an inverse proportion relation. Moreover, this modification is permanent.

The beat frequency change along with a magnetic field from 0 to 4500 G in a step of 500 G was then measured and shown in Fig. 5. The solid squares and triangles are for beat frequencies obtained by tuning through transversal force and CO2-laser treatment, respectively, which match the calculated curves by Eq. (4) quite well, confirming the validity of the theoretical model. The measured results are slightly smaller than theoretical calculations for the beat frequency of 19 MHz and magnetic field greater than 3500 G because the beat frequency shift is comparable to the beat frequency of free state, resulting in a fairly large overestimation due to the approximation used by Eq. (4). Therefore, for larger magnetic field induced beat frequency, Eq. (2) should be used to give more accurate theoretical results [1].

5. Conclusion

In this paper, we propose to enhance the sensitivity of Faraday effect and dual-polarization fiber grating laser based fiber-optic magnetic field sensors by lowering the intra-cavity intrinsic linear birefringence, which is demonstrated and confirmed by tuning the linear
birefringence through transversal force. Heat treatment of the fiber laser cavity by CO₂-laser irradiation is also proposed to permanently modify the linear birefringence and tune the sensitivity. The theoretical principle for this proposal is presented and confirmed by experiment results. The proposed technique makes this novel fiber-optic magnetic field sensor promising for practical applications.

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