Polarization- and frequency-stable fiber laser for magnetic-field sensing

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Received January 26, 1996

We report a novel polarimetric fiber laser sensor for magnetic-field–current measurement that is stable to variation of temperature and strain because it employs a Faraday rotating mirror. We obtained a sensitivity of 10.24 kHz/A with good linearity and greatly improved the signal-to-noise ratio by reducing the number of laser cavity modes with the help of a saturable absorber.

Over the past few years a number of polarimetric fiber laser sensors were demonstrated that used a simple electronic signal-processing scheme for frequency readout.[1–5] In those fiber laser sensors, external perturbations such as lateral stress,[1] temperature change,[2] strain,[2,3] twist,[4] and magnetic field[5] affect the fiber birefringence in the laser cavity and result in a shift in the beat frequency between the two polarization eigenmodes. The change in the polarization mode beat (PMB) frequency is proportional to the magnitude of the external perturbations. One of the main problems with polarimetric fiber laser sensors has been the instability of the PMB signal because of the large number of oscillating laser modes. Another difficulty is the control of the output eigenpolarization state when one cannot use a polarization-maintaining fiber cavity,[2] as in the case of a current sensor based on the Faraday effect.[5] Moreover, the current sensor requires the state of polarization (SOP) of light in the sensing region to be circularly polarized for the best sensitivity and stability.

In this Letter we propose and demonstrate a novel fiber laser sensor that is free from the above-mentioned problems because it uses a Faraday rotating mirror (FRM) and a saturable absorber. In this laser the PMB frequency change is sensitive to the applied magnetic field but is insensitive to other reciprocal perturbations in the laser cavity, leading to stable operation. An additional advantage is that two eigenpolarization components lase with almost the same intensity, even in the presence of a small polarization-dependent loss in the laser cavity. The use of a saturable absorber in the cavity reduces the number of laser modes to one or two for each polarization eigenmode, resulting in a great improvement in signal-to-noise ratio and stability.

Let us describe the polarization characteristics of a fiber laser formed with a FRM, an output planar mirror, and an amplifying fiber, as shown in Fig. 1. The FRM consists of a 45° Faraday rotator followed by a planar mirror,[6] and the SOP of the reflected wave is always orthogonal to that of the incoming wave, i.e., the principal axes of the SOP are rotated by $\pi/2$, and the circularity of the polarization is unchanged in a laboratory-coordinate frame.[6] On the other hand, the conventional planar mirror does not rotate the principal axes of the SOP but retains the circularity of the polarization as in the case of a FRM. As was described earlier,[1] the light in the laser cavity should satisfy the resonance condition such that the optical wave has to resume the same phase and SOP after a complete round trip. This requirement determines the eigenpolarizations of the laser output. It has been shown that a fiber laser with a conventional Fabry–Perot cavity has linear eigenpolarizations at the mirrors.[1] For the laser shown in Fig. 1, however, one can infer that the eigenpolarizations at the output mirror are circular to satisfy the resonance condition, regardless of the fiber birefringence. This new finding can be derived mathematically by the Jones matrix formalism.

In the laboratory-coordinate system the output mirror is represented by an identity matrix. The Jones matrix for the FRM, J_{FRM}, is

$$J_{\mathrm{FRM}} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \qquad (1)$$

where the common optical phase term is omitted. The Jones matrix that describes the evolution of the SOP of light traveling along the fiber in one direction is, in general, a unitary matrix, J_f. For light traveling in the opposite direction the Jones matrix becomes the transpose of J_f or ${J_f}^T$, if there is no nonreciprocal element.[1] For light that makes a complete round trip starting from the output mirror the Jones matrix that describes the propagation of light becomes

$$J_f J_{\mathrm{FRM}} {J_f}^T = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \qquad (2)$$

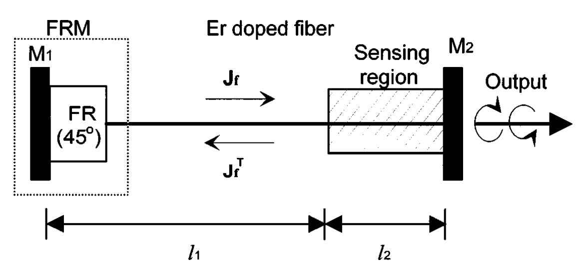

Fig. 1. Schematic of the fiber laser cavity with a Faraday rotating mirror. M1, M2, planar mirrors; FR, Faraday rotator.

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which is independent of the fiber birefringence. The eigenvectors of this matrix, $1/\sqrt{2}\ (1, i)$ and $1/\sqrt{2}\ (1, -i)$, represent two mutually orthogonal circular eigenpolarizations. The two eigenvalues are related to the optical frequencies for the two eigenpolarizations, and it can be shown that the PMB frequencies are odd harmonics of half of the longitudinal mode spacing. The PMB frequencies are independent of the fiber birefringence because the SOP's of an eigenpolarization mode traveling in each direction are mutually orthogonal, resulting in the compensation of the reciprocal fiber birefringence.

When a section of the fiber in the laser cavity is exposed to an axial magnetic field, a nonreciprocal circular birefringence is induced in the fiber section. If the SOP's of the eigenpolarizations are circular in the sensing region, they experience the maximum differential phase shift owing to the Faraday effect, leading to the maximum PMB frequency change. On the other hand, if the eigenpolarizations are linear in the region, the PMB frequency does not change. Therefore we ensure the maximum sensitivity by placing the sensing part near the output mirror where the eigenpolarizations are always circular.

For simplicity of calculation let us assume that the fiber has a uniform intrinsic linear birefringence β (in radians per meter) and that the fiber lengths of the sensing region and the rest of the cavity are l_2 and l_1, respectively. Then the Jones matrix J_1 for the fiber of length l_1 is

$$J_1 = \begin{bmatrix} \exp(i\delta_1/2) & 0 \\ 0 & \exp(-i\delta_1/2) \end{bmatrix}. \qquad (3)$$

Here the x and y axes are along the principal birefringence axes of the fiber, and $\delta_1 = \beta l_1$ denotes the differential phase delay in the region. In the sensing region the circular birefringence $\alpha_H = 2VH$ is induced by the magnetic field,[7] where $V = 7.7 \times 10^{-7}$ (rad/m) is the Verdet constant of fused silica at 1.53-μm wavelength[8] and H is the magnetic field. The resultant elliptical birefringence for the sensing part can be expressed by Jones matrix J_2:

$$J_2 = \begin{bmatrix} \cos(\delta_2/2) + i\cos 2B \sin(\delta_2/2) & \sin 2B \sin(\delta_2/2) \\ -\sin 2B \sin(\delta_2/2) & \cos \delta_2/2 - i \cos 2B \sin(\delta_2/2) \end{bmatrix}, \qquad (4)$$

where $B = (1/2)\arctan(\alpha_H/\beta)$ and $\delta_2 = (\beta^2 + {\alpha_H}^2)^{1/2} l_2$. For the light that makes a complete round trip in the laser cavity starting from the output mirror in Fig. 1, the Jones matrix becomes $J_2 J_1 J_{\mathrm{FRM}} {J_1}^T J_2$. Note that the Jones matrices for the oppositely traveling light in the sensing part are the same (J_2) even when the nonreciprocal birefringence α_H is present. This is true if the fiber section does not have reciprocal intrinsic circular birefringence. A straightforward calculation of the eigenvalue of the matrix leads to the PMB frequency f_P, given as

$$f_P = \frac{c}{2\pi n l} \arccos\left(\alpha_H l_2 \frac{\sin \delta_2}{\delta_2}\right), \qquad (5)$$

where c is the speed of light in vacuum, n is the refractive index of fused silica, and $l = l_1 + l_2$ is the total laser cavity length. Note that, if $\alpha_H = 0$, f_P is independent of the fiber birefringence β and has multiple solutions of odd harmonics of the laser mode spacing of $c/(2nl)$, as described above. The change Δf_P in the PMB frequency, when $\alpha_H l_2 \ll 1$, becomes

$$\Delta f_P \approx \frac{c}{2\pi n l}\left(\alpha_H l_2 \frac{\sin \delta_2}{\delta_2}\right). \qquad (6)$$

Note that the change of f_P in response to α_H becomes most sensitive when $\delta_2 \ll 1$, which means that the intrinsic birefringence βl_2 has to be much smaller than unity for sensitive magnetic-field measurement. In this case, $\Delta f_P \approx (c/2\pi n l)\alpha_H l_2$, which shows a linear relationship between Δf_P and α_H and thus H. If βl_2 is large such that $(\sin \delta_2)/\delta_2 \approx 1$ cannot be applied, Δf_P will have reduced sensitivity to applied magnetic field, and the scale factor will be dependent on the magnitude of βl_2, which may be sensitive to environmental perturbation in this region. As an example, if δ_2 changes from 0 to 0.5 rad, the responsivity of Δf_P to H will be reduced by 4.2%. Strictly speaking, the eigenstates of polarization deviate from the circular polarizations when $\alpha_H \neq 0$, but the deviation is insignificant when $\alpha_H \ll 1$, which is the case for most practical situations.

Figure 2 shows a schematic of the experimental fiber laser for magnetic-field–current sensing. A solenoid was used to produce a uniform axial magnetic field H proportional to the applied current (A) and was placed near the output mirror. The length of the solenoid was $l_2 = 42$ cm with 1530 turns of electrical wire. The total cavity length was 7.3 m, which corresponds to an axial mode spacing of ~13.7 MHz. A 30-cm-long erbium-doped fiber (2000-parts-in-10^6 erbium concentration) was placed in the middle of the cavity as a gain medium pumped by a laser diode at 980-nm wavelength. A 1.3-m-long unpumped erbium-doped fiber (80-parts-in-10^6 erbium concentration) placed near the output mirror was utilized as a saturable absorber, resulting in the reduction of the number of cavity modes to a few.[9,10] Because the 42-cm-long section of this fiber was used as the sensing region, the fiber was carefully maintained straight without twist. A measurement with a scanning Fabry–Perot optical spectrum analyzer revealed three longitudinal modes. One of the modes was polarized orthogonally to the other two modes and appeared approximately at the center position between them. This is consistent with

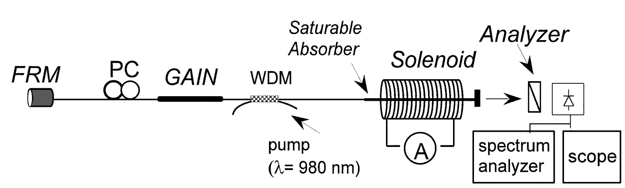

Fig. 2. Experimental setup: WDM, wavelength-division multiplexer; PC, polarization controller.

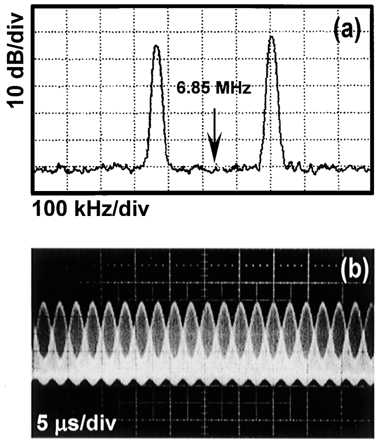

Fig. 3. (a) Polarization mode beat spectrum, (b) oscilloscope trace of the output signal from the fiber laser.

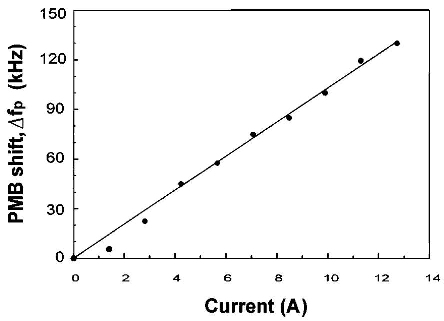

Fig. 4. Experimental (slope, 10.24 kHz/A) results for the shift of polarization mode beat frequency as a function of current applied to the solenoid.

the theoretical predictions. The laser output was directed to an analyzer and detected by a fast photodiode. A rf spectrum analyzer was used to measure the beat frequency of the detector current. Figure 3(a) shows a typical spectrum of a PMB signal when $H = 0$ with two PMB frequencies located symmetrically in reference to half of the longitudinal mode spacing (6.85 MHz). Only one PMB signal was expected based on Eq. (5). We attribute the small discrepancy to the deviation of the polarization rotation angle in the FRM from 90° because it was optimized for 1.55 μm rather than for the actual lasing wavelength of 1.53 μm. A theoretical simulation using the well-known dispersion of the Faraday effect[8] showed the separation of PMB frequency. The magnitude of the frequency separation depended on the fiber birefringence, as observed in the experiment. An oscilloscope trace of the signal is shown in Fig. 3(b). We confirmed that the magnitude of the PMB signal was invariant against the analyzer angle, as expected for the circular eigenpolarizations. The signal-to-noise ratio of the PMB signal was greater than 45 dB with good stability, which is a great improvement compared with those of previous polarimetric fiber laser sensors.

Figure 4 shows the shift of the PMB frequencies measured as a function of the current applied to the solenoid. A linear shape coefficient of 10.24 kHz/A was obtained, which was not sensitive to the fiber birefringence change when the intracavity polarization controller was arbitrarily changed. The theoretical prediction from relation (6) gives a slope coefficient of 10.54 kHz/A, which compares well with the experimental results. For comparison, we measured the response of the fiber laser with a solenoid placed on the FRM side and found a strong dependence on the fiber birefringence change.

In conclusion, we have demonstrated a novel fiber laser that has stable output polarizations with stable and large polarization mode beat signals. A magnetic-field–current sensor is demonstrated that uses the laser and is free from environmental perturbations such as temperature change and axial strain.

This research was supported by the Agency for Defense Development of Korea.

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