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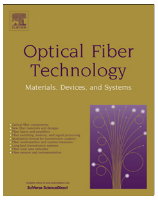

Magnetic field error in twin depolarized interferometric fiber optic gyroscopes induced by vertical magnetic field

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ABSTRACT

We put forward a theory that the magnetic field vertical to the sensing coil plane may induce a nonreciprocal phase error (NPE) in twin depolarized interferometric fiber optic gyroscopes (TD-IFOGs). A related mathematical model is established. The simulation analysis and experimental result show that the magnetic field error induced by a vertical magnetic field in a TD-IFOG is relatively stable. The error arising from the bending of the fiber is closely related with the radius of an optical fiber coil, fiber's diameter, fiber's length, the strength of the vertical magnetic field and so on. And as for a manufactured TD-IFOG, the vertical magnetic error is proportional to the magnitude of the vertical magnetic field.

1. Introduction

Due to the magneto-optical Faraday effect, a magnetic field will induce a NPE in an interferometric fiber optic gyro (IFOG). And the fiber sensing coil is the main source of the gyro's magnetic error [1]. According to different mechanisms that magnetic field affects an IFOG, the arbitrary magnetic field B can be decomposed into the radial magnetic field B_R perpendicular to the sensing axis of a fiber coil and the axial magnetic field B_A parallel to the sensing axis, as is shown in Fig. 1. Due to the existence of a helix angle in each circle fiber when produced, B_A can also be decomposed into a parallel vector $B_{A\|}$ parallel to the light's propagation direction and a vertical vector $B_{A\perp}$ perpendicular to this direction. The radial magnetic field B_R will induce magnetic error in IFOGs because of the magneto-optical Faraday effect, twisting and residual birefringence caused by drawing fiber and winding coil [2–4]. Radial magnetic errors, in a single depolarized interferometric fiber optic gyro with one Lyot depolarizer, a polarization maintaining fiber optic gyroscope, a TD-IFOG with double depolarizers in each side of the fiber coil, decrease in turn [5–6]. The magnetic error induced by the parallel vector $B_{A\|}$ is similar to that caused by the radial magnetic field B_R, both of which are based on magneto-optic effect. But the difference is that the magnetic error of the former comes from the length error between the two adjacent layers of the coil. And as $B_{A\|}$ is very small (typically less than 0.01), the magnetic error caused by $B_{A\|}$ is very small as well. For a TD-IFOG, the magnetic error induced by $B_{A\|}$ is closely related to the 45° angle error of the two Lyot depolarizers. And for an ideal TD-IFOG with the 45°angle error of the Lyot depolarizer to be zero, $B_{A\|}$ will not result in any magnetic error [7–10].

However, $B_{A\perp}$ perpendicular to the direction of the light's propagating, still induces magnetic error in TD-IFOGs because of the fiber bending after the fiber coils to be manufactured [11]. When being wound, fiber coils are bent inevitably. And this always makes the refractive index of the fiber increase near the curvature center and decrease away from the center [12,13]. This is similar to a waveguide, in which the two modes q-TM and q-TE exist [14,15]. Supposed that the bending as shown in Fig. 2a), the electric field components of the two modes are $(E_{q-M}, H_{q-M}) = (E_x, 0, E_z, 0, H_y, H_z)$ and $(E_{q-E}, H_{q-E}) = (0, E_y, E_z, H_x, 0, H_z)$ respectively [16]. In $B_{A\perp}$ as is shown in Fig. 2a), the forward and backward propagation constants of the q-TM mode are known as following respectively [11]

$$\beta_{q-M+} = \beta_0 + \delta\beta \tag{1}$$

$$\beta_{q-M-} = \beta_0 - \delta\beta \tag{2}$$

where $2\delta\beta = 2\lambda V B_{A\perp}/\pi n \cdot / \int\int_{c.s.} \partial|E_x|^2/\partial x dxdy / \int\int_{c.s.} |E_x|^2 dxdy = 2\lambda V B_{A\perp}/\pi n\chi$, with β_0 of an inherent propagation constant in the fiber, λ of the light's wavelength in the fiber, V of the Verdet constant, n of the core's refractive index, and χ of the asymmetry degree of the electric field component E_x distribution in the q-TM mode because of the fiber's bending.

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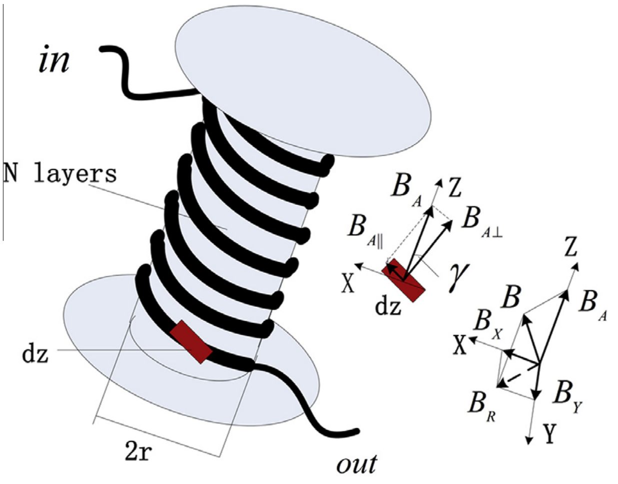

Fig. 1. The single-mode optical fiber coil under the effect of magnetic field.

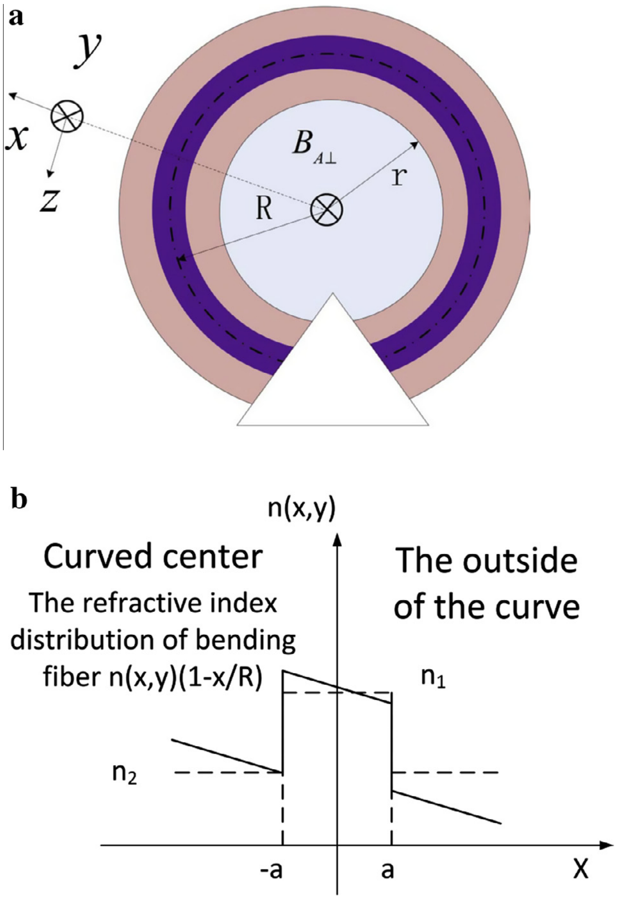

Fig. 2. Refractive index profile of a bent fiber. (a) The bent single-mode optic fiber under profile of the effect of the vertical magnetic field. (b) Refractive index bent single-mode optic fiber in the longitudinal sectional view.

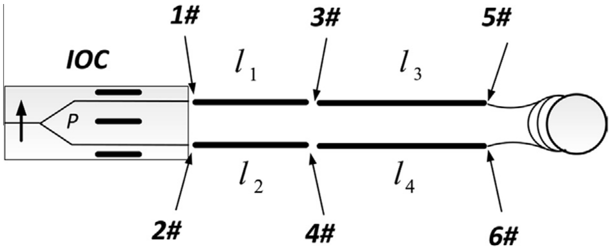

Fig. 3. The TD-IFOG system.

As for the q-TE mode, the forward and reverse propagation constants are equal, that is $\beta_{q-E-} = \beta_{q-E+} = \beta'_0$. Accordingly, $B_{A\perp}$ perpendicular to the curved plane, causes perturbation to the q-TM mode in the fiber, which leads the propagation constant of the q-TM mode to be non-reciprocal. This NPE is closely related to the diameter of the fiber coil, the fiber length and $B_{A\perp}$.

And as to an actual TD-IFOG, other optical devices, such as depolarizers, may modulate the non-reciprocal magnetic error. But in this paper, based on the viewpoint of [11], the expression of NPE caused by $B_{A\perp}$ in a TD-FOG is derived, and the simulation and experimental verifications are carried on, too.

Considering the ordinary single-mode fiber coil and the fiber's winding direction to be shown in Fig. 1, the average radius of the coil is r and the VMF $B_{A\perp}$ is perpendicular to the propagating direction of the light. Fig. 3 is a TD-IFOG system which consists of a polarizer P in IOC, the fast axis of the two polarization maintaining fibers l_1 and l_2 is parallel to P and is set to x-direction, while the slow axis vertical to the polarizer P, is set to y-direction.

2. Theoretical derivation of a NPE induced by the VMF in a TD-IFOG

As shown in Fig. 3, the CW (clockwise) light passes through the fiber coil from port #5 (the entrance port, *in* port in Fig. 1) to port #6 (the exit port, *out* port in Fig. 1), while for CCW (counterclockwise) light, *out* indicates the entrance port, *in* indicates the exit port.

As shown in Fig. 1, provided the fiber coil with N layers is wound in a circle with the radius of r, and the fiber which connects any adjacent two layers has no torsion, that is, if the polarization direction of the linearly polarized light is in y-direction on the ith layer, when it reaches the $(i+1)$th layer, the polarization direction is still in y-direction. l_1, l_2, l_3 and l_4 are four polarization maintaining fibers, whose birefringence difference between the fast axis and slow axis is $\Delta\beta$. l_1 and l_3 compose one Lyot depolarizer, and the angle between their fast axes is $45° + \theta_3$. l_2 and l_4 compose another Lyot depolarizer, and the angle between their fast axes is $45° + \theta_4$. The angle between the y-direction and the fast axes of l_3 is θ_5, and the one between the y-direction and the fast axes of l_4 is θ_6. Considering the entire system shown in Fig. 3, assuming the electric field component of the light passes through the polarizer P from the source is $\sqrt{2}E_0$, then it will be divided into two beams with the same magnitude in the Y waveguide, whose transverse electric field component is E_0. Suppose the transverse electric field vector of the light propagating in CW direction is E_{0+}, while the transverse electric field vector in the CCW direction is E_{0-}. So when the transverse electric field vector of E_{0+} reaches the port #5, it is

$$\begin{aligned} E_{5+} = \begin{bmatrix} E_{5+x} \\ E_{5+y} \end{bmatrix} &= C(\theta_5)\cdot T(\Delta\beta l_3/2)\cdot C(45^\circ+\theta_3)\cdot T(\Delta\beta l_1/2)\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} E_0 \\ &= \begin{bmatrix} \cos\theta_5\cos(45^\circ+\theta_3)\mathrm{e}^{-j\Delta\beta l_3/2} - \sin\theta_5\sin(45^\circ+\theta_3)\mathrm{e}^{j\Delta\beta l_3/2} \\ -\sin\theta_5\cos(45^\circ+\theta_3)\mathrm{e}^{-j\Delta\beta l_3/2} - \cos\theta_5\sin(45^\circ+\theta_3)\mathrm{e}^{j\Delta\beta l_3/2} \end{bmatrix} \mathrm{e}^{-j\Delta\beta l_1/2} E_0 \end{aligned} \tag{3}$$

where $C(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$, $T(\theta) = \begin{bmatrix} \mathrm{e}^{-j\theta} & 0 \\ 0 & \mathrm{e}^{j\theta} \end{bmatrix}$.

The transverse electric field vector is E_{5+x} when it enters the fiber coil, whose q-TM mode's propagation constant is

$$\begin{aligned} \beta_{5+x} &= \beta_0 + \delta\beta' \\ &= \beta_0 + \sqrt{[\cos\theta_5\cos(45^\circ+\theta_3)]^2 + [\sin\theta_5\sin(45^\circ+\theta_3)]^2}\,\delta\beta \end{aligned} \tag{4}$$