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Research on Axial Magnetic Field Sensitivity in the Polarization-Maintaining Optical Fiber Coil of Fiber Optic Gyroscope

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ABSTRACT The magnetic field sensitivity is the main source of errors in a fiber optic gyroscope (FOG) and the polarization-maintaining (PM) optical fiber coil is a major sensitive source. In this paper, a theory that an orthogonal magnetic field vertical to the light propagating direction in a PM optical fiber coil can induce a non-Faraday nonreciprocal phase difference in a FOG is presented. The theoretical simulation and experimental results show that the orthogonal magnetic drift proportional to the orthogonal magnetic field is the main cause of the axial magnetic field sensitivity in a FOG, which is closely related to the skeleton radius of the optical fiber coil and depends neither on the fiber coil's size nor the shape. Furthermore, the orthogonal magnetic field sensitivity will increase with decreasing skeleton radius. Aiming at the application demand of miniaturized gyroscope, the research results of this paper have certain guiding significance and engineering application value.

INDEX TERMS Fiber optics, fiber optic gyroscope, axial magnetic field sensitivity, polarization-maintaining optical fiber coil.

I. INTRODUCTION

Fiber optic gyroscopes (FOGs) based on the Sagnac effect have been applied extensively in aviation, navigation, military, and civil fields because of a series of unique advantages [1]–[3]. So far, much work has been done to achieve high-accuracy and super high-accuracy FOGs, and the development of light weight and compactification FOGs with high accuracy has also received more and more attention recently [4]–[6]. The main method of gyro miniaturization is increasing the axial size and reducing the radial size of optical fiber coils, which results that FOGs are more sensitive to the axial magnetic field. There exist other nonreciprocal effects generating nonreciprocal phase errors (NPEs) except the Sagnac effect in FOGs. Besides, the magnetic drift caused by the Faraday effect is one of the main error sources [7]–[9]. For medium and high accuracy FOGs, the magnetic error can reach an intolerably high level without effective measures, which leads to a substandard magnetic sensitive parameter. An easy way to reduce the impact of the external magnetic field is to cover the magnetic shielding with metal materials possessing high magnetic permeability on the sensing coils of FOGs. Since this configuration will increase the weight and cost and go against the gyro miniaturization, much effect should be devoted to the design improvements of FOGs and suppression methods according to the influence mechanism of the magnetic field to diminish the magnetic sensitivity. The optical fiber coils as the main sensitive source of FOGs can respond to the surrounding magnetic field. A major factor of the drift induced by the radial magnetic field in FOGs appears with the generation of fiber axes' random twist resulting from the fiber drawing and the coil winding due to the Faraday effect and the residual birefringence, regardless of whether in a single-mode optical fiber coil or a PM optical fiber coil [10]–[14]. The mechanism of the Faraday magnetic drift reduction by using a small diameter coil or additional PM fibers in FOGs is presented in [13]. Tabe K and Hotate K's research shows that the magnetic drift can be effectively reduced by using polarizing fibers or absolute single-polarization fibers as sensing fiber coils because of a

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large loss difference between two polarization modes [15]. Other methods such as using low Verdet constant light guides or adopting proper ways of fiber coil winding are also useful in magnetic drift reduction [16].

Experimental results show that the axial magnetic field can also induce a NPE in a FOG, and the axial magnetic field sensitivity in PM optical fiber coils is more obvious than the radial magnetic field sensitivity. A magnetic drift induced by parallel component of the radial magnetic field is also based on Faraday effect. While, a non-Faraday-based drift caused by orthogonal component of axial magnetic field come from both mode shifting and fiber bending from fiber coils fabrication process [14], [17], [18]. In this paper, based on the pioneering study proposed by V. N. Logozinskii [19], a NPE in a PM optical fiber coil from orthogonal component field is derived and relevant simulations. The goal of this study is to discuss the influence mechanism of the axial magnetic field sensitivity in small FOGs. A new experiment scheme is proposed to measure the magnetic drift of a FOG caused by the orthogonal magnetic field and study the relationship of the magnetic drift and optical fiber coils' skeleton radius. Experimental results show that axial magnetic drift is too large to ignore, and the orthogonal magnetic field is the main cause. As a consequence, the drift caused by the orthogonal magnetic field must be suppressed as much as possible.

II. PRINCIPLE

In the PM optical fiber coil, the arbitrary magnetic field in space is decomposed into axial magnetic field and radial magnetic field. Due to the helix angle α after winding a fiber coil, the axial magnetic field H parallel to the sensing axis of the optical fiber coil can be decomposed into a parallel component $H_{/\!/}$ and an orthogonal component $H_\perp$, as shown in Figure 1. $H_{/\!/}$ is parallel to the light propagating direction in the fiber, while $H_\perp$ is vertical to the direction. The influences of $H_{/\!/}$ and radial magnetic field on FOG are similar, both of which are caused by the Faraday magneto-optical effect. The difference is that the magnetic drift caused by the former comes from the length difference between the two adjacent layers of the fiber in the PM optical fiber coil. Because α is small and $H_{/\!/}$ is generally less than 1% of $H_\perp$, the drift caused by $H_{/\!/}$ is also very small and can be ignored. Therefore, in this paper, we mainly study the mechanism of the orthogonal magnetic field $H_\perp$ affecting a FOG.

Since the field distribution of mode in the fiber is extremely complicated, the scalar approximation based on linear polarization is adopted to simplify the calculation. Assume a bent fiber mode under the $H_\perp$ shown in Figure 2 (solid curve): z-axis is directed along the fiber axis, x-axis is along the radius of the fiber coil plane, and y-axis is vertical to the coil plane.

By establishing the Maxwell equation and analyzing in mode field theory, the mode shifting for the light polarized in x-direction over the fiber cross section has the form [18]:

$$\delta_x = \frac{3VH_\perp}{2\pi^2}\left(\frac{\lambda}{n}\right)^2, \tag{1}$$

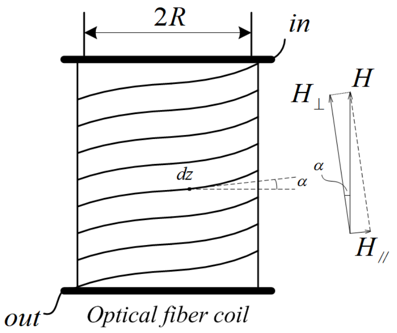

FIGURE 1. Decomposition of the axial magnetic field H.

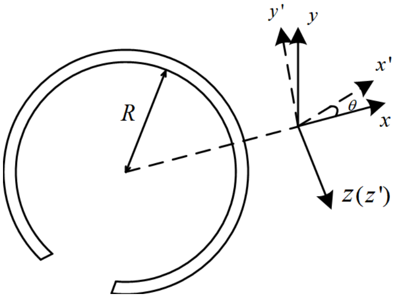

FIGURE 2. Bent fiber mode.

where V is the Verdet constant, λ is the light wavelength, n is the refractive index of the fiber core. Since the helix angle α is very small, the vector $H_\perp$ in the equation (1) can be substituted with H. And the sign of the mode shifting is opposite for the counter propagating light waves.

Since the optical path difference between the two counter propagating light waves polarized along the x-axis in a fiber coil is $\Delta L = N \cdot 2\pi \cdot 2\delta_x$, the NPE caused by $H_\perp$ is:

$$\phi = 4\pi N\beta\delta_x, \tag{2}$$

where N is the total number of turns of the coil, assuming $\beta \approx kn$, k is the wave number in vacuum and $k = w/v = 2\pi/\lambda$. By substituting β into the equation (2), the NPE is rewritten as:

$$\phi = \frac{12HV\lambda N}{n}. \tag{3}$$

When the angular velocity $\Omega \neq 0$, the propagation time of the two light waves satisfies:

$$t_{CW} = \frac{2N\pi R}{c_{CW}} = \frac{2N\pi R}{c - R\Omega}, \tag{4}$$

$$t_{CCW} = \frac{2N\pi R}{c_{CCW}} = \frac{2N\pi R}{c + R\Omega}, \tag{5}$$

where c is the light velocity in vacuum, c_{cw} is the speed at which light travels clockwise, c_{ccw} is the speed at which light travels counter-clockwise, and R is the radius of the fiber coil. Due to $c^2 \gg (R\Omega)^2$, the phase difference between the clockwise and counter-clockwise light waves can be written as:

$$\phi = \frac{2\pi c}{\lambda} \cdot (t_{CW} - t_{CCW}) \approx \frac{8\pi S}{\lambda c} \cdot \Omega = \frac{4\pi RL}{\lambda c} \cdot \Omega, \tag{6}$$

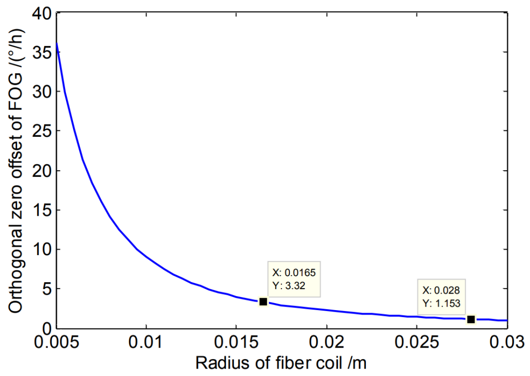

FIGURE 3. Relation curve between skeleton radius of a optical fiber coil and orthogonal zero offset.

where $L = N \cdot 2\pi R$ is the length of the fiber and $S = N \cdot \pi R^2$ is the equivalent area of the fiber coil.

From equations (3) and (6), the FOG orthogonal zero offset caused by the NPE is derived as:

$$\Omega(°/h) = \frac{3HV\lambda^2 c}{2n\,(\pi R)^2} \cdot \frac{3600 \times 180}{\pi}. \tag{7}$$

In general, each turn of fiber produces about 10^{-3} μrad/(turn Guass). Thus, the magnetic field overall effect will be significant due to the typical number of turns in small FOGs of more than 10^3. In addition, for a light with y polarization, the mode shifting will not be produced.

III. ANALYSIS AND SIMULATION

As shown in equation (3), the NPE ϕ caused by $H_\perp$ is closely related with the number of turns N and the orthogonal magnetic intensity. Since the parameters V, λ, N, and n are constants after manufacturing the fiber coil, the ϕ is only proportional to the orthogonal component $H_\perp$ and unaffected by the size and the shape of the coil. Besides, from equation (7), the orthogonal zero offset of a FOG caused by ϕ is inversely proportional to the skeleton radius of a fiber coil. Therefore, adopting a fiber coil with larger diameter for a certain length is effective to reduce the influence of external magnetic field on FOG.

In order to verify the theory above, the orthogonal zero offset of a FOG with different skeleton radius fiber coils under the $H_\perp$ of 1 Guass is simulated. The simulation result is shown in Figure 3. It is easy to see that the smaller the skeleton radius of fiber coil is, the greater the orthogonal zero offset will be. The orthogonal zero offset of the FOG is 1.153°/h when the skeleton radius is 0.0280m. And the orthogonal zero offset is 3.320°/h for a coil with the skeleton radius of 0.0165m. The above theoretical derivation is based on that the x-axis lies strictly in fiber coil plane. In fact, a random angle θ may exist between the x-axis and coil plane due to the random longitudinal twisting of the fiber shown in Figure 2 (dotted line). Thus, the theoretical value obtained by simulation is maximal, while the actual value varies from theoretical value (maximal) to zero (minimal).

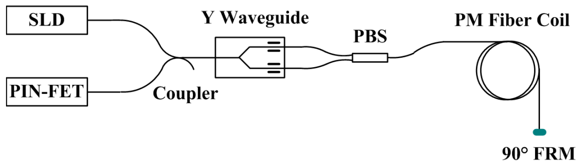

FIGURE 4. Experimental scheme.

IV. EXPERIMENTS AND DISCUSSIONS

To test and confirm the fiber coils' axial magnetic field sensitivity caused by H, we designed a new experimental scheme shown in Figure 4 and carried out several tests. The principle of optical path is as follows: light from a superluminescent light-emitting diode (SLD) is directed through a coupler to a Y waveguide, which comes into being two linear polarized lights. The two forward propagating light waves are combined to orthogonal waves in a polarization beam splitter (PBS). The two orthogonal waves travel through a PM fiber coil where a NPE associated with $H_\perp$ is generated between the two waves. They reflect off the 90° Faraday rotation mirror (FRM) at the end of the sensing region and retrace their way through the PM fiber coil. However, their modes of polarization are swapped at the FRM. The polarized light in the x-axis returns along the y-axis and the polarized light in the y-axis returns along the x-axis. Thus the two beams double their phase shift during their return trip through the fiber coil. They are returned to linear polarization modes on passing through the polarization beam splitter again on the return trip. The two waves are brought back together and interfered by the Y waveguide and finally coupled to the P-Intrinsic-N Field-Effect Transistor (PIN-FET) detector. Both waves have traveled along x-axis and y-axis of the PM fiber coil, only in reverse order. Thus, the system is effective to resist the external interferences owing to the perfect reciprocity of the optical path. Since the fiber in the coil is twisting randomly, the Faraday magnetic drifts caused by parallel component $H_{/\!/}$ for two counter propagating waves are approximately equal, while the mode shift caused by orthogonal component $H_\perp$ is opposite. The only source of phase shift between these two beams is resulting from the $H_\perp$.

To verify the feasibility and accuracy of our method, we designed the experimental setup as Figure 5 shows. The experimental setup consists of a square Helmholtz coil, a constant current source and a data acquisition computer (not shown in Figure 5). The Helmholtz coil can generate three-dimensional even intensity magnetic field and the magnetic field intensity can be adjusted by controlling the current.

Using a FOG system shown in Figure 4, with the light source's center wavelength of $\lambda = 1310$nm, the PM optical fiber's diameter of 165μm, experiments were done with two different optical fiber coils whose skeleton radius are 0.0280m (No. 1 coil) and 0.0165m (No. 2 coil), respectively. Put the No. 1 coil and No. 2 coil into a test platform in the center of the Helmholtz coil, respectively. The direction of the axial magnetic field was kept parallel to the sensing axis of the fiber coil during the experiments and the axial magnetic

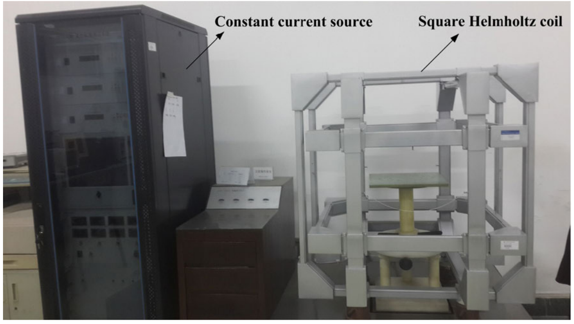

FIGURE 5. Experimental setup.

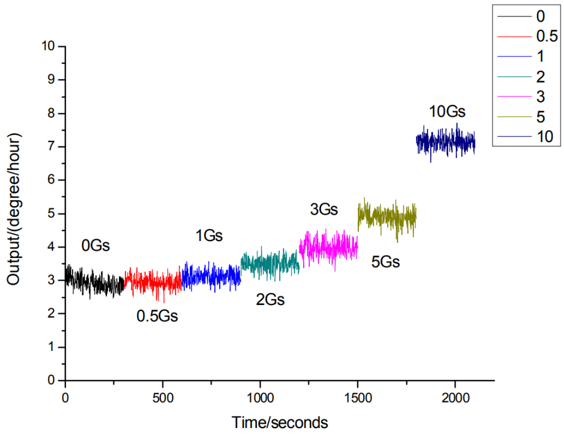

FIGURE 6. FOG (No. 1 coil) output in different axial magnetic fields.

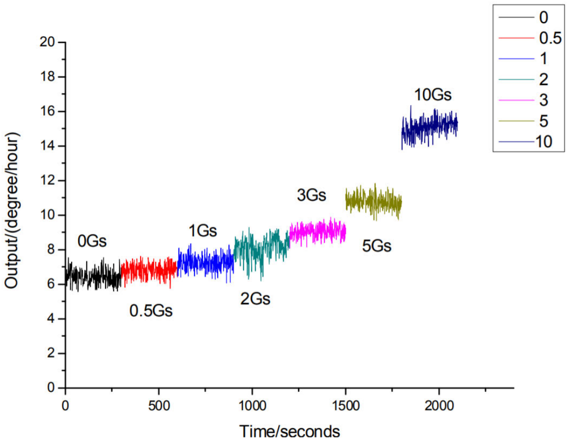

FIGURE 7. FOG (No. 2 coil) output in different axial magnetic fields.

intensity was adjusted to 0, 0.5, 1, 2, 3, 5, 10, respectively. The experimental results are shown in Figure 6 and Figure 7. And the FOG output signal (°/h) versus the test time (s) is plotted in the Figures. After data processing, the No. 1 and No. 2 coils' orthogonal zero offsets in the same FOG system are 0.340 and 0.865 °/(h·Guass), respectively. With reference to the simulation result, it can be seen that the experimental results and the theoretical results are consistent.

In addition, we proposed another FOG system shown in Figure 8 to measure the fiber coil's total axial magnetic field sensitivity caused by H. Light from a SLD is directed through a coupler to a Y waveguide and split into two linear polarized lights. The two waves travel through a PM fiber coil along the clockwise and counter-clockwise directions under the axial magnetic field. The two waves finally return and interfere at the Y waveguide. Based on the FOG system, some experiments were carried out with the No. 1 and No. 2 fiber coils, and the results are shown in Figure 9 and Figure 10. Finally, we obtain that the No. 1 and No. 2 fiber coils' total zero offsets caused by H are 0.340 and 0.865 °/(h·Guass), respectively.

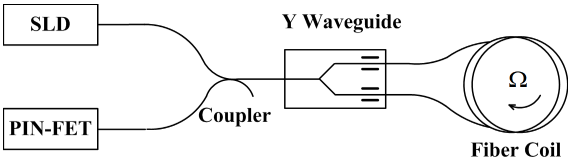

FIGURE 8. Optical path of FOG.

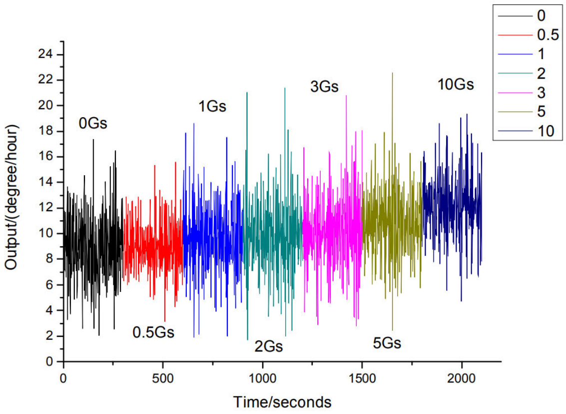

FIGURE 9. FOG(No. 1 coil) output in different axial magnetic fields.

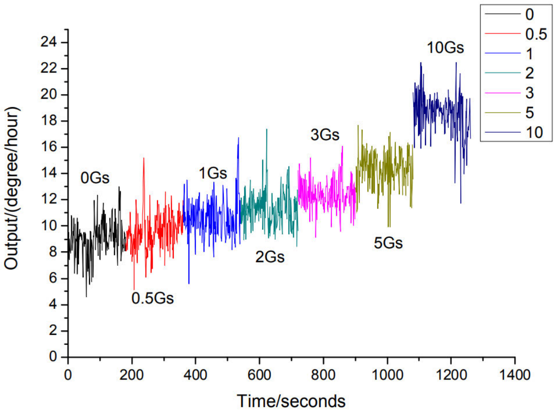

FIGURE 10. FOG (No. 2 coil) output in different axial magnetic fields.

In the Figures 6, 7, 9 and 10, the FOG zero offsets increase with the enhancing of the axial magnetic field intensity. Besides, the magnetic drift is more obvious in a smaller diameter optical fiber coil. Corresponding to the above simulation and experiments, the comparison results are shown in Table 1.

In Table 1, the experimental results are within the range of the simulation results. Therefore, the test results fit the

TABLE 1. Simulation and experiment results of optical fiber coils with different skeleton radius

Fiber Coil		No. 1	No. 2
Skeleton Radius (m)		0.0280	0.0165
Simulation result (°/(h·Guass))	Orthogonal zero offset	0~1.153	0~3.320
Experiment result (°/(h·Guass))	Orthogonal zero offset	0.436	0.875
	Total zero offset	0.340	0.865

theory very well. Then, it can be seen from the experimental data that the fiber coil's orthogonal zero offset caused by $H_{\perp}$ is so large that it exceeds the total zero offset caused by H, which indicates that NPE caused by orthogonal component magnetic field is the main reason of FOG axial magnetic field sensitivity. This phenomenon can be explained that the sign of magnetic drift caused by parallel component $H_{/\!/}$ may be opposite to the drift from the $H_{\perp}$. Thus, the total magnetic drift is smaller than orthogonal magnetic drift.

V. CONCLUSION

On the basis of the mode field theory, the FOG orthogonal zero offset caused by orthogonal component magnetic field is derived. Correlative experimental schemes were proposed to measure the FOG axial magnetic field sensitivity. The experimental results show that the FOG axial magnetic drift is closely related to the axial magnetic field intensity and the optical fiber coil's skeleton radius. And experiments confirm that the orthogonal component magnetic field is the main cause of the FOG axial magnetic field sensitivity, which increases with decreasing skeleton radius of the fiber coil. It indicates that using relatively large optical fiber coils in FOGs is beneficial to decrease magnetic drift. Since demand grows for the miniaturized gyroscope, it has great application value to suppress the axial magnetic field error. The results presented in this paper will be useful for the improvement of gyro precision and optimization of gyro magnetic field sensitivity.

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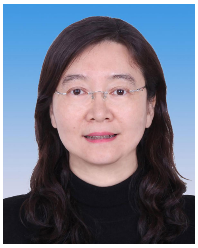

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