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Single-mode fiber gyroscope with three depolarizers

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ABSTRACT

In this letter we present a single-mode fiber gyroscope (FOG) with low long-term drift. Only single-mode fiber components except for three fiber depolarizers were used. A simplified mathematic model has been proposed to explain the bias stability of the gyro. Several open-loop and closed-loop FOGs with 0.1–0.5°/h drift have been demonstrated.

1. Introduction

Fiber optic gyroscopes can be classified into two types: resonant gyros (RFOG) [1,2] and interferometric gyros (IFOG) [3]. RFOG are still in experimental phase because of the strong Kerr effect and Rayleigh backscattering occurring in the resonant cavity. These problems can be solved using air-core photonic-bandgap fiber [4] but the coupler used in RFOG and splicing with low loss still are problems. IFOG is successful for engineering aim [5]. A recent progress in IFOG is to use both solid and air core photonic crystal fiber instead of conventional polarization-maintaining fiber for the sensing coil [6–10]. IFOG can be classified further into polarization maintaining IFOG (PM-IFOG) and depolarized IFOG (D-IFOG). PM-IFOG employs polarization-maintaining fiber coil and components while D-IFOG employs single-mode fiber (SMF) coil with depolarizers. At the present time most commercial FOGs are made with PM fiber. However, because of their substantial cost advantages over PM-IFOGs, D-IFOGs have been the subject of continuous investigation in several laboratories in the world. D-IFOG using one Lyot depolarizer within a SMF sensing coil exhibited large long-term drift over 2°/h. Two kinds of high performance of D-IFOG were reported [11,12]. In these gyros reported in the references [11,12] expensive components such as polarization maintaining fiber directional coupler and/or Y-type $LiNbO_3$ chip with PMF pigtails were still used. In this paper we present the results of a low-cost D-IFOG with low long-term drift 0.1–0.5°/h. Only low-cost single-mode fiber components except for three fiber depolarizers were employed.

2. Gyroscope structure and characteristics

The new gyros prototype is shown in Fig. 1. The low coherence light source is an edge light emitting diode (ELED) with a linewidth $\Delta\lambda = 50$ nm at output wavelength of 1.3 µm. It is pigtailed with more than 6.75 m in length of Oblong-fiber which acts as the depolarizer $\mathbf{D}_1$. The principal axis of Oblong-fiber is 45° with respect to the axis of the ELED chip. Oblong-fiber is a kind of high-birefringence fiber with square-shaped core shown in Fig. 2 (made by the Institute of Wire and Cable, Shanghai, China) with beat length 2.5–3.0 mm at average of transmission loss 3.5–5 dB/km. C_1 and C_2 are usual single-mode fiber directional couplers. $\mathbf{D}_2$ and D_3 are Lyot depolarizers made with 3 m and 0.75 m in total of Oblong-fiber, respectively. The phase modulator is either PZT for open-loop operation or $LiNbO_3$ in line-type waveguide connected by two SMF pigtails at input and output respectively for closed-loop operation. $\mathbf{D}_2$ and $\mathbf{D}_3$ are randomly spliced into the optical path without aligning the principal axis direction of Oblong-fiber. This made the splicing easier.

The most important parameter for gyros is the bias stability. The nonreciprocal polarization phase shifts have been divided into the amplitude-type error ϕ_{amp} and the intensity-type error ϕ_{int} [13],

$$\phi_{\text{amp}} = \frac{\int Im(g_{11}^{*} g_{12} E_{\text{xin}}^{*}(\omega) E_{\text{yin}}(\omega) + g_{11} g_{21}^{*} E_{\text{xin}}(\omega) E_{\text{yin}}^{*}) d\omega}{\int \left| g_{11} E_{\text{xin}}(\omega) \right|^2 d\omega} \tag{1}$$

$$\phi_{\text{int}} = \frac{\int Im(g_{12} g_{21}^{*}) \left(\left| E_{\text{xin}}(\omega) \right|^2 - \left| E_{\text{yin}}(\omega) \right|^2 \right) d\omega}{\int \left| g_{11} E_{\text{xin}}(\omega) \right|^2 d\omega} \tag{2}$$

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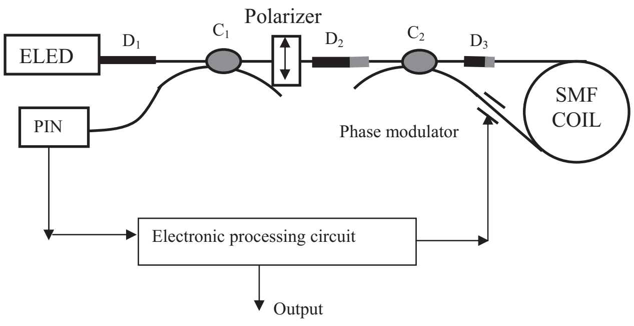

Fig. 1. Schematic configuration of single-mode fiber gyros with three all fiber depolarizers.

where ω is the optical angle frequency and the g_{ij}'s are the elements of clockwise wave transfer Jones matrix $\mathbf{G_{cw}} = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix}$ from a reference point to the left of the imperfect polarizer. Counter-clockwise wave (CCW) transfer matrix $\mathbf{G_{ccw}} = \mathbf{G}^{T}_{\mathbf{ccw}}$. The input optical field vector is expressed in frequency domain as $\mathbf{E_{in}} = \begin{pmatrix} E_{xin}(\omega) \\ E_{yin}(\omega) \end{pmatrix}$, assuming x is the transmissive coordinate of the polarizer while y is the attenuation coordinate at the input/output common path. The integral must be taken over all optical frequencies.

Fredricks and Ulrich [14] only analyzed amplitude error of D-IFOG with one depolarizer inserted in the sensing coil that is proportional to the product of the extinction ratio of the polarizer and the degree of polarized reduction accomplished by the depolarizer within the coil. However, the ϕ_{int} cannot be simply omitted in D-IFOG with about 40–50 dB imperfect polarizer because ϕ_{int} and ϕ_{amp} are not independent of each other and the coil is not made of polarization maintaining fiber in which g_{12} and g_{21} have the same order as that of g_{11}. Utilizing a simplified model, we will demonstrate that the errors of the new D-IFOG with three depolarizers in Fig. 1 are much smaller than those of the conventional D-FOG with only one depolarizer.

We need several transfer matrixes that will be used in our mathematic model. The matrix below describes the rotation transfer of any two coordinate systems with an angle difference θ:

$$\Theta\left(\theta\right) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{3}$$

For $\theta = \pi/4 + \Delta\theta$, assuming $\Delta\theta$ is a small value, we obtain:

$$\Theta\left(\frac{\pi}{4} + \Delta\theta\right) \approx \frac{1}{\sqrt{2}} \begin{pmatrix} 1 - \Delta\theta & 1 + \Delta\theta \\ -1 - \Delta\theta & 1 - \Delta\theta \end{pmatrix} \tag{4}$$

The high birefringence Oblong fiber with length of L is described as:

$$\mathbf{B}(\Delta\beta L) = \begin{pmatrix} \exp\ (-i\Delta\beta L/2) & 0 \\ 0 & \exp(i\Delta\beta L/2) \end{pmatrix} \exp(i\bar{\beta}L) \tag{5}$$

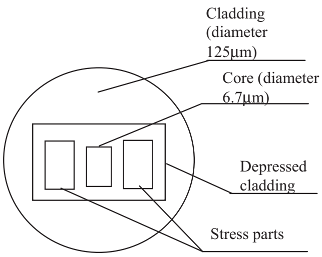

Fig. 2. Diagram of the Oblong fiber.

here $\Delta\beta \equiv \beta_a - \beta_b$, $\bar{\beta} = (\beta_a + \beta_b)/2$ express the difference of propagation constants of two principal axes in the Oblong fiber and the average value of those, respectively. The common phase term $\exp(i\bar{\beta}L)$ can be omitted because of common phase rejection for CW and CCW in fiber gyro.

P is the polarizer matrix with extinction ratio:

$$\mathbf{P} = \begin{pmatrix} 1 & 0 \\ 0 & \in \end{pmatrix} \tag{6}$$

Assume that the ELED light source with unit intensity is a gauss spectrum with the central frequency ω_o, two orthogonal independent polarization components and the degree of polarization of the source P_s. The light beam is launched into the polarizer through long high birefringence fiber $\mathbf{D}_1$. The angle difference between the principal axis of source and the principal axis of depolarizer $\mathbf{D}_1$ is $\pi/4 + \Delta\theta_1$, and θ_s is the angle between the transmissive axis of the polarizer and the principal axis of depolarizer $\mathbf{D}_1$. We can regard the source plus $\mathbf{D}_1$ as a quasi-unpolarized source because the birefringence of **D1** is much larger than those of other parts in the optical circuit. We get input intensities at the input/output path of the polarizer:

$$\begin{cases} \left\langle \left|E_{xin}(t)\right|^2 \right\rangle = \frac{1}{2}(1 - 2\Delta\theta_1 P_s \cos 2\theta_s) \\ \left\langle \left|E_{yin}(t)\right|^2 \right\rangle = \frac{1}{2}(1 + 2\Delta\theta_1 P_s \cos 2\Delta\theta_1) \\ \left\langle E_{xin}(t)E^*_{yin}(t) \right\rangle = \left\langle E^*_{xin}(t)E_{yin}(t) \right\rangle = \Delta\theta_1 P_s \sin 2\theta_s \end{cases} \tag{7}$$

where <> means time average. We assume that θ_{d2} is the angle between the transmissive axis of the polarizer and the principal axis of the first segment Oblong fiber of the second depolarizer $\mathbf{D}_{2.}$ $\pi/4 + \Delta\theta_2$ is the angle between the first segment Oblong fiber axis and the second segment Oblong fiber axis of $\mathbf{D}_2$. The depolarizer $\mathbf{D}_2$ transfer matrix can be expressed as, including incident angle θ_{d2}:

$$\mathbf{D}_2 = \mathbf{B}(\Delta\beta \cdot 8l)\,\Theta\left(\frac{\pi}{4} + \Delta\theta_2\right)\,\mathbf{B}(\Delta\beta \cdot 4l)\,\Theta(\theta_{d2}) \tag{8}$$

$12l$ is the total length of $\mathbf{D}_2$.

The depolarizer $\mathbf{D}_3$ transfer matrix is:

$$\mathbf{D}_3 = \mathbf{B}(\Delta\beta \cdot 2l)\,\Theta\left(\frac{\pi}{4} + \Delta\theta_2\right) \cdot \mathbf{B}(\Delta\beta \cdot l)\,\Theta(\theta_{d3}) \tag{9}$$

where θ_{d3} is the angle between the second segment PM fiber axis of $\mathbf{D}_2$ and the first segment PM fiber axis of the third depolarizer $\mathbf{D}_3$ and $\pi/4 + \Delta\theta_2$ is the angle between the first segment PM fiber axis and the second segment Oblong fiber axis of $\mathbf{D}_3$.

The transfer matrix of the single-mode fiber coil is described as, including input and output coordinate transfers:

$$\mathbf{S_m} = \begin{pmatrix} s_{11} & s_{12} \\ s^*_{12} & -s^*_{11} \end{pmatrix} \tag{10}$$

where $|s_{11}|^2 + |s_{12}|^2 = 1$ that imply conversation of energy. The second row of the $\mathbf{S_m}$ has opposite sign compared to conventional single-mode fiber matrix because there is a transfer from right-hand coordinate to left-hand coordinate.

Assuming that the coil-coupler is ideal, i.e. no polarization-dependent-loss and the same phase for any polarization light, so there is 1/2 factor to be added to the equation as below:

$$\mathbf{G_{cw}} = \frac{1}{2}\mathbf{P}\mathbf{D}_2^{\mathbf{t}}\mathbf{S_m}\mathbf{D}_3\mathbf{D}_2\mathbf{P} \tag{11}$$

Eq. (11) means that the clockwise wave (CW) travels from the polarizer, depolarizer $\mathbf{D}_2$, coupler C$_2$, depolarizer $\mathbf{D}_3$, single mode coil, then back to coupler C$_2$,depolarizer $\mathbf{D}_2$, polarizer.