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Minimal Scheme for Optically Compensated Interferometric Fiber-optic Gyroscopes

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Abstract: Polarization Nonreciprocity (PN) is one of the most significant error sources in Interferometric Fiber-Optic Gyroscopes (IFOGs). In IFOG applications, PN errors must be effectively suppressed to achieve a low bias drift. Optical compensation is a recently discovered mechanism for suppressing PN errors in IFOGs. The minimal scheme for the optically compensated IFOG is proposed, which has structural complexity even lower than the conventional IFOG's minimal scheme. In the proposed scheme, optical compensation is achieved by using depolarized light and no polarizer or polarization maintaining device is required. Experimental test targeting the Earth's rotation rate shows this scheme works stably and achieves a low bias drift of 0.02°/h.

Key words: Fiber-optic gyroscope, rotation sensor, optical compensation, minimal scheme

INTRODUCTION

Interferometric Fiber-Optic Gyroscopes (IFOGs) are optical rotation sensors widely used in industrial and military applications. The basic structure of an IFOG is a Sagnac interferometer, in which the Sagnac phase shift is detected to determine the rotation rate (Post, 1967; Lefevre, 1993). The most simplified design for a stable IFOG is call the "minimal scheme". For conventional IFOGs, the minimal scheme requires at least two directional couplers and a polarizer besides the light source and the Sagnac coil (Andronova and Malykin, 2002).

One of the most important problems the minimal scheme has to cope with is the Polarization Nonreciprocity (PN). As Sagnac effect requires a reciprocal loop for two counter-propagating light waves, additional PN effects cause crucial detection errors. Typically, the PN induced errors enlarge the bias drift of an IFOG and thus degrade its performance of rotation sensing. The conventional minimal scheme places a polarizer between two couplers for reciprocal operation, in which the polarizer is the key component for eliminating PN errors. This structural principal is applied in most tradition IFOGs, including polarization-maintaining IFOGs (PM-IFOGs) (Ulrich and Johnson, 1979; Carrara *et al*., 1987; Wang *et al*., 2012) and depolarized IFOGs (Jones and Parker, 1986; Szafraniec and Blake, 1994). In these structures, PN errors cannot be completely eliminated because of the non-ideality of the polarizer and other polarization-sensitive devices. Remaining PN errors cause long term instability in the IFOG, which also results in enlarged bias drift.

Recently, optical compensation was proposed for PN error reduction in a dual-polarized IFOG (Yang *et al*., 2012). In this configuration, two orthogonal polarizations are simultaneously used for rotation sensing. PN errors in two polarizations are proved to possess different polarities and thus they can be eliminated by simply adding up two signals. The dual-polarized IFOG was the first structure to verify the mechanism of optical compensation, but it had a high structural complexity. On top of that, an IFOG with less complexity was designed to apply optical compensation (Wang *et al*., 2013). The second structure verified that the polarization-maintaining fiber (PMF) coil was not necessary. Alternatively, the coil can be constructed by ordinary Single-Mode Fiber (SMF) with two depolarizers, similar with conventional depolarized IFOGs. Hence, the cost and complexity of the optically compensated IFOG is decreased.

In this study, an optical compensated IFOG is demonstrated and analyzed with further reduced complexity. More detailed theory analysis is carried out, so that basic requirements for optical compensation is put forth more clearly. With the supporting theory, the minimal scheme for IFOGs based on the compensation

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principle is proposed. Different from the conventional minimal scheme, only one coupler is required in this minimal scheme with optical compensation. The scheme is also verified by our experimental results in detection of the Earth's rotation rate. It is a promising model for designing the next generation of IFOGs, which possesses high stability and low complexity.

MATERIALS AND METHODS

Figure 1 shows the conventional minimal scheme for IFOGs. It uses at least two couplers and one polarizer to ensure reciprocity. However, for sensitive and stable operation, more structural principles should be followed to design an applicable IFOG. For example, the PM-IFOG requires polarization maintaining components and a PMF coil. Furthermore, a phase modulator is necessarily used in a practical IFOG for the sensitive working point. An applicable structure of the depolarized IFOG is showed in Fig. 2, to avoid expensive polarization maintaining devices. The piezoelectric transducer (PZT) works as the phase modulator. For open-loop IFOGs, sinusoidal phase modulation is commonly used. The interference signal is detected by the Photodetector (PD).

The "one polarizer between two couplers" principle for conventional IFOGs is essential to obtain both polarization reciprocity and coupler reciprocity (Lefevre, 1993). Coupler nonreciprocity induces comparatively stable bias to the output of the IFOG. It can be calibrated and thus does little harm to the IFOG's bias stability. On the other hand, PN induced errors are fluctuations over time, which degrades IFOG performance crucially. The usage of the polarizer stands for a single polarization operation way, in which PN errors are reduced by eliminating one of the light polarizations. However, this is not the only way for PN error reduction. In optically compensated IFOGs, two polarizations can be simultaneously used and PN errors are suppressed by compensation (Yang *et al*., 2012; Wang *et al*., 2013). In these designs, PN errors in the two polarizations have opposite polarities and thus the summation of two signals has notably reduced instability.

A novel structure for optically compensated IFOG is proposed here, with further reduced complexity. The structure needs no polarizer or polarization maintaining devices, as shown in Fig. 3. The structure has several Lyot depolarizers constructed by PMF pieces and an ordinary SMF coil. Here the Depolarizer 3 is the key component for generating two orthogonally polarized light beams. Theory analysis shows that PN errors can be totally reduced when two polarizations have same intensity and no coherence, which are assured by an optimally fabricated depolarizer.

Detection results of both two PDs in Fig. 3 have reduced PN errors by optical compensation. This advantage is verified both theoretically and experimentally in the following sections. Differently in conventional IFOGs, the output port of Coupler 2 has large PN errors and thus it is call the "nonreciprocal port". Without the concern of PN errors, the nonreciprocal port turns to be reciprocal in optically compensated IFOGs. From this point of view, two couplers are now redundant. Only one coupler is necessary for the minimal scheme of optically compensated IFOGs, as shown in Fig. 4. The rotation sensing signal detected by the PD in Fig. 4 has reduced PN errors. The remaining coupler nonreciprocity at this port contributes a stable bias which can be aligned and do not influence IFOG performance. Based on this structural principle, stable IFOG can be achieved with only one coupler and with no polarizer or polarization maintaining devices.

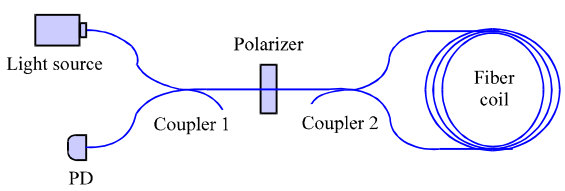

Fig. 1: Conventional minimal scheme for IFOGs

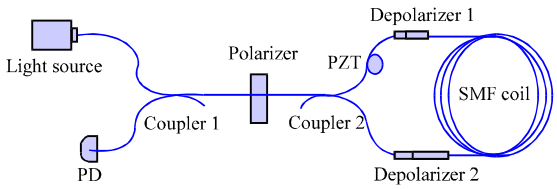

Fig. 2: Conventional depolarized IFOG

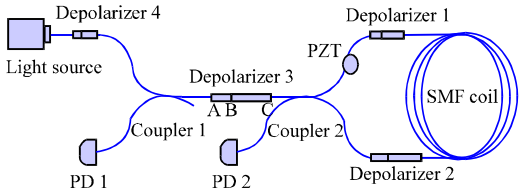

Fig. 3: All-depolarized IFOG with optical compensation

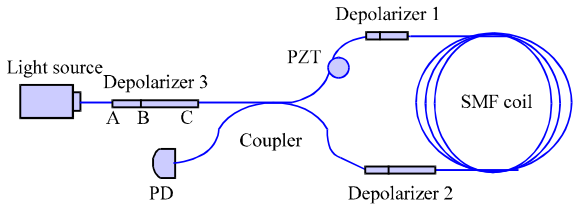

Fig. 4: Minimal scheme for optically compensated IFOGs

The PD in Fig. 4 is equivalent to PD 2 in Fig. 3. Here, matrix analysis is used to clarify the amount of PN errors of PD 1 and PD 2 in Fig. 3 and to show how optical compensation works.

The Degree of Polarization (DOP) at point B in Fig. 3 is noted as d, normalized fields here are written as (Mathis *et al*., 1994):

$$E_B = \begin{bmatrix} \sqrt{(1+d)/2} \\ \sqrt{(1-d)/2} \end{bmatrix} e^{j\omega_0 t} \tag{1}$$

Here ω_0 is optical frequency, which is much higher than the cutoff frequency of PDs. BC part of the Lyot depolarizer can be regarded as two orthogonal polarizers with a delay for decoherence as:

$$P_x = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} e^{-j\Delta\beta L_{BC}}, \quad P_y = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{2}$$

The transmission matrices for optical circuits after Point C have reciprocal forms, as given by (Andronova and Malykin, 2002):

$$M^+ = \begin{bmatrix} C_1 & C_2 \\ C_3 & C_4 \end{bmatrix}, \quad M^- = \begin{bmatrix} C_1 & C_3 \\ C_2 & C_4 \end{bmatrix} \tag{3}$$

where, the superscripts '+' and '-' stands for clockwise (CW) and counterclockwise (CCW), respectively. C_1, C_2, C_3 and C_4 are complex coefficients.

There are eight paths for light to reach PD 1, four paths finally coupled into x polarization and the other four into y polarization as:

$$\begin{aligned} E^+_{xx} &= P_x M^+ P_x E_B e^{j\phi}, \quad E^-_{xx} = P_x M^- P_x E_B \\ E^+_{yx} &= P_x M^+ P_y E_B e^{j\phi}, \quad E^-_{yx} = P_x M^- P_y E_B \end{aligned} \tag{4}$$

$$\begin{aligned} E^+_{yy} &= P_y M^+ P_y E_B e^{j\phi}, \quad E^-_{yy} = P_y M^- P_y E_B \\ E^+_{xy} &= P_y M^+ P_x E_B e^{j\phi}, \quad E^-_{xy} = P_y M^- P_x E_B \end{aligned} \tag{5}$$

Here, $\phi = \phi_S + \Delta\phi$ (t) includes both the Sagnac phase shift ϕ_S and the modulated phase $\Delta\phi$ (t). The interference signals in two polarizations at PD 1 are then derived as:

$$\begin{aligned} I_x &= <| E^+_{xx} + E^-_{xx} + E^+_{yx} + E^-_{yx} |^2> \\ &= I_{x0} + q_x \cos\phi + p_x \sin\phi \\ &= I_{x0} + \sqrt{p_x^2 + q_x^2} \cos(\phi - \phi^x_{err}) \end{aligned} \tag{6}$$

$$\begin{aligned} I_y &= <| E^+_{yy} + E^-_{yy} + E^+_{xy} + E^-_{xy} |^2> \\ &= I_{y0} + q_y \cos\phi + p_y \sin\phi \\ &= I_{y0} + \sqrt{p_y^2 + q_y^2} \cos(\phi - \phi^y_{err}) \end{aligned} \tag{7}$$

where, I_{x0} and I_{y0} are direct-current components $\phi^x_{err} = \arctan(p_x/q_x)$ and $\phi^y_{err} = \arctan(p_y/q_y)$ are PN errors in two polarizations, with:

$$\begin{aligned} p_x &= -\frac{1}{2}(1-d)\,|C_2C_3|\,\Gamma(z_{23})\sin\phi_{23} \\ q_x &= \frac{1}{2}|C_1|^2(1+d) + (1-d)\,|C_2C_3|\,\Gamma(z_{23})\cos\phi_{23} \end{aligned} \tag{8}$$

$$\begin{aligned} p_y &= \frac{1}{2}(1+d)\,|C_2C_3|\,\Gamma(z_{23})\sin\phi_{23} \\ q_y &= \frac{1}{2}|C_4|^2(1-d) + (1+d)\,|C_2C_3|\,\Gamma(z_{23})\cos\phi_{23} \end{aligned} \tag{9}$$

Here, Γ (z) is the degree of coherence for the light source (Szafraniec and Sanders, 1999), z_{23} is the birefringent delay induced by $C_2C_3^*$ and ϕ_{23} is the phase of $C_2C_3^*$. Here, p_x and q_x have different signs, which leads to opposite polarities of PN errors ϕ^x_{err} and ϕ^y_{err}.

Optically compensated result is derived by summing up I_x and I_x as:

$$\begin{aligned} I_{sum} &= I_{x0} + I_{y0} + (q_x + q_y)\cos\phi + (p_x + p_y)\sin\phi \\ &= I_{DC} + \sqrt{(p_x + p_y)^2 + (q_x + q_y)^2}\cos(\phi - \phi^{sum}_{err}) \end{aligned} \tag{10}$$

And thus the PN error after compensation is:

$$\begin{aligned} \phi^{sum}_{err} &= \arctan\frac{p_x + p_y}{q_x + q_y} \\ &= \arctan\frac{2d\,|C_2C_3|\,\Gamma(z_{23})\sin\phi_{23}}{|C_1|^2(1+d) + |C_4|^2(1-d) + 2\,|C_2C_3|\,\Gamma(z_{23})\cos\phi_{23}} \end{aligned} \tag{11}$$

Clearly, a balance intensity distribution between two polarizations (d = 0) will achieve eliminated PN errors ($\phi^{sum}_{err} = 0$). In this way, optical compensation is verified effective for PN error reduction.

Likewise, the signal detected at PD 2 in Fig. 3 (or the PD in Fig. 4) can be derived. Without going back through Depolarizer 3, it contains only four possible light paths as:

$$E^+_x = M^+ P_x E_0 e^{j\phi}, \quad E^-_x = M^- P_x E_0 \tag{12}$$

$$E^+_y = M^+ P_y E_0 e^{j\phi}, \quad E^-_y = M^- P_y E_0 \tag{13}$$

With the same deriving process as Eq. 6-9, parameters got for this conventionally "nonreciprocal" port are:

$$\begin{aligned} p^N_x &= (1-d)\,|C_2C_3|\,\Gamma(z_{23})\sin\phi_{23} \\ q^N_x &= -|C_1|^2(1+d) - (1-d)\,|C_2C_3|\,\Gamma(z_{23})\cos\phi_{23} \end{aligned} \tag{14}$$

$$p_y^N = -|C_2C_3|(1+d)\Gamma(z_{23})\sin\phi_{23}$$
$$q_y^N = -|C_4|^2(1-d) - |C_2C_3|(1+d)\Gamma(z_{23})\cos\phi_{23} \quad (15)$$

Comparing Eq. 8-9 with Eq. 14-15, PD 1 and 2 has the same PN noise pattern as $p_x/q_x = P^n_x/q^N_x$ and $p_y/q_y = P^N_y/q^N_y$. Optical compensation also functions to suppress PN errors at PD 2 in absolutely the same way as in PD 1.

In addition to this conclusion, optically compensated IFOG actually requires only one coupler for polarization reciprocity. Hence, Fig. 4 is proved to be the minimal scheme for optically compensated IFOGs.

RESULTS AND DISCUSSION

The minimal scheme for optically compensated IFOGs in Fig. 4 differs from the conventional one in Fig. 1 in the number of required couplers. Only one coupler is required in this depolarized structure. This is the advantage of optical compensation over the convention polarizer.

To verify this advantage, signals of both two PDs are detected in the optically compensated IFOG. The experiment was carried out under uncontrolled room temperature, targeting the Earth's rotation rate (9.666°/h projected at our laboratory latitude). Detection results are shown in Fig. 5a and b, consistent with our theory analysis. Two results have similar and stable performance, both of which have reduced PN errors. The only difference between two results is a stable bias induced by coupler nonreciprocity, which can be corrected by simply subtracting the offset.

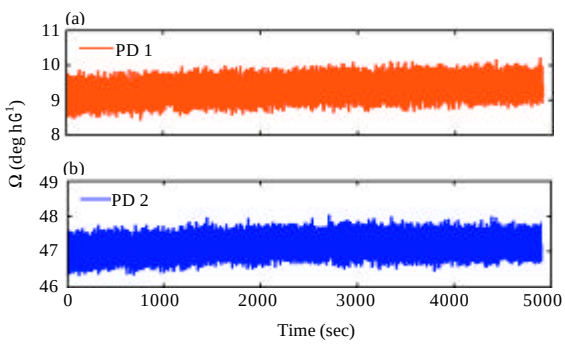

Fig. 5(a-b): Rotation detection results by two PDs in the optically compensated IFOG (a) PD 1 and (b) PD 2

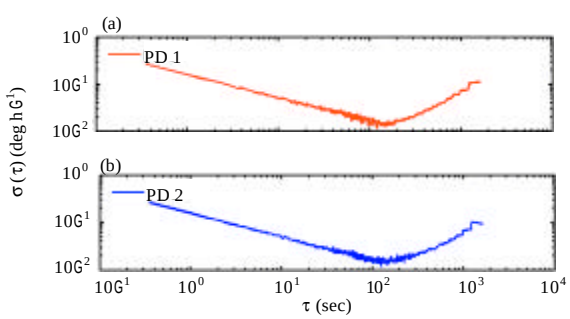

Fig. 6(a-b): Allan variance analysis for two results in the optically compensated IFOG (a) PD 1 and (b) PD 2

The stable IFOG performance is further verified by Allan variance analysis (IEEE, 2008) as shown in Fig. 6a and b. A low bias drift of 0.02° h^{-1} is achieved by both detecting ports.

The experimental results have shown that the conventional "nonreciprocal" port of the IFOG change into a "reciprocal" port in optically compensated IFOG. Both two PDs are capable to receive stable results of rotation sensing in our IFOG.

In previous studies on optically compensated IFOGs, two polarizations in the "reciprocal" port were utilized for compensating PN errors (Yang *et al*., 2012; Wang *et al*., 2013). In this study, the conventional "nonreciprocal" port is also proved effective in the IFOG based on optical compensation. In other words, two couplers are no more necessary in this case, as one coupler is already enough for constructing a high performance IFOG. Hence, Fig. 4 is verified to be the minimal scheme for optically compensated IFOGs and it is the simplest setup for high performance among all current IFOGs.

CONCLUSION

The optical compensation mechanism in IFOGs is analyzed, and a minimal scheme for optically compensated IFOGs is achieved. Different from the minimal scheme for conventional IFOGs, the new minimal scheme required only one coupler instead of two. Besides less structural complexity, it also has the advantage that no polarizer or any other polarization maintaining device is required. The rotation sensing performance of this design mainly relies on the performance of depolarizers. With Lyot depolarizes constructed by PMF, high performance IFOG can be achieved with less structural complexity and less cost than conventional ways. Further works can be carried out to optimize the optically compensated IFOG design by constructing better depolarizers.

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REFERENCES

Andronova, I.A. and G.B. Malykin, 2002. Physical problems of fiber gyroscopy based on the Sagnac effect. Phys. Uspekhi, 45: 793-817.

Carrara, S.L.A., B.Y. Kim and H.J. Shaw, 1987. Bias drift reduction in polarization-maintaining fiber gyroscope. Opt. Lett., 12: 214-216.

IEEE, 2008. IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros. Institute of Electrical and Electronics Engineers, New York, USA..

Jones, E. and J.W. Parker, 1986. Bias reduction by polarisation dispersion in the fibre-optic gyroscope. Electron. Lett., 22: 54-56.

Lefevre, H.C., 1993. The Fiber-Optic Gyroscope. Artech House, USA., ISBN-13: 9780890065372, Pages: 313.

Mathis, R.F., B.A. May and T.A. Lasko, 1994. Polarization coupling in unpolarized Interferometric Fiber Optic Gyros (IFOGs): Effect of imperfect components. Proceedings of the SPIE Conference on Fiber Optic and Laser Sensors XII, Volume 2292, July 24-29, 1994, San Diego, USA., pp: 283-291.

Post, E.J., 1967. Sagnac effect. Rev. Mod. Phys., 39: 475-493.

Szafraniec, B. and J. Blake, 1994. Polarization modulation errors in all-fiber depolarized gyroscopes. J. Lightwave Technol., 12: 1679-1684.

Szafraniec, B. and G.A. Sanders, 1999. Theory of polarization evolution in interferometric fiber-optic depolarized gyros. J. Lightwave Technol., 17: 579-590.

Ulrich, R. and M. Johnson, 1979. Fiber-ring interferometer: Polarization analysis. Opt. Lett., 4: 152-154.

Wang, Z., Y. Yang, Y. Li, X. Yu, Z. Zhang and Z. Li, 2012. Quadrature demodulation with synchronous difference for interferometric fiber-optic gyroscopes. Opt. Express, 20: 25421-25431.

Wang, Z., Y. Yang, P. Lu, Y. Li, C. Peng, Z. Zhang and Z. Li, 2013. Optical compensation for compressing polarization nonreciprocity induced errors in interferometric fiber-optic gyroscopes. Applied Mech. Mater., 303-306: 82-85.

Yang, Y., Z. Wang and Z. Li, 2012. Optically compensated dual-polarization interferometric fiber-optic gyroscope. Opt. Lett., 37: 2841-2843.