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Polarizer Requirements for Fiber Gyroscopes with High-Birefringence Fiber and Broad-Band Sources

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Abstract—Polarizer requirements for fiber-optic gyroscopes with high-birefringence fiber and broad-band sources are investigated theoretically by employing a model with a single coupling center between polarization modes. The phase bias offset due to a finite polarizer extinction ratio is greatly reduced by incoherent effects, and may be further reduced by using a depolarized source or by appropriate orientation of the polarizer transmission axis. Some experimental data is presented which supports the theoretical model.

I. Introduction

Optical polarization requirements were recognized early in the development of fiber-optical gyroscopes [1], [2]. The preferred position of the polarizer in the optical gyro circuit was given by Ulrich [3]. An analysis of the effect of a realistically imperfect polarizer in that position was carried out by Kintner [4], who showed that a phase bias results which is proportional to the polarizer amplitude extinction ratio. This phase bias causes an offset in the apparent rotation rate from its true value. Estimates of the required polarizer quality for specified gyroscope performance have been difficult to state. Bergh *et al.* [5] have inferred from one gyro experiment that the intensity extinction ratio of a fiber-optic polarizer was of the order of 90 dB, a value so high that it could not be measured by other means. More recently, work at our laboratory demonstrated a high-performance fiber gyroscope [6], [7] with a conventional bulk optic polarizer having an intensity extinction ratio of only ~50 dB. However, our device also had two significant differences from the experiment of [5]: it employed a broad-band superluminescent diode (SLD) [8] as the source, and it employed high-birefringence polarization-holding optical fibers. Neither of these features were explicitly considered in the analysis of Kintner. In this paper we provide a theoretical analysis which accounts for these factors. We follow closely our earlier analysis of fiber-optic gyros with broad-band sources [9], which treated the cases of ideally polarized and ideally unpolarized sources. In that treatment we found that coherence effects arising from the source bandwidth and fiber polarization-mode dispersion greatly reduced potential noise contributions in the gyro output. In a similar manner we show here that coherence effects can greatly reduce the phase bias offset, and the instability in the offset, that would otherwise result from an imperfect polarizer. This result, already experimentally indicated [7], is of considerable importance to the development of fiber-optic gyroscopes. In addition, we provide some experimental data which shows how the bias offset error varies with the polarizer orientation and extinction ratio for our setup.

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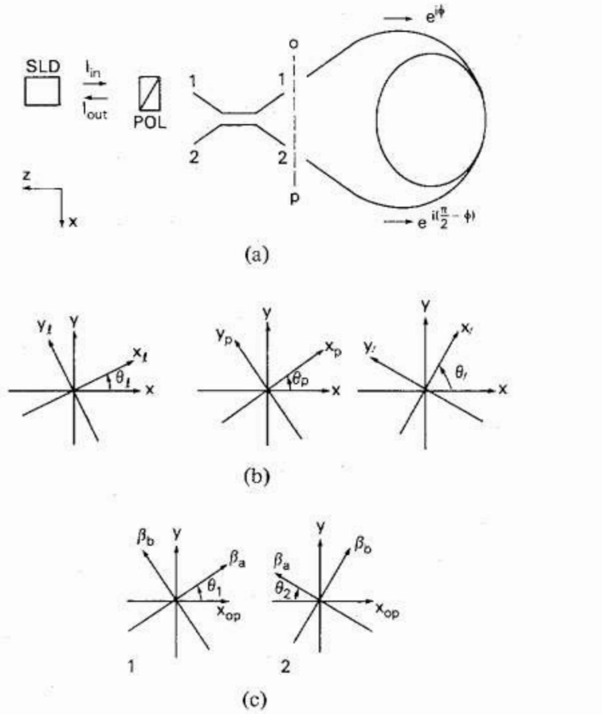

Fig. 1. (a) Fiber gyro configuration assumed in the calculations. (b) Orientation of the source, polarizer and fiber coupler lead. (c) Orientation of the fiber-coil ends.

II. Theory

We consider a gyroscope arrangement, shown in Fig. 1(a), consisting of a superluminescent diode (SLD) with an arbitrary degree of polarization, an imperfect polarizer, a fiber coupler, and a fiber coil. The gyro signal is taken as that intensity of light returning to the source through the polarizer. The 2×2 directional coupler is assumed to be fabricated from high-birefringence fiber such that it provides 3 dB of coupling for each polarization mode. The fiber comprising the coil is assumed to have linear high birefringence with resulting difference in mode propagation constant $\Delta\beta = \beta_b - \beta_a$ and length L. The Sagnac phase shift is 2ϕ and we assume an additional nonreciprocal phase shift of $\pi/2$ for propagation in the counterclockwise direction, to give output equations with maximum sensitivity at zero rotation rate. Various ways for achieving this result experimentally are described in the literature [3]. In Fig. 1(a), the fiber coil lies in the X-Z-plane and the Y-axis is normal to the figure. In Fig. 1(b), we define coordinate axes (X_l, Y_l), (X_p, Y_p), and (X_f, Y_f), and corresponding orientation angles θ_l, θ_p, and θ_f relative to the X-Y frame to define the orientation of the SLD source, polarizer transmission axis, and fiber birefringence axes of the coupler input, respectively. The orientation of the birefringence axes a and b at the fiber-coil ends 1 and 2 are defined in Fig. 1(c) by the orientation angles θ_1 and θ_2. The birefringence axes undergo a reflection about the Y-Z-plane as the loop is traversed. Thus, with our convention in Fig. 1(c), we have $\theta_1 = \theta_2$ for an untwisted fiber. For a fiber loop with axes aligned with the axes of the coupler fiber, as is desirable, we require $\theta_1 = \theta_f$ and $\theta_2 = -\theta_f$. We assume twisting in the fiber loop to be small and gradual, so that induced circular birefringence can be neglected.

For a broad-band source with an arbitrary degree of polarization, the time-dependent output field may be expressed as

$$\begin{bmatrix} E_{xl}(t) \\ E_{yl}(t) \end{bmatrix} = \begin{bmatrix} a e_{xl}(t) \\ b e_{yl}(t) \end{bmatrix} e^{i\omega_0 t} \tag{1}$$

where ω_0 is the source center frequency and we have

$$\langle e_{xl}(t)\, e_{yl}^*(t) \rangle = \langle e_{yl}(t)\, e_{xl}^*(t) \rangle = 0 \tag{2}$$

where $\langle\,\rangle$ signifies time average. Equation (2) expresses the fact that in a partially polarized source there exist axes along which orthogonal field components are uncorrelated. For example, in a SLD, these axes are parallel and perpendicular to the junction plane. The source of (1) is defined by its coherency matrix $\boldsymbol{J}$ which is [10]

$$\boldsymbol{J} = \begin{bmatrix} \langle E_{xl} E_{xl}^* \rangle & \langle E_{xl} E_{yl}^* \rangle \\ \langle E_{yl} E_{xl}^* \rangle & \langle E_{yl} E_{yl}^* \rangle \end{bmatrix}. \tag{3}$$

For example, the source intensity is defined by $I = \text{trace}\, \boldsymbol{J}$, and can be normalized to unity by choosing

$$\langle e_{xl}(t)\, e_{xl}^*(t) \rangle = \langle e_{yl}(t)\, e_{yl}^*(t) \rangle = 1 \tag{4a}$$

and

$$a^2 + b^2 = 1. \tag{4b}$$

The source degree of polarization is defined by [10]

$$P = \left[1 - \frac{4 \det \boldsymbol{J}}{(tr \boldsymbol{J})^2}\right]^{1/2} \tag{5a}$$

or, using (1)-(4)

$$P = |(2a^2 - 1)|. \tag{5b}$$

To describe the source in a rotated coordinate frame we introduce the rotation matrix

$$C(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{6}$$

where θ is the angle between frames. The source field in the polarizer coordinate system is then given by

$$\begin{bmatrix} E_{xp} \\ E_{yp} \end{bmatrix} = C(\theta_{lp}) \begin{bmatrix} E_{xl} \\ E_{yl} \end{bmatrix} \tag{7}$$

where $\theta_{lp} = \theta_l - \theta_p$. Transmission in our imperfect polarizer is defined by

$$\begin{bmatrix} E_{xp} \\ E_{yp} \end{bmatrix}_{\text{trans}} = \begin{bmatrix} 1 & 0 \\ \delta & \epsilon \end{bmatrix} \begin{bmatrix} E_{xp} \\ E_{yp} \end{bmatrix}_{\text{inc}} \tag{8}$$

where X_p is the transmission axis, ϵ is the amplitude extinction coefficient, and we include a term δ which allows for scattering with 90° polarization rotation of the incident beam. This latter term may be the limiting factor in the best crystal polarizers. We assume ϵ and δ small compared to 1. The transmitted source field incident on the birefringent fiber coupler, in its coordinate frame, is then

$$\begin{bmatrix} E_{xf} \\ E_{yf} \end{bmatrix} = C(\theta_{pf}) \begin{bmatrix} E_{xp} \\ E_{yp} \end{bmatrix}_{\text{trans}} \tag{9}$$

where $\theta_{pf} = \theta_p - \theta_f$.

The coupler transfer matrix is defined by

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_{\text{out}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -i \\ -i & 1 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_{\text{in}} \tag{10}$$

for both polarizations and in either direction. The subscripts 1 and 2 refer to the coupler leads as shown in Fig. 1(a). We assume the orientations of the birefringent fibers in the coupler are identical and are maintained throughout the coupler. For an input at port 1, the outputs to the fiber loop are

$$\begin{bmatrix} E_{xf} \\ E_{yf} \end{bmatrix}_{\text{out},1} = \frac{1}{\sqrt{2}} \begin{bmatrix} E_{xf} \\ E_{yf} \end{bmatrix}_{\text{in}} \tag{11a}$$

$$\begin{bmatrix} E_{xf} \\ E_{yf} \end{bmatrix}_{\text{out},2} = \frac{-i}{\sqrt{2}} \begin{bmatrix} E_{xf} \\ E_{yf} \end{bmatrix}_{\text{in}} \tag{11b}$$

With the orientation of the birefringent fiber ends of the coil defined by θ_1 and θ_2 in Fig. 1(c), we assume axis alignment between the coupler leads and the coil ends such that $\theta_1 = \theta_f$ and $\theta_2 = -\theta_f$. The inputs to the fiber loop are then given by

$$\begin{bmatrix} E_{a1} \\ E_{b1} \end{bmatrix} = \begin{bmatrix} E_{xf} \\ E_{yf} \end{bmatrix}_{\text{out},1} \tag{12a}$$

$$\begin{bmatrix} E_{a2} \\ E_{b2} \end{bmatrix} = \begin{bmatrix} -E_{xf} \\ E_{yf} \end{bmatrix}_{\text{out},2} \tag{12b}$$

which results in a sign reversal of the field along the a-axis at 2. Equation (1) and (7)-(12) define the time-dependent input fields to the fiber loop.

In the fiber loop we assume a polarization-mode-coupling center which couples a fraction of power α between the modes at a location l, measured from fiber end 1 (Fig. 2). We assume no mode coupling at other points along the fiber. The transfer matrix for the mode-coupling center, for propagation from $1 \to 2$ may be expressed

$$\begin{bmatrix} E_a(l^+) \\ E_b(l^+) \end{bmatrix} = \begin{bmatrix} \sqrt{1-\alpha} & \sqrt{\alpha} \\ -\sqrt{\alpha} & \sqrt{1-\alpha} \end{bmatrix} \begin{bmatrix} E_a(l^-) \\ E_b(l^-) \end{bmatrix} \tag{13}$$

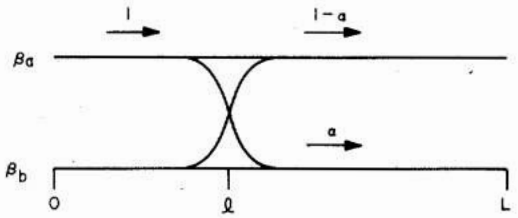

Fig. 2. Model for a mode-coupling center which couples power α between the polarization modes.

where l^+ and l^- refers to just after and just before the coupling center at l, respectively. For propagation from $2 \rightarrow 1$, the inverse of the matrix in (13) must be employed.

Propagation in the fiber is governed by the frequency-dependent propagation constants $\beta_a \equiv \beta_a(\omega)$ and $\beta_b \equiv \beta_b(\omega)$. Employing the transfer matrix in (13) and the loop phase shifts shown in Fig. 1(a), we obtain the frequency-dependent fiber-transfer equations

$$\begin{bmatrix} E^o_{a2}(\omega) \\ E^o_{b2}(\omega) \end{bmatrix} = e^{i\phi} \begin{bmatrix} \sqrt{1-\alpha}\, e^{-i\beta_a L} & \sqrt{\alpha}\, e^{-i[\beta_b l + \beta_a (L-l)]} \\ -\sqrt{\alpha}\, e^{-i[\beta_a l + \beta_b (L-l)]} & \sqrt{1-\alpha}\, e^{-i\beta_b L} \end{bmatrix} \begin{bmatrix} E_{a1}(\omega) \\ E_{b1}(\omega) \end{bmatrix} \tag{14a}$$

$$\begin{bmatrix} E^o_{a1}(\omega) \\ E^o_{b1}(\omega) \end{bmatrix} = ie^{-i\phi} \begin{bmatrix} \sqrt{1-\alpha}\, e^{-i\beta_a L} & -\sqrt{\alpha}\, e^{-i[\beta_a l + \beta_b (L-l)]} \\ \sqrt{\alpha}\, e^{-i[\beta_b l + \beta_a (L-l)]} & \sqrt{1-\alpha}\, e^{-i\beta_b L} \end{bmatrix} \begin{bmatrix} E_{a2}(\omega) \\ E_{b2}(\omega) \end{bmatrix} \tag{14b}$$

where the superscript o denotes an output field. We note that (12) is time dependent whereas the inputs required in (14) are frequency dependent. Using equations (10) and (12) we can obtain the coupler output at port 1, in the coupler frame $E^o_{xf}(\omega)$ and $E^o_{yf}(\omega)$. In the polarizer coordinates, the output becomes

$$\begin{bmatrix} E^o_{xp}(\omega) \\ E^o_{yp}(\omega) \end{bmatrix} = C(-\theta_{pf}) \begin{bmatrix} E^o_{xf}(\omega) \\ E^o_{yf}(\omega) \end{bmatrix}_1. \tag{15}$$

The output of the polarizer, to first order in δ and ϵ, is just $E^o_{xp}(\omega)$. However, what we want is the time averaged output intensity, which may be expressed in terms of the time-dependent field as

$$I_p = \langle |E^o_{xp}(t)|^2 \rangle. \tag{16}$$

To calculate (16) for the case of broad-band light we employ the rule for interference of quasi-monochromatic light [10], [11], which is rederived in [9] for the case of polarization modes in a dispersive medium. The result for the gyro signal returned to the source is

$$I_p \simeq \tfrac{1}{2}(1-\alpha)\, a^2 [1 + \sin(2\phi + \phi_\epsilon)] \tag{17a}$$

where the phase-bias offset ϕ_ϵ is given by

$$\phi_\epsilon \simeq \left(\delta + \frac{\epsilon P \tan\theta_{lp}}{a^2}\right) \left\{ \left(\frac{\alpha}{1-\alpha}\right) \sin 2\theta_{pf}\, \gamma(L-2l) \sin \Delta\beta_o (L-2l) + \sqrt{\frac{\alpha}{1-\alpha}} \cos 2\theta_{pf} [\gamma(L-l) \sin \Delta\beta_o (L-l) - \gamma(l) \sin \Delta\beta_o l] \right\}. \tag{17b}$$

In (17) we ignore the frequency dependence of the Sagnac phase shift 2ϕ, and we have assumed $\theta_l \simeq \theta_p$, i.e., θ_{lp} is small.

The input intensity through the polarizer is then a^2, in first order. P is the source degree of polarization defined by (5), and $\Delta\beta_o \equiv \Delta\beta(\omega_o)$. $\gamma(z)$ is the degree of coherence [10], which for a Gaussian-shaped spectral intensity $|\nu(\omega)|^2$

$$|\nu(\omega)|^2 = \exp\left\{-\ln 2 \left[\frac{(\omega - \omega_o)}{\delta\omega}\right]^2\right\} \tag{18a}$$

is given by [12]

$$\gamma(z) = \exp\left[-\left(\frac{\delta\omega\delta\tau_g z}{2\sqrt{\ln 2}}\right)^2\right]. \tag{18b}$$

In (18) $\delta\omega$ is the half-width at half intensity of the Gaussian spectrum, and $\delta\tau_g = d\Delta\beta/d\omega$ is the fiber group delay difference or polarization-mode dispersion. We note that $\gamma(z)$ varies between 1 and 0 and exponentially decays to e^{-1} at a length

$$L_\gamma = \frac{2\sqrt{\ln 2}}{\delta\omega\delta\tau_g} \tag{19}$$

which may be considered typical of the distance over which the light can propagate in the two modes and still interfere upon recombination. L_γ is the depolarization length [11] for a source with bandwidth $\delta\omega$ in a fiber with group delay difference $\delta\tau_g$.

III. Discussion

Equation (17) for the phase bias offset ϕ_ϵ is our desired result. This result is equivalent to that derived by Kintner [4] except that we explicitly considered a broad-band source with a high-birefringence fiber in which mode coupling is represented by the single coupling center model of Fig. 2. Because any real fiber has many mode-coupling centers, our model cannot give quantitative results, but can only be used as a guide to understand the effects of mode coupling.

Looking first at the second bracketed term in (17b), we see that as in the previous analysis with a perfect polarizer or with no polarizer, the effect of the coherence terms $\gamma(z)$ is to allow coupling contributions only from sections of the fiber where $\gamma(z)$ is nonzero. This occurs, as shown in Fig. 3, at each end and at the middle of the fiber coil where $l \leqslant L_\gamma$, $L - l \leqslant L_\gamma$, or $|L - 2l| \leqslant L_\gamma$, respectively. Mode coupling from other sections of the fiber does not lead to interference terms in the output and does not contribute to the phase bias offset. Since the depolarization length L_γ in a high-birefringence fiber can

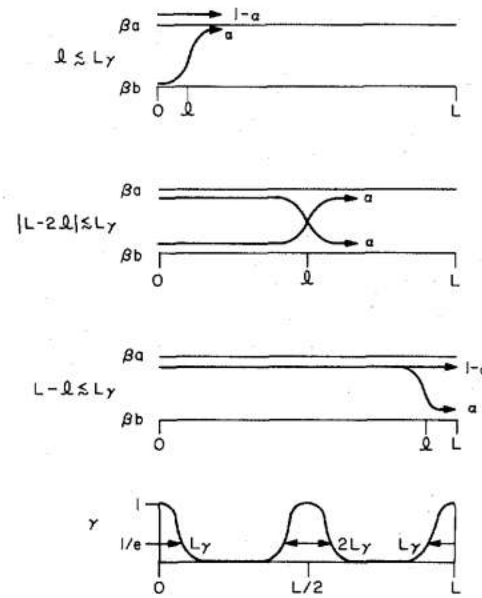

Fig. 3. (a) Models for mode-coupling centers at the ends and middle of the fiber coil that contribute to phase bias offset in the fiber gyro output. (b) The corresponding value of the degree of coherence for each case in (a) when $L_\gamma << L$.

be on the order of 10 cm with an SLD source [9], only a very small fraction of the total number of mode-coupling centers will contribute. Most of the coupled power is incoherent with the signal at the output. This term also has an alignment factor such that if the polarizer axis and an input coupler fiber axis are aligned, the contribution from the middle of the fiber is removed.

Looking at the first bracketed term in (17b), we see that the term in ϵ can be reduced to zero either by making the degree of polarization P zero or by aligning the polarizer such that its transmission axis is parallel to an axis of the source. In the latter case, the power ϵ^2 transmitted by the attenuating axis of the polarizer is uncorrelated with the power transmitted by the polarizer transmission axis, and interference between these powers with resulting phase bias offset in the output signal cannot result. This is analogous to Kintner's result when his (assumed) polarized input is aligned parallel to the transmission axis. If the input light is completely depolarized ($P = 0$), the alignment angle θ_{lp} becomes irrelevant because in a depolarized source the field along any two orthogonal axes is uncorrelated. Thus for perfectly depolarized light incident on the polarizer, the extinction ratio ϵ drops out of the problem. Of course, a 3-dB power penalty is paid at the polarizer.

The term in δ does not depend on the state of polarization of the input. Since a power δ^2 is assumed to be scattered from the transmitted beam, it is always coherent with it. However, for $P \neq 0$, the contributions from δ and ϵ to the phase bias offset can presumably be made to cancel each other by appropriate adjustment of the alignment angle θ_{lp}.

It is appropriate now to consider the effect of one assumption in the preceeding calculation, that of alignment between the coupler fiber leads and the fiber-coil ends. If in manufacture small errors are made in these alignments, they will appear as fixed-mode-coupling centers with coupled power proportional to the alignment error. To eliminate the effect of these misalignments in the gyro output, one should simply make the coupler leads long compared to the depolarization length L_γ.

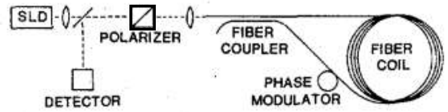

Fig. 4. Configuration of optical components of the gyroscope used in the experiment.

IV. Experiment

We attempted to verify some aspects of the theory derived here using a high-precision fiber gyroscope reported previously [6], [7]. The arrangement of the optical components used is shown in Fig. 4. Since the components before the gyro coupler were all bulk optical components, both the degree of polarization of the source and the polarizer transmission axis orientation and extinction ratio could be varied. All fibers used in the gyro were polarization-holding high-birefringence fibers. The fiber coil was 430 m long, wound on a 16-cm-radius coil. The SLD was run at 3-mW output. The gyro coil was horizontal so that earth's rate signal was +9.4 deg/h at our location.

For these experiments, we measured the phase bias offset by measuring the earth's rotation rate and comparing the measured value with the expected value. The polarizer extinction ratio was varied by using a prism polarizer ($\epsilon^2 = 10^{-5}$) and different Polaroid sheet polarizers. The source degree of polarization is normally $P = 0.43$ and can be reduced to $P = 0.04$ by inserting glass slides in the beam at an appropriate angle. There were several experimental difficulties in taking this data. We noticed a dependence of the results on the cleave at the fiber end where input coupling into the fiber coupler occurred. Also, there were two joints between the coupler leads and fiber-coil ends formed with Si-Vee grooves, at which alignment had to be maintained. Changes in these alignments would affect the second term in (17b) and thus the bias offset. Occasionally these joints had to be readjusted and the previous condition would be lost.

Nevertheless, we show in Figs. 5–7 illustrative data that we were able to obtain. In this data we plot the gyro sensitivity [9] and the measured rotation rate versus the polarizer angle θ_p. The source major axis was aligned near vertical which corresponds to $\theta_p = 90°$ so we would expect maximum gyro sensitivity and minimum phase bias offset near that position. In Fig. 5 we had $\epsilon^2 = 6 \cdot 10^{-5}$ and $P = 0.43$, and in Fig. 6, which was data taken with the same fiber end cleave $\epsilon^2 = 0.34$ and $P = 0.04$. In each case, the measured rate crosses earth's rate near the maximum in gyro sensitivity, but with the poorer polarizer in Fig. 6 the slope of the curve is much steeper. In each case, the rate curves eventually began to reverse direction, which we did not understand. In Fig. 7 with a different fiber cleave and with $\epsilon^2 = 10^{-5}$, $P = 0.04$, we saw a monotonic decrease of the measured rate with θ_p, but at a much faster rate than in Fig. 5.

The data in Figs. 5–7 was taken over a period of about 1 h in each case. No attempt was made to demonstrate long-term stability as in [7]. For each orientation of the polarizer, the

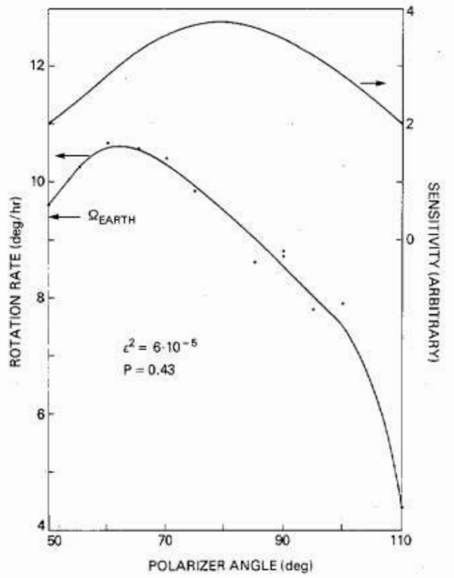

Fig. 5. Gyro sensitivity and rotation rate versus polarizer orientation angle for $\epsilon^2 = 6 \cdot 10^{-5}$, $P = 0.43$.

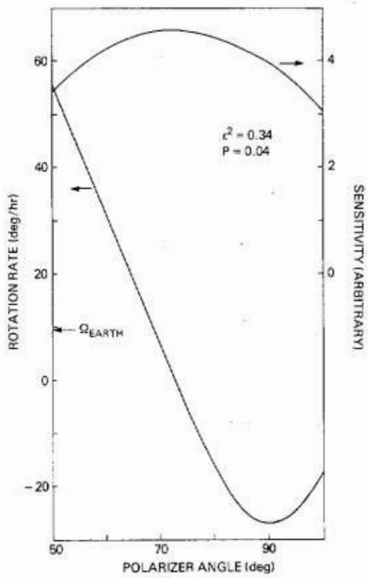

Fig. 6. Gyro sensitivity and rotation rate versus polarizer orientation angle for $\epsilon^2 = 0.34$, $P = 0.04$.

observed rotation rate was stable and reproducible compared to the changes induced by variation of the polarizer orientation. The gyroscope was not enclosed in an insulated chamber for these runs, but temperature stability was within 0.5°C.

In general, this data does demonstrate the tunability of the phase bias offset by adjustment of the polarizer orientation. It also shows the expected dependence on extinction ratio. We were not able to explicitly show the degree of polarization dependence predicted by the theory with a polarizer in place. However, without any polarizer at all, we noticed that the bias offset was reduced from ~2000 deg/h with $P = 0.43$ to -280 deg/h with $P = 0.04$. For this situation, other terms would appear in (17) because in our derivation we assumed ϵ small.

V. Conclusions

We have considered the problem of polarizer requirements in a fiber-optic gyroscope using high-birefringence fiber and a

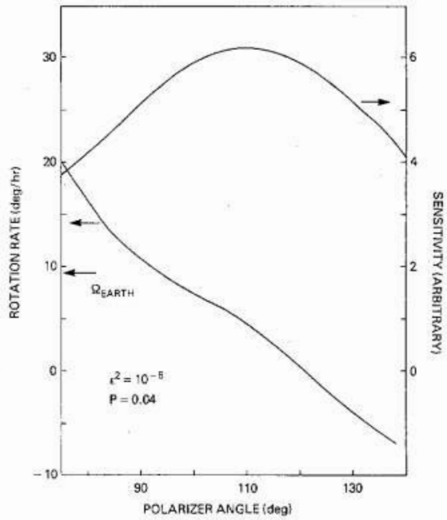

Fig. 7. Gyro sensitivity and rotation rate versus polarizer orientation angle for $\epsilon^2 = 10^{-5}$, $P = 0.04$.

broad-band source. Using a model with one mode-coupling center in a high-birefringent single-mode fiber we derived an output equation for a fiber-optic gyro which shows that contributing mode-coupling effects to the phase bias offset are limited to very small regions at the ends and middle of the fiber coil due to coherence effects. Furthermore, the phase bias offset may be tuned to zero by adjusting the orientation of the polarizer transmission axis, and in addition may be reduced by reducing the degree of polarization of the light incident on the polarizer. Although our model is not quantitative, it implies that extremely small values of polarizer extinction ratio are not necessarily required to achieve a small phase bias offset.

We then experimentally investigated fiber gyro polarizer requirements by measuring the apparent rate in a gyro with a broad-band source and high-birefringence fiber, while varying polarizer extinction ratio, orientation, and incident degree of polarization. Although this type of investigation is experimentally difficult, we did demonstrate the expected dependence on polarizer orientation and extinction ratio. In particular, we showed that the phase bias offset could be reduced to zero by adjusting the polarizer orientation and that this could be done even with a polarizer intensity extinction ratio as poor as -5 dB ($\epsilon^2 = 0.34$). We were less successful in demonstrating the theoretical dependence on the source degree of polarization.

We conclude then that optimum performance of a fiber gyroscope of this type will be obtained with depolarized light incident on the polarizer, and with the polarizer transmission axis oriented such that the phase bias offset is reduced to zero. In addition, splices between the ends of birefringent fiber within the coil should be made more than a depolarization length away from the fiber coupler.

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Polarization Preservation in Circular Multimode Optical Fibers and Its Measurement by a Speckle Method

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***Abstract*—The first-order statistics of the Stokes parameters (SP's) are used to investigate the polarization properties of a circular multimode optical fiber. Linearly polarized light launched into an optical fiber 3 m in length is found to be partially preserved. The degree of polarization P was a proper parameter to measure quantitatively the polarization preservation in our experiments. P was especially high, when the speckle field produced at the end of the fiber was nonuniform. In all experimental investigations, the probability density functions (PDF's) of the Stokes parameters, calculated theoretically, coincide well with the experimental results. The spatial stationarity of the fiber speckle pattern has been verified when all modes are equally excited.**

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I. Introduction

ABOUT A DECADE AGO the depolarization effects in multimode optical fibers were theoretically and experimentally investigated by Cohen [1]. Experimentally he found

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