Polarization-induced noise in a fiber-optic Michelson interferometer with Faraday rotator mirror elements

L. A. Ferreira, J. L. Santos, and F. Farahi

Faraday rotator mirror elements have been used in a number of applications as compensators for induced birefringence in retracing paths. In interferometric systems, such as the fiber-optic Michelson interferometer, this approach proved to be useful in providing maximum fringe visibility and insensitivity to the polarization state of light injected into the interferometer. However, it is found that, when the characteristics of the fiber coupler depend on the polarization state of the input beam, the efficiency of the Faraday mirror elements is limited. Theoretical analysis and experimental results in support of this statement are presented.

Key words: Fiber-optic sensors, interferometers, polarization-induced fading, fiber birefringence, Faraday rotator mirror elements, fiber couplers.

In interferometric optical-fiber sensors using a conventional low-birefringence fiber, random fluctuations in the state of polarization (SOP) of the interfering beams give rise to variations in the output fringe visibility[1–4] and consequently to fading of the detected interferometric signal. This polarization-induced fading phenomenon is an important drawback that affects the practical applicability of interferometric sensors in a number of areas. Several schemes have been used to overcome this effect.[2–9] Probably the most successful has been the one based on the use of reciprocal birefringence compensation in a retraced fiber path in which Faraday rotator mirror elements were used. When this technique was used, it was possible to achieve constant visibility (close to one) regardless of the input polarization state to the interferometer and the birefringence in the input fiber and in the interferometric fiber arms.[9] This technique has been applied to a number of sensor configurations,[10,11] always with a very good performance.

However, in interferometric applications using, for example, the fiber-optic Michelson interferometer, no reference has been made, to our knowledge, to the coupler influence on the efficiency of the Faraday rotator mirror elements with retracing paths. It is well known that standard couplers exhibit birefringence and that the splitting ratio depends on the input polarization state as does the phase shift between the split waves ($\pi/2$ for an ideal 2×2 coupler).[2,3,12–14] This happens because in general the fiber directional coupler is not exactly a symmetrical element. Here we show both theoretically and experimentally that this characteristic of the fiber coupler can seriously affect the efficiency of the Faraday-rotator-based schemes in eliminating the polarization-induced noise.

Typically, in practical applications of the birefringence-compensated Michelson interferometer (Fig. 1), the reciprocal output port of the interferometer is used (output 2 in Fig. 1) rather than the nonreciprocal port (output 1 in Fig. 1). Hence we focus our analysis on the behavior of the signal received from the reciprocal output. The electric field can be calcu-

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Received 14 February 1995; revised manuscript received 15 May 1995.
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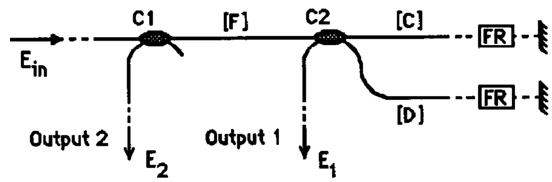

Fig. 1. Diagram of an all-fiber Michelson interferometer with the retardations of its components represented by Jones matrices [**C**], [**D**], and [**F**]; FR, Faraday rotator.

lated with the Jones matrix formalism:

$$\begin{aligned}\overrightarrow{\mathbf{E}}_2 = {}& \frac{1}{2}[(1-\alpha[\mathbf{P}_F])\cdot(1-\alpha[\mathbf{P}_C])]^{1/2}\cdot[\overleftarrow{\mathbf{F}}]\cdot[\overleftarrow{\mathbf{X}}']\cdot[\overleftarrow{\mathbf{C}}]\\ &\cdot[\mathbf{FRM}]\cdot[\overrightarrow{\mathbf{C}}]\cdot[\overrightarrow{\mathbf{X}}']\cdot[\overrightarrow{\mathbf{F}}]\cdot\overrightarrow{\mathbf{E}}_{\text{in}}\\ &\times\exp\left[i\left(2\phi_F+2\phi_C-\frac{\phi[\mathbf{P}_F]}{2}-\frac{\phi[\mathbf{P}_C]}{2}\right)\right]\\ &+\frac{1}{2}(\alpha[\mathbf{P}_F]\cdot\alpha[\mathbf{P}_D])^{1/2}\cdot[\overleftarrow{\mathbf{F}}]\cdot[\overleftarrow{\mathbf{X}}]\cdot[\overleftarrow{\mathbf{D}}]\\ &\cdot[\mathbf{FRM}]\cdot[\overrightarrow{\mathbf{D}}]\cdot[\overrightarrow{\mathbf{X}}]\cdot[\overrightarrow{\mathbf{F}}]\cdot\overrightarrow{\mathbf{E}}_{\text{in}}\\ &\times\exp\left[i\left(2\phi_F+2\phi_D+\frac{\phi[\mathbf{P}_F]}{2}+\frac{\phi[\mathbf{P}_D]}{2}\right)\right].\end{aligned}\tag{1}$$

In Eq. (1) $\overrightarrow{\mathbf{E}}_{\text{in}}$ is the input field to the system, [**X**] and [**X**′] are the Jones matrices representing the coupler birefringence for the coupled wave and the direct wave, respectively, and $\alpha[\mathbf{P}_F]$, $\alpha[\mathbf{P}_C]$, and $\alpha[\mathbf{P}_D]$ are the splitting ratios for coupler C2 in situations in which the light comes from [**F**] to the coupler ($\alpha[\mathbf{P}_F]$), from [**C**] to the coupler ($\alpha[\mathbf{P}_C]$), and from [**D**] to the coupler ($\alpha[\mathbf{P}_D]$). We assume different splitting ratios because α is considered to be a scalar function of polarization, and in general the states of polarization (represented by $\mathbf{P}_F$, $\mathbf{P}_C$, and $\mathbf{P}_D$) of the light entering the coupling region from each coupler's port are different from one port to the other. Similarly, we make the phase difference between the coupled and direct waves to be $\phi[\mathbf{P}_F]$, $\phi[\mathbf{P}_C]$, and $\phi[\mathbf{P}_D]$ in each case. These terms can be written as

$$\phi[\mathbf{P}_i] = \frac{\pi}{2} + \gamma(\mathbf{P}_i),\tag{2}$$

with $i = F, C, D$, and $\gamma(\mathbf{P}_i)$ being the residual phase deviation from the ideal value of $\pi/2$, dependent on the input polarization state ($\mathbf{P}_i$). Without a loss of generality it is assumed that coupler C1 is an ideal component with a constant splitting ratio of 1/2, independent of the input polarization state. This assumption is valid because this coupler has no role in the interferometer's operation and it is used only to facilitate access to the reciprocal output. Terms ϕ_C, ϕ_D, and ϕ_F give the optical phases corresponding to the propagation in fibers [**C**], [**D**], and [**F**], respectively. The [**MFR**] matrix refers to the path FR + mirror + FR and can be written (with the Faraday rotator tuned to a 45° rotation)[15,16]

$$[\mathbf{MFR}] = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix},\tag{3}$$

which means that the polarization state of the reflected wave is rotated by 90° relative to the polarization state of the input wave (considering the coordinate rotation in the reflection).

Referring to a single optical element, we use two notations (opposite arrow directions in the matrix) depending on the direction of light propagation. For example, $[\overrightarrow{\mathbf{F}}]$ is the Jones matrix describing the propagation in the input fiber in the forward direction, and $[\overleftarrow{\mathbf{F}}]$ is the Jones matrix describing the propagation in the same fiber but in the backward direction. The two matrices are related by[17,18]

$$[\overleftarrow{\mathbf{F}}] = [\mathbf{R}]\cdot[\overrightarrow{\mathbf{F}}]^t\cdot[\mathbf{R}]^{-1},\tag{4}$$

where $[\overrightarrow{\mathbf{F}}]^t$ is the transpose of $[\overrightarrow{\mathbf{F}}]$ and

$$[\mathbf{R}] = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}\tag{5}$$

gives the coordinate rotation caused by reflection. The intensity of the output signal can be calculated with Eqs. (1)–(5):

$$\begin{aligned}I_2 = {}& \ldots\{(1-\alpha[\mathbf{P}_F])\cdot(1-\alpha[\mathbf{P}_C])+\alpha[\mathbf{P}_F]\cdot\alpha[\mathbf{P}_D]\}\\ &\cdot\overrightarrow{\mathbf{E}}_{\text{in}}{}^{\dagger}\cdot\overrightarrow{\mathbf{E}}_{\text{in}}+\ldots[(1-\alpha[\mathbf{P}_F])\cdot(1-\alpha[\mathbf{P}_C])\\ &\cdot\alpha[\mathbf{P}_F]\cdot\alpha[\mathbf{P}_D]]^{1/2}\cdot\{\overrightarrow{\mathbf{E}}_{\text{in}}{}^{\dagger}\cdot\overrightarrow{\mathbf{E}}_{\text{in}}\cdot\exp(-i\Delta\phi)+\overrightarrow{\mathbf{E}}_{\text{in}}{}^{\dagger}\\ &\cdot\overrightarrow{\mathbf{E}}_{\text{in}}\cdot\exp(+i\Delta\phi)\}.\end{aligned}\tag{6}$$

In these equations the dagger denotes the complex conjugate transpose and $\Delta\phi$ is the phase difference for

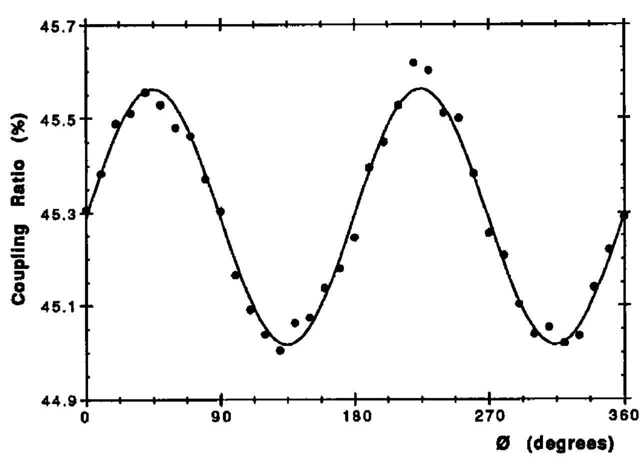

Fig. 2. Splitting ratio of the coupler as a function of the azimuth (Ø) of the linearly polarized input state.

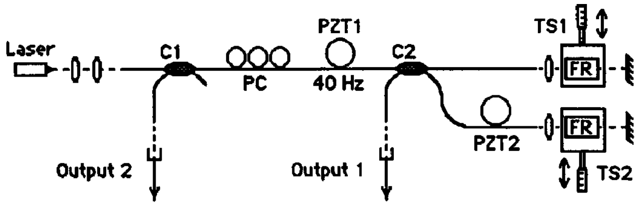

Fig. 3. Experimental arrangement used to test the effectiveness of the Faraday rotators. TS1 and TS2, translation stages.

the unbalanced Michelson interferometer:

$$\Delta\phi = 2(\phi_C - \phi_D) - \gamma[\mathbf{P}_F] - \frac{\gamma[\mathbf{P}_C]}{2} - \frac{\gamma[\mathbf{P}_D]}{2} - \pi. \quad (7)$$

Equations (6) and (7) are independent of matrices $[\mathbf{X}]$ and $[\mathbf{X}']$, which shows that output 2 is truly reciprocal and that the birefringence in coupler C2 is compensated by the Faraday rotator mirror elements. A similar analysis for output 1 of Fig. 1 shows that the signal remains dependent on $[\mathbf{X}]$ and $[\mathbf{X}']$ even when the Faraday rotator mirrors are in place. Equations (6) and (7) also clearly show that the perturbation effect in the input fiber cannot be fully eliminated as long as factors α and γ are affected by the change in the SOP of the input light. In fact, because of the coupler action, polarization fluctuations related to fiber birefringence variations induced by environmental noise can give rise to modulation in the mean power, in the visibility, and in the phase of the interferometric signal. In other words, even with Faraday rotators, complete elimination of polarization-induced noise is not possible.

The couplers used in our experiments were tested separately, and it was observed that the splitting coefficient of each coupler depends on the input SOP. The results in Fig. 2 were obtained for one of the couplers (SIFAM 22S82C50). A peak-to-peak change of 0.5% for the splitting coefficient α was measured as the azimuth of the linear input state was varied. Also, deviations to as high as 3° from the ideal value of 90° have been demonstrated for the phase difference between the coupled and direct waves in standard couplers.[14]

Figure 3 shows the experimental arrangement utilized to test the influence of the coupler on polarization-induced phase and amplitude noises in an interferometric system. The optical source was an Hitachi 8311E laser diode with a wavelength of $\lambda = 825$ nm. Light is injected into the fiber Michelson interferometer through one port of coupler C1. A 1.5-m length of the fiber lead was wrapped around piezoelectric transducer 1 (PZT1). By the application of electrical signals to this PZT environmental perturbations can be simulated. The polarization state of the injected light into the interferometer could be modified with a polarization controller (PC). The arms of the Michelson interferometer had an air path to permit the insertion of the Faraday rotators (OFR Model IO-5-NIR with input and output polarizers removed) by translation stages. PZT2 was used to produce the phase modulation in the interferometer.

Figure 4 shows data from output 2. A 40-Hz signal was applied to PZT1 to simulate an environmentally induced birefringence in the fiber lead (differential phase modulation with amplitude of $\approx$70 mrad). In the absence of Faraday rotators, a strong signal appeared at this frequency that is similar to the signal that could have appeared at this frequency if PZT2 were also modulated. We checked this by disconnecting the applied signal to PZT1 and connecting to PZT2. An identical signal was generated that demonstrates that these effects cannot be distinguished from one another. The effect of induced birefringence in the fiber lead was reduced [Fig. 4(b)] by the use of the Faraday rotators in the interferometer. The input SOP was then modified with the PC to test whether the Faraday rotators were effective for any input polarization state. The spectrum of signals from output 2 is shown in Fig. 5 for two different cases, namely, without [Fig. 5(a)] and with Faraday rotators [Fig. 5(b)]. As can be seen, in this case the effect of the Faraday rotators is negligible (in both cases the average visibility values were close to one).

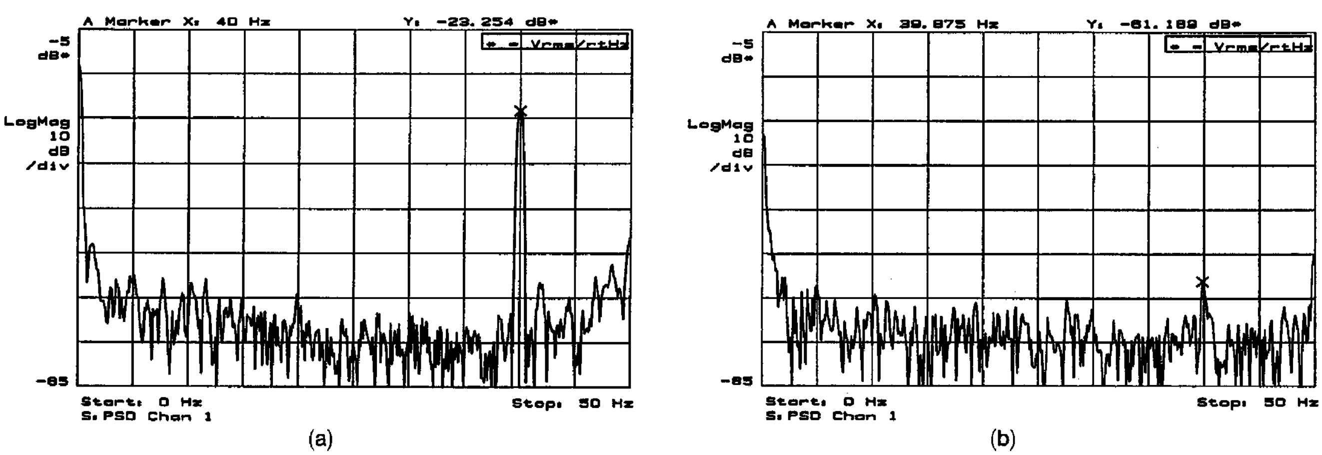

Fig. 4. Signal at output 2 with a 40-Hz perturbation applied to the fiber lead and with the PC adjusted to an optimum position (a) without Faraday rotators and (b) with Faraday rotators.

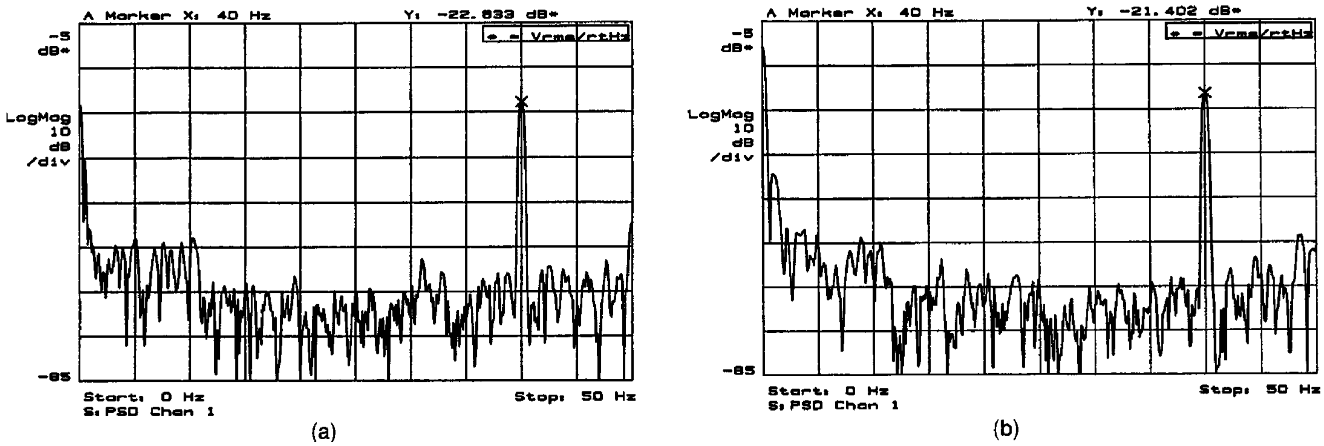

Fig. 5. Signal at output 2 with a 40-Hz perturbation applied to the fiber lead and with the PC adjusted to a new position where the effect of Faraday rotator mirrors is minimum (a) without Faraday rotators and (b) with Faraday rotators.

Figures 4 and 5 represent two extreme situations; i.e., the input polarization state is selected so that Faraday rotators are either highly effective or almost entirely ineffective in the elimination of coupler-birefringence-induced noise.

The signals in Figs. 4 and 5 were observed to depend strongly on the interferometric quasi-static phase. This behavior shows that the phase effect [Eq. (7)] makes the major contribution to the polarization-induced noise. We have confirmed this conclusion by blocking one of the arms of the interferometer: in this situation only small peaks of constant amplitude could be observed [related to the α parameters in the noninterferometric term of Eq. (6)]. It was also observed that the polarization characteristics of coupler C1 do not affect the system performance. This behavior is clear from Eq. (6), which shows that all the fluctuations in the SOP have already been eliminated at the ports of this coupler.

In conclusion, we have presented experimental results that show that the Faraday-rotator-based scheme for elimination of the polarization-induced noise in a fiber Michelson interferometer has limited efficiency. A theoretical analysis was presented that indicates that the origin of this phenomena was the dependence of the coupler splitting characteristics on the polarization state.

L. A. Ferreira acknowledges financial support from Junta Nacional de Investigação Científica e Tecnológica.

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