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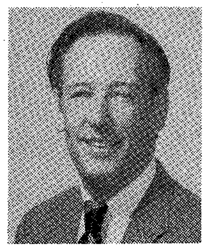

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Polarization Fading in Fiber Interferometric Sensors

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Abstract—**Mach–Zehnder interferometer sensors fabricated with conventional nonpolarization-preserving fibers are subject to polarization fading caused by temperature variations and minor positional changes in the sensor. For such sensors, we calculate the probability of a given decrease in sensitivity and in signal-to-noise ratio due to fading assuming the polarization of the light in the signal and reference legs is uncorrelated and drifts randomly. The resultant reduction of the signal-to-noise ratio may exceed 10 dB 10 percent of the time and exceed 20 dB more than 2 percent of the time.**

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INTRODUCTION

FIBER optic Mach–Zehnder interferometers have been investigated for sensing a variety of environmental parameters such as acoustic pressure [1]-[4], acceleration [5], temperature [6], and magnetic field [7]. In these sensors, the environmental parameter of interest alters the phase of the light in the signal fiber relative to the phase of the light in the reference fiber (Fig. 1), causing a shift in the resultant interference pattern.

Although the all-fiber interferometer is very sensitive, its performance may be degraded by polarization fading which occurs when the two interfering beams approach quasi-orthogonal polarization states. For interferometric sensors

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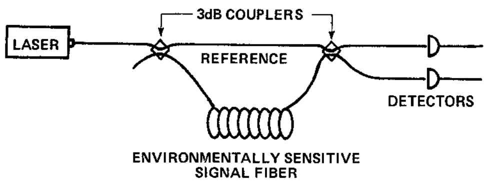

Fig. 1. Mach–Zehnder configuration for fiber interferometer.

fabricated from nonpolarization-preserving fibers, it is well known [8], [9] that the polarization of the two interfering beams may drift randomly due to alterations in the residual birefringence of the fiber caused by minor variations in temperature or position of the fiber. To maintain constant sensitivity as the polarization changes, investigators have applied feedback in the form of automatic gain control (AGC) [10] to their sensors or have otherwise compensated the signal. However, even in these approaches, the signal-to-noise ratio may decrease substantially as the polarization fades. In this paper, we evaluate the probability of a specific decrease in sensitivity and in signal-to-noise ratio for a fiber interferometer sensor assuming the polarization in the signal and reference legs is uncorrelated and drifts randomly. These calculations are of interest because they predict the long-term performance of interferometer sensors in which handling, temperature drifts, and variations in laser output are sufficient to cause the polarization changes between fibers to be uncorrelated over the time period of interest.

Probability Evaluation

The output of a single-mode fiber interferometer is of the form

$$I = I_o(1 + m \cos (q + \theta)). \tag{1}$$

Here q is the small signal induced phase variation for which we wish to determine the sensor sensitivity. The phase θ represents the overall phase difference between the signal and reference arms. The mixing efficiency m is unity if the state of polarization in the two arms is identical and zero if it is orthogonal. The quantity I_o is proportional to the optical power driving the interferometer.

The phase sensitivity to small signals is

$$S' = I_o |m \sin \theta| \tag{2a}$$

or normalized to I_o

$$S = |m \sin \theta|. \tag{2b}$$

In order to calculate the probability P that S is greater than S_o, it is helpful to consider a calculation of m using the Poincaré sphere construction [11], [12]. The state of polarization in an arm of the interferometer can be specified by a unit vector joining the center of the Poincaré sphere to a point on its surface. Thus, the state of input polarization at the output combiner can be specified by two unit vectors, one for the signal arm η_s and one for the reference arm η_R. The mixing efficiency m is given by

$$m = \cos (\phi'/2) \tag{3}$$

where ϕ' is the angle between the unit vectors. Using (3), results can be derived for two cases. Case I is the totally unstabilized interferometer (both polarization and phase drift) and case II is the phase-stabilized polarization-unstabilized interferometer.

Case II: Quadrature Stabilized Interferometer

The result for this case is somewhat simpler to obtain so it is discussed first. In this case, feedback electronics hold θ at the quadrature condition $\theta = \pi/2$. Thus, from (2b), $S = m$. If it is assumed that the thermal and position fluctuations cause the polarizations in the arms to drift in a random fashion, the unit vectors η_R and η_s will wander randomly on the surface of the Poincaré sphere. In statistical terminology this is equivalent to saying that the unit vectors are both distributed uniformly on the surface of the Poincaré sphere. The probability P that the angle between η_R and η_s is less than some value ϕ, is the ratio of A, the area of the spherical cap defined by the opening half angle ϕ to B, the area of the Poincaré sphere.

This ratio is

$$P = \frac{2\pi(1 - \cos \phi)}{4\pi}$$

$$= 1 - \cos^2 (\phi/2). \tag{4}$$

Consideration of the discussion leading up to (3) shows that P is the probability that m is greater than the value $S_o = \cos (\phi/2)$. From (4),

$$P = 1 - S_o^2. \tag{5}$$

This is the essential result for Case II, $P_{II}(S_o) = 1 - S_o^2$. In Fig. 2, P_{II} is plotted as a function of 20 log (S_o).

Case I: Unstabilized Interferometer

The situation for Case I is somewhat more complex. In addition to the polarization fluctuations of Case II, the phase θ also varies randomly. The key to the calculation of $P_I(S_o)$ is the observation that the variations in the polarization and in the phase are statistically independent. One is thus led to consider the situation for specific values of θ and then to average in an appropriate way over θ. For a particular value of θ, the polarizations must be such that $m > S_o/|\sin \theta|$. For $|\sin \theta| < S_o$, the fraction of polarization states that meet this criterion is zero. Otherwise, the fraction is $P_{II}(S_o/|\sin \theta|)$. The appropriate average over θ is therefore

$$P_I(S_o) = \frac{\int_{\arcsin S_o}^{\pi/2} P_{II}(S_o/|\sin \theta|)\, d\theta}{\int_0^{\pi/2} d\theta} \tag{6}$$

with P_{II} given by the form following (5). The integration is straightforward and gives

$$P_I(S_o) = 1 - \frac{2}{\pi} [\arcsin (S_o) + S_o\sqrt{1 - S_o^2}\,]. \tag{7}$$

In Fig. 2, P_I is plotted as a function of 20 log (S_o).

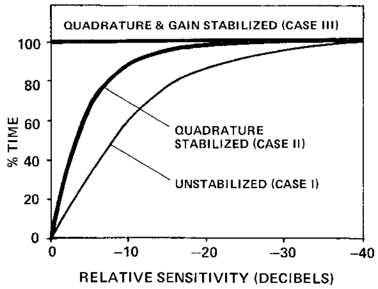

Fig. 2. Percent of time that observed (relative) sensitivity is within specified amount of maximum sensitivity.

Case III: Quadrature-Stabilized Interferometer with Adaptive Gain

The quadrature-stabilized interferometer can be improved further by applying adaptive gain (AGC) [10] to hold the sensitivity constant. Such an AGC control may be implemented by applying a phase dither of constant amplitude to the interferometer and using the AGC to keep the output of the interferometer constant at the dither frequency. In this case, no fading of the ac signal is observed, and the sensitivity of the interferometer is constant regardless of the polarization state as shown in Fig. 2. Nonetheless, the signal-to-noise ratio may be affected.

Signal-to-Noise Ratio

Since no fading of the ac signal is observed for a quadrature-stabilized interferometer with adaptive gain, an observer may believe that all polarization effects have been eliminated, particularly if the interferometer is operating in the presence of large environmental noise. In fact, however, the signal-to-noise ratio of both types of quadrature-stabilized interferometers is polarization-dependent and will decrease as the polarization fades. This effect can be illustrated by considering the combined effects of environmental noise and photodetector shot noise. The photocurrent i_p is proportional to the optical intensity (1) with proportionality constant K

$$i_p = 2K(1 - m \sin q). \tag{8}$$

If the phase term q contains small rms signal and environmental noise terms q_s and q_n, respectively, then the mean square signal current from (8) is

$$i_s^2 = 4K^2 m^2 q_s^2. \tag{9}$$

The associated mean square noise current is given by

$$i_n^2 = 4K^2 m^2 q_n^2 + 2e i_p B \simeq 4K^2 m^2 q_n^2 + 4KeB \tag{10}$$

where the second term represents the photodetector shot noise over a bandwidth B with electronic charge e. The associated signal-to-noise ratio is

$$\frac{i_s^2}{i_n^2} = \frac{q_s^2}{q_n^2 + eB/Km^2}. \tag{11}$$

This expression is valid for an interferometer with or without gain stabilization because the gain is applied to both the signal and noise currents, cancelling its effect. Equation (11) shows that if the quadrature-stabilized interferometer is dominated by environmental noise $q_n^2 \gg eB/Km^2$, then the signal-to-noise ratio is relatively unaffected by polarization fading (changes in m). However, if the polarization fades sufficiently, the shot-noise term may become dominant, in which case the signal-to-noise ratio decreases as m^2. But the curve shown for Case II in Fig. 2 is precisely the probability (percent time) that 20 log m will be larger than the specified value. Consequently, this figure can also be used to determine the likelihood of a given decrease in signal-to-noise ratio. For instance, suppose that the environmental noise term (q_n) of a quadrature-stabilized interferometer is 10 dB greater than the shot noise when the polarizations are optimally oriented. According to Fig. 2, about 88 percent of the time, no significant decrease in signal-to-noise ratio will occur because the fading has enhanced the shot noise less than 10 dB relative to the environmental noise. However, about 2 percent of the time, polarization fading will enhance the shot noise by 20 dB or more, giving rise to an apparent decrease in signal-to-noise ratio of 10 dB.

Conclusion

The importance of controlling the polarization in interferometer sensors is emphasized by these calculations which show the expected degradation in performance for uncorrelated random drifts of the polarization. Polarization effects are least severe in the quadrature-stabilized interferometer with gain stabilization because this sensor provides a constant response to applied signals. However, this sensor may suffer significant decreases in the signal-to-noise ratio due to polarization fading. The use of polarization preserving fiber will effectively eliminate polarization fading for all three sensor implementations. Alternatively, by making a compact rigid sensor with all components held in a fixed position relative to each other, it may be possible to correlate the polarization drifts in the signal and reference fibers so that orthogonal polarization states are never encountered. In this case, the polarizations do not drift randomly relative to each other, and the optimum sensitivity and signal-to-noise ratio may be obtained at all times.

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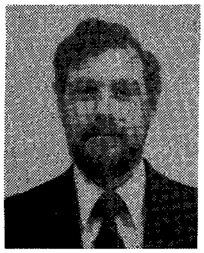

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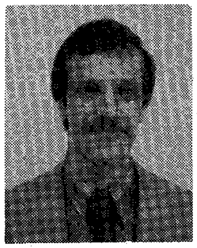

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Richard G. Priest, for a photograph and biography, see p. 511 of the April 1982 issue of this TRANSACTIONS.

Homodyne Demodulation Scheme for Fiber Optic Sensors Using Phase Generated Carrier

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***Abstract*—A method of homodyne demodulation using a phase generated carrier is described and experimentally demonstrated. The method has a large dynamic range, good linearity, and is capable of detecting phase shifts in the microradian range. The detection scheme obviates the phase tracker resetting problem encountered in active homodyne detection schemes. Two methods of producing the carrier are presented, one employing a piezoelectric stretcher, the other using current induced frequency modulation of the diode laser source. These two methods are compared. The origins of the noise limiting the system are briefly discussed.**

I. INTRODUCTION

RECENTLY, there has been considerable interest in using optical fibers as the sensing element in devices such as hydrophones, spectrophones, magnetometers, accelerometers, and ac current sensors [1]. One of the configurations which has shown high sensitivity is that of the Mach-Zehnder all-fiber interferometer. In this configuration, there are many methods of detecting relative optical phase shift between the signal and reference fibers. The design of the detection scheme is made nontrivial by the presence of low frequency random temperature and pressure fluctuations which the arms of the interferometer experience. These fluctuations produce differential drifts between the arms of the interferometer. The drift causes changes in the amplitude of the detected signal (signal fading), as well as distortion of the signal (frequency up-conversion).

Several detection schemes are currently available: passive homodyne, active homodyne (phase tracking), true heterodyne, and synthetic heterodyne. Each of these techniques has both advantages and disadvantages. The current state of these detection schemes is reviewed in [1]. At this time, only the active homodyne system has reached a level of high performance ($10\text{-}10^{-6}$ rad sensitivity with good linearity and low harmonic distortion), packageability (<24 cm^3), and low power consumption. In order to achieve this high level of performance, the technique requires relatively large piezoelectric phase modulators and fast reset circuitry. Large modulators are undesirable in multielement sensors since they increase the active sensor's size and decrease its reliability. Additionally, the need for the sensor circuitry to reset itself every time the environmental noise drives it past its dynamic range adds additional noise. In this paper, a passive homodyne technique which obviates the two problems discussed above is presented. Unlike other passive techniques previously reported [2], this technique has been shown to offer a very high level of performance with a linear dynamic range of $\sim 10^7$. This large linear dynamic range allows both small and large amplitude signals commonly encountered in applications to be observed with excellent fidelity. Two methods of utilizing this approach

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