Analysis of Input-Polarization-Induced Phase Noise in Interferometric Fiber-Optic Sensors and Its Reduction using Polarization Scrambling

ALAN D. KERSEY, MICHAEL J. MARRONE, AND ANTHONY DANDRIDGE

Abstract—The dependence of the phase shift of an interferometric fiber sensor on the input state of polarization is analyzed and it is shown that fluctuations in the input polarization to a fiber interferometer can lead to the generation of excess phase noise. The relationship between this effect and the variation in visibility with input polarization is described and theoretically confirmed. The use of depolarized source light to eliminate input-polarization-induced excess phase noise is theoretically and experimentally demonstrated.

I. INTRODUCTION

GENERALLY, in coherent optical fiber systems based on conventional low-birefringence fiber and fiber components, such as coherent communications and interferometric fiber sensors, random fluctuations in the state of polarization (SOP) of the interfering beams guided in the nominally circular fiber core can lead to fading of the interference signal. This polarization-induced fading (PIF) phenomenon has led to significant research interest in the development of techniques to overcome the problem in both the communications [1]–[4] and sensor [5]–[11] communities. Several schemes have been proposed to overcome PIF, ranging from the use of manual or automatic polarization controllers [1]–[4] to adjust the SOP of the interfering beams, polarization diversity detection schemes based on output polarization state selection [4], [7], [8], or the use of high-birefringence (polarization preserving) fiber in the construction of the system.

Analysis of the dependence of fringe visibility on the input polarization in interferometric sensor systems, as presented in recent papers [10], [11], has shown that the polarization properties of a low-birefringence fiber “two-beam” interferometer (i.e., of the Mach-Zehnder or Michelson types) can be described by a single elliptical birefringent element, the exact nature of which depends on the polarization properties of the two fiber arms. Based on this analysis we showed that polarization-induced signal fading can be overcome by maintaining the input polarization to the interferometer aligned with one of the eigenmodes of the elliptical retarder describing the inter-

ferometer. This was subsequently demonstrated using active feedback control of the input SOP to the interferometer [11]. An input-polarization diversity mode of operation, based on our previous analysis, has also recently been reported [12].

Recently, we reported the observation of a phenomenon closely related to the PIF effect which can arise due to fluctuations in the SOP guided to an interferometric fiber sensor [13]. In this paper we present an in-depth analysis of this source of excess phase noise. It is commonly assumed that interferometric fiber sensors are “lead insensitive,” that is, perturbations of the input fiber to, or output fiber from an interferometer do not give rise to a shift in the phase of the interference signal generated at the detector. Here, however, we present theoretical and experimental results which show the fluctuations in the input SOP to an interferometric sensor can result in the generation of phase noise in the demodulated sensor output. We then show that by using depolarized source light, the dependency of the interferometer visibility and phase on the birefringence properties of the input fiber is eliminated at the cost of a generally reduced, but stable visibility.

II. INPUT-POLARIZATION-INDUCED PHASE NOISE

Expressions relating the dependence of visibility on input polarization have been presented in full in previous publications [10], [11]. In order to understand the dependence and connection between the interferometer visibility and phase shift on the input SOP, we refer to Fig. 1 which shows a schematic of a Mach-Zehnder interferometer and the Poincare sphere [14]–[16] representation of the SOP's of the light at various points in the system: the input to the first coupler (C_i), and in the signal (C_s) and reference (C_r) arms of the interferometer at the point of recombination in the output coupler. The output fringe visibility is simply given by

$$V = \cos \eta \quad (1)$$

where 2η is the angle subtended by the great circle arc $C_s - C_r$ at the center of the sphere, and we have assumed polarization insensitive 1:1 coupling in both couplers (as exhibited by many commercially available components). The coordinates of C_s and C_r depend on the net polarization evolution along the signal and reference arms and

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The authors are with the Optical Sciences Division, Naval Research Laboratory, Washington, DC 20375.
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Fig. 1. Schematic of a fiber Mach-Zehnder interferometer and the evolution of the input SOP, C_i , into the SOP's C_s and C_r along the signal and reference arms as shown on the Poincare sphere representation of polarized light.

the input SOP C_i . Consequently, the visibility is dependent on both C_i , which in turn depends on the birefringence in the input fiber lead, and the net SOP evolutions of the signal and reference light in the interferometer itself caused by birefringence in the two fiber arms. It is well known that the net birefringence in a length of fiber can be described by means of a general elliptic retarder [14]–[16] R_r of rotational magnitude (phase delay) Ω_r on the Poincare sphere. It can be shown that the polarization dependence of an interferometer can be described by a single differential elliptical retarder R_{r-s} (Ω_{r-s}) (Fig. 2(a)) which depends on the birefringence properties of the two fiber arms. For an input SOP aligned with either of the eigenvectors of R_{r-s} , the SOP's of light derived from the signal and reference arms *must* be coincident. Consequently, the two input SOP's aligned with the eigenvectors of R_{r-s} behave as eigenmodes of the interferometer for which optimum visibility can be achieved. For an arbitrary input SOP C_i the visibility and output phase shift can be calculated by resolving the input state onto the two eigenmodes, and summing the output interference intensities (scalar summation of orthogonal polarization components). If the input SOP subtends an angle θ to the eigenmode vector R_{r-s} then the output interference comprises two components given by

$$I_a = \frac{1}{2} I_0 [\cos^2(\theta/2) \{1 + \cos(\phi + \Omega_{r-s}/2)\}] \quad (2a)$$

$$I_b = \frac{1}{2} I_0 [\sin^2(\theta/2) \{1 + \cos(\phi - \Omega_{r-s}/2)\}] \quad (2b)$$

where Ω_{r-s} is the rotation magnitude of R_{r-s} . The total output interference intensity is thus

$$\begin{aligned} I &= I_a + I_b \\ &= \frac{1}{2} I_0 [1 + \cos^2(\theta/2) \{ \cos(\phi) \cos(\Omega_{r-s}/2) \\ &\quad - \sin(\phi) \sin(\Omega_{r-s}/2) \} \\ &\quad + \sin^2(\theta/2) \{ \cos(\phi) \cos(\Omega_{r-s}/2) \end{aligned}$$

Fig. 2. (a) Poincare sphere representation of the differential eigenmode R_{r-s} which can be used to describe the polarization properties of an interferometric system. (b) Effect of input polarization noise on the angle θ .

$$\begin{aligned} &+ \sin(\phi) \sin(\Omega_{r-s}/2) \} \} \\ &= \frac{1}{2} I_0 [1 + \cos(\phi) \cos(\Omega_{r-s}/2) - \cos(\theta) \\ &\quad \cdot \sin(\phi) \sin(\Omega_{r-s}/2)] \\ &= \frac{1}{2} I_0 [1 + \{ \cos^2(\Omega_{r-s}/2) + \cos^2(\theta) \sin^2 \\ &\quad \cdot (\Omega_{r-s}/2) \}^{1/2} \cos(\phi - \gamma)] \end{aligned} \quad (3)$$

where

$$\tan \gamma = \tan(\Omega_{r-s}/2) \cos \theta. \quad (4)$$

This phase offset term γ is dependent on the position of the input SOP relative to the eigenvector R_{r-s} and the rotational magnitude Ω_{r-s} . Random fluctuations in the SOP reaching the interferometer due to, for example, mechanical perturbations of the input fiber give rise to changes in θ as shown diagrammatically using the Poincare sphere representation in Fig. 2(b). This fluctuation in θ leads to variations in γ according to (4) resulting in input-polarization induced phase noise. The phase noise $\Delta\gamma$ resulting from a polarization-noise fluctuation $\Delta\theta$ (assuming $\Delta\theta \ll 1$) is, by (4):

$$\begin{aligned} \Delta\gamma &= (\partial\gamma/\partial\theta) \cdot \Delta\theta \\ &= \frac{\tan(\Omega_{r-s}/2) \cdot \sin \theta}{(1 + \tan^2(\Omega_{r-s}/2) \cdot \cos^2 \theta)} \cdot \Delta\theta. \end{aligned} \quad (5)$$

From (3), the visibility can be seen to be given by the expression

$$\begin{aligned} V &= \{ \cos^2(\Omega_{r-s}/2) + \cos^2(\theta) \sin^2(\Omega_{r-s}/2) \}^{1/2} \\ &= \{ 1 - \sin^2 \theta \cdot \sin^2(\Omega_{r-s}/2) \}^{1/2} \end{aligned} \quad (6)$$

which is identical to that predicted following an analysis based solely on the Poincare sphere description of the polarization behavior of the interferometer [10], [11]. Clearly, (6) shows that if $|\Omega_{r-s}| \neq \pi$ (modulo 2π), then $V > 0$ for all input SOP's, i.e., the visibility varies between the limits

$$V_{\max} = 1$$

Fig. 3. Theoretical curves showing the dependence of the sensitivity of the interferometer to input polarization noise $\delta\gamma/\delta\theta$, as a function of θ , as defined by (5), for various values of Ω_{r-s} .

and

$$V_{\min} = \cos(\Omega_{r-s}/2) \quad (7)$$

which occur when $\theta = 0$ and $\theta = \pi/2$, respectively. For a constant value of Ω_{r-s} , the input-polarization-induced phase noise ($\delta\gamma/\delta\theta$) is minimum when $\theta \sim 0$ (i.e., around maximum visibility) and is maximized when $\theta \sim \pi/2$ (i.e., close to minimum visibility). Fig. 3 shows theoretical curves of ($\delta\gamma/\delta\theta$) versus visibility for various values of Ω_{r-s} . As seen from this figure, in cases where the visibility can fade close to zero due to fluctuations in the input polarization (i.e., for Ω_{r-s} approaching π), the input-polarization noise to phase-noise conversion factor ($\delta\gamma/\delta\theta$) can be quite large.

III. OPERATION WITH UNPOLARIZED LIGHT

The operation of an interferometric sensor using unpolarized light has not previously been reported. Intuitively, however, it would be expected that the use of unpolarized source light would eliminate the effects of the input fiber on the polarization behavior of the interferometric system. This is shown to be the case in the following analysis which describes the operation of the interferometer with unpolarized source light.

Here, we assume the input light is completely unpolarized, such that it can be resolved into two mutually incoherent orthogonal polarization components of equal intensity [17]. As any arbitrary pair of orthogonal components can be chosen to represent the unpolarized input light, they can be chosen to match the eigenmodes of the differential operator R_{r-s} . The interferometer output is thus composed of two interference terms generated by the two components of the unpolarized input light. Furthermore, as we have chosen orthogonal input components which align with the eigenmodes of R_{r-s} , these interference terms are each of optimum visibility and have a relative phase shift of Ω_{r-s} between them, i.e.,

$$I_1'' = \frac{1}{4} I_0 \{ 1 + \cos(\phi + \Omega_{r-s}/2) \}$$

$$I_2'' = \frac{1}{4} I_0 \{ 1 + \cos(\phi - \Omega_{r-s}/2) \}.$$

The total output interference intensity I'' of an interferometer illuminated using unpolarized source light is thus

$$\begin{aligned} I'' &= \frac{1}{4} I_0 [2 + \cos(\phi + \Omega_{r-s}/2) + \cos(\phi - \Omega_{r-s}/2)] \\ &= \frac{1}{2} I_0 [1 + \cos(\Omega_{r-s}/2) \cos(\phi)] \end{aligned} \quad (8)$$

where ϕ is the mean phase shift experienced by the light on propagation through the signal and reference arms, and I_0 is the input intensity of the unpolarized light. The output visibility of a fiber interferometer illuminated using unpolarized light is thus $V_{up} = \cos(\Omega_{r-s}/2)$, which is independent of the polarization properties of the input fiber lead, but depends on the rotational magnitude of the differential operator R_{r-s} . The phase shift of the interference output is also independent of the polarization properties of the input lead, and thus input-polarization-induced phase noise can be eliminated by depolarization of the input light at the price of a reduced, but stable visibility (assuming a stable Ω_{r-s}).

IV. POLARIZATION SCRAMBLER

In order to investigate the operation of an interferometric system using unpolarized light, a polarization scrambler was used. This device comprised simply a birefringent modulator oriented such that its principle birefringence axes were at $\pm 45^\circ$ to the azimuth of the linearly polarized light from the isolator. When the modulator is sinusoidally excited (at ω_m) with a differential polarization-mode phase delay amplitude of 2.4 rad, it can be shown that this arrangement effectively scrambles the polarization of the light, which then appears depolarized for signal frequencies $\ll \omega_m$ [18]. The principle of operation is briefly described below.

If polarized light from a monochromatic source is passed through a linearly birefringent medium such that both eigenmodes are excited equally, the output SOP will depend on the polarization mode phase delay (retardance) between the eigenmodes and the input SOP. The output SOP is, however, confined to a great circle on the Poincaré sphere which passes through the poles R and L (right and left circular SOP's) in a plane normal to the eigenvectors of the birefringent medium, as shown in Fig. 4(a). If the retardance of the birefringent element is sinusoidally modulated, the retardance can be expressed $\delta = \phi_1 - \phi_2 = \phi_0 + \Delta\phi \sin \omega_m t$, and the output SOP modulation is as shown in Fig. 4(b). The time averaged degree of polarization of the output light is reduced by this modulation in the output SOP and can be calculated using the coherency matrix J [17], noting that the eigenmodes are equally excited:

$$\begin{aligned} J &= \begin{bmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{bmatrix} \\ &= a^2 \begin{bmatrix} 1 & \exp[i(\phi_1 - \phi_2)] \\ \exp[-i(\phi_1 - \phi_2)] & 1 \end{bmatrix} \end{aligned} \quad (9)$$

Fig. 4. Operation of the polarization scrambler (see text).

where a represents the electric field amplitude of the light in the eigenmodes of the birefringent modulator and $\phi_1 - \phi_2$ is the polarization mode phase delay (retardance) of the modulator. Equation (9) can be written as

$$\mathbf{J} = a^2 \begin{bmatrix} 1 & \mu \\ \mu^* & 1 \end{bmatrix} \quad (10)$$

where μ is the complex degree of coherence. The degree of polarization is then

$$P = |\mu|. \quad (11)$$

With the time-varying modulation applied to the birefringent element, the effective time-averaged degree of output polarization can be expressed as

$$P_{\text{eff}} = |\langle \mu \rangle| \quad (12)$$

where $\langle \dots \rangle$ denotes a time average over an interval τ much longer than the period ($T = 2\pi/\omega_m$) of the modulation applied to the birefringent modulator. P_{eff} is thus given by

$$P_{\text{eff}} = |\langle \exp[i(\phi_0 + \Delta\phi \sin \omega_m t)] \rangle| \quad (13)$$

which when expanded in terms of Bessel components yields

$$\begin{aligned} P_{\text{eff}} &= \left| \left\langle \left[J_0(\Delta\phi) + 2 \sum_{n=1}^{\infty} J_{2n}(\Delta\phi) \cos(2n\omega_m t) \right] \cdot [\cos \phi_0 + i \sin \phi_0] \right. \right. \\ &\quad \left. \left. - \left[\sum_{n=0}^{\infty} J_{2n+1}(\Delta\phi) [\cos((2n+1)\omega_m t)] \cdot [\sin \phi_0 - i \cos \phi_0] \right] \right\rangle \right| \\ &= |J_0(\Delta\phi) [\cos \phi_0 + i \sin \phi_0]| \\ &= |J_0(\Delta\phi)| \end{aligned} \quad (14)$$

where $J_n(\Delta\phi)$ is the Bessel function of order n . Equation (14) shows that the time-averaged degree of polarization is given by the magnitude of the zero-order Bessel function and is thus zero for $\Delta\phi = 2.4, 5.5, 8.7$ rad and other zero crossings of the function. It should, of course, be

Fig. 5. Experimental setup used to investigate input-polarization-induced phase noise in an interferometric system, and its reduction using polarization scrambling.

noted that the instantaneous degree of polarization is always unity; however, due to the high frequency SOP modulation, the "time-averaged degree of polarization" is reduced to zero at the above mentioned values of $\Delta\phi$. Experimentally, this polarization scrambler has been implemented in both bulk (photoelastic modulator) and fiber (high-birefringence fiber modulator) forms for use in this work. An integrated optic implementation of the polarization scrambler has also been reported [19]. Operation of the fiber device at a scrambling frequency of 850 kHz was possible, well beyond the baseband signal frequency regime typically of interest in fiber optic interferometric sensor systems.

V. EXPERIMENTAL

In order to demonstrate this input-polarization-induced phase-noise phenomenon in interferometric fiber optic sensors and its reduction using depolarization of the input light, we used the experimental setup shown in Fig. 5. Here, the input lead to a single-mode fiber Mach-Zehnder interferometer was loosely coiled around a ~ 1 -cm-diameter rod and vibrated as shown using an electromechanical shaker. This shaker was driven by a low frequency band-limited noise source to simulate input polarization noise. The polarization fluctuations produced in the input lead were monitored by polarization analysis of light tapped off just before the interferometer using a coupler. The light available at this output was analyzed using a $\lambda/4$ plate and Glan polarizer, with both elements being rotated to the position which produced maximum noise modulation in the detected intensity passes by the polarizer. This provided an approximate quantitative assessment of the magnitude of the polarization noise induced at the interferometer input by the action of the shaker. The interferometer output was demodulated using a synthetic-heterodyne approach [20], and final phase demodulation was performed using a lock-in amplifier configured as a phase analyzer. In order to allow the effect of depolarizing the input light on the input-polarization-in-

duced phase noise to be assessed, we included a photoelastic modulator (PEM) in the optical train between the isolator and input fiber which was driven at a peak polarization-mode phase delay of 2.4 rad, thus effectively depolarizing the input light. Fibers in the reference and signal arms were secured to a base plate to produce a stable interferometric system with little variation in its polarization properties (i.e., the birefringence properties of the interferometer arms were stable over long periods).

VI. RESULTS

A. Characterization of Input-Polarization-Induced Phase Noise

The input polarization dependence of the interferometer was characterized by scanning the input polarization using the Babinet-compensator and $\lambda/2$ combination at the input to the system shown in Fig. 5. These components allow any input SOP to be generated at the input to the fiber system. Scanning the input SOP from a left circular SOP to right circular in the manner described in [11] produced a dependence of visibility on input SOP exhibiting a minimum $V_{\min}$ which depended on the birefringence properties of the fiber arms of the interferometer. Initially, the interferometer was adjusted to give a minimum visibility of 0.47. The optimum visibility of the system was determined to be 0.97, thus $V_{\min}$ (minimum normalized visibility) was ~ 0.485 . From this, and using (6), we get $\Omega_{r-s} \sim 120^\circ$ (2.2 rad). Once adjusted, the polarization properties of the interferometer (i.e., primarily the magnitude of Ω_{r-s}) were found to remain stable for long periods (several days).

The dependence of the magnitude of the input-polarization-induced phase-noise component in the interferometer output on θ , and thus the system visibility predicted by (6), is demonstrated by the results shown in Fig. 6(a) and (b). Here we show oscilloscope photographs of the output synthetic-heterodyne carrier signal generated by the processing electronics observed without and with the input shaker for situations where the input polarization controllers were set to produce optimum fringe visibility (~ 0.97), minimum output visibility (~ 0.47), and an intermediate visibility (~ 0.67) (note that in the case with the shaker off, only the optimum and minimum visibility condition are shown). These outputs clearly demonstrate that close to optimum visibility (i.e., when $\theta \rightarrow 0$) input-polarization noise leads to slight fluctuations in the carrier amplitude resulting from direct fluctuations in the visibility due to the relatively large polarization modulation induced by the shaker. (Note: a high level of shaker induced polarization noise, estimated to be approximately 1 rad p-p, was used in this example to graphically illustrate the effect of input-polarization noise on the interference output under conditions of optimum and minimum visibility.) In contrast, at or close to minimum visibility, the polarization noise leads to the generation of a significant phase-noise component in the output, as can be seen by the blurring of the zero crossing of the carrier signal in Fig. 6(b) for $V \sim 0.47$. In the case of the intermediate

Fig. 6. (a) Output synthetic-heterodyne carrier signals observed with the input fiber shaker off, and the input PC's set to give 1) optimum visibility (0.97), and 2) minimum visibility (0.47). (b) Output synthetic-heterodyne carrier signals observed with the input fiber shaker on, and the input PC's set to give 1) optimum visibility (0.97), 2) minimum visibility (0.47), and 3) an intermediate visibility of 0.67.

visibility, the input-polarization noise produces both significant amplitude (due to visibility fluctuations) and phase noise in the carrier signal.

Fig. 7(a) shows typical time domain outputs observed at the input-polarization tap-off (detector D1 signal) and the lock-in amplifier phase output (demodulated interferometer phase) with the noise source signal applied to the input fiber shaker assembly. An input-polarization noise, $\Delta\theta \sim 400$ mrad p-p (50-Hz bandwidth) was estimated by polarization analysis of the picked-off light at the input, which was observed to produce a phase-noise component of ~ 200 mrad p-p in the interferometer output phase shift. Fig. 7(b) shows the spectral densities of the noise signals at the polarization pickoff and interferometer output. The ratio of these two noise spectra is shown by the lower trace in Fig. 7(c), whereas the upper trace in this photograph shows the coherence function between the two noise signals. As can be seen, at frequencies > 20 Hz the correlation between the noise signals is high, clearly demonstrating the dependency of the interferometer phase shift on the input polarization predicted by (5). The results of Fig. 7 were obtained with the input PC's set to produce an output visibility of ~ 0.65 . From (5), with $\Omega_{r-s} \sim 120^\circ$, θ is $\sim 60^\circ$, and (4) predicts a maximum $\partial\gamma/\partial\theta$ of ~ 0.8 assuming the polarization rotation noise is aligned with the direction of θ (which may

Fig. 7. (a) Upper trace shows polarization noise at input pickoff (D1), lower trace shows interferometer phase output. (b) Frequency spectrum of polarization pickoff noise and interferometer phase noise over the range 0 to 50 Hz with the input fiber shaker. (c) Correlation between noise spectra in (b).

not generally be the case); the observed value of ~ 0.5 is thus in fair agreement with this calculation.

In order to evaluate further the dependence of the polarization-induced phase noise on the interferometer visibility, we measured the change in phase noise induced by the input fiber shaker against visibility by adjusting the input polarization controllers. As the input-polarization noise induced by the shaker-driven input fiber coil will depend on the actual input polarization to the system, we made a ratio of the phase noise to amplitude noise (induced by visibility variations) of the carrier signal while varying the actual visibility by control of the nominal input SOP. From (6), the variation in visibility ΔV due to a small change in θ ($\Delta\theta$) is given by (for $\Delta\theta \ll 1$)

$$\begin{aligned} \Delta V &= (\delta V / \delta \theta) \cdot \Delta \theta \\ &= - \frac{\sin 2\theta \sin^2(\Omega_{r-s}/2)}{2\sqrt{1 - \sin^2 \theta \sin^2(\Omega_{r-s}/2)}} \cdot \Delta \theta. \end{aligned} \quad (15)$$

For a constant input optical power the synthetic heterodyne carrier amplitude is directly proportional to the output visibility, i.e., $S_c = k \cdot V$, where k simply represents the voltage gain of the postdetection electronics normalized to the detector voltage corresponding to unity normalized visibility (volts per absolute units). The ratio of the carrier phase noise to amplitude noise is thus, by (5) and (15), given by

$$\begin{aligned} \Delta \gamma / \Delta S_c &= (\partial \gamma / \partial \theta) \cdot [k(\delta V / \delta \theta)]^{-1} \\ &= - \frac{2\sqrt{1 - \sin^2 \theta \sin^2(\Omega_{r-s}/2)}}{k \sin(\Omega_{r-s}) \cos \theta (1 + \tan^2(\Omega_{r-s}/2) \cos^2 \theta)}. \end{aligned} \quad (16)$$

Providing $\Delta\theta \ll 1$, this equation is independent of the actual magnitude of the input polarization noise $\Delta\theta$, but is dependent on θ and thus on the normalized visibility V . Fig. 8 shows the experimentally measured ratio of output carrier amplitude modulation to phase modulation induced by modulation of the input SOP against θ for different $V_{\min}$ conditions of the interferometer. In this experiment, the interferometer arms were first adjusted to produce a particular $V_{\min}$ in the dependence of visibility on input SOP (the input SOP was scanned to determine $V_{\min}$ in each case). The rotational magnitude Ω_{r-s} of the eigenvector R_{r-s} , describing the polarization properties of the interferometer can then, via (7), be determined using

$$\Omega_{r-s} = 2 \cos^{-1}(V_{\min}). \quad (17)$$

Three values of $V_{\min}$ were used: 0.18, 0.41, and 0.63, corresponding to Ω_{r-s} values of 160° , 132° , and 102° , respectively. Once set at a particular $V_{\min}(\Omega_{r-s})$, the interferometer arms and couplers were not perturbed. An input modulation signal at a frequency of ~ 30 Hz was applied to the input fiber coil shaker to produce a small input polarization modulation at a fixed frequency, and the ratio of resulting amplitude and phase modulation components of the output synthetic-heterodyne carrier were measured while the normalized visibility was adjusted between unity and $V_{\min}$ by control of the input-polarization controllers (Babinet compensator and $\lambda/2$ plate). As expected, controlling the input SOP at this point invariably altered the amplitude of the polarization noise induced by the action of the shaker on the input fiber coil. However, as discussed above and shown by (5) and (15), both the carrier phase and amplitude modulation components are directly proportional to $\Delta\theta$ ($\Delta\theta \ll 1$), and experimentally, variations in $\Delta\theta$ were found to have little effect on the measured ratio $\Delta\gamma / \Delta V$. Experimentally, the ratio $\Delta\gamma / \Delta V$ was measured against visibility, whereas in Fig. 8, the results are plotted against θ ; the conversion between these was made using the expression

$$\theta = \sin^{-1} \left\{ \sqrt{1 - V^2} / (1 - V_{\min}^2) \right\} \quad (18)$$

which is obtained using (6) and (7). The results presented in Fig. 8 show reasonably good agreement (± 2 dB for

Fig. 8. Ratio of carrier phase to amplitude noise against θ for various interferometer $V_{\min}$ conditions. Lines show theoretical curves according to (16) for the Ω_{r-s} values given.

most data points) with the theoretical curves calculated using (16) for each of the $V_{\min}(\Omega_{r-s})$ values used experimentally.

B. Excess Noise Reduction Using Polarization Scrambling

Reduction of the input-polarization-induced phase noise by scrambling the input polarization was also demonstrated. The results are presented in Fig. 9, which shows the frequency spectrum of the demodulated interferometer phase output over the frequency range 0 to 100 Hz with, 1) the interferometer free-running (i.e., no input-polarization noise) and with the polarization controllers in the system set to maximize the output visibility, 2) the input-polarization-induced phase noise with the shaker on at near optimum visibility, and 3) the input-polarization-induced phase noise with the shaker on at minimum visibility ($V_{\min}$ in this case was again set at 0.47 by adjusting the birefringence in the interferometer arms), and its reduction by scrambling the input polarization to the system. Clearly, as shown in Fig. 9(a), the input-polarization noise has little effect on the output phase when the input SOP is adjusted to give maximum output visibility. When the input polarization is adjusted to give minimum visibility in the output, however, the input-polarization-induced phase noise increases (Fig. 9(b)). In this demonstration of the phenomenon, we calculated that the polarization rotation induced in the input SOP by the action of the input fiber shaker was ~ 4.5 mrad/Hz $^{1/2}$ rms over the frequency range 0 to 50 Hz, which produced a phase-noise component of ~ 6.0 mrad/Hz $^{1/2}$. Again, this polarization-rotation to phase-noise conversion factor of ~ 1.35 is in reasonably good agreement with a maximum $\partial\gamma/\partial\theta$ of ~ 1.7 predicted by (4) for $\Omega_{r-s} \sim 120^\circ$ (i.e., $V_{\min} = 0.47$). The lower trace in Fig. 9(c) shows the resulting reduction in phase noise observed when the input light to the system was effectively depolarized by scrambling the input polarization using the PEM. A reduction in the input-polarization-induced phase noise of ~ 30 to

Fig. 9. Polarization-induced phase noise at the interferometer output and its reduction using input-polarization scrambling. (a) Visibility near optimum; lower trace—free-running phase-noise floor (~ 100 μ rad/Hz $^{1/2}$ at 30 Hz), upper trace—noise floor with shaker on. (b) Visibility set at $V_{\min}$; lower trace—noise floor with shaker off, upper trace—noise floor with shaker on. (c) Visibility at $V_{\min}$; upper trace—noise floor with shaker on, lower trace—noise floor with shaker on and input polarization scrambler on, showing a 30- to 35-dB reduction in the input-polarization-induced phase-noise level.

35 dB was observed, with an interferometer phase sensitivity equivalent to the free running sensitivity of ~ 100 μ rad/Hz $^{1/2}$ (at ~ 30 Hz) being achieved using input SOP scrambling.

VII. DISCUSSION AND CONCLUSIONS

The results presented in the preceding section show that input-polarization-induced phase noise can be eliminated by using unpolarized source light. In general, the visibility obtained using unpolarized source light in an interferometric system will be finite and insensitive to perturbations of the input fiber. However, the visibility of the interferometric output obtained depends on the polarization properties of the interferometer itself, and consequently polarization-induced fading of the interferometric signal can still arise due to perturbation of the fiber arms (i.e., if $|\Omega_{r-s}| = (2n + 1)\pi$). Consequently, the use of unpolarized light to eliminate input-polarization-induced noise and visibility fluctuations would only be practical in applications where the fiber arms of the interferometer could be adjusted to ensure that the inequality $\Omega_{r-s} \neq (2n + 1)\pi$ held. Alternatively, the technique could be utilized if the interferometer, once adjusted to give a dependence of visibility on input SOP which did not exhibit a strong signal fade (i.e., say $V \geq 0.3$ for all input SOP's), could then be packaged and operated in a relatively benign environment. Under such conditions, one may expect that the dominant source of polarization-induced phenomena to occur due to perturbations of the input fiber. Depolarization of the input light would, therefore, reduce the input-lead sensitivity and the possible generation of excess noise.

In conclusion we have presented both a theoretical analysis and experimental results which demonstrate a relationship between the input SOP to an interferometric sensor and the output phase shift of the device. This analysis shows that, contrary to the widely held opinion that interferometric fiber sensors are "lead-insensitive," polarization fluctuations in the input fiber to an interferometric sensor can lead to a change in the phase shift of the interference output signal. We have used this to show that low-frequency polarization fluctuations in the input fiber to an interferometric sensor can result in the generation of excess phase noise at the output—an effect which may have serious implications in the design of interferometric sensors for certain applications, such as vibration or acceleration sensors, where input-polarization noise may be encountered due to mechanical perturbations of the input fiber. The use of polarization scrambling to eliminate this noise source has been theoretically treated and experimentally demonstrated.

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Alan D. Kersey was born in Milford Haven, Wales, on June 15, 1956. He received the B.Sc. degree in physical electronics from the University of Warwick, England, and the Ph.D. degree from the University of Leeds, England. In his graduate research he studied spectroscopic applications of magneto-optical effects in atomic vapors.

From 1981 to 1984 he was employed at the University of Kent, Canterbury, as a Research Fellow, where he worked on optical-fiber sensors and related signal processing techniques. Since

1984 he has been involved with the fiber-optic sensor research program at the U.S. Naval Research Laboratory, Washington, DC, where he currently heads a research team working in the areas of multiplexed fiber-optic sensors, interferometric sensing and signal processing techniques, polarization phenomena in fiber-optic systems, and optical communications. He has written or coauthored over 150 journal and conference publications in the area of fiber optics, and holds a number of patents in the field.

Michael J. Marrone received the B.S. degree from the University of Notre Dame, Notre Dame, IN, the M.S. degree from the University of Pittsburgh, Pittsburgh, PA, and the Ph.D. degree from the Catholic University of America, Washington, DC, all in physics.

He joined the Naval Research Laboratory, Washington, DC, in 1961. His research interests have included self-trapped exciton luminescence in alkali halides and EPR in the excited state of the self-trapped exciton, picosecond phenomena in gas phase photolysis, and radiation-induced luminescence effects in optical fibers. His recent work concerns the polarization properties of single-mode fibers and the effects of polarization in fiber-optic sensors.

Dr. Marrone is a member of the American Physical Society and the Optical Society of America.

Anthony Dandridge was born in Kent, England. He received the B.Sc. and Ph.D. degrees in physics from the Sir John Cass School of Science and Technology, City of London Polytechnic, England.

His postgraduate and postdoctoral research work included flow birefringence, viscometric, and light-scattering studies of short-chain polymers. In 1979 he was a Lecturer in Physics at the University of Kent, Canterbury, England. Since 1980, he has been associated with Georgetown University, Washington, DC, John Carroll University, Cleveland, OH, and the Naval Research Laboratory, Washington, DC. In 1984 he became Head of the Optical Sensor Section at the Naval Research Lab. His research work covers fiber-optic sensor systems as well as the noise and spectral characteristics of semiconductor lasers. He has authored and co-authored over one hundred and fifty journal and conference publications.

Dr. Dandridge is a Fellow of the Royal Astronomical Society.