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An Electric Field Sensor Utilizing a Piezoelectric Polyvinylidene Fluoride (PVF₂) Film in a Single-Mode Fiber Interferometer

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Abstract—A polyvinylidene fluoride (PVF₂) phase shifter is characterized in terms of amplitude response linearity, frequency response uniformity, and ultimate sensitivity to electric field. Phase-drift compensation with this PVF₂ device is demonstrated in a Mach-Zehnder fiber interferometer. The compensator can be operated at the $\pi/2$ -phase mode for maximum sensitivity in detection applications, or the π -phase mode for maximum frequency mixing efficiency.

I. INTRODUCTION

IN RECENT YEARS, research in fiber-optic sensors has demonstrated that highly sensitive devices are possible and often competitive with the best conventional devices. Areas of active research include acoustic [1], magnetic [2], temperature [3], acceleration [4], and current sensing [5]. In addition to this list, the possibility of electric field sensing should be considered. One approach would involve coating or bonding a fiber onto a piece of piezoelectric polyvinylidene fluoride

(PVF₂) materials and incorporating it as a sensor element in a fiber interferometer.

Initial work [6], [7] demonstrated the feasibility of using PVF₂ film as a phase shifter and frequency mixer in an optical fiber interferometer. The attractions of PVF₂ material are that it is lightweight and possesses a large phase-shifting capability (~ 4 rad/V (peak)-meter at 6328 Å wavelength) as compared to that of a conventional ceramic PZT (~ 0.39 rad/V (peak)-meter at 6328 Å wavelength). Also, PVF₂ material has the potential of being coated directly onto optical fibers during fabrication, thus forming an integral part of the sensor.

In this paper, we present results on the characteristics of a PVF₂ phase shifter or fiber stretcher of modest length (60 cm) and its application as a lightweight, low drive-voltage, phase-drift compensator in a fiber interferometer. Important phase-shifting characteristics of the PVF₂ are the amplitude response linearity, frequency response uniformity, and the ultimate sensitivity in terms of minimal detectable electric field. Also, two operational modes of the compensator will be discussed. These include 1) the $\pi/2$ -phase (quadrature) locking mode desirable for maximum sensitivity in fiber interferometric sensor

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applications, and 2) the π -phase locking mode desirable for applications requiring maximum frequency mixing efficiency.

II. PVF₂ FIBER STRETCHER

Short lengths (~ 10 cm) of PVF₂ film have been demonstrated to be usable as a phase shifter and frequency mixer in fiber interferometers [6], [7]. To assess potential application in fiber sensors, the performance of a longer length of PVF₂ must be evaluated. In the present paper, a 60-cm-long PVF₂ strip was chosen for evaluation of: 1) its response linearity to driving signal strength, 2) its frequency response uniformity and, 3) its ultimate sensitivity in terms of minimal detectable voltage or electric field.

The experimental system used in this study is shown schematically in Fig. 1. Two single-mode optical fibers (supplied by ITT) form the two arms of a Mach-Zehnder interferometer. A microscope objective is used to couple a HeNe laser (Tropel Model 100) light into the fiber. Splitting of the optical beam in the input end and combining of the output beams of the interferometer are both achieved with solid-state fiber couplers. Fringe visibility over 65 percent is readily obtained in this system. A section of one of the fiber interferometer arms is stripped of its plastic jacket and is then epoxied onto a 25- μ m-thick PVF₂ strip. The bonded length of 60 cm is obtained by repetitively folding the fiber back and forth over the PVF₂ strip. An alternative approach is to curl the PVF₂ strip into a cylinder and then wind the fiber over it. Both schemes have been shown to work satisfactorily. Also, a section of the reference fiber arm of the interferometer is wound around a PZT cylinder which serves as a reference signal generator for the PVF₂ phase-drift compensator described later. The PVF₂ is driven by sinusoidal signals with variable dc offsets. The interferometer output is detected by a silicon detector and is monitored simultaneously with both an oscilloscope and a spectrum analyzer.

For a small modulation induced by the PVF₂ fiber stretcher or modulator, the interferometer response was observed to be linear. Data illustrating this type of behavior are shown in Fig. 2. Current results on a 60-cm-long PVF₂ strip agree well with earlier data for 10 or 6 cm lengths of PVF₂ strip. With the longer length of fiber bonded to the PVF₂, not only is it more sensitive at lower driving voltage, but the maximum PVF₂ driving voltage that can be applied before nonlinearity sets in is also lower. Depending on whether the minimal detectable signal (down to the noise floor) is fixed or varying with the length of PVF₂ strip, the dynamic range of the linear response may or may not change with the length of PVF₂ strip. From the stabilized interferometer noise level data presented in this paper, a dynamic range varying from 10^2 at near dc frequencies to 10^4 at frequencies above 4 kHz is achievable with a 60-cm-long PVF₂ fiber stretcher.

The frequency response of the 60-cm-long PVF₂ fiber stretcher is relatively constant at frequencies up to 1 kHz beyond which there is a system resonance observed as indicated in Fig. 3. Included in this figure is a similar frequency response curve for a 6-cm-long PVF₂ strip. The resonance frequency around 3 kHz is probably of a mechanical nature due to the particular geometry employed in the sensor. Fur-

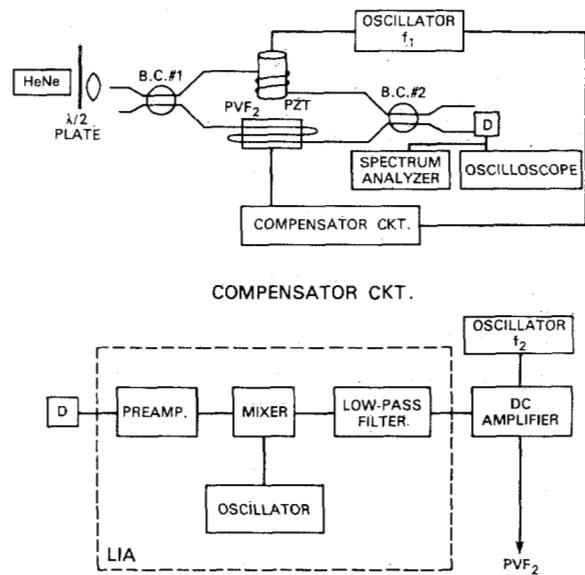


Fig. 1. A schematic of the fiber interferometer setup and the phase-drift compensator circuit.

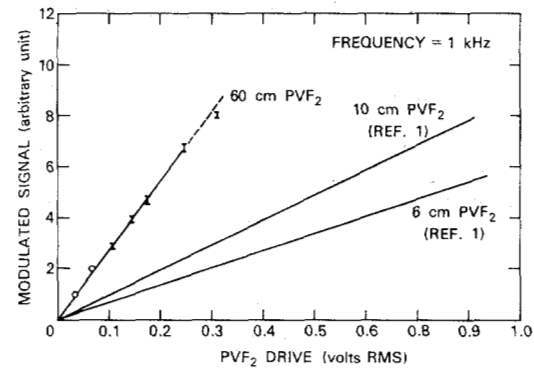


Fig. 2. A plot of the interferometer response linearity versus PVF₂ driving voltages for three different lengths of fiber bonded to the PVF₂.

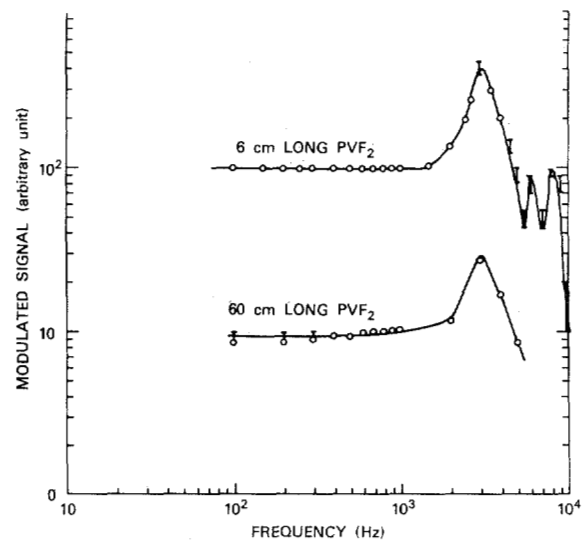


Fig. 3. A plot of the interferometer responses versus frequencies for two different lengths of fiber bonded to the PVF₂.

ther work is needed to pinpoint the source or sources of this resonance.

The phase shifting capability of a PVF₂ fiber stretcher or modulator is measured by noting the lowest driving voltage to the PVF₂ which gives a minimal or zero response signal at the fundamental driving frequency, a technique discussed by various authors previously [6], [8]. The phase shifting coefficient η can be defined as

$$\eta = \frac{\phi}{V_p L} \quad (\text{rad/V} \cdot \text{m}) \quad \text{or} \quad \eta^1 = \frac{\phi}{EL} \quad (\text{rad}/(\text{V/cm}) \cdot \text{m}) \quad (1)$$

where ϕ is the phase shift corresponding to a sinusoidal drive at peak voltage of V_p (or electric field of E V/cm) and for a fiber length (bonded to the PVF₂) of L meters.

Typical data for calibration are shown in Fig. 4. It shows that a driving voltage of 3 V peak-to-peak or 1.5 V peak value applied to the 60-cm-long PVF₂ gives a sufficiently large phase shift so that the output signal at the fundamental frequency (1 kHz) is zero. This state corresponds to a phase shift of 3.83 rad. Thus, the phase shifting coefficient η for the 60 cm length of PVF₂ is 4.2 rad/ $V_p \cdot \text{m}$ of fiber. It agrees well with earlier results of $\eta = 4.1$ rad/ $V_p \cdot \text{m}$ for a 6 cm PVF₂ and $\eta = 3.6$ rad/ $V_p \cdot \text{m}$ for a 10 cm PVF₂.

III. PVF₂ COMPENSATOR

Since the 60-cm-long PVF₂ phase shifter or fiber stretcher described above has a large phase shifting capability, it can be used as a lightweight phase-shift compensator operable at low driving voltage (± 15 V). Previously, [9], [10] such a phase-drift compensator typically required winding ~ 10 m of fibers around a PZT cylinder in order to work satisfactorily with regular electronics with voltage output between +15 and -15 V.

A PVF₂ (like PZT) phase-drift compensator is essentially a fiber stretcher which makes use of a negative feedback to lock the interferometer at a fixed phase relationship between the two interferometer arms. To facilitate phase locking at a phase difference of 1) $\pi/2$ or 2) π , a phase sensitive detection scheme is used. In a fiber interferometer, the two interferometer arms should be kept at a phase difference of $\pi/2$ for maximum sensitivity, or a phase difference of π for maximum frequency mixing efficiency. These two modes are mutually exclusive and can be seen in the following analysis.

Consider a Mach-Zehnder fiber interferometer system shown schematically in Fig. 1. If the two arms of the interferometer are respectively phase modulated by $x_1 \cos \omega_1 t$ and $x_2 \cos \omega_2 t$, the photodetector output is represented by

$$\begin{aligned} I = & I_1 + I_2 + 2\epsilon(I_1 I_2)^{1/2} \cos \phi_0 J_0(kX_1) J_0(kX_2) \\ & - 4\epsilon(I_1 I_2)^{1/2} \sin \phi_0 J_0(kX_2) J_1(kX_1) \cos(\omega_1 t + \sigma_1) \\ & + 4\epsilon(I_1 I_2)^{1/2} \sin \phi_0 J_0(kX_1) J_1(kX_2) \cos(\omega_2 t + \sigma_2) \\ & - 4\epsilon(I_1 I_2)^{1/2} \cos \phi_0 J_0(kX_2) J_1(kX_1) \cos(2\omega_1 t + 2\sigma_1) \\ & - 4\epsilon(I_1 I_2)^{1/2} \cos \phi_0 J_0(kX_1) J_1(kX_2) \cos(2\omega_2 t + 2\sigma_2) \\ & + 4\epsilon(I_1 I_2)^{1/2} \cos \phi_0 J_1(kX_1) J_1(kX_2) \\ & \cdot \cos\{(\omega_1 - \omega_2)t + \sigma_1 - \sigma_2\} + 4\epsilon(I_1 I_2)^{1/2} \\ & \cdot \cos \phi_0 J_1(kX_1) J_1(kX_2) \cos\{(\omega_1 + \omega_2)t + \sigma_1 + \sigma_2\} \\ & + \dots \text{higher order terms} \end{aligned} \quad (2)$$

where

ϵ = a dimensionless number varies from 0 to 1 representing the interferometer mixing efficiency (i.e., fringe visibility)

X_1, X_2 = amplitude of the phase modulated signals at frequency ω_1 or ω_2

ϕ_0 = environmentally induced (thermally or acoustically) phase difference between the two arms of the interferometer

σ_1, σ_2 = arbitrary phase angle of input signal at frequency ω_1 or ω_2

I_1, I_2 = intensities of the two arms of the interferometer.

It can be seen from (2) that signals at fundamental frequencies ω_1 and ω_2 are modified by $\sin \phi_0$, whereas signals at $2\omega_1, 2\omega_2$, and $\omega_1 \pm \omega_2$ are modified by $\cos \phi_0$ as a result of random phase shift ϕ_0 caused by environmental temperature or air current fluctuations. In a phase sensitive detection scheme using a lock-in amplifier, the interferometer output can be mixed with a reference signal either at frequency ω_1 or $2\omega_1$. If a reference signal at ω_1 is chosen, the lock-in amplifier output is proportional to $\sin \phi_0$ and this can be used as an error signal to the PVF₂ compensator so that the signal at ω_1 will be kept at a minimum. This implies $\sin \phi_0 = 0$, or $\phi_0 = \pi$ since $J_0(kX_2)J_1(kX_1)$ is not zero for small X_2 and X_1 . Note that $\phi_0 = \pi$ also implies $\cos \phi_0 = -1$ which means that signals at $\omega_1 \pm \omega_2, 2\omega_1$, and $2\omega_2$ are at their maximum. In other words, highest frequency mixing efficiency occurs when the individual constituent signals are at their minimum, and vice versa. Similarly, if the interferometer output is mixed with a reference signal at frequency $2\omega_1$ then the same feedback scheme will lock the interferometer at $\cos \phi_0 = 0$ or $\phi_0 = \pi/2$ giving rise to minimal signals at $2\omega_1, 2\omega_2$, and $\omega_1 \pm \omega_2$. Since $\phi_0 = \pi/2$ implies $\sin \phi_0 = 1$, the interferometer signals at ω_1 and ω_2 are at their maximum as desired in sensor applications.

Both the π -phase and $\pi/2$ -phase locking modes with the PVF₂ compensator have been achieved using the setup shown in Fig. 1. Typical results for the $\pi/2$ -phase locking mode are shown in Fig. 5. In Fig. 5(a), the upper trace is the interferometer output, and the lower trace is the "dither" or ac drive to the PZT required for phase sensitive detection. Fig. 5(b) shows the spectrum of the interferometer output. The output frequency component at $\omega/2\pi = 2.72$ kHz is due to the 500 mV (peak-to-peak) "dither" to the PZT and it corresponds to a phase shift of 0.5 rad. The output frequency component at $\omega_1/2\pi = 1$ kHz is a simulated signal due to ~ 50 mV (peak-to-peak) sinusoidal drive to the PVF₂ and it corresponds to a phase shift of ~ 0.05 rad. Feedback voltages below ± 15 V to the PVF₂ are sufficient to maintain the phase locking. The high suppression of frequency components at $\omega_1 \pm \omega_2$ is an indication of the proximity to $\pi/2$ -phase locking according to (2). Small signal components at $(2\omega_2 - \omega_1)/2\pi, 2\omega_2/2\pi$, and $3\omega_2/2\pi$ are also observed as expected if higher order terms are kept in (2).

Similarly, typical results for the π -phase locking mode are shown in Fig. 6. It can be seen that signals at fundamental frequencies $\omega_1/2\pi = 2.72$ kHz and $\omega_2/2\pi = 1$ kHz are suppressed by >40 dB compared to the π -phase locking mode case, and the mixed frequency components at $(\omega_1 + \omega_2)/2\pi =$

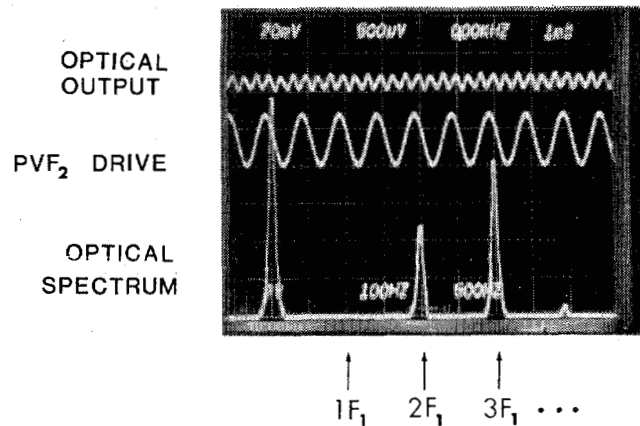


Fig. 4. Oscilloscope showing the interferometer output (upper trace) caused by a PVF₂ drive (middle trace) which gives rise to an optical spectrum with a missing fundamental frequency component (lower trace).

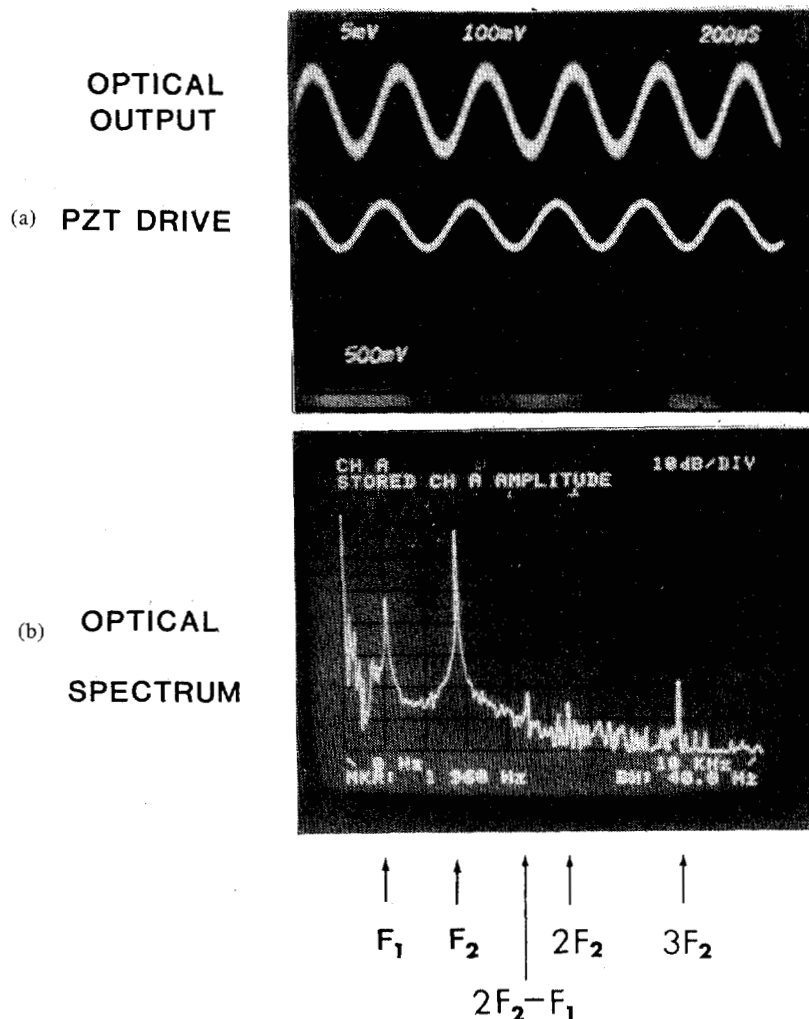


Fig. 5. Oscilloscope showing (a) the interferometer output [upper trace of (a)] and (b) its frequency spectrum due to a 500 mV (peak-to-peak) voltage drive to the PZT [lower trace of (a)], and a 50 mV (peak-to-peak) voltage drive to the PVF₂ when the interferometer arms are locked at a phase difference $\phi = \pi/2$.

3.72 kHz and $(\omega_1 - \omega_2)/2\pi = 1.72$ kHz are enhanced >30 dB above noise floor. Higher frequency components at $(3\omega_2 - \omega_2)/2\pi = 7.16$ kHz and $(3\omega_1 + \omega_2)/2\pi = 9.16$ kHz with smaller amplitudes are also observed as expected from theoretical analysis. A frequency mixing efficiency ξ can be defined as the ratio of the sum of signal levels at $\omega_2 - \omega_1$ and $\omega_1 + \omega_2$ to the sum of signal levels at ω_1 and ω_2 . Using data

from Fig. 5(b) and Fig. 6, the measured frequency mixing efficiency is ~ 0.059 as compared to the computed value of ~ 0.046 using (2) and the phase-shifting capabilities of the PVF₂ and the PZT.

To evaluate the ultimate sensitivity of the fiber interferometer sensor locked at its maximum sensitivity point (the $\pi/2$ -phase mode), only the "dither" drive to the PZT at ω_2 is ap-

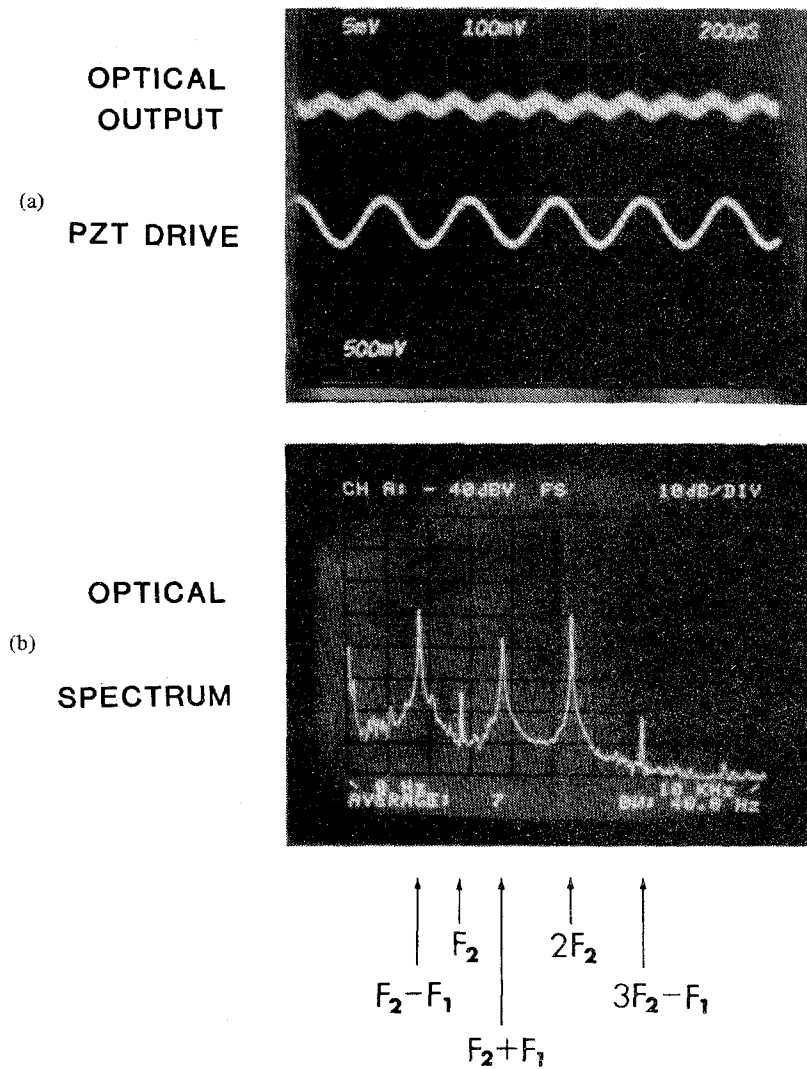


Fig. 6. Oscillograms showing (a) the interferometer output [upper trace of (a)] and (b) its frequency spectrum due to a 500 mV (peak-to-peak) voltage drive to the PZT [lower trace of (a)] and a 50 mV (peak-to-peak) voltage drive to the PVF₂ when the interferometer arms are locked at a phase difference $\phi = \pi$.

OPTICAL SPECTRUM

$$\left(\phi = \pi/2 \right)$$

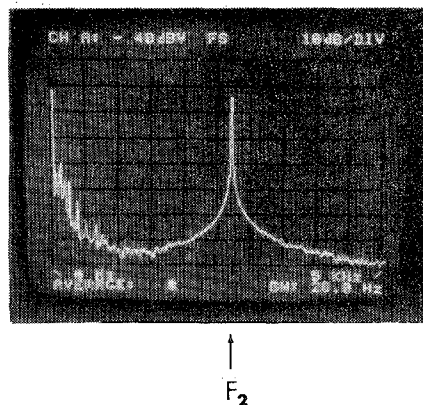


Fig. 7. Oscillogram of the frequency spectrum of the interferometer at the $\pi/2$ -phase locking mode.

plied and the frequency spectrum of the interferometer output is recorded as shown in Fig. 7. The optical signal at the “dither” frequency is calibrated by the method described in the previous section and it corresponds to a phase shift of 0.5

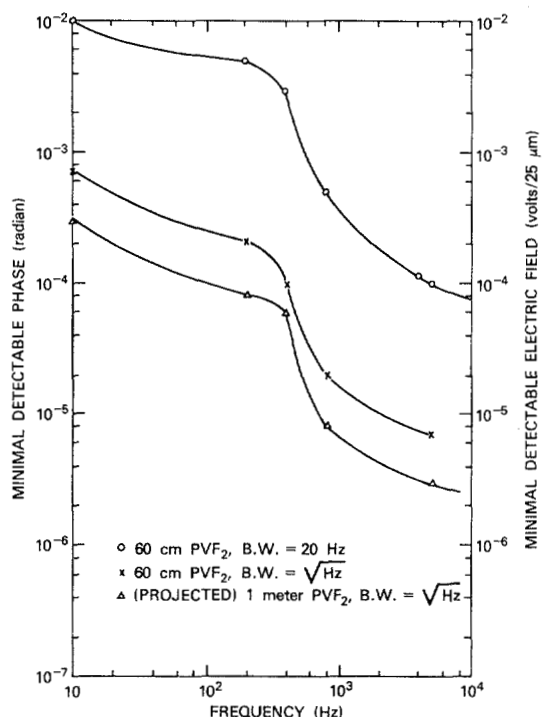


Fig. 8. A plot of the minimum detectable phases or electric fields versus frequency of the phase-drift compensated interferometer, (a) a 60 cm length of fiber bonded to the PVF₂ and a receiver bandwidth of 20 Hz, (b) the same PVF₂ strip with results normalized to $\sqrt{\text{Hz}}$, and (c) a projected 1 m of fiber bonded to the PVF₂ and a receiver bandwidth of $\sqrt{\text{Hz}}$.

rad. The noise floor versus frequency shows a $1/f$ dependence. At low frequencies, the noise background appears to be dominated by deterministic, spurious signals at 60 cycles and its harmonics which are present at the output of the dc amplifier. However, reduction of noise at low frequencies is conceivable with improvements in the signal processing. Using the noise level shown in Fig. 7 as the limit, the minimal detectable phase shifts or electric fields for the phase-drift compensated interferometer are computed, and the results are shown in Fig. 8. The three curves correspond to data obtained from 1) a 60-cm-long PVF₂ strip with a receiver bandwidth of 20 Hz, 2) the same PVF₂ strip with receiver bandwidth normalized to $\sqrt{\text{Hz}}$, and 3) a projected 1-m-long PVF₂ strip with a receiver bandwidth of $\sqrt{\text{Hz}}$.

IV. CONCLUSIONS

The response linearity, the frequency response, and the sensitivity of a PVF₂ fiber stretcher have been characterized. A lightweight PVF₂ phase-drift compensator using 60 cm of fiber has been demonstrated for the first time in an all fiber

interferometer. Improvements in the signal processing aspects of the compensator circuit are currently underway and are expected to further upgrade the performance of the device.

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