A Sensitive Fiber-Optic Fabry–Perot Interferometer

S. J. PETUCHOWSKI, T. G. GIALLORENZI, AND S. K. SHEEM

Abstract—**A Fabry–Perot interferometric sensor utilizing a single-mode optical fiber has been demonstrated, exhibiting a finesse of 18 and a sensitivity to phase modulation of 7.9×10^{-7} rad/$\sqrt{\text{Hz}}$ at 1 kHz.**

I. Introduction

THE USE of optical fibers as sensors has recently received considerable attention. Of the various fiber sensor embodiments, those with highest demonstrated sensitivities involve configurations which interferometrically measure the optical phase shift induced by the field to be sensed. All-fiber Mach–Zehnder interferometers, comprised of separate signal and reference optical paths, have been shown to detect periodic phase changes in the 10^{-6} rad regime [1], [2].

The Mach–Zehnder fiber interferometer requires two directional couplers which serve as the beam splitting/recombining elements. The concept of exploiting the interference among multiple passes in a *single* fiber has been considered by Cielo [3] and Yoshino [4]. In this letter, we report the implementation of a Fabry–Perot configuration utilizing single-mode optical fibers. High finesse and high sensitivity to minute phase shifts have been demonstrated for the first time in this new class of sensor. The finesse expresses the ratio of peak spacing to peak full-width at half-maximum for the transmitted power as a function of phase delay. Sufficient finesse has been achieved to demonstrate phase sensitivity equal to the best achieved to date in any fiber sensor, and theoretical studies indicate that order-of-magnitude improvements should still be possible.

II. Fabry–Perot Sensitivity

For a purely monochromatic source, the fractional transmitted power through an etalon comprised of two parallel mirrors with transmission (reflection) coefficient of $t_i(r_i)$, $i = 1, 2$, respectively, is readily shown to be a periodic function of phase delay per pass ϕ:

$$T = T_{\max} f(\phi)$$

where

$$T_{\max} = \frac{|t_1|^2 \, |t_2|^2}{(1 - \alpha R)^2}; \quad R = r_1 r_2 \tag{1}$$

$$f(\phi) = (1 + \rho \sin^2 \phi)^{-1}; \quad \rho = (2\mathcal{F}/\pi)^2$$

with the finesse $\mathcal{F}$ defined above and equal to $\pi\sqrt{\alpha R}/(1 - \alpha R)$, for $(1 - \alpha)$ the attenuation per pass.

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The phase delay depends on the source wavelength λ, fiber length L, and index of refraction n as

$$d\phi = \frac{2\pi}{\lambda}(ndL + Ldn) - \frac{2\pi nL}{\lambda^2}\, d\lambda \tag{2}$$

where excitation of a single polarization mode is assumed. In the experiment reported here, the second and third terms are negligible. The sensitivity of the interferometer to length changes, lumped or distributed, is thus proportional to

$$\frac{dT}{d\phi} = -T_{\max} \frac{\rho \sin 2\phi}{(1 + \rho \sin^2 \phi)^2}. \tag{3}$$

Since the maximum excursion in transmission corresponds to a phase shift of $\pi/2$, we can express the minimum detectable phase shift as

$$\Delta\phi|_{\min} = \frac{\pi}{2} \frac{I_{\text{noise}}}{I_o T_{\max}} \left(\left.\frac{df}{d\phi}\right|_{\phi_o} \right)^{-1} \tag{4}$$

where I_{noise} is the photodetector current corresponding to the limiting noise, I_o is the current corresponding to the optical power coupled into the interferometer, and ϕ_o is the point of maximum sensitivity.

An attractive feature of the Fabry–Perot configuration is the sensitivity enhancement over two-arm interferometers achieved by maintaining ϕ at the optimal operating point, given by

$$\phi_o = \tfrac{1}{2} \cos^{-1} \left(\tfrac{1}{2}\sqrt{9 + 4/\rho + 4/\rho^2} - 1/\rho - \tfrac{1}{2}\right). \tag{5}$$

At this point, the phase sensitivity is

$$\left|\frac{dT}{d\phi}\right|_{\max} = \frac{T_{\max}}{\rho} \left[(\sin 2\phi_o)^{-3} - (\sin 2\phi_o)^{-1}\right]. \tag{6}$$

This slope is plotted in Fig. 1 versus reflectivity for three values of loss per pass, for cases of equal and unequal mirror reflectivities. By way of comparison, the two-arm interferometer, with a transmission function of $T = \frac{1}{2}(1 + \cos\phi)$, is limited to a phase sensitivity of $|dT/d\phi|_{\max} = \frac{1}{2} T_{\max}$, where $T_{\max}$ is unity in theory but limited by component losses. We thus see that the Fabry–Perot sensor configuration offers at least an order of magnitude improvement in fiber sensor sensitivity when compared with the more conventional two-arm interferometric sensors.

III. Experimental Configuration

The experimental configuration, depicted in Fig. 2, consisted of a single-mode optical fiber (ITT, 4.75 μm-diameter core) of length ~40 cm. A Fabry–Perot cavity was formed by butting the cleaved fiber ends to two dielectric-coated glass partial mirrors M_1 and M_2. The mirror transmissivities were 2.6 percent and 8.3 percent, respectively, at the 6328 Å wavelength of the single-frequency Tropel 100 helium-neon laser source,

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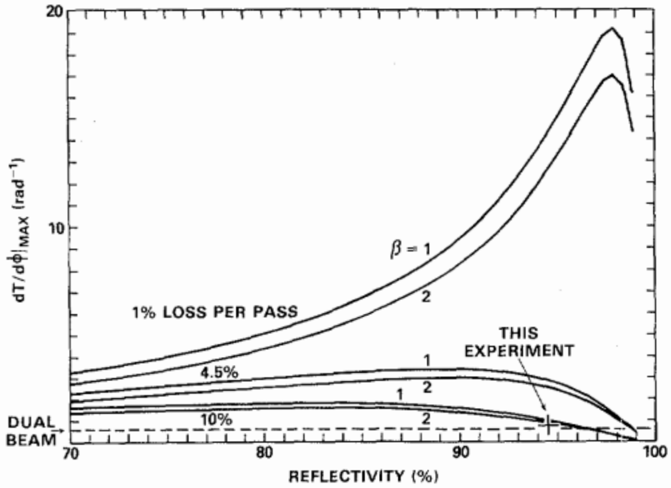

Fig. 1. Fabry–Perot phase sensitivity at optimal operating point, for three values of attenuation per pass and for $\beta \equiv (t_1/t_2)^2 = 1, 2$. Dashed line indicates two-arm interferometer phase sensitivity.

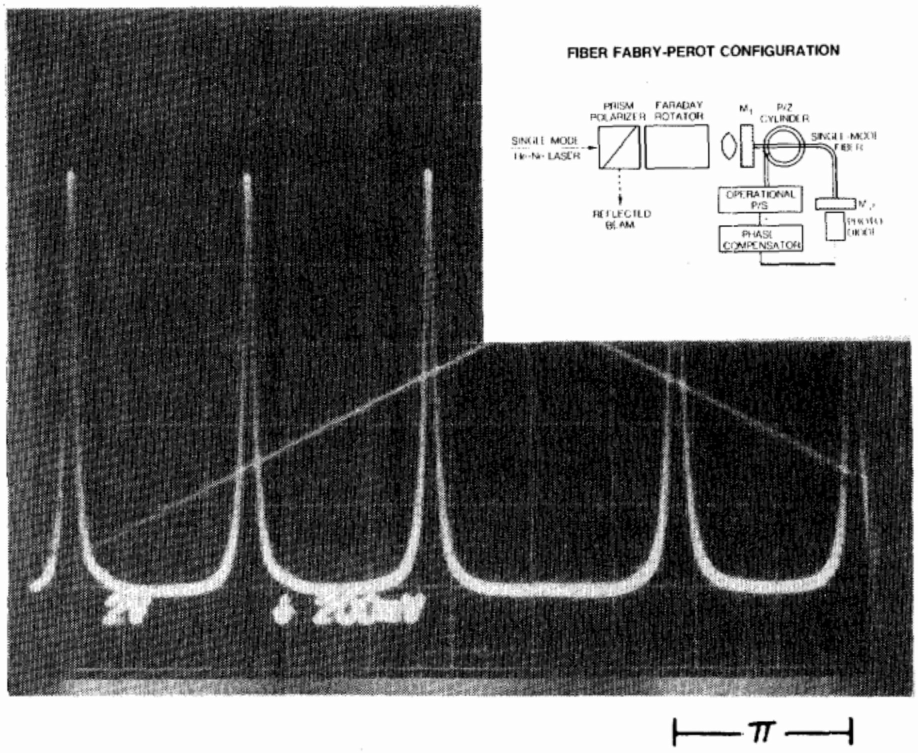

Fig. 2. Voltage across piezoelectric cylinder and Fabry–Perot transmission, $\mathcal{F} = 11$ (inset: Fabry–Perot configuration).

and their radii of curvature were 200 cm and ∞, respectively. The reflective surfaces were accurately positioned normal to the fiber axis by means of alignment with a precision prism relative to grooves etched in a silicon holder.

The helium-neon beam was coupled into the fiber by focusing through M_1, with a Faraday rotator and Glan-Thomson polarizer providing optical isolation of the laser from the reflected beam. A coupling efficiency of 55 percent was possible through M_1.

Length modulation was imposed on the fiber by bonding the fiber jacket to two points along a diameter of a hollow piezoelectric cylinder. A voltage was applied between the conductively coated inner and outer surfaces of the cylinder by means of a programmable high voltage supply. In the present experiment, a dc bias component was supplied by a servo-circuit such as described by Jackson *et al.* [1] to compensate for phase drift from a fixed dc level of detector current corresponding to the optimal phase point (5). A sinusoidal component could also be applied, although responsivity versus frequency depended critically on the bonding technique and static tension on the fiber. Calibration at a given frequency was performed by noting the minimum sinousoidal voltage amplitude required to induce a signal of maximum peak-to-peak excursion.

In order to evaluate the achievable sensitivity with a fiber Fabry–Perot configuration, two interferometers were tested in succession, employing the same optical components. In the first, A, a finesse of 18.0 ± 3.7 was attained on first alignment with degradation to 13.1 ± 2.7 in the course of a day. This was attributed to inadequate mechanical support of the butt-coupling. In the second Fabry–Perot interferometer, B, the maximum transmitted power was measured with a calibrated photodetector to be $14.0\ \mu W$, corresponding to $T_{max} = 4.5$ percent and a finesse of 13.9. A representative sweep showing the applied driving ramp signal to the piezoelectric element and transmission response of the interferometer appears in Fig. 2.

IV. Measured Sensitivity

The optical power coupled into the fiber after normalizing for the transmission of M_1 was $300\ \mu W$. Fig. 3 depicts the spectrum of interferometer B, servolocked to maximum sensitivity, with a sinusoidal dither of rms amplitude 0.34 Å, or 5.0×10^{-4} rad, at 1 kHz. Two spectra are shown: the upper indicating noise limitation by laser amplitude noise. After replacing the source, the lower noise spectrum was obtained, indicating a noise floor 10–20 dB above the shot-noise limit for frequencies >500 Hz. The detector was a photoconductively configured photodiode and the observed noise floor is attributed to electromagnetic shielding problems.

Comparison of the signal level and noise floor at 1 kHz indicates a minimum detectable rms phase modulation of $7.9 \times 10^{-7}\ \text{rad}/\sqrt{\text{Hz}}$, equal, within experimental accuracy, to that reported for the fiber Mach–Zehnder sensor in a drift-free environment [1].

V. Discussion and Conclusions

The finesse of 18 attained in interferometer A corresponds to a maximum transmission T_{max} of 7.5 percent. The Mach–Zehnder sensitivity measurements cited above [1] were performed with optical power, both coupled into the fiber and incident on the detector, comparable to the conditions of this experiment. More recent development of lower loss components has brought T_{max} in the Mach–Zehnder to within a factor of 2 of unity [5]. Thus, an order of magnitude more power is incident on the detector and a 10 dB increase in the ratio of signal to shot noise is to be expected in the Mach–Zehnder.

The sensitivity factor, for the Fabry–Perot sensor $df/d\phi$, equals 7.4 for $\mathcal{F} = 18$; however, in our experiment this enhancement over 0.5 for the two-arm interferometer was degraded by the poor throughput. Thus, the measured experimental sensitivity $dT/d\phi|_{\phi_o} = 0.56$ was marginally superior to the lossless two-arm interferometer. A significant enhancement is expected when the 11.1 percent loss per pass, dominated by coupling loss at the cavity ends, is reduced, as is apparent in Fig. 1. On the other hand, Fabry–Perot interferometer configurations do impose more stringent coherence requirements on the source than do Mach–Zehnder configurations, and further, necessitate increased optical isolation of the source.

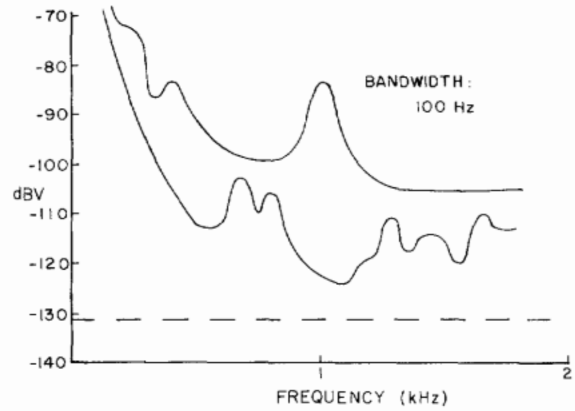

Fig. 3. Measured noise spectra (100 Hz bandwidth)—see text. Dashed line indicates shot-noise limit.

VI. Summary

In summary, we have demonstrated a fiber interferometer employing no couplers and exhibiting a sensitivity to phase shifts equalling, and potentially exceeding, the most sensitive fiber sensors demonstrated to date.

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