# Miniaturized fiber-optic Michelson-type interferometric sensors

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We present a novel, miniaturized Michelson-type fiber-optic interferometric sensor that is relatively insensitive to temperature drifts. A fused-biconical tapered coupler is cleaved immediately after the coupled length and polished down to the region of the fused cladding, but short of the interaction region. The end of one core is selectively coated with a reflective surface and is used as the reference arm; the other core serves as the sensing arm. We report the detection of surface acoustic waves, microdisplacements, and magnetic fields. The sensor is shown to be highly stable in comparison to a classic homodyne, uncompensated Michelson interferometer, and signal-to-noise ratios of 65 dB have been obtained.

## I. Introduction

Single-mode fiber-optic interferometric sensors (FOIS's) have been shown to possess high sensitivities for various applications. Measurement of real-time phase shifts has been demonstrated in acoustic, temperature, magnetic, and strain sensors.[1-4] In the FOIS's reported so far, the reference and the sensing arms usually are physically at different locations and hence a minuscule change in temperature in the reference arm may affect the phase difference detected at the output of the sensor. This may lead to a misinterpretation of the observed change in phase due to temperature drifts being attributed to the external perturbation to be measured.

It is essential to maintain the FOIS's continuously at the quadrature point of operation. To achieve such performance, Jackson et al used a piezoelectrically stretched fiber and active feedback in the reference arm to solve this problem.[5] Similarly, an integrated-optic microdisplacement sensor, which uses a $Y$ junction and a polarization-preserving fiber, has been reported.[6] Passive stabilization schemes using $3 \times 3$ couplers and active optical schemes have also been demonstrated.[7,8]

In this paper we present a miniaturized Michelson-type interferometer and demonstrate its stable opera-

tion in several applications. Section II describes the construction of the sensor from a fused-biconical coupler. The stability of the sensor is tested and the details of the experiment are given in Section III. In Section IV we measure the sensitivity of the sensor to variations in the angular and vertical displacements. In Section V the sensor is used to detect surface acoustic waves generated along a metallic bar. The stable subangstrom readings are used to measure the velocity of the propagating wave. In Section VI we briefly describe the application of this sensor in magnetic field measurement. The method of transduction used in this sensor is different from most sensing mechanisms described in the previous literature. A discussion of the results forms part of the concluding section.

## II. Sensor Construction

The construction of the sensor can be described as follows:

(1) A fused-biconical tapered coupler was constructed from a 4/125-$\mu$m single-mode fiber with a numerical aperture of 0.1.

(2) The two output arms of the coupler were cleaved immediately after the coupling length.

(3) The coupler was attached to Invar strips with epoxy and polished until two cores, within 20 $\mu$m of each other, could be observed.

(4) Aluminum was selectively deposited at the end of one of the cores.

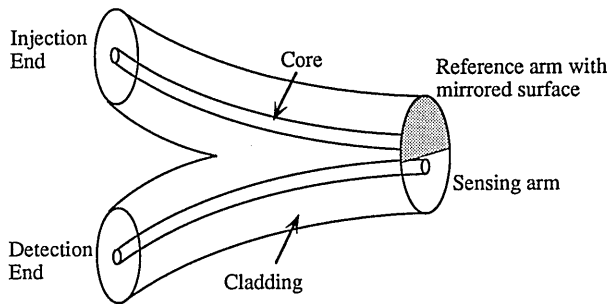The core with the mirrored end was used as the reference arm and the uncoated core served the

Fig. 1. Details of the miniature FOIS.
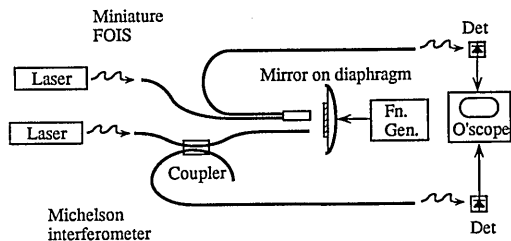


Fig. 2. Experimental setup for comparing the miniature FOIS and homodyne Michelson interferometer.



(a)  Time/Div = 0.2 ms

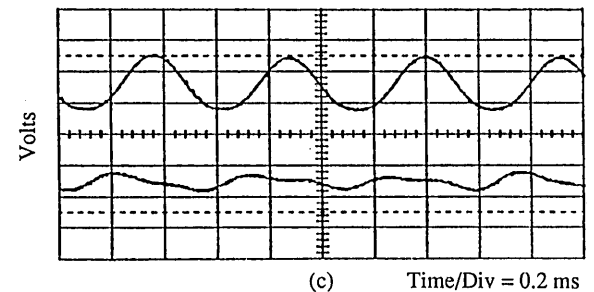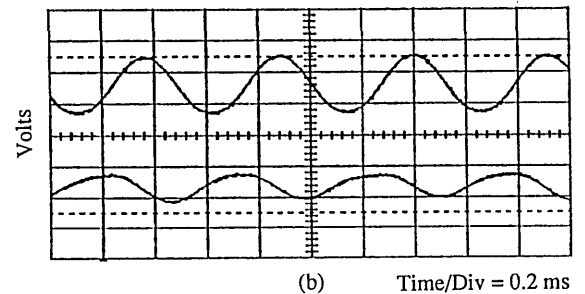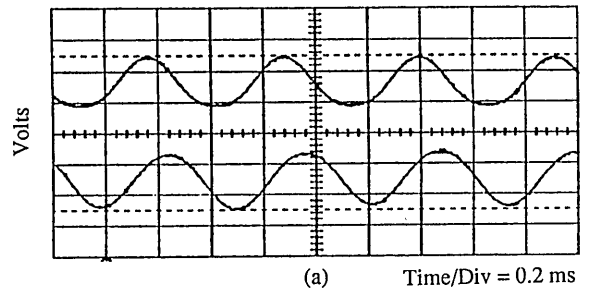(b)  Time/Div = 0.2 ms

(c)  Time/Div = 0.2 ms

Fig. 3. Comparison of the miniature FOIS and homodyne Michelson interferometer for a single fringe: (a) $t = 0$ ms, (b) $t = 100$ ms, (c) $t = 200$ ms.

purpose of the sensing arm. A schematic of the sensor is shown in Fig. 1.

## III. Stability Experiments

In order to test the stability of this sensing scheme, two Michelson configurations were placed side by side and their performance was evaluated in terms of temperature drifts. The experimental setup, shown in Fig. 2, consists of the miniaturized FOIS and a standard, simple, homodyne Michelson interferometer placed in front of a vibrating mirror attached to a vibrating diaphragm. We would normally expect a $\pi/2$ phase shift in the detected signal for a 1-m length homodyne Michelson arrangement for a temperature gradient of 10 mdeg between the arms.[1] The miniaturized FOIS has both arms close to each other, which makes it difficult to predict the expected phase shifts due to a given temperature gradient. One way of comparing the two schemes is to monitor the outputs continuously and observe the drifts due to small changes in the environmental conditions. Figures 3(a)–3(c) show the oscilloscope waveforms of the two sensors at millisecond intervals for a single fringe, and Figs. 4(a) and 4(b) depict the same for multiple fringes. Signal fading is observed in the standard Michelson due to temperature-induced shifts in the quadrature point of operation. In comparison, we have observed stability of the FOIS waveforms over more than 3 h.

We have obtained signal-to-noise ratios of 65 dB with a minimum detectable phase shift of 0.0017 rad, which corresponds to a minimum detectable displacement of 0.18 nm. The fringe contrast is determined by the relative intensities of the reference and the sensing signals. The relative amplitudes of the interfering signals depend intrinsically on the reflectivity of the sensing surface and the distance of the sensor head from the reflective surface. In this sense, it is useful to know the optical properties of the microdisplaced surface prior to the construction of the sensor. In practice, we have found that reflectivities of 40% at the reference reflection result in high fringe contrast for metallic sensing surfaces. Shot-noise-limited detectors should allow signal-to-noise ratios in the 70–80-dB range, as predicted theoretically.[1]

## IV. Sensitivity Analysis

For the measurement of microdisplacements, the stability of the sensor placement itself plays an important role in the observed signals. One would expect the sensor sensitivity to be highly dependent on the vertical displacement of the probe from the surface as well as on the angular orientation. To determine this dependence, we analyzed the change in the output voltage obtained from the detector as the distance $x$ and the angle $\theta$ were varied. A schematic of the experiment is shown in Fig. 5. Figures 6 and 7 show the results of this analysis. As can be seen, the miniaturized FOIS needs to be precisely positioned on the tripodlike stand in order to obtain high sensitivities. Both figures show the critical depen-

(a)   Time/Div = 0.2 ms
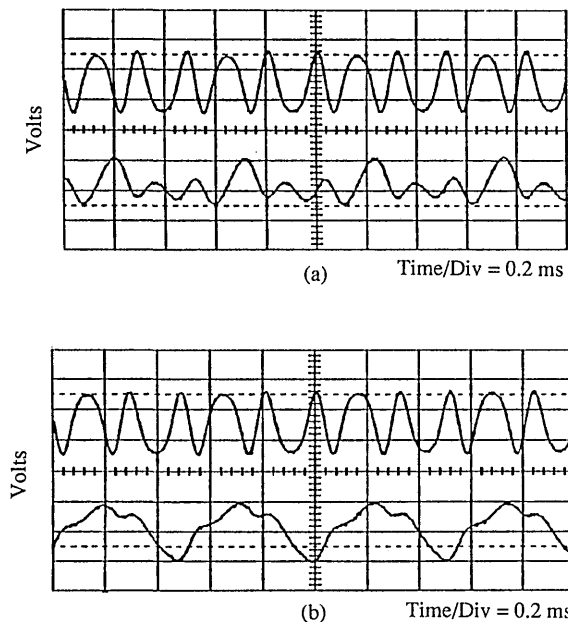


(b)   Time/Div = 0.2 ms

Fig. 4.  Comparison of the miniature FOIS and homodyne Michelson interferometer for multiple fringes: (a) $t = 0$ ms, (b) $t = 100$ ms.

dence of the sensor performance on the orientation of the sensor. An angular misalignment of 0.05° or a vertical displacement of 30 μm is shown to result in a 3-dB drop in the detected signal. This result implies that the probe can be used in applications where the sensor can be brought close to the surface that experiences the microdisplacements.

## V. Surface Acoustic Wave Detection

The detection of ultrasonic surface acoustic waves (SAW's) has been shown to have important applications in determining microstructural properties, the inspection of materials for quality control, and the detection of flaws in materials. Since noncontact, noninvasive temperature insensitive probes are ideally suitable for such measurements, we present basic results of the miniaturized Michelson interferometer applied to SAW detection. Optical techniques for the generation and detection of ultrasound have been
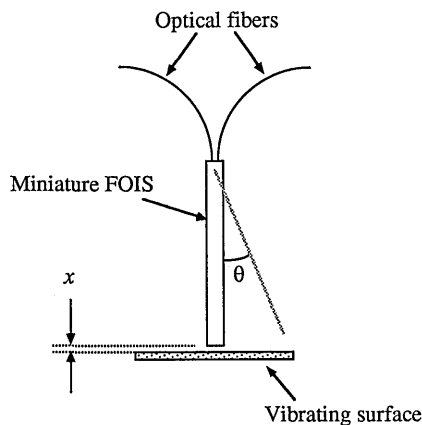


Fig. 5.  Experimental setup to measure sensor sensitivity.
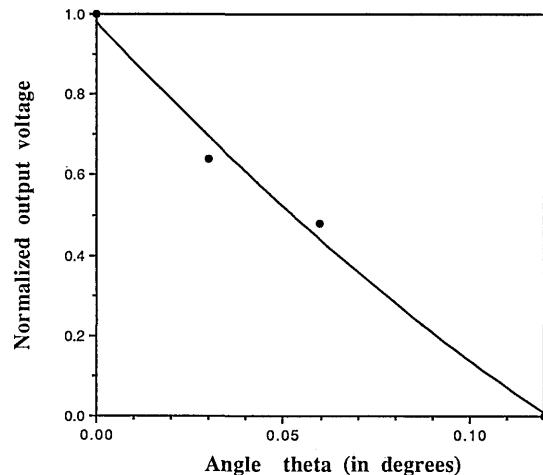


Fig. 6.  Dependence of output voltage on the angular orientation of the sensor. The graph shows experimental points (●) and a simple curve fit.

shown to be particularly useful as noncontact methods.[9] Fiber-optic sensors are preferred over bulk-optic systems because of their high sensitivity, small size, and easy implementation.

The generation and detection of SAW's is conventionally performed by using piezoelectric transducers (PZT's) such as lead zirconate titamate. The particle (atomic or molecular) motion associated with SAW propagation generally follows a retrograde elliptical orbit with the major axis of the ellipse perpendicular to the surface. Such SAW displacements are usually of the order of a few angstroms ($10^{-10}$ m), and many different optical methods have been suggested for the detection of such displacements.[9]

Our basic experimental setup is shown in Fig. 8. We generated SAW's on an aluminum bar, using PZT driven by a rf gated amplifier at a frequency of 1 MHz. A 10-mW He–Ne laser launched light into the sensor fiber through a 5× lens. An avalanche photodiode (APD) was used as the optical detector with an envelope detection scheme. The miniature FOIS was mounted on a tripodlike stand on the specimen surface and could be moved from one point to another.

Figure 9 shows a real-time output pattern, the two peaks corresponding to (1) the fiber-optic SAW sensor mounted midway atop the bar, and (2) the PZT at the end of the aluminum bar. The high noise level in the output waveform is due to the vibration in the tripod relative to the aluminum bar. Figure 10 shows the movement of the FOIS by 4 cm on the bar, which gives the SAW velocity to be 2940 m/s. The envelope of the fringe pattern was averaged 1000 times and then observed on the oscilloscope. Using standard piezoelectric methods for comparison, we found the SAW velocity to be 2940 m/s.

The miniaturized FOIS has several advantages over PZT's for the detection of SAW's. The miniature FOIS does not have to be in contact with the surface along which the SAW propagates. The FOIS can operate at higher temperatures than standard PZT's
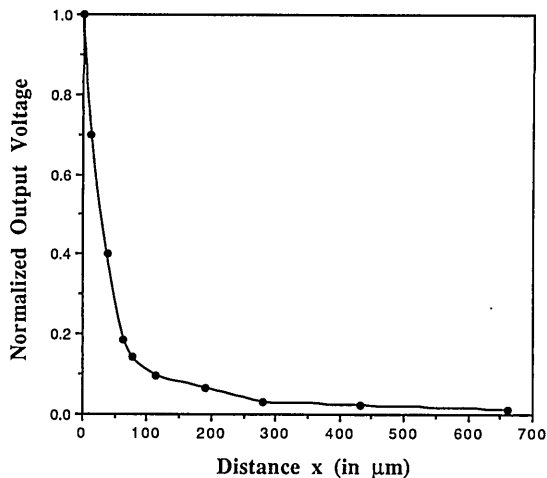
Fig. 7. Dependence of output voltage on the lateral displacement of the sensor.



Fig. 9. Real-time (not averaged) SAW detection by a miniature FOIS (left) and a PZT (right).

depending on the fiber coatings and the packaging material of the fiber coupler. The material and geometry of the PZT determines the resonant frequency at which the detection scheme is most sensitive. This resonant frequency limits the PZT bandwidth of operation. The miniature FOIS is bandwidth limited only by the detection electronics.

## VI. Magnetic Field Sensing

Magnetostrictive materials are commonly used as strain transformers in fiber-optic magnetic field sensors. Most widely used are metallic-glass alloys, which have the advantage that they may be conveniently drawn into different shapes. Metallic glasses such as unannealed $Fe_{74}Co_{10}B_{16}$ have been reported to have low hysteresis losses, and their use as magnetic field modulators has been discussed.[10] In most magnetic field sensors, the optical fiber is attached directly to the metallic glass and a direct strain transfer from the magnetostrictive material to the fiber is achieved. In the experiments described in this section, the fiber-optic sensor acts as a probe and faces the magnetostrictive material that undergoes modulation depending on the applied magnetic field.

Here we report preliminary results of a Terfenol-based fiber-optic magnetic field sensor. Terfenol, typ-
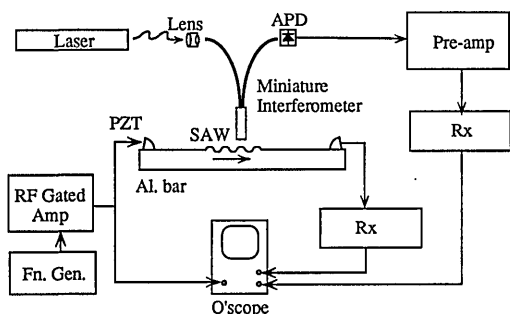
ically composed of $Tb_{0.3}Dy_{0.7}Fe_2$, is a relatively new alloy and, reportedly, has a high magnetostriction compared to other commercially available metallic glasses.[11]

A schematic of the experimental setup is shown in Fig. 11. A cylindrical coil is used to generate ac magnetic fields proportional to the input current. Figure 12 shows a detailed picture of the mounting scheme used to position the FOIS within a Helmholtz coil. The FOIS is mounted on an aluminum spacer that is attached to a sliding brass tube so that the distance between the end of the FOIS and the Terfenol surface can be adjusted to obtain the optimum operation point. No effort was made to maximize the sensitivity of the Terfenol as a function of the dc bias field; hence the results that follow should not be considered as an indication of the efficiency of Terfenol as a magnetostrictive material in fiber-optic sensors.



Fig. 10. Oscilloscope output showing detection of the SAW by the miniature FOIS at two locations separated by 4 cm.



Fig. 8. Experimental setup for SAW detection: APD, avalanche photodiode; Rx, Receiver; PZT, pioezoelectric transducer.



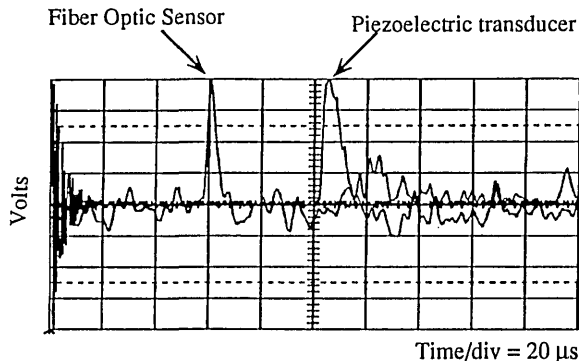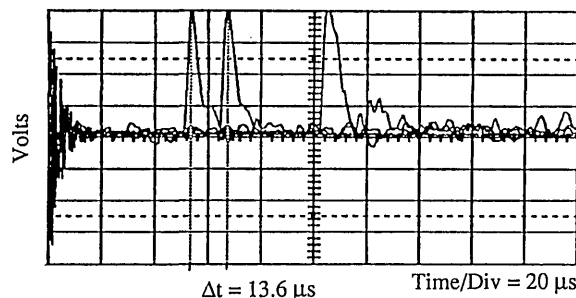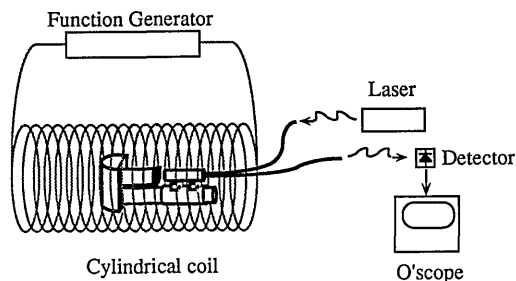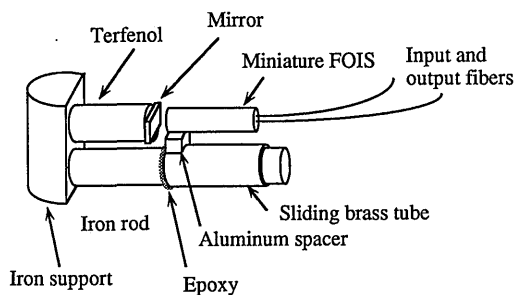Fig. 11. Experimental setup for magnetic field sensing.

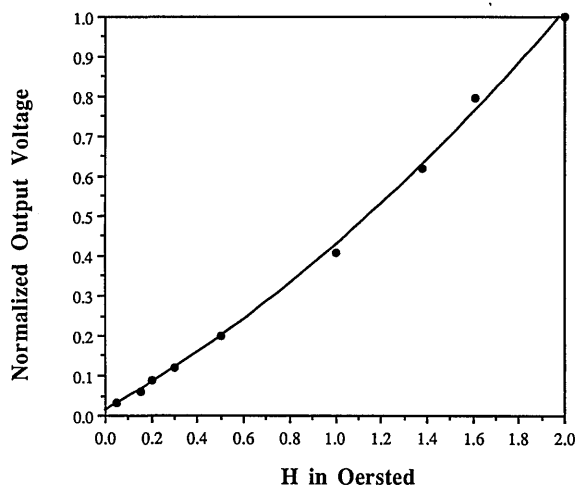Fig. 12. Mounting scheme for the miniaturized magnetic field sensor.



Fig. 13. Typical input-versus-output curve for the magnetic field sensor. The graph shows experimental points (●) and a second-order polynomial curve fit.

A typical input-versus-output curve of the magnetic field sensor at 3.5 kHz is shown in Fig. 13. The horizontal axis indicates the input current to the Helmholtz coil and the vertical axis represents the output voltage from the photodetector when the sensor is operated in the linear range. Minimum detectable signals of the order of $10^{-7}$ Oe were obtained. Current research is concerned with the characterization of the Terfenol frequency response.

## VII. Discussion

A miniaturized FOIS has been developed and used in several different applications. The FOIS is virtually insensitive to temperature drifts when compared to the simple, homodyne, Michelson interferometer. It can be used for the measurement of microdisplace-

ments in high-temperature ($T \geq 700°C$ for specialized fibers) environments and is not bandwidth-limited.

The miniaturized FOIS is not restricted to the applications described in this paper and can be used for the measurement of any external perturbation that manifests itself as a microdisplacement. Standard Michelson or Mach–Zehnder configurations provide for piezoelectric coils to be introduced for stabilization or electronic circuitry to be combined for phase-error feedbacks. The proximity of the two arms in the miniaturized version makes it difficult to introduce such stabilization schemes. The inherent stability of the sensor, however, eliminates the need for feedback circuitry. The sensor allows low-frequency measurements and fringe hopping prevalent in stabilized interferometric sensors is not observed in this scheme.

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