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# Phase Modulation at 125 kHz in a Michelson Interferometer Using an Inexpensive Piezoelectric Stack Driven at Resonance

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# Phase modulation at 125 kHz in a Michelson interferometer using an inexpensive piezoelectric stack driven at resonance

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Fast phase modulation has been achieved in a Michelson interferometer by attaching a lightweight reference mirror to a piezoelectric stack and driving the stack at a resonance frequency of about 125 kHz. The electrical behavior of the piezo stack and the mechanical properties of the piezo-mirror arrangement are described. A displacement amplitude at resonance of about 350 nm was achieved using a standard function generator. Phase drift in the interferometer and piezo wobble were readily circumvented. This approach to phase modulation is less expensive by a factor of roughly 50 than one based on an electro-optic effect.
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## I. INTRODUCTION

A Michelson interferometer provides a powerful technique for measuring the optical properties of a medium. When measurements are made at many spatial points in the medium, the data can be assembled to form a three-dimensional image; this is the rapidly growing field of optical coherence tomography or microscopy (OCT or OCM).[1] Examination of the fringes at the output of a Michelson interferometer can yield the amplitudes and relative phases of the two beams traversing sample and reference arms, respectively, and this information can in turn be used to determine the optical properties of the medium placed in the sample arm. To generate output fringes, the path length difference between the two arms is often varied periodically by oscillating the reference mirror position. This mirror oscillation varies the phase difference between the two beams, and is often referred to as phase modulation of the instrument. A high frequency of phase modulation results in a high fringe frequency and facilitates a rapid measurement of the amplitudes and phases, and hence of the optical properties of the medium. A high modulation frequency, therefore, can also increase the speed of image acquisition in an OCM. In this article we describe an inexpensive but rapid method for phase modulation using a piezoelectric stack driven at one of its resonance frequencies.

Piezoelectric crystals are used in a variety of forms for phase modulation in interferometry.[2–4] The mirror in the reference arm of a Michelson interferometer is often attached to a piezo stack that is driven at frequencies up to 10 kHz, well below its resonance frequency. With driving amplitudes of some ten to a hundred volts, path length modulations on the order of a few microns can be achieved.[2] In fiber optic interferometers, the fiber can be wound in a large number of turns around a hollow piezoelectric cylinder. Driving the cylinder up to frequencies of a few kilohertz will cause it to expand and contract radially, stretching and relaxing the fiber accordingly and thus providing the modulation of the optical path length.[3] However, this method typically requires tens of meters of fiber, introducing into the interferometer static polarization mismatch which must be eliminated with polarization controllers, e.g., paddles that twist the fiber and induce stress birefringence. In addition, stretching and relaxing long lengths of fiber introduces dynamic birefringence modulation which requires a Faraday rotator for compensation.[4] Recently, fibers coated with piezoelectric films have also been used. When a voltage is applied to the piezo jacket, the fiber is squeezed radially and thus increases in length. In this way, fast phase modulations can be achieved, but the modulation amplitude is typically small. In order to produce a change in optical path length of 1 $\mu$m at 100 kHz, a fiber coated over a length of 20 cm would require more than 100 V of driving amplitude.[5]

We are using a fiber optic Michelson interferometer as the primary component in an optical coherence microscope (OCM).[6] The OCM utilizes a superluminescent diode operating at 843 nm. In order to reduce the time required to collect an OCM image, we need a method of phase modulation with a frequency greater than 100 kHz and a displacement amplitude of roughly 350 nm (nearly one fringe at the interferometer output). In this paper, we describe the use of a piezoelectric stack that is driven at a resonance frequency of 125 kHz to produce a displacement amplitude of 350 nm with a peak-to-peak driving voltage of only 5.8 V and a current of 80 mA. In Sec. II we discuss the electrical properties of the unmounted piezo stack, and in Sec. III we describe the behavior of the piezo-mirror system in a Michelson interferometer. In Sec. IV we discuss the implementation of phase modulation in an optical coherence microscope, and outline our solutions to the problems of phase drift and piezo wobble.

## II. TESTS OF THE ELECTRICAL BEHAVIOR OF THE PIEZOELECTRIC STACKS

We tested piezoelectric stacks manufactured by NEC Corporation of Japan (type AE0203D04 available from

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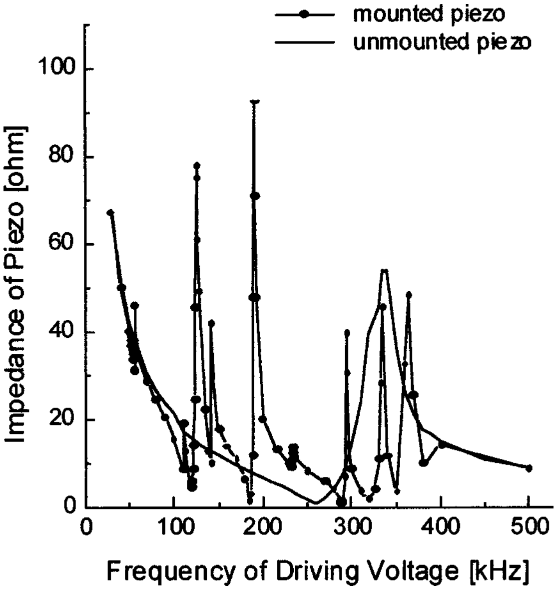

FIG. 1. Impedance of mounted and unmounted piezo vs driving voltage frequency.

Thorlabs Inc., Newton, NJ) for possible use in our Michelson interferometer. The dimensions of these piezos are 2.5 mm×5 mm×5 mm. The manufacturer's specifications indicate a displacement of about 3 $\mu$m at 100 V dc. Since the impedance of the piezo decreases initially with increasing frequency ($Z = 1/\omega C$ where $C = 100\,\text{nF}$), the larger currents necessary to maintain this applied voltage might lead to overheating of the stack at higher frequencies. In any case, for operation at higher frequencies, a power amplifier would be needed in addition to a function generator in order to supply the driving signal for the piezo stack. Driving the piezos at their resonance frequency, however, proved to be a method for circumventing these problems.

We first tested the electrical behavior of the unmounted piezo. Figure 1 shows its impedance as a function of frequency. At frequencies well below resonance, the piezo behaves like a capacitor, with the impedance inversely proportional to the frequency and the voltage lagging the current by approximately 90°. At 255 kHz the unmounted piezo experiences a minimum in impedance, and voltage and current are in phase. This frequency is commonly referred to as the electrical resonance frequency of the piezo. At 330 kHz a maximum in impedance occurs, and again voltage and current are in phase—the electrical antiresonance frequency of the piezo.[7] Between resonance and antiresonance the impedance increases with frequency, while the voltage leads the current by about 90°. At frequencies higher than the antiresonance, the piezo again shows a capacitorlike behavior.

We tested several unmounted piezos of the same model and found their electrical characteristics to be consistent within a few percent. We repeated these measurements for a different brand of piezo stack with slightly larger dimensions (3.5 mm×3.5 mm×9 mm, from Piezomechanik, Munich, Germany). We observed the same type of behavior, with the impedance minimum and maximum occurring at 153 and at 191 kHz, respectively, hence at lower frequencies than for the smaller NEC piezos.

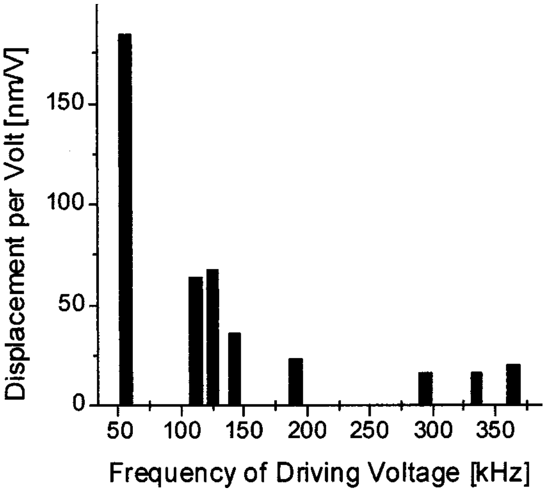

FIG. 2. Displacement of the mounted piezo per volt applied at the resonance frequencies.

In order to use the piezo stack for phase modulation, we attached a small, lightweight mirror (1.5 mm×1.5 mm×0.1 mm, from Edmund Scientific Co., Barrington, NJ) to its face with cyanoacrylate (generically termed ''super glue''—we used Duro Super Glue Tube retailed by Manco in Avon, OH). The piezo stack with the attached mirror was either glued directly onto a standard adjustable mirror mount or glued onto a 25-mm-diam aluminum disk of 5 mm thickness, which was then held by a mirror mount. Although gluing the lightweight mirror to the piezo did not alter its electrical behavior, attaching the stack to the aluminum disk or the mirror mount significantly changed the piezo's electrical resonance characteristics. Instead of the single electrical antiresonance of the unmounted piezo, several antiresonances at frequencies both lower and higher than the original one appeared. Figure 1 also shows the impedance of the mounted piezo as a function of the driving voltage frequency. This piezo had been glued to an aluminum disk with an epoxy intended for fiber optic connectors (F120, from Thorlabs Inc., Newton, NJ).

## III. MECHANICAL BEHAVIOR OF THE PIEZO-MIRROR IN A MICHELSON INTERFEROMETER

The mechanical behavior of the piezo-mirror was tested in one arm of a Michelson interferometer with a helium–neon laser (633 nm) as a light source. In the measurements with the mounted piezo, we observed that the frequencies of maximum piezo displacement are those of maximum impedance. The mechanical resonance of the piezo is thus coincident with its electrical antiresonance. In the following, we will refer to those frequencies as resonances for which the piezo experiences a maximum in displacement. Figure 2 shows the displacement of the piezo per volt applied at each of the resonance frequencies. For a particular resonance frequency, the piezo displacement was observed to increase linearly with increasing driving voltage amplitude. However, the displacement per volt varies for the different resonances of the same piezo and decreases at higher frequencies. Although the displacement per volt is higher at the 56 kHz resonance by almost a factor of 3, we chose to drive the piezo in our Michelson interferometer at the 125 kHz resonance because of the higher frequency.

Both the frequencies of the resonances and the corresponding displacement amplitudes were dependent on the details of mounting the piezo in a way that could be understood at least qualitatively. Attaching the stack with super glue resulted in lower resonance frequencies and larger displacement amplitudes than in the case where the softer epoxy was used. We interpret this result to mean that the very thin layer of super glue between the piezo and the mounting substrate forces the piezo to expand in the free direction only. This results in a larger displacement of the mirror than when a thicker layer of the more elastic epoxy is used, presumably because the epoxy can be squeezed by the expanding piezo. Also, if the piezo mounted with super glue expands primarily in the free direction, its center of mass translates, in contrast with the piezo in epoxy, which may expand and contract about its center of mass. The piezo mounted with super glue then has a greater effective mass as it resonates, yielding lower resonance frequencies.

Similarly, the disk on which the piezo is mounted can play an important role in determining the positions of the resonance frequencies. We examined the difference between epoxy-glued NEC piezos on 5- and 10-mm thick aluminum disks, both of 25 mm diameter. They exhibited essentially the same resonance frequencies between 100 and 360 kHz, but the lowest resonance, which also has the largest displacement amplitude, was shifted from 56.7 kHz for the thinner to 85.6 kHz for the thicker aluminum disk. Plate theory predicts that the resonance frequency of the lowest (drumhead) mode for a 25-mm-diam, 5-mm-thick aluminum disk should be around 80 kHz and a factor of 2 higher for the 10-mm-thick disk.[8] The formula used is valid under the assumptions that the disk is held rigidly at its periphery and that the thickness of the disk is small compared to its diameter. Neither of these assumptions is well fulfilled in our case. Further investigation using a finite element analysis software package (SAP 2000 Nonlinear V6.15) revealed that the resonance frequencies are very sensitive to the precise mounting conditions, with the observed frequencies roughly consistent with our three-point mounting technique. Measurements with two three-point mirror mounts of different masses yielded the same mechanical resonances and piezo amplitudes. These measurements and calculations have led us to conclude that the lowest frequency resonance for the stack-epoxy-disk system is probably a fundamental vibration of the disk, while the higher frequency resonances can be attributed to the ''piezo-in-epoxy'' part of the system.

The results for resonance frequencies and displacement amplitudes for the same brand of piezo and the same mounting technique for the piezo did not differ by more than a few percent. Operating the piezo-mirror system in our OCM Michelson interferometer for hours at a time over the course of two years has not caused a shift in the resonance frequency or a change in the piezo displacement. Even after hours of continuous operation, the stack does not heat up noticeably, and the system seems remarkably stable. With a driving voltage of 5.8 V peak to peak, the described NEC piezo with a super glue-mounted mirror, epoxy mounted onto a 5-mm-thick aluminum disk, provides a displacement of about 350 nm at a resonance frequency of about 125 kHz, making it ideally suited for phase modulation in our OCM.

## IV. IMPLEMENTATION IN AN OPTICAL COHERENCE MICROSCOPE

We have achieved a high fringe frequency by driving a piezo at the desired frequency and using a piezo resonance to obtain a modulation amplitude of roughly one fringe. It is also possible to achieve high fringe frequencies by driving a piezo at low frequencies but with large displacement amplitudes. By wrapping 100 m of fiber around a piezo tube, Cruz *et al.*[9] reached fringe frequencies of 1 GHz with a peak-to-peak path length difference of 14 mm. However, the large interferometer path differences inherent in this approach are incompatible with the operation of our OCM.

Our OCM collects three-dimensional images by performing a series of fast two-dimensional scans in planes normal to the incident beam and at regular depth intervals in the sample.[6] These two-dimensional ''*en face*'' scans are performed at depths determined by the interferometer's equal path length position in the sample. Because the typical depth interval for our OCM is about 5 $\mu$m, modulation in the path length difference must be limited to about 1 $\mu$m during one of the *en face* scans. Larger modulations would degrade the depth resolution of our OCM. Hence a piezo stack driven at its resonance frequency has provided both a high fringe frequency for fast OCM image acquisition and a small modulation amplitude for good depth resolution.

It is important to note that the small modulation amplitude of about one fringe renders our OCM vulnerable to slow phase drifts arising from thermal expansion and contraction in the optical fibers comprising the two arms of the interferometer. These phase drifts result in variations in the amplitude of the fringes as measured in the ac-coupled output signal of the OCM interferometer. We have described previously[6] a technique for circumventing this problem. We simply drive the piezo stack so that the mirror oscillations amount to 0.42 $\lambda$, yielding 0.84 of a fringe at the interferometer output. For this particular amplitude of mirror oscillation, the sum of the powers in the fundamental and second harmonics in the OCM fringe signal is independent of the phase drift. We use the square root of the sum of these powers as a measure of the amplitude of the fringes in the OCM interferometer output. In this way we have achieved phase-drift insensitive operation to within a few percent.

The piezo-mirror system is placed in a cat's-eye retroreflector in the reference arm of our OCM Michelson interferometer (see Fig. 3). The converging lens of the retroreflector focuses the reference beam to a waist of approximately 20 $\mu$m in diameter onto the small (1.5 mm$\times$1.5 mm) plane mirror mounted on the piezo stack. As the piezo elongates and shortens, the mirror is translated, producing the desired phase modulation. But the mirror rotates very slightly as well, and this piezo ''wobble'' can cause small fluctuations in the amount of light coupled back into the reference arm optical fiber. While these fluctuations are small ($\sim$1 part in

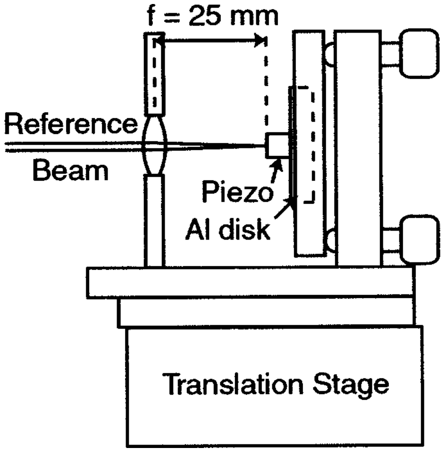

FIG. 3. Sketch of the cat's eye retroreflector with reference mirror mounted on the piezoelectric stack.

$10^5$), they occur at the piezo-driving frequency and can compete significantly with the effects of phase modulation when the optical electric field returned from the sample is comparably small.

We have found that a judicious design of the retroreflector can reduce the effect of piezo wobble to a level below that of photon noise in our OCM. Snyder[10] has analyzed the effect of mirror tilt in a cat's-eye retroreflector. Following Snyder's analysis, we have derived expressions for the (radial) height and slope of the retroreflector output ray in the plane of the lens. The deviations in this ray resulting from a mirror tilt $\alpha$ and a lens–mirror separation $d=f+\Delta d$ that differs slightly from the focal length $f$ of the lens are given by

$$\begin{aligned}\Delta r_{\text{out}}&=2\left(r'_{\text{in}}-\frac{1}{f}r_{\text{in}}+\alpha\right)\Delta d+2f\alpha,\\ \Delta r'_{\text{out}}&=\frac{2}{f}\left(\frac{1}{f}r_{\text{in}}-r'_{\text{in}}-\alpha\right)\Delta d.\end{aligned} \tag{1}$$

In Eq. (1), $\Delta r_{\text{out}}$ and $\Delta r'_{\text{out}}$ are the deviations in the height and slope of the output ray in the plane of the lens, and $r_{\text{in}}$ and $r'_{\text{in}}$ are similarly the height and slope of the input ray in the plane of the lens. In our case the mirror tilt $\alpha$ can be expressed as an average value $\alpha_0$ plus an oscillatory part $\alpha_1(t)$:

$$\alpha=\alpha_0+\alpha_1(t). \tag{2}$$

To minimize the deviations given by Eq. (1), our retroreflector design provides independent adjustment of mirror tilt and lens–mirror separation, so that $\alpha_0\rightarrow 0$ and $d\rightarrow f(\Delta d\rightarrow 0)$. The remaining oscillatory mirror tilt results ultimately in oscillation of the position of the retroreflected beam as it is focused onto and coupled back into the single mode optical fiber comprising the reference arm. (Our choice of a fiber-based interferometer exacerbates this piezo wobble problem.) Nevertheless, this oscillation in coupling efficiency results in less apparent OCM output fringe amplitude than is generated by fundamental photon noise. In fact, photon noise has a four-times stronger Fourier amplitude at the fringe frequency (125 kHz) than is produced by the piezo wobble. If referenced to a true OCM input, the piezo wobble is equivalent to a sample reflection that is $6\times 10^{-7}$ times that of a perfectly reflecting mirror.

During an OCM scan of a sample, the retroreflector is translated away from the fixed reference fiber to examine a deeper plane in the sample.[6] (See Fig. 3.) This translation is generally accompanied by a small, undesired rotation of the retroreflector, and can contribute an additional source of mirror tilt ($\alpha_0\neq 0$). Although this is potentially a serious problem, we have found that our translation stage (Model 462 Series from Newport Corp., Irvine, CA) in combination with our retroreflector design enable the OCM to perform depth scans greater than 1 mm with no discernible increase in the effect of piezo wobble. We rarely scan depths greater than 1 mm. Translations of several millimeters, on the other hand, lead to significant increases in piezo wobble signal, though at any given position the mirror tilt can be readjusted to reduce the piezo wobble signal to levels below that of photon noise.

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