FAST, MEMS-BASED, PHASE-SHIFTING INTERFEROMETER

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ABSTRACT

We demonstrate a MEMS-based, phase-shifting interferometer (MBPSI) that is much faster than conventional phase-shifting interferometers (PSI), which use piezoelectric actuators to obtain phase-shifted signals. In contrast, our system takes measurements using a comb-driven vertically resonating micromachined mirror that is illuminated by synchronized laser pulses (1 µsec duration at λ = 660 nm). Our MBPSI employs a four-frame phase-shifting technique (four CMOS-imager frames for each profile measurement) at a rate of 23 profile measurements per second (43.5 msec per measurement). At this rate, the MBPSI can capture more than 700 PSI measurements of a time-varying phenomenon in a 30.5-second interval which compares to 1 measurement in 1 second in conventional systems. The MBPSI in Twyman-Green configuration has accurately tracked the fast-changing, transient motion of a PZT actuator, with a precision of ±λ/110 (±6 nm). Measurements to check the repeatability of the system, performed in a 20-minute period, show that it is accurate to within ±20 nm.

NOMENCLATURE

f_r Mechanical resonant frequency
l Length of the optically active area
w Width of the optically active area
l_f Length of flexure
w_f Width of flexure
l_c Length of comb finger
w_c Width of comb finger
l_s Length of stress-relieving beam
w_s Width of stress-relieving beam
h Height of flexure
k Vertical stiffness of the MEMS resonant structure
m Total mass of resonant structure
t_{SOI} Thickness of the device layer of the SOI wafer
E_{Si} Young’s modulus for silicon
I(x, y) Intensity measurement as a function of x and y
I'(x, y) Intensity bias
I''(x, y) Amplitude of intensity modulation
λ Wavelength of interest
δ(t) Phase shift (angular variation)
ϕ(x, y) Phase information of the surface of the sample under measurement

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INTRODUCTION

Phase-shifting interferometry (PSI) is a well-established optical-characterization technique [1]. Typically, a conventional phase-shifting interferometer is constructed with both reference and test optical paths arranged in what is known as a Twyman-Green configuration, as shown in Figure 1.

The laser beam from the source is directed into two orthogonal optical paths by the polarizing beam splitter (PBS). The two beams travel their designated paths and are then directed towards a CMOS/CCD imager. As a consequence of the difference in optical path lengths, the beams constructively and destructively interfere to form fringe patterns.

The phase-shifting mirror is moved from position 1 to 2, and then finally to position 3 to form three different intensity-measurement patterns. The intensity of each pattern, captured by the CMOS/CCD imager, can be expressed mathematically as [2]

\[
I(x, y, t) = I'(x, y) + I''(x, y) \cos(\phi(x, y) + \delta(t))
\]  

In (1), \(I(x, y, t)\) is the intensity captured by the CCD imager, \(I'(x, y)\) is the intensity bias, \(I''(x, y)\) times the cosine term is the intensity modulation, and \(\delta(t)\) is the angular variation that results from the modulated phase-shifting distance. The wavefront phase...
\( \phi(x, y) \) contains the phase information for the wave reflected off the surface of the sample-under-test, and it is the information that we want to retrieve [2]. Knowing \( \phi(x, y) \), for example, we can generate the surface profile of the sample-under-measurement. The angular variation \( \delta(t) \) is known precisely because we control it in the experiment, and therefore the three unknowns to be determined are: \( I'(x, y) \), \( I''(x, y) \), and \( \phi(x, y) \). To solve for these quantities, we need at least three independent intensity measurements which we obtain by physically translating the reference mirror to three different, yet precisely known, positions [2]. After we make the three intensity measurements, we can solve for \( \phi(x, y) \). The three-step algorithm requires the minimum amount of data and is the simplest to use. However, this algorithm is also very sensitive to errors in the phase-shift between frames [1]. Because of this sensitivity, researchers often use a four-step algorithm or a five-step “Hariharan algorithm” [1].

The rate at which a PSI makes measurements is limited by how quickly and precisely one can position the phase-shifting mirror. Piezoelectric actuators (usually made with lead-zirconium titanate (PZT)), which are typically used in existent PSI systems, are limited in speed owing to unavoidable transients that need to subside before accurate measurements become possible. When a PZT actuator stops after a commanded phase step, there is a transient oscillation of the reference mirror (mounted on the PZT actuator) that must be allowed to decay [3]. As a result, in PZT systems, measurements are taken over intervals that vary between 0.5 and 5 seconds. Over time spans of these lengths, however, PSI measurements can be corrupted by changes that are due to variations in beam transmission over the optical path. As a result, PSI has generally been used to characterize the surfaces of static optical components such as mirrors and lenses.
or of device structures in optical systems built using such components. In order to apply PSI systems to measure transient phenomena such as turbulent flows, non-steady-state motions of structural elements, or crystal growth, to name a few examples [4-6], the required data sets must be taken at higher rates than are possible in PZT-driven systems. Another drawback to the use of conventional PZT actuators is that these components require relatively sophisticated control electronics, making them a costly part of the PSI system.

In this paper, we report a fast, MEMS-based, phase-shifting interferometer. In our MBPSI, the cost-effective micromachined mirror replaces the PZT actuator and serves as a phase-shifting component (Figure 2). Other changes include replacing the laser with a laser diode and the CCD imager with a faster CMOS imager. The micromachined mirror operates at resonance, with an amplitude at resonance that exceeds the wavelength of the laser used for measurement. We have implemented the four-step algorithm for measurement-data reduction in order to achieve processing speed while maintaining accuracy.
Figure 2. MBPSI setup using the Twyman-Green configuration: The micromachined MEMS mirror, laser diode, and CMOS imager replace the PZT mirror, continuous-wave laser, and CCD imager, respectively, in the conventional setup. The diagram in the inset shows the instantaneous visualization of four different phase-shift positions which occur in the path of mirror’s resonant motion. The distances of motions have been vastly exaggerated in the drawing for illustration purpose.

Figure 2 shows the optical setup used for the MBPSI. The MEMS mirror is driven at resonance, and a single PSI measurement is completed by making four intensity measurements at four different mirror positions that correspond to four phase angles in the resonant path of its surface. The laser illumination is pulsed precisely when the micromirror passes each phase position, and the resulting interference pattern for each phase position is captured in a single frame of the imaging sensor. Using the CMOS imager which is programmed to capture images at 92 frames per second (fps), a single four-step PSI measurement takes only 43.5 msec, a speed 12-115 times faster than conventional PZT-based PSI systems. Our system takes 23 measurements per second and produces as many as 700 successive measurements, which is limited by the size of the computer’s system memory. This successive measurement capability enables the observation of transient optical phenomena for the duration of 30 seconds at the time-
resolution of 43.5 msec. Achieving such successive measurements is a very unique capability that is impossible and impractical to achieve using conventional PSI systems.

**FAST PHASE-SHIFTING METHOD**

Our phase-shifting technique for MBPSI is directly related to the well-known stroboscopic method for observing vibrating specimens. By flashing the laser pulses synchronously at successively lengthened delays to the resonating micromirror in the reference path of the system, we capture repeated interference patterns for beams that traverse the two optical paths.

![Figure 3. Phase-shifting technique using our vertically resonating micromirror and a pulsed laser diode: ‘*’ indicates when the laser pulse is flashed. In this example, there are four phase steps; each frame of the CMOS imager integrates images generated by four laser pulses flashed for each phase step.](image)

In Figure 3, the sinusoidal wave represents the time-varying position of the resonating MEMS micromirror used as a phase shifter. The interference patterns corresponding to 0, $\lambda/4$, $\lambda/2$, and $3\lambda/4$ phase shifts are captured within the CMOS-imager frames 1, 2, 3, and 4, respectively. In each frame, while driving a MEMS mirror at its resonant frequency, we pulse the laser diode at the instant when the mirror is precisely displaced by the desired fraction of the illuminating wavelength from the initial position. For example, to achieve the phase shift of a 0 displacement, we flash the laser diode whenever the MEMS mirror passes the initial position. Similarly, to achieve the phase shift of a $\lambda/4$
displacement, we flash the laser diode whenever the MEMS mirror passes the position that is precisely $\lambda/8$ units away from the initial position. We do this by adding a precise amount of delay time with respect to the zero-crossing in the voltage wave that actuates the MEMS mirror before pulsing the laser-diode driving current. Because the integrating-bucket technique (the most common PSI data-collection technique) requires that the movement of the phase shifter be linear [7], we take the phase-shifted measurements in the quasi-linear region of the micromirror path. The path is approximately linear near the beginning of each resonant period as shown in Figure 3. Using this technique, the maximum profile-measurement rate is equal to the imager frame rate (fps) divided by the number of phase steps required by the PSI algorithm. For a MBPSI setup having a CMOS imager that operates at 92 fps and employs the 4-step algorithm, the measurement rate is 23 Hz. At this rate, the system can continuously capture 700 successive, PSI measurements in 30 seconds. The rate of measurements and the number of successive measurements can further be improved by using a faster imager and by installing a larger computer-system memory for storing captured images, respectively.

**FAST PHASE-SHIFTING MEMS MIRRORS: DESIGN, FABRICATION, AND CHARACTERIZATION**

**A. Design**

The sizes of the reflective areas of the micromirrors are determined by their uses in specific interferometric configurations. For example, in order to measure the quality of a laser beam using the Mach-Zehnder configuration, the size of the reflective area of the micromirror must be larger than the diameter of the laser beam, which can be as large
as a few mm in diameter. For our Twyman-Green configuration, the objective lens in the reference path of the system focuses the beam onto a small spot (usually smaller in diameter than a few hundred micrometers) on the reference-mirror surface. As a result, the required size of the micromirror reflective area is just slightly larger than the size of the spot formed by the objective lens. Although we report experimental results obtained using the Twyman-Green configuration in this paper, we plan other experiments using the Mach-Zehnder configuration and for these, we would need a square mirror that could be as large as 3 mm on a side. Hence, we designed our micromirror to have an optically reflective area larger than 3 mm by 3 mm (actual size: 3.6 mm by 3.6 mm). Figure 4 shows the schematic diagram of the representative micromirror that we used in our experiments.

**Figure 4.** Top view of the MEMS phase-shifting micromirror: The inset shows one of the four corners of the MEMS micromirror. Both the flexure and the fixed comb fingers are vertically thinned in order to increase their pliancy in the desired actuation (vertical) direction.

We have placed eight vertically-thinned, rectangular-beam flexures at the four corners of the micromirror so that the resulting stiffness to forces applied either rotationally or
laterally in-plane or else torsionally out-of-plane will be much larger than that in the vertical direction (perpendicular to the substrate) and will prevent any unwanted motions.

To fabricate the mirrors, using SOI (silicon-on-insulator) wafers, we made use of a process that we had described in earlier publications [8, 9]. In this process, the vertically offset actuating combs are formed when we use deep-ionic reactive etching to thin the fixed combs without eroding the surfaces of the moving combs. The flexing elements are simultaneously thinned vertically.

The vertical resonant frequency of the MEMS phase-shifting micromirror is calculated using (2) [10]

\[ f_r = \frac{1}{2 \cdot \pi} \sqrt{\frac{k}{m}} \]  \hspace{1cm} (2)

where \( k \) is the combined vertical stiffness of the 8 flexures and \( m \) is the mass of the moving structure. The stress-relieving beams are found to be 768 times stiffer in the vertical direction than the flexures, and we can assume that the stress-relieving beams will not bend in the vertical direction. Hence, the vertical stiffness \( k \) of the moving structure is given by [11]

\[ k = \frac{8 \cdot (h)^3 \cdot w_f \cdot E_{Si}}{l_f^3}. \]  \hspace{1cm} (3)

The actual values of the design parameters are given below in Table 1.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{SOI}$ (thickness of the device layer of the SOI wafer)</td>
<td>50 µm</td>
</tr>
<tr>
<td>$l_f$ (length of flexure)</td>
<td>1000 µm</td>
</tr>
<tr>
<td>$w_f$ (width of flexure)</td>
<td>50 µm</td>
</tr>
<tr>
<td>$h$ (height of flexure)</td>
<td>25 µm</td>
</tr>
<tr>
<td>$l_c$ (length of comb finger)</td>
<td>280 µm</td>
</tr>
<tr>
<td>$w_c$ (width of comb finger)</td>
<td>15 µm</td>
</tr>
<tr>
<td>Number of moving comb fingers</td>
<td>208 comb fingers</td>
</tr>
<tr>
<td>$l_s$ (length of stress-relieving beam)</td>
<td>500 µm</td>
</tr>
<tr>
<td>$w_s$ (width of stress-relieving beam)</td>
<td>75 µm</td>
</tr>
<tr>
<td>$l$ (length of the optically active area)</td>
<td>3600 µm</td>
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<tr>
<td>$w$ (width of the optically active area)</td>
<td>3600 µm</td>
</tr>
<tr>
<td>$m$ (total mass of resonant structure)</td>
<td>$2.06 \times 10^{-6}$ kg</td>
</tr>
<tr>
<td>$E_{Si}$ (Young’s modulus for silicon)</td>
<td>1.70 GPa</td>
</tr>
<tr>
<td>$k$</td>
<td>$1.06 \times 10^3$ N/m</td>
</tr>
</tbody>
</table>

**Table 1.** Design parameters of the micromirror

The precise value of the resonant frequency $f_r$ is relatively unimportant; it is important, however, that $f_r$ be much higher than the frame rate ($fps$) of the photo-sensor array. Our MEMS phase-shifting micromirror chosen for our MBPSI experiment has the design resonant frequency of 3.61 kHz. We calculated this resonant frequency using the parameters given in Table 1 in (2) and (3). For a CMOS-image array ($fps \sim 30$-100 Hz), each image frame will capture 36-120 pulses, depending on the duration of the frame. The advantage of having a larger number of pulses-per-frame is that unavoidable reference phase-shift errors contained in interferometric images, which can be introduced by the system electronics, can be averaged out improving the phase-shift accuracy in the image sets.

**B. Micromirror Fabrication**

The MEMS phase-shifting mirror with its support and actuator structures measures 7.9 by 7.9 by 0.05 mm (the optically reflective area is 3.6 by 3.6 mm), and is micromachined using a fabrication process that we have described earlier [8-9].
process uses three photolithography masks (two for defining features in the device layer of a SOI wafer and one for opening the backside of the microscanners). All process steps are made with conventional silicon-processing tools that have proven their effectiveness and user-friendliness through large-scale use in the integrated-circuits industry. All required processing temperatures are low enough to allow pre-fabrication of CMOS electronics directly on the same wafer as the microscanner devices. Steps in the fabrication process are illustrated in Figure 5.

1. **Figure 5-1**: Start with an SOI wafer. Grow 0.5-µm thermal or low-temperature oxide (LTO). Using the photolithography mask #1, pattern and remove the thermal oxide (or LTO) selectively where fixed combs will be later defined and vertically thinned.

2. **Figure 5-2**: Using mask #2, create patterns of micromirror including moving and fixed combs, flexures, and mirrors. The fixed combs must be defined within the windows from which the oxide has been removed to expose the silicon surface in the previous step, and the minimum gap between the moving and fixed comb fingers can be as small as twice the alignment accuracy of the photolithography process.

3. **Figure 5-3**: Use deep-reactive-ion-etch (DRIE) to define the micromirror structures in the device layer.

4. **Figure 5-4**: Remove the photoresist layer and deposit a very thin layer (~0.2 µm) of LTO.

5. **Figure 5-5**: Use timed-anisotropic-plasma etch to remove 0.2-µm thick LTO from the top-facing surfaces. This step exposes the silicon surface on top of the fixed
combs, but leaves all other surfaces covered by an approximately 0.5µm-thick oxide layer.

6. **Figure 5-6:** Then use timed-isotropic silicon-etch to create a set of vertically thinned combs. Only the fixed combs, which do not have any protective layer on top, will be vertically thinned.

7. **Figure 5-7:** Using mask #3, pattern and open the backside of the micromirror using DRIE process. Release the devices in HF and perform critical-point drying. More detailed description of the fabrication process, including additional comments on creating vertically offset-combs, is found in references [8-9].
Figure 5. Fabrication process for vertically actuated microscanners with self-aligned, vertically offset combs.

Figure 6 shows photos of five different fabricated micromirrors. Three of the micromirrors are mounted and wire-bonded on ceramic packages that have circular openings (indicated by white-dashed line in the photo) in the mounting area in order to minimize air damping and thus improve the mechanical quality factors.
Figure 6. Photos of fabricated MEMS phase-shifting micromirrors: Three micromirrors are mounted and wire-bonded on ceramic packages which have circular backside holes. The micromirror shown on right is the representative micromirror used to produce the results reported in this paper.

In Figure 7, the SEM image on the right-hand-side shows the vertically thinned flexures with reduced vertical stiffness. The SEM images show that the fabricated structures, including vertically offset combs and vertically thinned flexures, are sharply defined, precisely aligned, and uniformly etched. Using the WYKO white light interferometer, we have measured that the average offset height across the wafer is 24.9 \( \mu \text{m} \), and the offset height shows excellent uniformity (less than or equal to \( \pm 1.5 \% \) peak-to-peak deviation from the average value).
**Figure 7.** SEM images showing the key sections of the phase-shifting MEMS mirror: (a) A corner of the MEMS phase-shifting micromirror; and (b) close-up image of vertically offset combs as well as vertically thinned flexure – The offset height is 24.9 µm. The inset at bottom shows the magnified SEM image of precisely-aligned vertically-offset combs.

**C. Micromirror Characterization**

Using a white-light interferometer (WYKO NT3300), we measured the surface profile of one representative micromirror (of 18 that we have produced). An image from this measurement is shown in Figure 8; the radius-of-curvature at all points on the mirror surface is greater than 20 m, and the surface roughness is consistently below 20 nm. We carried out the radius-of-curvature measurements on all 18 fabricated micromirrors and found in all cases a value greater than 10 m.
In order to find the precise flash timings for laser pulses (synchronized with the micromirror’s resonant motion) required for MBPSI operation, we studied the resonance behavior of the micromirrors using a piezo-based, calibrated stroboscopic interferometer [12], which has an rms-measurement accuracy of 5 nm. In these measurements we tracked the relative motions of each of the four corners on the mirror and at the mirror center and recorded these measurements over one period of resonant motion to obtain the measurements shown in Figure 9. The measurement results indicate that a relatively small, peak-to-peak 1.5-μm resonant amplitude achieved with 18 V (peak to peak sinusoidal drive voltage) is sufficient for performing PSI measurements. With this drive voltage, the micromirror surface passes the desired phase-shifting positions of 0, λ/8, 2λ/8, and 3λ/8 at intervals of 0, 10, 20, and 30 μsec (see the inset of Figure 9), respectively. Using these intervals as delay times, we can achieve precise timings for the laser pulses which have a 1-μsec duration.
Figure 9 Resonant-motion analysis for our phase-shifting MEMS mirror measured with a calibrated laboratory Stroboscopic Interferometer developed at BSAC [11] – (a): One full period of resonant motion, with the quasi-linear region indicated by the dashed rectangle, (b): Quasi-linear region used for phase-shifting (peak-to-peak deviation in position: < 6 nm) (*1-4: Please refer to Figure 8.)

The dynamic deformation of the mirror, between the center and the four corners of the micromirror, within this quasi-linear region of operation, is less than 3 nm or $\lambda/220$, which is quite close to the measurement accuracy of the stroboscopic interferometer. We measured a resonant frequency of 3.55 kHz for this micromirror (design value is 3.61 kHz) and a mechanical Q of 63.

D. Optical Measurements

Details of our experimental setup are shown in Fig. 10. The CMOS imager has a maximum frame rate of 100 fps [13]. We ran the imager at a conservative 92 fps and employed the four-step phase-shifting algorithm in order to measure sample motions at a rate of 23 Hz. We used the surface of a flat, reflective mirror mounted on a commercial PZT actuator as a measurement sample [14] because we know its traveled distance with a precision of $\pm 10$ nm as read directly from a feedback-position sensor that is built directly
into the PZT actuator package. The MEMS phase-shifting micromirror was driven by a 3.55 kHz sine wave of amplitude $18 \, V_{ac,p-to-p}$. For a light source, we drove a pig-tailed laser diode ($\lambda = 660 \, \text{nm}$) [15] with 1$\mu$s-width synchronized pulses having rise/fall times shorter than 50 nsec. The laser driver was a precision-pulsed current source [16] controlled by a digital controller installed in an IBM-PC computer [17].

Figure 10 MBPSI optical-test setup (Twyman-Green configuration): PZT is not used as a phase-shifting element but rather serves as the object-under-test as well as a calibration reference.

In the experiments, we first used the PZT actuator as a calibration reference to measure repeatability of the system for transient measurements. We repeatedly measured the changing positions of the PZT actuator and found that the system repeatability was $< \pm 5 \, \text{nm (} \pm \lambda/132 \text{)}$ over a 30-second period and $< \pm 10 \, \text{nm (} \pm \lambda/66 \text{)}$ over a 20-minute period. Next, we measured the accuracy of the system also by using the moving PZT as a reference. We found that the system’s accuracy was $< \pm 5.5 \, \text{nm (} \pm \lambda/120 \text{)}$.

In order to demonstrate the fast measuring capability of our system, we used it to track, in real time, the fast-changing, transient motion of the PZT actuator. The actuator was stepped at intervals of 50 nm every 0.5 sec over a 6.478-sec period. Since our system continuously measured at a rate of 23 Hz, the total number of recorded profile
measurements was 150, where each profile measurement contained 4 separate phase-shifted intensity measurements. After using noise reduction (averaging over area within same measurement), the transient measurement was precise to within $\pm 3$ nm ($\pm \lambda/220$), lower than the 10nm-accuracy limit of the PZT-actuator’s position-read-out sensor (Figure 11).

![Figure 11](image)

**Figure 11** Section of a total 150 measurements made with our MBPSI system showing a PZT actuator moving at a step of 50 nm every 0.5 seconds during the 6.478-second period (PZT movement resolution: $<\pm 10$ nm from the readings of the PZT built-in feedback position sensor)

**CONCLUSIONS**

We have demonstrated a fast, accurate, MEMS-based PSI that can measure transient optical phenomena at measurement frequencies up to 23Hz. A cost-effective, batch-produced MEMS micromirror is used as the phase-shifting element. Proven, robust conventional PSI algorithms can be applied to our system without any modifications. The repeatability of the system was measured to be $< \pm 5$ nm for 30-second interval and $< \pm 10$ nm for 20-minute interval. The accuracy of the system was measured to be $< \pm 5.5$ nm (without noise reduction). The system has successfully tracked the fast changing motion of a PZT actuator. The transient measurement was
precise to within ±3nm (±λ/220, after noise reduction), lower than the 10nm-accuracy limit of the PZT-actuator movement.

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