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). For phase shifting, our system employs a comb-driven vertically resonating micromachined mirror illuminated by synchronized laser pulses ($\lambda=660\text{nm}$). Our MBPSI employs a four-frame phase-shifting technique (four CMOS-imager frames per one profile measurement), at a rate of 23 profile measurements-per-second (23Hz, 43.5msec per measurement). At this rate, the MBPSI can continuously capture more than 500 profile measurements of a transient phenomenon over 21.7 seconds. The MBPSI in Twyman-Green configuration has accurately tracked in real time the fast-changing, transient motion of a PZT actuator, within $\pm\lambda/110$ ($\pm 6\text{nm}$).

INTRODUCTION

PSIs are desired for precision measurements of moving objects, and increasing the PSI data-collection rate makes it possible to observe faster motions. Our MBPSI system can capture 500 or more profile measurements of a transient phenomenon continuously at a rate of 23 Hz. Besides sizably expanding the range of PSI applications (for example, to transient optical phenomena such as chemical diffusion, crystal growth, and measurements of rapidly varying object temperatures [1-2]), the MBPSI's rapid measurement rate reduces the data noisiness caused by low-frequency vibrations. Batch-fabricated, MEMS phase-shifting components are not only faster, but also much more cost-effective to fabricate and operate than are the piezoelectric actuators that are now typical in PSI systems.

FAST PHASE-SHIFTING METHOD

Our phase-shifting technique (illustrated in Figure 1) is, in principle, similar to that used to obtain a stroboscopic movie of a periodically moving object.

Figure 1. Fast 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.

In the MBPSI, we obtain stable interference patterns using a periodically moving mirror and synchronized laser pulses. The interference patterns corresponding to 0 , $\lambda/4$, $\lambda/2$, and $3\lambda/4$ phase shifts are captured in the CMOS-imager frames 1, 2, 3, and 4, respectively [3]. In each frame, while driving a MEMS mirror at its resonant frequency, we pulse the laser diode when the mirror is displaced by the desired fraction of the illuminating wavelength from its initial position. Because the integrating-bucket technique for CMOS imagers requires that the movement of the phase shifter be linear [3], we use the linear region of the mirror's resonant

motion, which is in the beginning of each period, as shown in Figures 1 and 5. When using this technique, the maximum profile-measurement rate is equal to the CMOS-imager frame rate (fps) divided by the number of phase steps required.

MEMS PHASE-SHIFTING MIRROR: FABRICATION AND CHARACTERIZATION

The phase-shifting mirror measures 5 by 5 by 0.05 mm and is micromachined using a fabrication method that we have described earlier [4] and applied to produce high-precision torsional microscanners (Figure 2).

Figure 2. Fabrication Process: The left column shows top views while the right column shows cross-sectional views along the dotted lines in our CMOS-compatible mirror-fabrication process. 1. Grow $0.5\text{-}\mu\text{m}$ thermal or low-temperature oxide (LTO). Using the photolithography mask #1, pattern and remove the thermal oxide selectively where fixed combs will be later fabricated; 2. Using mask #2, create patterns of micromirror including moving and fixed combs, flexures, and mirrors; 3. Use deep-reactive-ion-etch (DRIE) to define the micromirror in the device layer; 4. Remove the photoresist layer and deposit a very thin layer ($\sim 0.2\text{ }\mu\text{m}$) of LTO; 5. Use timed-anisotropic-plasma etch to remove $0.2\text{-}\mu\text{m}$ thick LTO from the top-facing surfaces. Then use timed-anisotropic or isotropic silicon-etch to create a set of vertically thinned combs; and 6. Using mask #3, pattern and open the backside of the micromirror. Release the devices in HF and perform critical-point drying.

A new feature of our mirror design for the MBPSI is the incorporation of stress-relieving beams which improve the flatness of the mirror (Figures 3 and 4). We have measured the surface profile of a representative mirror (of more than 100 that we have produced) using a WYKO NT3300 (Figure 3) and determined that its radius of curvature exceeds 20m, and its surface-roughness values do not exceed 20nm. In order to time the laser pulses precisely, the mirror resonance has been analyzed using a piezo-based, calibrated stroboscopic interferometer (Figure 5) [5]. The

measured resonant frequency and mechanical quality factor of the mirror are 3.55 kHz and 63, respectively. When the mirror achieves a resonant amplitude of $1.5\mu\text{m}$ (actuation voltage= $18V_{ac_p-to-p}$), the pulses (1- μsec duration) for 0, $\lambda/4$, $\lambda/2$, and $3\lambda/4$ ($\lambda=660\text{nm}$) occur at intervals of 0, 10, 20, and $30\mu\text{sec}$ (Figure 5). Dynamic deformation of the mirror, between the center and the four corners of the mirror, within this linear region of operation, is less than 6nm ($\lambda/110$) (Figure 5).

Figure 3. WYKO profile measurement of fabricated MEMS mirror

Figure 4. SEM images showing the key sections of the phase-shifting MEMS mirror

Figure 5 Resonant-motion analysis for our phase-shifting MEMS mirror using calibrated laboratory Stroboscopic Interferometer – Left: One full period of resonant motion, with the linear region indicated by the red rectangle, Right: Linear region used for phase-shifting (peak-to-peak deviation in position: $< 6\text{ nm}$) (*1-4: Please refer to Figure 3.)

OPTICAL MEASUREMENT RESULTS OF MBPSI

The MBPSI in Twyman-Green configuration (Figure 6) has tracked in real time the fast-changing, transient motion of a PZT actuator [6]. The actuator was stepped at intervals of 100 nm every 0.5 sec over a 6.478-sec period (150 profile measurements, Figure 7). The maximum frame rate of our CMOS-imager is 100 fps . We ran the imager at a conservative 92 fps , reflecting a 23 Hz profile-measurement rate. The transient measurement was precise to within $\pm 6\text{ nm}$ ($\pm \lambda/110$), lower than the 10 nm -accuracy limit of the PZT-actuator movement (from the readings of the PZT's built-in feedback position sensor), as shown in Figure 7.

Figure 6 MBPSI optical test setup (Twyman-Green configuration)

Figure 7 Section of a total 150 measurements made with our MBPSI system showing a PZT actuator moving at a step of 100 nm every 0.5 seconds during the 6.478-second period (PZT movement resolution: $< \pm 10\text{ nm}$ from the readings of the PZT built-in feedback position sensor)

CONCLUSIONS

We have demonstrated a fast, accurate, MEMS-based PSI, which can continuously measure transient optical phenomena at 23 Hz . We plan to report long-term repeatability, analysis for the effects of various error/noise sources, performance in the presence of mechanical vibrations, and new application(s) in our presentation.

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