Low-cost Electrothermally Actuated MEMS Mirrors for High-Speed 3D Laser Scanning Applications

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Abstract—We demonstrate reliable raster scanning of a low-cost electrothermally actuated MEMS mirror at speeds of up to 300 Hz using a simple pulse design technique, achieving a large angular range of motion (± 40° optical) while maintaining 99% linearity in an ambient environment.

Keywords—MEMS, beam steering, OCT, LIDAR, micromirrors

I. INTRODUCTION

Microelectromechanical systems (MEMS) are widely used in applications where a laser beam is scanned over a physical space to perform various sensing and imaging tasks (ranging, composition analysis, depth profiling). Optical Coherence Tomography (OCT) and LIDAR are two popular examples with rapidly expanding applications. Recent solutions for beam steering involve integrated phase arrays which suffer from poor angular resolution and large cross-talk [1], or electrostatic MEMS mirrors which are costly due to need for hermetic packaging and high voltage control circuits [2]. Here, we demonstrate an ultra-low cost electrothermally actuated micromirror (Fig. 1.a) operational in an ambient environment, driven by digitally generated PWM signals for 2D scan-speeds of up to 300 Hz. We achieve wide optical deflection range of up to ± 40°. Simultaneous actuation of all four legs consumes less than 160 mW power at a nominal operation voltage of 3.3 V, making it suitable for low-voltage electronic applications. Despite the advantages, thermally actuated devices suffer from inherent non-linearities arising from their operation at fast speeds and wider angular ranges, thus requiring sophisticated calibration for system-specific non-linearities and general drift due to thermal fatigue. Here, we also demonstrate a procedure for linearizing these scans using a multi-step drive signal.

II. DESIGN AND FABRICATION

The scanning micromirror was fabricated in the PolyMUMPS process by MEMSCAP [3]. The basic layout is similar to a previously published design [4] of a Poly1/Poly2 based 500 µm diameter mirror driven by four thermal actuators. By creating high resistance microheaters along the actuator arms we can impedance match to low voltage electronics, reducing the power requirement with respect to previous implementations. The basic layout is the following – a soft Poly2 serpentine spring connects the mirror with each of the actuators. The actuators are made of a Poly2/Metal stack with a stress gradient across its thickness, resulting in an upward bend upon release, and consequently suspending the mirror ~200 µm above the substrate. Contrary to the standard design in [4], we do not deposit a metal layer on the mirror, which would result in a rather low radius of curvature of 8 mm. Instead, the released Poly1/Poly2 mirror is shadow-mask-evaporated with a low stress TiAu film, yielding a radius of curvature of 100mm (feature-size less than a wavelength for our mirror size). Due to a mismatch in the coefficient of thermal expansion of the two layers, Joule heating flattens each actuator stack towards the substrate at about 40mW. By suitable combination of the electrical power dissipated in each actuator, piston (~200 µm displacement) and tip tilt motion (± 40°) can be obtained in our driving system. In a conventional use case, we dedicate opposite pair of actuators for single axis tip-tilt motion.

Fig. 1. a) False-colored SEM image of the MEMS mirror with the standard and fast actuator legs. The etched microheaters are highlighted b) Thermal response of the two actuator designs is characterized by their 10:90 response times, τ, using an exponential fit to a 2-step pulse response [5]. c) The total moment-of-motion of the fast axis is plotted against the input sinusoidal frequency and representative scan patterns for one oscillation period is shown in the inset diagrams (red traces).
As seen in Fig. 1.b, the 10:90 response time of our standard actuator is 4.2 ms. The standard design is modified by keeping heat generation closer to the actuator’s anchor while adding a fin-like structure to the other end to aid in heat dissipation, resulting in a response time of 2.3 ms for the fast design. As evident in Fig. 1.c, a higher frequency resonance at ~900 Hz, with a quality factor (Q) of ~10 is observed for the mirror-supporting springs system. As a consequence, the faster response time of the modified actuator is now closer to the mechanical oscillation period of the Poly2 springs, and we observe significant ringing and cross-talk when driven at higher frequencies, resulting in poor scan (or velocity) uniformity and linearity. Analysis of the scan patterns shown in Fig. 1.c from a sinusoidal drive revealed that the frequency window for linear scanning extends up to 300 Hz. Operation at frequencies close to harmonics of the response frequencies of the actuators results in Lissajous patterns. These non-linear effects manifest in a conventional triangular (or linear) ramp (see Fig. 2.a) at frequencies as low as 125 Hz for our mirror. Achieving higher speeds with a traditional linear ramp often results in tradeoffs between angular range, response time, and physical design parameters like mirror and/or actuator mass (or size). We next demonstrate a technique for minimize such effects and assess high scan speeds reliably in a pulsed operation by utilizing a multi-step pulse design defined by the mirror-springs resonance.

III. RESULTS AND DISCUSSION

Similar to the approach used by Imboden et al. [5], we use advanced pulse-shape control techniques to improve the step-and-settle response time. As seen in Fig. 2.a, a 2 ms triangular ramp leads to ringing, which is significantly minimized with the multi-step and filtered multi-step waveforms designed for the same scan speed. The advanced multistep control of these MEMS devices consists of three steps — 1) measure the mechanical resonance frequency (here 900 Hz), 2) define the total scan time as multiples of the half-period of one oscillation of the spring (here 550 ms), 3) adjust the step amplitudes, 4) low-pass filter to block mechanical resonances and overtones (here we filter > 800 Hz), and finally 5) evaluate the resulting scan pattern for temporal linearity using a position sensitive detector (PSD). In principle, we iteratively repeat steps 3 and 5 until the deviation in scan velocity through a forward sweep is less than 10%. We implement raster scanning by repeating the optimized 1D scans and gradually increasing the orthogonal axis power. Because we scan in 2D using a single mirror mounted at a 45° angle relative to the incident beam, we observe a keystone effect in the scan pattern image as shown in Fig. 2.b. We observe a maximum linearity distortion of 1%, measured over each single raster.

In conclusion, we have demonstrated a low-cost electrothermally actuated MEMS mirror which does not require hermetic packaging and operates under ambient air. These mirrors are capable of fast linear scanning at speeds up to 300 Hz using a tunable multi-step design, achieving a wide angular range of ± 40°. Although further work is needed to realize 2D images and characterize distortions, we are confident that these mirrors can serve as reliable long-term beam steering solutions for handheld or low spatial footprint optical devices like OCT and LIDAR.

REFERENCES