A Large Aperture 2-Axis Electrothermal MEMS Mirror for Compact 3D LiDAR

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***Abstract*—Low-cost LiDAR with long distance, high resolution, and stable laser scanning are needed for robotics and automobiles. This paper reports a large-aperture, 2-axis electrothermal MEMS mirror for LiDAR applications. The MEMS mirror has a mirror plate of 2 × 2.5 mm^2 and an optical field view (FoV) of 15° by 12°. The beam divergence of 0.5 mrad is achieved with a 1.3-mm laser beam. The rotational scanning resonant mode is at 0.7 kHz, which is achieved by the meshed bimorph actuators with improved stiffness.**

Keywords—electrothermal actuation, MEMS micromirror, LiDAR, large aperture

I. INTRODUCTION

Low-cost, compact Light Detection and Ranging (LiDAR) systems are integral components in autonomous driving, robotics, and unmanned aerial vehicles (UAVs) [1]. Wide FoV (Field-of-View) is typically achieved by motorized scanning, but then stacking multiple channels of lasers and detectors is needed [2]. Such motor-based LiDAR are usually bulky, expensive, and power intensive, which greatly limits their applications in small UAVs.

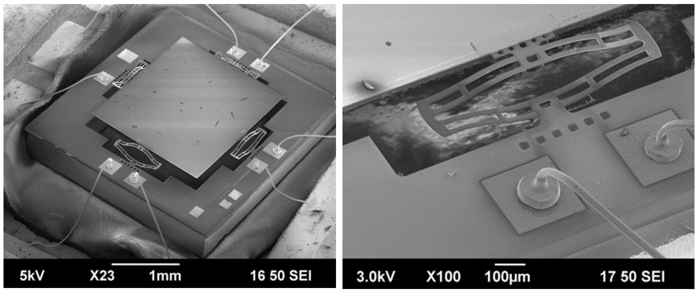
MEMS mirrors can accomplish 2D scanning without moving lasers or photodetectors while being compact and affordable [3][4]. The scanning characteristics of MEMS mirrors, such as scanning frequency, scanning angle, and aperture, are largely determined by the actuation methods employed. Electrostatic MEMS mirrors can scan wide 2D FoV only when both axes operate at resonance and with high Q [5], but resonant operation is very sensitive to environmental changes and aging, which require position sensing and sophisticated control [4]. Piezoelectric MEMS mirrors must deal with hysteresis, coupling non-uniformity while scanning at resonance, and charge leakage issues [6]. High-power consumption, complexity of packaging permanent magnets, and electromagnetic interference of electromagnetically actuated MEMS mirrors constrain their applications in compact LiDAR systems [7]. On the other hand, electrothermally actuated MEMS mirrors feature large 2-axis scanning at non-resonant operation as well as simple packaging [8]. A MEMS LiDAR with a 1-mm-aperture electrothermal MEMS mirror was demonstrated [9], but the small mirror aperture greatly reduced the detection range for the monostatic LiDAR, where the MEMS mirror was on the path of the returning light. A larger MEMS mirror aperture, in the range of 2 – 4 mm, is suitable for mid-range LiDAR on small UAVs.

In this work, a large-aperture, wide-angle electrothermal MEMS mirror has been designed and fabricated. The MEMS mirror has a mirror plate of 2 × 2.5 mm^2 and a laser beam with a small divergence angle of 0.5 mrad is achieved with this MEMS mirror.

II. DESIGN OF THE MEMS MIRROR

The MEMS mirror is electrothermally-actuated and based on the inverted-series-connected (ISC) bimorph actuation structure reported in [9]. In this MEMS mirror, SiO_2 and Al are used as the two bimorph materials while Pt is used as the embedded heater material. The mirror plate is 47 µm thick to balance the mass of the mirror plate and the surface flatness. A meshed ISC actuator structure is designed with a pair of ISC bimorph parallelly connected. The meshed ISC bimorph design can double the stiffness without losing the actuation range. To achieve a small beam divergence under 0.5 mrad, a laser beam of 1.3 mm(50%) or larger is required. So the MEMS mirror with a width of 2 mm is designed to capture the 1.3 mm laser beam. The length of the mirror is 2.5 mm to account for the extension of the laser beam incident at 45°. The device fabrication is similar to the one reported in [9].

Fig. 1 shows SEM images of a fabricated device, where the micromirror is suspended by four ISC electrothermal Al/SiO_2 bimorph actuators. The initial elevation of the mirror plate shown in Fig. 1(a) is about 145 µm. The actuators form dual-S-shaped structures because of the residual stresses in the bimorph beams.

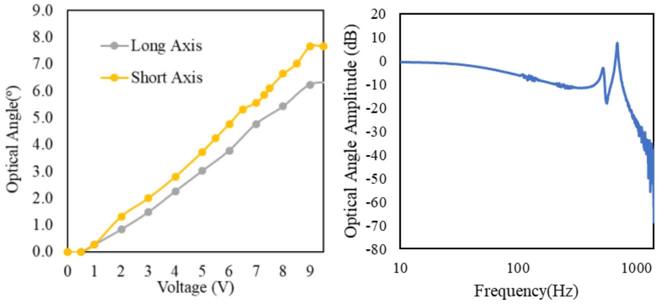


(a) (b)

Fig. 1 SEM images of (a) the fabricated device, (b) the meshed bimorph actuator structure.

III. EXPERIMENT RESULT

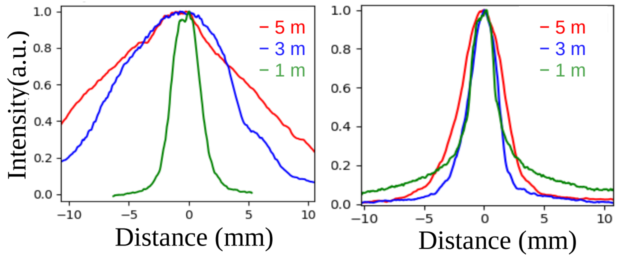
The measured quasi-static response of the MEMS mirror is plotted in Fig. 2(a), showing the maximum optical scan angles reached 6° along the long axis and 7.5° along the short axis, respectively. The frequency response was also measured using a position-sensitive detector. As shown in Fig. 2(b), there were two resonance peaks found at 531 Hz and 695 Hz; the 3 dB bandwidth of the thermal response was about 155 Hz.



(a) (b)

Fig. 2 (a) The tip-tilt angles versus applied voltage on actuators at each side. (b) Measured frequency responses.

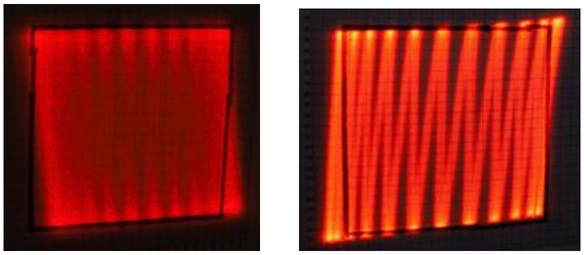
The curvature of the mirror surface was measured with a Bruker Optical Profilometer. The measured radius of curvature was about 2.0 m, thanks to the 47 μm-thick silicon mirror plate. An optical experiment has been performed to characterize the beam propagation profile. A He-Ne laser, expanded using a 2× beam expander, was incident on the MEMS mirror plate with a beam diameter of 1.3 mm. Fig. 3 compares the beam propagation measurement result of this 2mm×2.5mm MEMS mirror with that of a ϕ0.7mm circular mirror. Both mirrors have almost the same radius of curvature. As shown in Figs. 3(a) and 3(b), the output beam from the ϕ0.7mm mirror diverges much faster than the 2mm×2.5mm one. For instance, at 5 m away, the beam size corresponding to the 2mm×2.5mm mirror is only 4.5 mm, only 30% of that corresponding to the ϕ0.7mm circular mirror. The measured divergence angles are 1.5 mrad and 0.53 mrad for the ϕ0.7mm and 2mm×2.5mm mirrors, respectively.



(a) (b)

Fig. 3 Intensity profiles of the reflected beams (incident beam size ~0.5 mm) from a 0.7-mm MEMS mirror (a) and profiles (incident beam size 1.3 mm) from the 2×2.5 mm^2 mirror (b) at distances of 1m, 3 m, and 5 m, respectively.

Small beam divergence is essential to LiDAR for high resolution and extended measurement range. Fig. 4 shows the scan patterns at a distance of 7 m by those two mirrors. The pattern in Fig. 4(a) was generated by the 2mm×2.5mm MEMS mirror driven by two sine waves of 50 Hz (vertical) and 2 Hz (horizontal), respectively, which is equivalent to a 25 vertical line scan. The scan area was 10×10 cm^2 at 7 m and the laser line width was 8 mm. In contrast, the laser line width was 15 mm and the scan pattern became blurring for the ϕ0.7mm mirror.



(a) (b)

Fig.4 Raster scanning patterns achieved with 50×2 Hz with a scanning area of 10×10 cm^2 at 7 m away with a 0.7-mm mirror (a) and the 2×2.5 mm^2 mirror (b).

IV. CONCLUSION

An electrothermal MEMS mirror with a relatively-large aperture of 2×2.5 mm^2 has been demonstrated. This MEMS mirror can generate large raster scan at low driving voltage. Due to the increased aperture size, divergence angle as small as 0.5 mrad has been achieved. This electrothermal MEMS mirror has great potential to be used for LiDAR scanners.

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REFERENCES

[1] Stann, Barry L., et al. "MEMS-scanned ladar for small unmanned air vehicles." Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. Vol. 10636. 2018.

[2] Javanmardi, Ehsan, et al. "Autonomous vehicle self-localization based on multilayer 2D vector map and multi-channel LiDAR." 2017 IEEE Intelligent Vehicles Symposium (IV). IEEE, 2017.

[3] Hofmann, Ulrich, et al. "Resonant biaxial 7-mm MEMS mirror for omnidirectional scanning." Journal of Micro/Nanolithography, MEMS, and MOEMS 13.1 (2013): 011103.

[4] Wang, Dingkang, et al. "A compact 3D LiDAR based on an electrothermal two-axis MEMS scanner for small UAV." Laser Radar Technology and Applications XXIII. Vol. 10636. International Society for Optics and Photonics, 2018.

[5] Hung, Andrew C-L., et al. "An electrostatically driven 2D micro-scanning mirror with capacitive sensing for projection display." Sensors and Actuators A: Physical 222 (2015): 122-129.

[6] Liu, Wenjing, et al. "A tip–tilt–piston micromirror with a double S-shaped unimorph piezoelectric actuator." Sensors and Actuators A: Physical 193 (2013): 121-128.

[7] Ye, Liangchen, et al. "Large-aperture kHz operating frequency Ti-alloy based optical micro scanning mirror for LiDAR application." Micromachines 8.4 (2017): 120.

[8] Tanguy, Quentin, et al. "Design and fabrication of a 2-axis electrothermal mems micro-scanner for optical coherence tomography." Micromachines 8.5 (2017): 146.

[9] Jia, Kemiao, et al. "An electrothermal tip–tilt–piston micromirror based on folded dual S-shaped bimorphs." Journal of Microelectromechanical systems 18.5 (2009): 1004-1015..