

FULLY-FUNCTIONAL TIP-TILT-PISTON MICROMIRROR ARRAY

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A fully-functional 2x2-element array of tip-tilt-piston micromirrors with large deflection angles and large piston range is presented. A control system has also been developed which includes an extensive software package and a multi-channel high-voltage amplifier that allows the user to independently control all available degrees of freedom (i.e. tip, tilt, or piston) for each individual device in the array. The micromirrors are fabricated from monolithic single crystal silicon and employ bonded, metal-coated, low-inertia mirror-apertures 1 mm x 1 mm in size (Fig. 1.) At a neutral pistoning position, each actuator provides tip-tilt mechanical rotations of the micromirror from -5° to 5° (i.e. 20° of peak-to-peak optical deflection.) As the devices piston in the vertical direction (common mode actuation) a maximum displacement of -12 μm to 12 μm is realized. Overall array fill factor is 95% - chosen such that the mirrors would have sufficient space for large rotations without making contact to neighboring elements. Lowest resonant frequencies for rotation modes are >440 Hz in all devices, while for pistoning mode >1520 Hz.

Our implementation of the actuator element is based on pre-engaged vertical combdrives in SOI and a dual axis gimbal-less design (Fig. 1a) demonstrated previously in large tip-tilt devices [4]. Each actuator (Fig. 1b) consists of 4 vertical combdrive rotators connected by 2 degree-of-freedom (DoF) linkages to a central stage. Each of the four rotators can raise or lower its linkage in response to control voltage, with the position governed approximately by $Y_R = K(V^2)$ due to the electrostatic nature of the actuation. Maximum downward deflection of the central stage with all rotators in maximum downward rotation is 24 μm . Linear combinations of downward deflections of the four rotators provide the mirror stage with the required 3 degrees of freedom (DoF). In simple tip-tilt mode for vector graphics demonstrations shown in Fig. 3, opposing pairs of rotators are actuated in differential mode. In simple piston-only mode, all four rotators are actuated in common mode.

Low inertia micromirrors are fabricated in a separate SOI wafer in a 3-level selective DRIE process which results in mirrors with a 125 μm stand-off pedestal, a thin membrane (typically <4 μm), and support trusses of 15 μm thickness (Fig. 1a). Micromirrors are metalized with a 100 nm thick layer of Al, and their radii of curvature remain >1 m due to single-crystal silicon construction and truss-support mechanical design. Lowest resonant mode of each mirror without the actuator is >60 kHz. Therefore they can be considered perfectly stiff for operation of our arrays in the 1 kHz bandwidth. Transfer and bonding of micromirrors onto the actuators was achieved by using custom fabricated electrostatically actuated microinstruments [6]. Previously, we have demonstrated individual tip-tilt-piston actuators and the method of transfer [5]. Other past efforts have emphasized the benefits for such arrays but have not demonstrated fully-functional arrays with all three degrees of freedom (tip-tilt-piston) [1],[2],[3].

The demonstration system includes software that allows the user to independently control every available degree of freedom (i.e. tip, tilt, or piston) for each individual device in the array, as well as to maintain look-up-tables (LUTs) and calibration settings for each individual rotator in the array. Any changes in the calibration or drive settings are then communicated to a 16-channel analog output card which can either provide the control voltages in a single burst, or repeatedly at a user-determined refresh-rate (e.g. for static vector graphics.) The 16 analog outputs are conditioned and amplified via a custom high voltage 16-ch. amplifier which provides a ribbon-cable connection to a PCB which hosts the array's 64-pin PGA package (Fig. 2a.) As fabricated, devices have small variations in voltage vs. angle characteristics, i.e. their LUTs. Simple adjustments of gain and offset calibration settings for each rotator in the software were demonstrated to be sufficient to drive multiple elements to share a common center point with equal deflections, as shown in the example of Fig. 3c.

A large number of devices have been successfully tested in the described software-controlled system. Videos and devices will be presented at the conference for further demonstration of the system.

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- [2] Solgaard, O., *et al*, "Microoptical phased arrays for spatial and spectral switching", *IEEE Comm. Magazine*, vol. 41, no. 3, pp. 96-102, Mar. 2003.
- [3] J.-C. Tsai, *et al*, "Analog Micromirror Arrays with Orthogonal Scanning Directions for Wavelength Selective 1xN2 Switches," *Transducers '03*, pp. 1776-1779, Jun. 2003.
- [4] V. Milanović, D. T. McCormick, G. Matus, "Gimbal-less Monolithic Silicon Actuators For Tip-Tilt-Piston Micromirror Applications," *IEEE J. of Select Topics in Quantum Electronics*, Volume: 10 , Issue: 3 , May-June 2004, Pages:462 – 471.
- [5] V. Milanović, G. Matus, D. T. McCormick, "Tip-Tilt-Piston Actuators for High Fill-Factor Micromirror Arrays," at the Hilton Head 2004 Solid State Sensor, Actuator and Microsystems Workshop, Hilton Head, SC, Jun. 6-10, 2004.
- [6] *MEMS Precision Instruments*, www.memspicom.com.

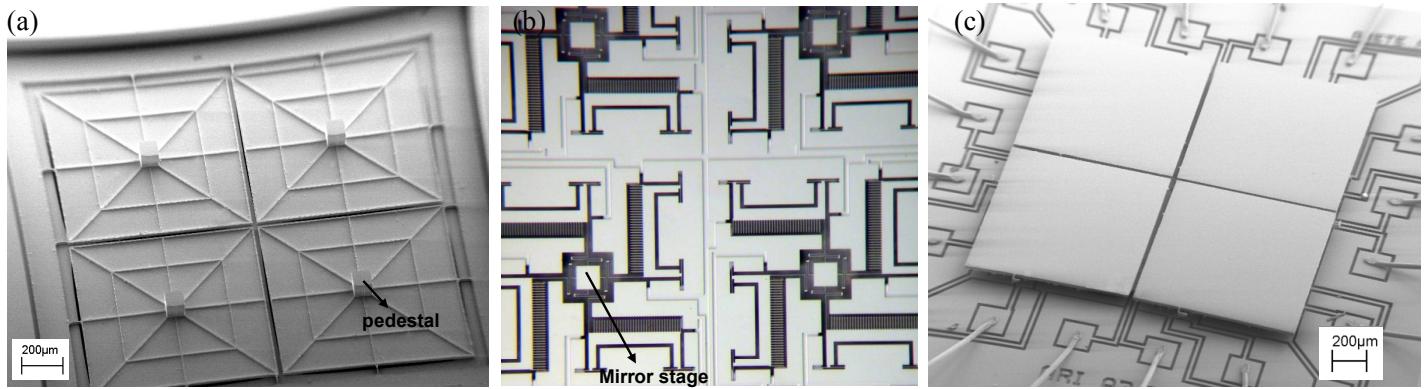


Figure 1. (a) SEM micrograph of the backside of a 2x2 array of low-inertia silicon micromirrors; both sides of the mirrors are metalized; mirrors are ready for transfer/bonding into a 2x2 array of actuators, (b) Optical micrograph of an array of tip-tilt-piston actuators; each actuator has four vertical combdrive rotators surrounding a 100 µm x100 µm stage for bonding of micromirror pedestals (c) SEM micrograph of a fully assembled, functional 2x2 element array of 1.0 mm x 1.0 mm mirrors. Each actuator is bi-directional tip-tilt and piston type.

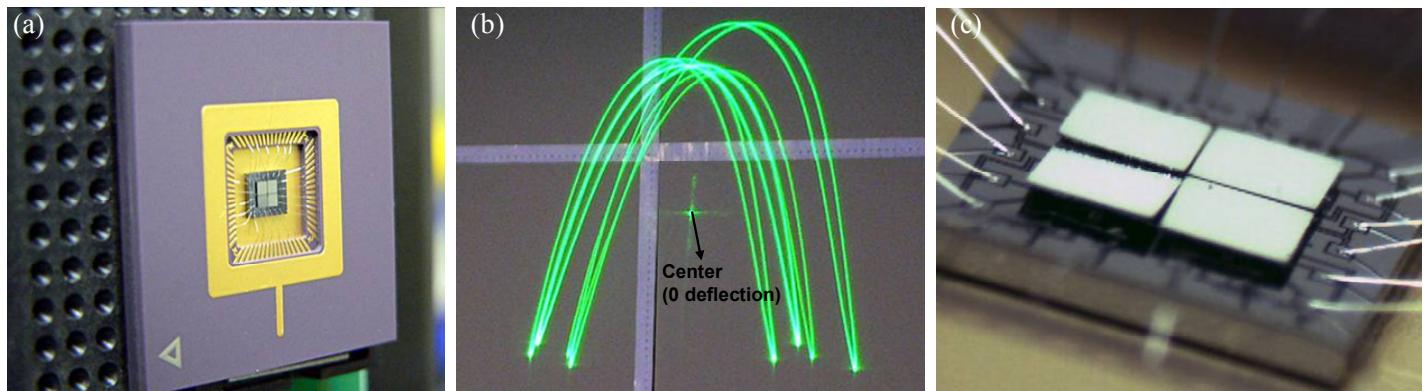


Figure 2. (a) Photograph of an array in a 64-pin PGA package placed in the demonstration system board with a ZIF socket, (b) all four elements in the array operate in bi-directional tip-tilt rotations (about the marked center), forming four Lissajous patterns, and (c) stereo microscope image of the actuated array with each of the four elements being driven by the software to act independently, some mirrors rotating in one or both axes, and one mirror pistoning.

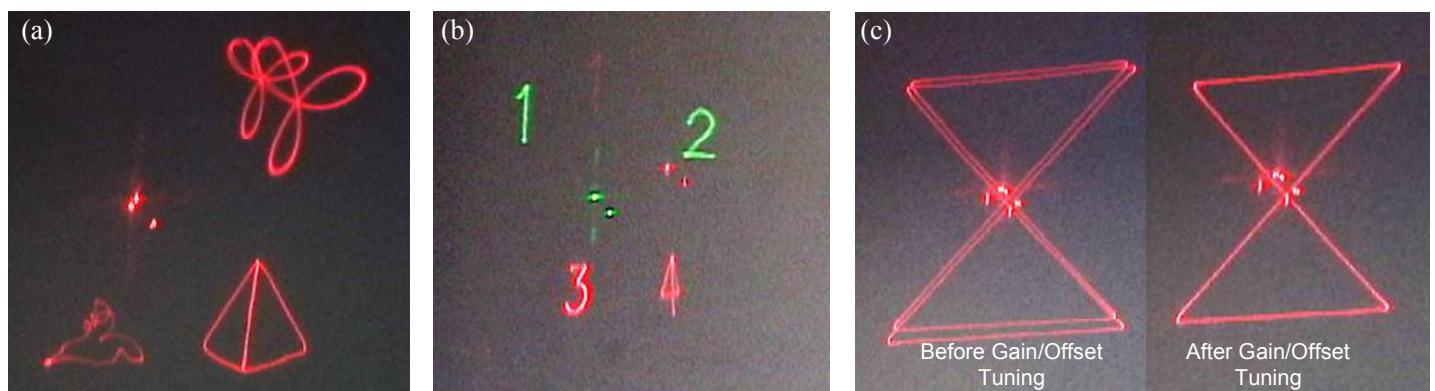


Figure 3. Demonstrations of bi-directional tip-tilt performance of all 4 elements of the array: (a) each element is being driven to trace out a different vector drawing or animation on the wall. One laser is illuminating all four elements, and their animations are offset to arrive to different areas on the wall; (b) two different lasers are colinearly illuminating the array such that the 532nm laser illuminates first row of elements and the 630nm laser the 2nd row. Each element is drawing a number representing its number for identification, and (c) As fabricated, devices have small variations in voltage vs. angle characteristics. We show a demonstration of two devices having their look-up-tables calibrated to trace out equal tip-tilt angles.