Linearized Gimbal-less Two-Axis MEMS Mirrors

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Abstract: Gimbal-less Two-Axis Scanning MEMS Mirrors provide ultra low-power and fast optical beam scanning at angles of up to 32° in both axes, while dissipating less than 1 mW of power. Linearized driving scheme and 4-quadrant addressable electrostatic combdrive design gives nearly linear voltage-angle characteristics. Devices are made entirely of single-crystal silicon, resulting in excellent repeatability and reliability. Mirrors from 1mm to 4mm allow users to optimize in their application.

OCIS codes: 130.3990 Micro-optical devices, 230.4040 Mirrors

1. Introduction

Gimbal-less two-axis scanning mirrors based on Multi-level Beam SOI-MEMS [1] fabrication technology provide low-power and fast optical beam scanning in two-axes [2]. The devices deflect laser beams to optical scanning angles of up to 32° at very high speeds in both axes. Due to their small scale of millimeters in size, and electrostatic combdrive-based actuation, typical devices dissipate less than 1 mW of power. The structures are made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Flat, smooth mirror surfaces are coated with a thin film of metal.

2. Mirror Types and Sizes

Silicon mirrors of up to 1.2 mm diameter can be fabricated as a monolithic part of a device. Larger mirror sizes and shapes can be utilized by fabricating those separately and assembling them on top of gimbal-less actuators. The diameter, as well as geometry, of the mirror is selected for each individual application, in order to optimize the trade-offs between speed, beam size, and scan angle for each individual application. The mirrors are subsequently bonded to the actuators, providing the ability to economically adapt a small set of fabricated devices for a wide range of applications.

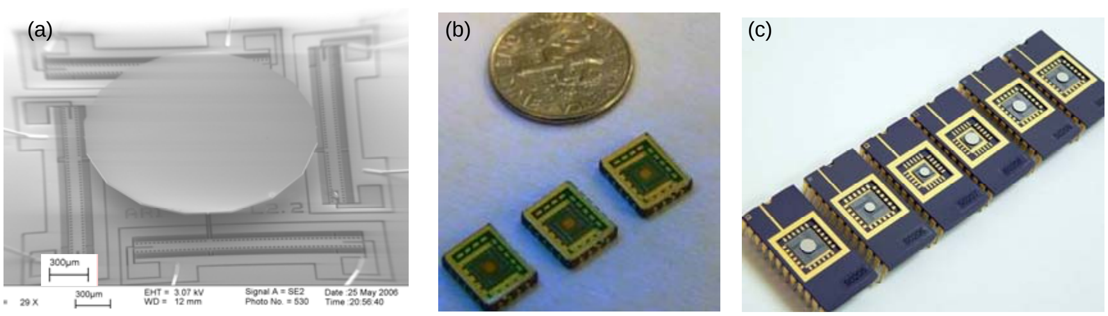

Figure 1. Various actuators with mirrors of different sizes (from left to right:) 2.0mm diameter bonded mirror, 1.2 mm integrated mirrors, various bonded mirror sizes.

3. High Speed Point-to-Point Optical Beam Scanning

The devices are designed for point-to-point optical beam scanning mode of operation. A steady-state analog actuation voltage results in a steady-stage analog angle of rotation of the mirror. This actuation is based on electrostatically driven vertical combdrives, seen in the SEM micrograph of Fig. 2c. Each individual finger (blade) of the suspended structure in the center of the micrograph is electrostatically attracted between two opposing fingers on the static structures on either side of the center structure. When the suspended structure is rotated in the clockwise direction, capacitance between the fingers is increased due to the increased overlap area. Finally, at each end of the suspended structure are torsional springs which mechanically support the suspended structure as well as provide restoring force. Positional precision in open loop driving of the mirrors is at least 14 bits, i.e. within 0.6 milli-degrees. In specific applications such as high-speed 3D tracking and position measurement [3], 16-bit precision in angle has been demonstrated. Devices can be operated over a wide bandwidth from dc to several thousand Hertz. This fast and broadband capability allows arbitrary waveforms such as vector graphics [4], constant velocity scanning, point-to-point step scanning, object tracking in a 3D volume [3], etc.

The major advantage of the gimbal-less design is the capability to scan optical beams at equally high speeds in both axes. The design combines one-axis rotators [2], and allows their operation to be nearly independent of the other axis' operation without the added inertia of a gimbal frame. This methodology is schematically shown in Fig. 2. Two one-axis rotators are utilized for each axis of the overall 2D scanner. For the *x*-axis, actuators A and A' are utilized, and for the *y*-

axis, actuators B and B'. The inside linkages have to be designed to allow these two degrees of freedom (2 DoF) of rotation.

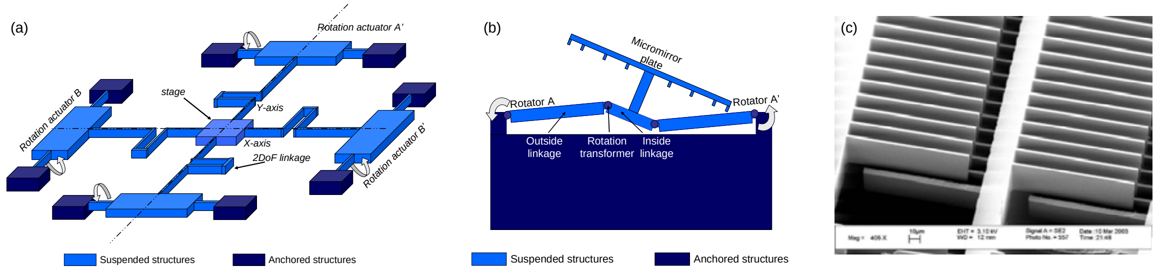

Figure 2. (a) Schematic diagram of a gimbal-less two-axis scanning actuator based on four high aspect ratio rotators connected to the central pedestal by two degrees-of-freedom (2 DoF) linkages. (b) Cross-sectional depiction of device operation [2]. (c) SEM of a section of a combdrive rotator showing upper and lower combfingers arranged for pure rotation.

A typical device with a 0.8 mm diameter-sized mirror achieves angular beam scanning of up to 600 rad/s and has first resonant frequency in both axes above 5.0 kHz. In closed-loop operation, point-to-point large step 99% settling time for such a device is around 100 μs. Devices with larger-diameter mirrors are correspondingly slower due to the increased inertia. Figure 1a illustrates this dependence in terms of increasing settling times for different mirror sizes.

(a)

Mirror Diameter	Typ. Mechanical Angle	Typ. Step Settling Time
0.8 mm	-6° to +6°	0.10 ms
1.2 mm	-6° to +6°	0.26 ms
2.4 mm	-6° to +6°	0.68 ms
3.6 mm	-6° to +6°	1.80 ms

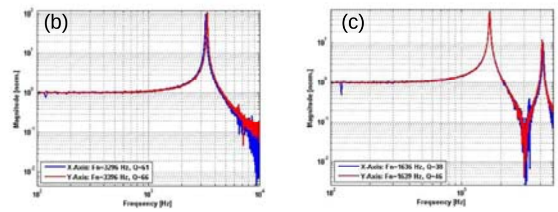

Figure 3. (a) Table compares closed-loop step-response 99% settling times for 4-quadrant devices of various diameters; (b) Typical small-signal frequency response for an integrated-mirror 0.8mm device; (c) response for a bonded-mirror device with a 1.6mm diameter.

4. One-quadrant (1Q) vs. Four-quadrant Devices (4Q)

In the past, all devices fabricated in the Multi-level beam SOI-MEMS [1] have been one-quadrant, or uni-directional type devices. This refers to the fact that each axis (these are still two-axis or dual-axis or 2D devices) is able to deflect a mirror from rest position (0°) to one side (e.g. 8°,) but not to the opposite side (e.g. -8°.) So a typical one-quadrant (1Q) device achieves mechanical tilt of 0° to 8° on the X axis and 0° to 8° on the Y axis. Referring back to Fig. 2c and explanation in Sec. 3, this is simply due to the fact that the combdrive only actuates in one (clock-wise in that example) direction. However it is possible to have a rotator designed in such a way that ½ of the combfingers actuate clock-wise, while another ½ of the combfingers actuate counter clock-wise, and also route to an independently powered pad. This is schematically depicted in Fig. 4a.

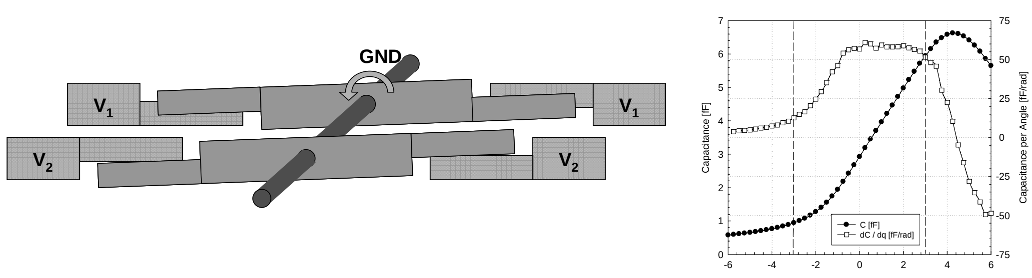

Figure 4. (a) Rotator with opposing combdrive sections which can be independently activated. Front set of combfingers create clock-wise torque while the back set create counter clock-wise torque. They are mechanically connected to form one common rotator, allowing overal 4-quadrant mirror actuation. (b) Calculated capacitance of a combfinger with rotation angle starting with large negative (disengaged position) rotation.

Figure 5 below provides a graphical explanation as to the difference between the two types of devices. In both examples, device is optically setup such that at 0V actuation, the laser beam is deflected normally to the wall at the origin of the co-ordinate system. Under such conditions, 1Q devices address points only in the 1st quadrant, while 4Q devices in all four quadrants. The figure also shows typical characterization results for representative devices of each type. Note that negative DC actuation voltage in the bi-directional device represents voltage applied to parts of rotators that provide negative rotation, and not actually necessarily negative voltage.

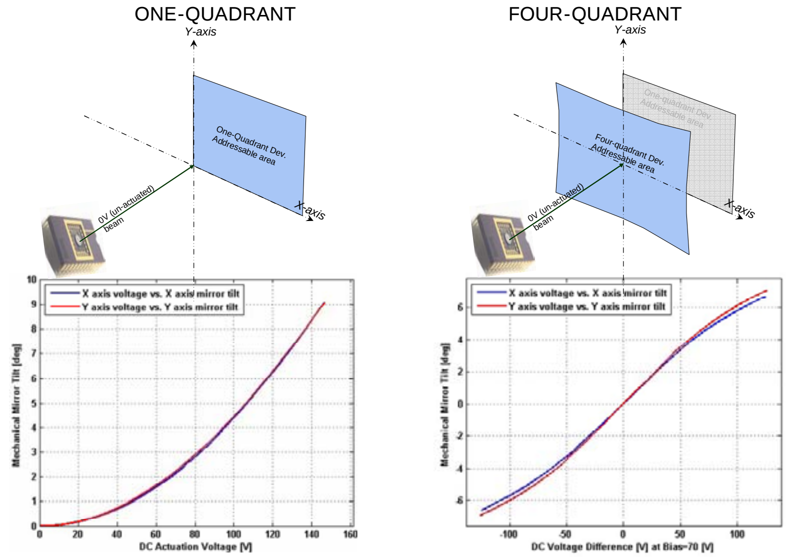

Figure 5. Comparison of addressable angles/areas by 1-Q and 4-Q devices, and representative voltage vs. angle measurement of each.

4. Linearized Driving of Four-Quadrant (4Q) Devices

We utilize a new method of driving the 4Q (bi-directional) devices with Differential+Bias scheme in order to linearize devices as well as to provide smooth transitions from one quadrant to another, i.e. form one combdrive actuator to another within the device. In this mode both the positive rotation portion and the negative rotation portion of each rotator are always (differentially) engaged, and therefore the voltages and torques are always continuous. As can be seen in Fig. 4, capacitance of the combdrive is a strong function of angle. As expected it is increasing with increased overlap area, and decreasing with decreased overlap area. If we confine the range of rotation to -3deg to +3deg range this capacitance curve is very well behaved and the change of capacitance per angle which creates torque is always positive. Therefore we can actually create a push-pull situation with both opposing combdrives able to create torque at any point in their rotation, even when at negative rotation angle (where combfingers are mostly disengaged.) Therefore we bias both sections of the combdrives with a voltage in the middle of the range and apply desired voltage differentially as shown in Fig. 6, obtaining nearly linear voltage vs. angle mirror characteristics (Fig. 6c) for all such devices.

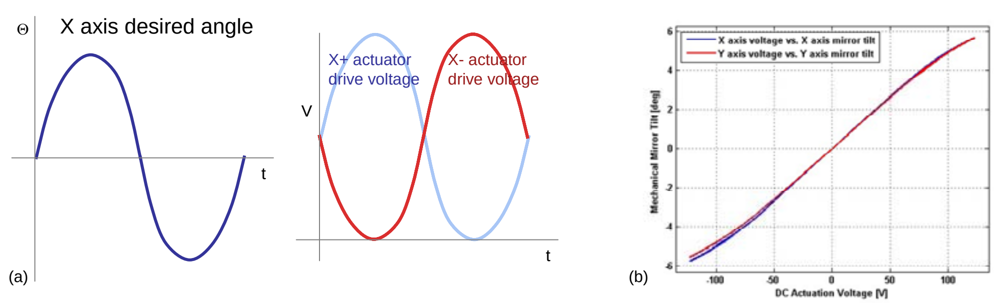

Figure 6. Methodology of linearized driving of the 4-Quadrant devices: a) desired angle of the x-axis has positive and negative angles, which is possible with 4Q devices. Amplifier has 2 channels for the x-axis, one drives the X+ actuator with the desired angle voltage at a positive dc-bias. The other drives the X- actuator with the inverted desired angle voltage, at same positive dc-bias. The actuators are therefore opposing each other. b) example of a voltage vs. angle characteristic for a 4Q device using the 4-channel linearized amplifier.

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