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Advanced MEMS systems for optical communication and imaging

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Abstract. Optical communication and adaptive optics have emerged as two important uses of micro-electromechanical (MEMS) devices based on electrostatic actuation. Each application uses a mirror whose surface is altered by applying voltages of up to 300 V. Previous generations of adaptive-optic mirrors were large (~1 m) and required the use of piezoelectric transducers. Beginning in the mid-1990s, a new class of small MEMS mirrors (~1 cm) were developed. These mirrors are now a commercially available, mature technology. This paper describes three advanced applications of MEMS mirrors. The first is a mirror used for coronagraphic imaging, whereby an interferometric telescope blocks the direct light from a distant star so that nearby objects such as planets can be seen. We have developed a key component of the system: a 144-channel, fully-scalable, high-voltage multiplexer that reduces power consumption to only a few hundred milliwatts. In a second application, a MEMS mirror comprises part of a two-way optical communication system in which only one node emits a laser beam. The other node is passive, incorporating a retro-reflective, electrostatic MEMS mirror that digitally encodes the reflected beam. In a third application, the short (~100-ns) pulses of a commercially-available laser rangefinder are returned by the MEMS mirror as a digital data stream. Suitable low-power drive systems comprise part of the system design.

1. Introduction

Over the past few decades, micro-electromechanical systems (MEMS) have become a mature technology found in cell phones, automobiles, cameras, medical devices, and optical imaging systems. MEMS deformable mirrors (DMs), the topic of this paper, are thin-film devices that shape and selectively reflect light. While the numerous capacitive MEMS actuators inside a DM require almost no power, the driving circuit can represent a substantial power demand for a DM optical system. This paper discusses several applications of MEMS mirrors and some new power-saving driver circuits.

2. Structure, Fabrication, and Actuation

Our mirrors, reported elsewhere [1,2], are fabricated by the following or similar process: Thin films of phosphosilicate glass (PSG) and silicon nitride are deposited on a silicon substrate, followed by 90-nm of gold. The gold is patterned and etched with 4- μm holes; these holes serve as a mask for reactive-ion etching to make holes in the silicon nitride. Unused gold is removed and electrostatic actuators that support the mirror are formed by under-etching the PSG with acid (HF) through the holes, leaving support anchors. This process yields mirrors, depicted in figure 1, that are optically flat to within 6 nm.

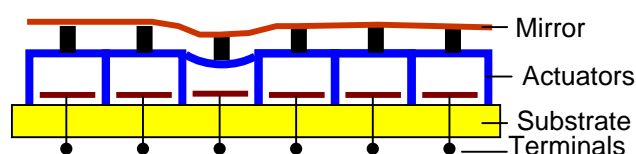


Figure 1. DM array structure.

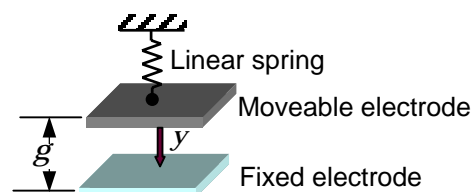


Figure 2. Simplified spring-capacitor actuator.

Each supporting actuator can be modeled, to first order, as a two-electrode capacitor of area A and spacing g , as in figure 2. A voltage V causes deflection y of the upper electrode. The balance of electrostatic and $-ky$ mechanical forces yields the well-known deflection versus voltage equation [3]:

$$y(g - y)^2 = V^2 \epsilon_0 A / 2k \quad (1)$$

Tests of our mirrors at 300 V show deflection of at least 200 nm, more than an optical wavelength. The need for driving signals as high as 300 V puts an extra burden on the driver circuitry.

3. Space-Based Interferometry

We have built several interesting optical systems using our electrostatic mirrors. In one system, the surface profile of a DM is continuously altered to clear up blurry or distorted images. Such DMs will play an important role in high-resolution telescope systems being developed by NASA for its exoplanet mission – the search for life on other planets [4,5]. Light from a distant star is canceled by interferometric mirrors, leaving only the images of planets in the star’s halo. These optical systems must orbit the earth to avoid atmospheric distortion, hence they can consume only very small amounts of power. At the same time, however, they must have extraordinary precision approaching the picometer range. They therefore may contain up to 10^4 closely spaced actuators having picometer resolution.

Presently, all commercial analog DM-drivers use a one-amplifier-per-actuator architecture, in which analog signal processing and multiplexing are performed at low voltage. Signals are then fed to a large array of high-voltage (HV) amplifiers. This approach is necessary because, to date, no integrated circuits exist that are capable of multiplexing HV analog signals. With conventional approaches, the very large number of power-consuming HV amplifiers needed for a 10^4 -element array would require many large circuit boards and tens-of-watts of quiescent power. For NASA’s planned and future space-based missions, a better approach is needed. We have developed a high-voltage multiplexing circuit (MUX) that distributes the output of a *single* HV amplifier to each actuator in an array. Over a “raster” cycle, a given actuator is momentarily connected and energized by the amplifier. The MUX then holds the actuator’s voltage until the next refresh event. With only one HV amplifier used, total system power, size, and cost are dramatically reduced. Our current prototype drives 144 actuators with 0-300 V HV analog signals over a 10-ms refresh cycle. Total system power consumption is about 400 mW, and the architecture is scaleable to an arbitrarily large number of actuators. The circuit configuration is also compatible with existing, commercial HV CMOS (integrated-circuit) fabrication processes. The focus of our current efforts is a 10^3 -actuator mirror driver fabricated on a single high-voltage integrated circuit.

The architecture of our system is shown in figure 3. A logic-level digital bus feeds a low-voltage digital-to-analog (D/A) converter which, in turn, drives the HV amplifier. Within the MUX, each actuator has its own transistor-based driving cell (figure 4) that, when addressed by logic-level row and column lines, momentarily connects the actuator to the HV-amplifier output. A 100-nF “holding” capacitor is connected in parallel with the actuator’s tiny 150-fF capacitance to enhance holding time.

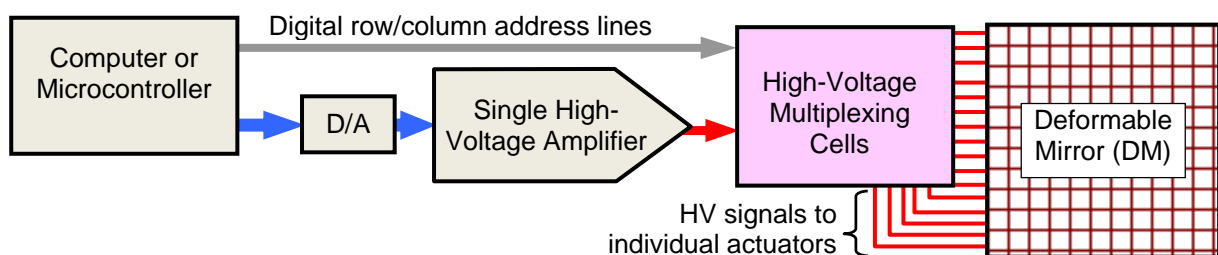


Figure 3. Block diagram of our high-voltage multiplexer configuration.

One anomaly of this scheme is that the voltage of a cell's holding capacitor will, at times, be higher than the output of the HV amplifier (V_{CA} positive). Conventional transistor circuit design relies on the upper voltage bus being the highest in the system. Thus a key feature of the circuit of figure 4 is the emitter-coupled BJT pair Q_1 - Q_2 which can maintain a high-impedance for either polarity of V_{CA} .

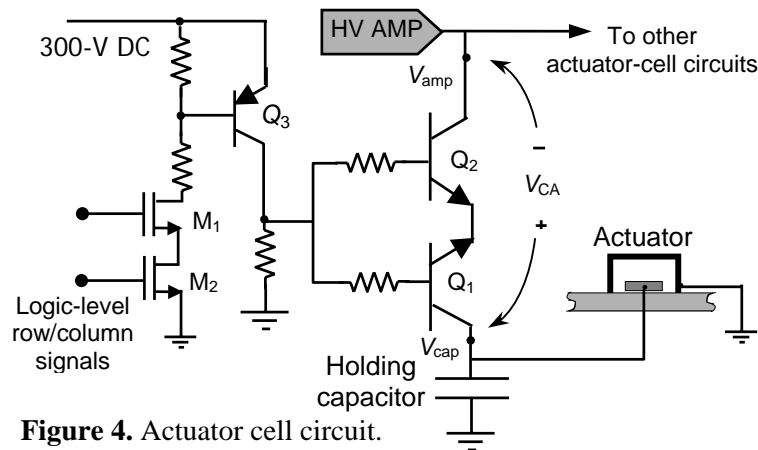


Figure 4. Actuator cell circuit.

Circuit performance was verified by measuring actuator position drift over a 10-s interval using an optical surface-mapping profilometer accurate to 1 nm. Data were then interpolated to find the actual droop over the system's 10-ms refresh cycle. The results show drift rates between 0.32 and 4.39 pm/ms ($1 \text{ pm} = 10^{-12} \text{ m}$). Holding-capacitor voltage droop over a refresh cycle was typically less than 3 mV for a full 300-V signal (i.e., one part in 2^{16} , or one LSB of a 16-bit D/A conversion). This drift is due to charge leakage over undesirable impedance paths to ground, which we minimize in our design.

4. Laser Communication via MEMS Retroreflective Mirror

Our second application involves point-to-point, stealth data communication via laser [6]. In many military and sensing applications, radio is not practical because transmission may be disrupted, unavailable, or easily detected. Also, both communication nodes must radiate power. In our alternative system, one node is active (emits laser power), but the other is passive (only reflects power). As shown in figure 5, the active node beams a constant (CW) laser toward the passive node which contains a MEMS DM retro-reflector. The mirror is digitally (on/off) modulated at high data rates to either reflect the beam (logic 1) or scatter it (logic 0).

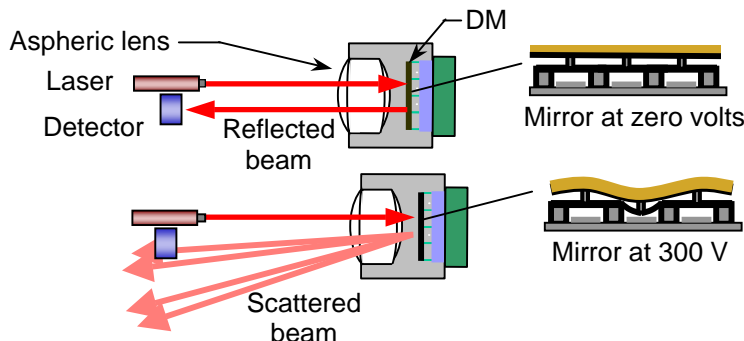


Figure 5. Laser beam is reflected (logic 1) or scattered (logic 0) to send back digital data.

Power consumption at the passive node is dramatically reduced via the boost-converter circuit of figure 6. Conventional MEMS switching circuits waste energy by discarding stored capacitor charge after each switching operation. Our system, on the other hand, reuses energy from cycle to cycle. The HV logic-0 pulses that drive the DM are produced as follows: Energy is first stored in the inductor via the MOSFET switch, then transferred to the capacitor to produce a half-resonant sinusoidal pulse. The

energy is recaptured by the inductor, then returned to the battery, ready for the next cycle. Equating the peak inductor energy $\frac{1}{2} LI_p^2$ with the peak transferred capacitor energy $\frac{1}{2} CV_p^2$ yields:

$$V_p = I_p \sqrt{L/C} = V_o T / \sqrt{LC} \quad (2)$$

for an inductor charging time T . In this way, 300-V-peak pulses can be produced when V_o is less than 10 V. The communication system operates at a predetermined bit rate. A voltage pulse disrupts mirror reflection, yielding a logic-0. The absence of an expected pulse, allowing laser reflection, sends a logic-1. Our goal is mirror driver that operates from a single, standard, 9-V battery for up to 24 hours.

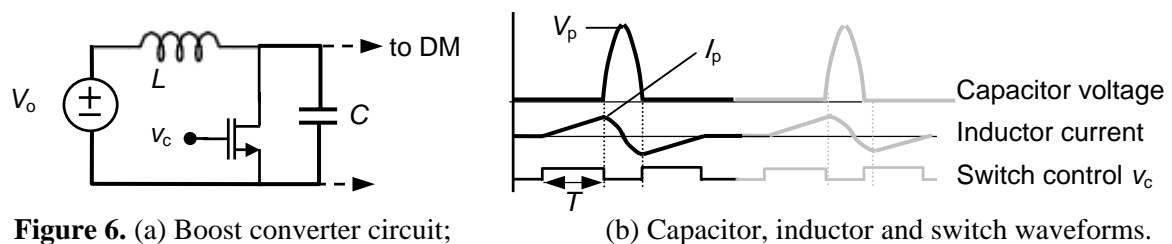


Figure 6. (a) Boost converter circuit;

(b) Capacitor, inductor and switch waveforms.

5. Laser-Rangefinder Communicator

Another optical communicator builds upon a standard-issue laser ranging device [7]. For distance measuring purposes, a rangefinder measures the return time of very short (~ 100 ns) laser pulses emitted at about a 20-kHz rate. In our modified system, shown in figure 7, a receiving node first times the rangefinder pulses to determine their periodicity. It then synchronizes the reflective state of the mirror with the pulses to send back either a logic-1 or logic-0 data stream on a pulse-by-pulse basis. Because the pulses are of such miniscule duration, as is required of most rangefinders, unique timing circuitry at the passive node is required. As before, the passive node emits no radiation, hence it can operate at very low power from a single 9-V battery for long periods of time.

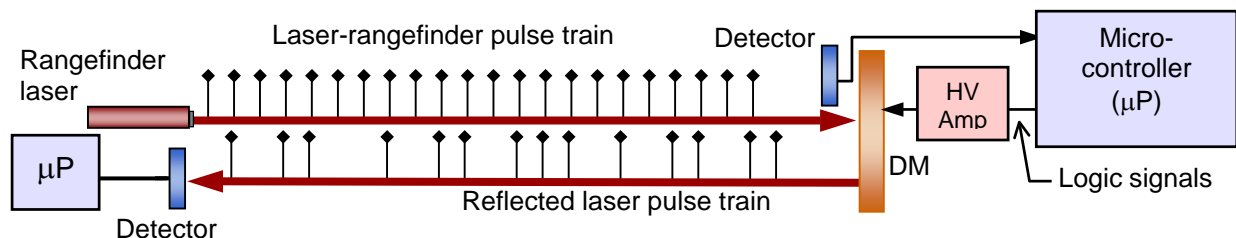


Figure 7. MEMS DM selectively returns 100 ns pulses from the laser rangefinder.

6. Conclusion

We have demonstrated the use of MEMS deformable mirrors for optical communication and imaging, and we have disclosed several techniques for reducing power consumption of the requisite driving electronics. These devices and techniques show promise for a variety of future planned systems.

7. Acknowledgements

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8. References

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