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A 3-Degree-of-Freedom MEMS Mirror with Controllable Static and Dynamic Motion for Beam Steering †

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† Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Published: 17 December 2018

Abstract: A 3 Degree-of-Freedom (DOF) MEMS mirror is presented which can direct the light beam on an objective point and also operate in a continuous resonance 2 DOF mode. The micro-mirror is actuated by Lorentz force and has 4 actuators embedded in 4 sides of a square mirror. By enabling the actuators, different types of tilting and linear motion can be achieved. The micro-mirror is able to work in either static mode by applying dc current or dynamic mode by applying an ac current at the mirror resonance frequency. The mirror showed a maximum tilt angle of 14.5° and 20° for an input rms power of 2 mW in the resonance mode. A linear motion of 200 μm was achieved by 65 mW of dc power.

Keywords: MEMS mirror; Lorentz force actuation; scanning micro-mirror; 3 degrees of freedom

1. Introduction

Scanning MEMS mirrors have been developed for many systems including micro projectors [1], imaging, and catheters [2]. In some applications, the objective area needs to be scanned vertically and horizontally which requires the mirror to mechanically move in 2 or 3 dimensions. Multi-DOF MEMS mirrors have been developed to fulfill this requirement. In addition to scanning a pattern, focusing the light beam on an objective point is also desired for focal point alignment and depth scanning purposes [3].

Multi-DOF MEMS mirrors have been reported in two types of structures including gimballed [4] and gimbal-less [5] structures. Gimballed structures consist of inner and outer frames and the mirror is located inside the inner frame. Each frame tilts about one axis which is perpendicular to the tilt axis of the other frame. Gimballed structures work in two resonant modes known as fast and slow scan modes [6]. This type of structures has been reported with electrostatic [4], piezoelectric [7] and electromagnetic [6] actuation. There are benefits and drawbacks to each type of actuation. Electrostatically actuated MEMS mirrors are of high resonance frequency but require a large input voltage for tilting. For example, in MEMS mirror reported by ref [8], an input of 16.7 V was used per 1 μm of displacement. Comparing to the other types of actuations, Piezoelectric-actuated MEMS mirrors have less been reported due to the complexity in fabricating PZT material. Electromagnetically actuated gimballed structures have large tilt angle but are usually limited to two degrees of freedom [9]. This limit comes from the difficulty of aligning the magnetic field orientation with different directions of current.

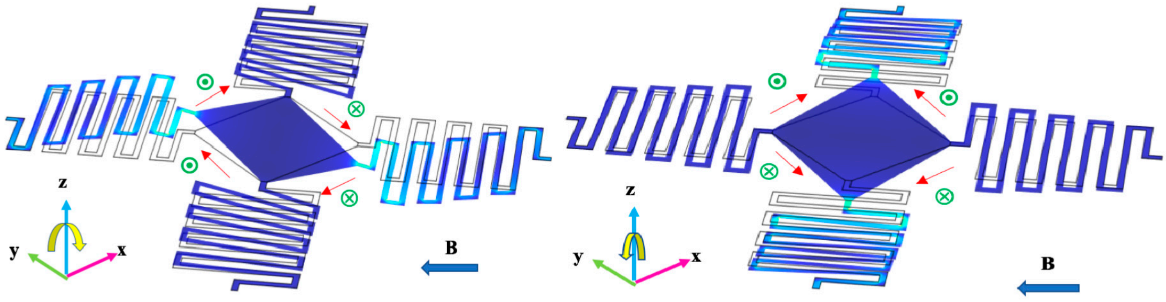
In gimbal-less structures, the mirror is directly connected to a frame using several flexures. Electro thermally actuated gimbal-less MEMS mirrors have shown very good tilt angle in 3 degrees of freedom [5]. However, the generated heat on the flexures can cause problem in temperature-sensitive applications.

In this work, an electromagnetically actuated gimbal-less micro-mirror is reported. This mirror can tilt in two directions and move linearly in one direction. The simulation analysis of this design was previously reported in [10]. The impact of this mirror is having large amplitude of motion with respect to the consumed power in 3 directions, while possessing the ability to work in both resonance and static modes of motion.

2. Materials and Methods

2.1. Design

Figure 1 shows the schematic of the micro-mirror device. The square-shaped mirror is connected to a fixed frame using 4 flexures at its corners. An external magnetic field of 0.1 T was supplied by a permanent magnet. The magnetic field is oriented 45° with respect to the mirror sides. Each flexure has two conductors, allowing electrical current (I1, I2, I3, I4) on each side of the mirror to be individually controlled. Figure 2 shows the four coils and the possible current paths. Each flexure has two wires on it, carrying separate currents. For example, wires for I1 and I2 are on the top flexure in Figure 2. Therefore, all the four sides of the mirror can be individually actuated. The Lorentz force exerted on the flexures and mirror sides is governed by Equation (1).



(**a**) (**b**)

Figure 1. Schematic of the MEMS mirror, blue arrow shows the direction of magnetic field B, red arrows show the directions of current, green circles show the directions of force. (**a**) The ϕ tilt mode. (**b**) The θ tilt mode.

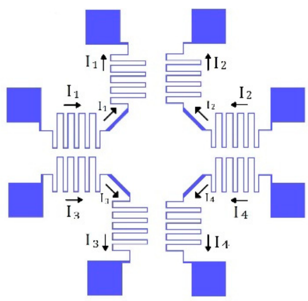


Figure 2. The four current paths showed separately.

$$F_{Lorentz} = \vec{I} l \times \vec{B} \tag{1}$$

where I is the current, l is the length of wire and B is the magnetic flux density. The different tilting modes are formed by changing the direction of current in wires passing through the mirror sides and flexures. Figure 1. a and b show the mirror tilting about φ and θ axis.

2.2. Fabrication

The MEMS mirror was fabricated out of a <100> silicon wafer. A layer of 1.5 μm silicon dioxide was grown on both sides of the wafer. The SiO_2 on the backside of the wafer was patterned and the silicon on the patterned area was chemically etched in potassium hydroxide solution. A layer of 1.5 μm aluminum was deposited on the front side of the wafer and patterned to form the wires and mirror. Lastly, the patterns on the front side of the wafer was covered by a thick layer of photoresist and the structure was released from the back and front sides, using isotropic and anisotropic plasma etching processes. Figure 3 shows a fabricated MEMS mirror.

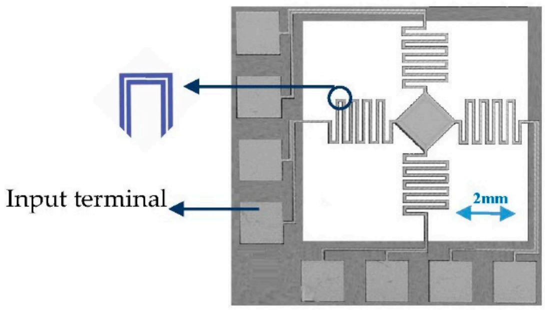


Figure 3. A fabricated mirror. Expanded view (**left**) shows the two conductor wires on the spring.

3. Results and Conclusions

The device was tested by shining a laser diode on the mirror and measuring the displacement of the reflected laser spot. The initial angle of incidence was 45° with respect to the normal of the mirror plane. An electrical current of 1–18 mA was applied.

The static and dynamic modes were measured by applying dc and ac current. In the static mode, tilt angles of 5.1° in ϕ mode and 11.8° in θ mode were measured. In the dynamic mode, tilt angles of 14.5° in ϕ and 20° in θ were measured at 238 Hz and 244 Hz resonance frequencies respectively. The power consumption with an input current of 18 mA was 2 mW which caused a temperature rise of 15 °C on the flexures. The variation of tilt angles of ϕ and θ versus applied current are shown in graphs of Figures 4 and 5 for static and dynamic actuations. The third mode of motion was operated by actuating all the 4 sides together. The mirror showed a linear motion of 200 μm with 65 mW of dc power.

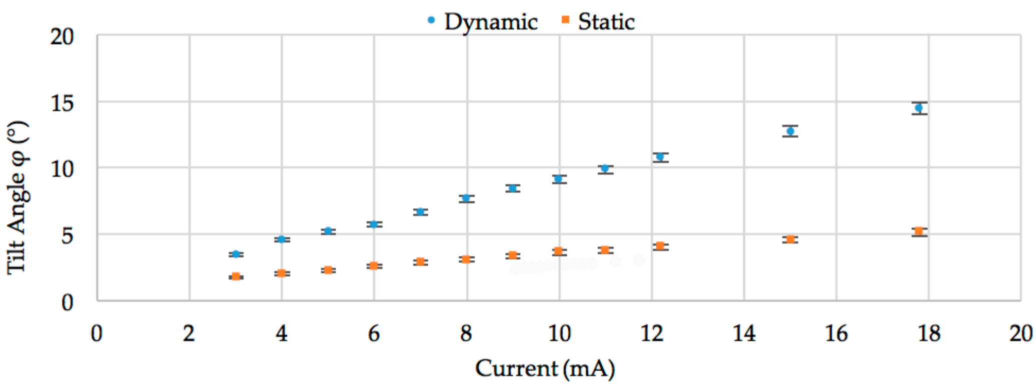


Figure 4. Angle of ϕ tilt mode vs. current. Red squares show the tilt angle with dc current, and the blue circles show the tilt angle with ac current of 238 Hz, using configuration of Figure 1a.

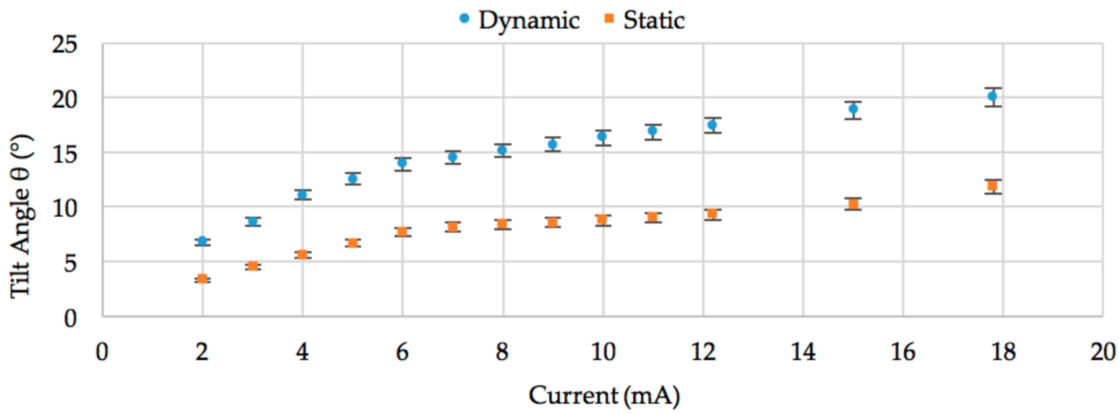


Figure 5. Angle of θ tilt mode vs. current. Red squares show the tilt angle with dc current, and the blue circles show the tilt angle with ac current of 244 Hz, using configuration of Figure 1b.

Author Contributions: E.A., C.S. and B.P. conceived and designed the device and experiments; E.A. performed the experiments; R.S. contributed materials and analysis tools.

Acknowledgments: This research was financially supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the University of Manitoba Graduate Fellowship (UMGF).

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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