ELECTROSTATICALLY ACTUATED 2-DIMENSIONAL MEMS MICROMIRROR

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ABSTRACT

Electrostatically actuated Micro-Electro-Mechanical-Systems (MEMS) based micromirror is a fundamental building block for a variety of optical network applications, such as optical wavelength-selective switching, add/drop multiplexing, and optical cross-connecting. The design, analysis and testing of a 2-Dimensional (2D) electrostatically actuated torsional MEMS micromirror is presented in this paper. The dual-axis system has been modeled theoretically and the equations describing device behaviors are validated using numerical mathematical software MATHEMATICA. The static and dynamic behaviors of the double-gimbaled electrostatic torsional micromirror have been investigated using Finite Element Analysis (FEA) tools COMSOL and ANSYS. Prototype devices are fabricated using a standard surface micromachining MEMS process through the CMC Microsystems. Both the static and the dynamic testing results are discussed in the paper.

Keywords: MEMS micromirror; electrostatic; torsional

INTRODUCTION

In the past two decades, MEMS based micromirrors have found a wide range of applications in many fields of engineering including free-space fiber-optic switches [1], projection displays [2–4] and confocal microscopes [5]. Torsion micromirrors have also found their application in telecommunications as optical switches [6]. Recently, torsion micromirror arrays have been used as virtual masks for DNA patterning [7]. Moreover, torsion micromirrors can be incorporated with other micro-optical devices, such as micro lenses, micro gratings, and optical waveguides [8] to achieve more complex system functions. Different actuation mechanisms can be used to actuate a micromirror either statically or dynamically. For the device described in this paper, electrostatic actuation has been chosen as actuation mechanism because of inherent simplicity of their design, fast response, ability to achieve rotary motion and low power consumption. The performance specifications for torsion micromirrors generally consist of mirror size, resonant frequency, quality factor, rotation angle, operation voltage, mirror flatness and reflectivity, operation linearity, and power handling capability.

Modeling and analysis of a 2D electrostatically actuated torsional micromirror has been discussed in this paper. A micromirror is described analytically and simulations are performed using FEA packages. The prototypes have been fabricated using the Multi-User MEMS Process (MUMPs) through CMC Microsystems. Characteristics of the fabricated 2D micromirror including tilting angle, resonant frequencies, stability of coupled 2D tilt and quality factors have been tested using a Veeco NT-9100 In-Motion system.

DEVICE MODELLING

A gimbal structure is used in a 2D micromirror to allow the mirror to tilt in two directions. As shown in Fig. 1, the mirror plate is suspended with two inside torsional hinges within a rigid gimbal. The gimbal is suspended by another pair of hinges perpendicular to the direction of the inside torsion springs. Underneath the mirror plate, there are four individual electrodes. When there is an electrical potential difference between the mirror plate and the two bottom electrodes on one side of the X-axis (V₁ and V₃ in Fig. 1), an electrostatic torque will be applied to the mirror plate. Under this torque, the mirror plate will rotate about the X-axis and further cause the deformation in the inside torsion beams, resulting in a mechanical torque to balance the electrostatic torque.
Similarly, a potential difference between two electrodes on one side of Y-axis (V1 and V2) and the mirror plate will cause the rotation of both the gimbal and the mirror plate about the Y-axis. Furthermore, by applying voltages on different bottom electrodes and adjusting voltage amplitudes, 2D torsion micromirrors can achieve rotation around any axis lying on the X-Y plane.

In our prior work [9], the analytic model for 2D electrostatic micromirror is discussed in detail. The electrostatic torque due to four bottom electrodes in both X and Y direction can be calculated by [8]:

\[
T^\phi_E = \sum_{i=1}^{4} \frac{1}{2} \varepsilon_0 V^2 \int_{x} \left( \frac{\sin \alpha}{\alpha g - x \cos \theta + y \sin \theta} \right) ds, \quad (1)
\]

and

\[
T^\theta_E = \sum_{i=1}^{4} \frac{1}{2} \varepsilon_0 V^2 \int_{y} \left( \frac{\sin \alpha}{\alpha g - x \cos \theta + y \sin \theta} \right) ds, \quad (2)
\]

where \( g \) is the initial gap between mirror plate and the bottom electrodes, \( \varepsilon_0 \) is the dielectric constant of vacuum, \( ds = dx \cdot dy \) denotes the unit area of the electrode, \( \phi \) and \( \theta \) are the tilting angles about X and Y axis respectively. The slope between the mirror plate and the substrate is \( \alpha \), and the expression is given by [10]:

\[
\alpha = \cos^{-1}(\cos \theta \cos \phi), \quad (3)
\]

Mechanical restoring torques of the torsion springs can be written in linear terms of the angles as [8]:

\[
T^\phi_M = 2K^\phi_M, T^\theta_M = 2K^\theta_M, \quad (4)
\]

where \( K^\phi_M \) and \( K^\theta_M \) are the spring constants of the torsion springs.

The values of \( \phi \) and \( \theta \) can be determined under mechanical equilibrium by solving:

\[
T^\phi_E = T^\phi_M, T^\theta_E = T^\theta_M. \quad (5)
\]

Using four independent voltages makes the control system complicated. Therefore, two independent control parameters (as denoted by \( V_x \) and \( V_y \) in Fig. 3 and Fig. 4) along with a biasing voltage are used to simplify the control mechanism and improve the linearity of the system.

**SIMULATIONS AND FABRICATION**

A scanning electron microscopy (SEM) of a micromirror with a 200\( \mu \)m \( \times \) 200 \( \mu \)m \( \times \) 2 \( \mu \)m mirror plate is shown in Fig. 2. The initial gap between the mirror and the bottom electrode is 4.75 \( \mu \)m. The device is fabricated using the Polysilicon-Multi-User MEMS Process (Poly-MUMPs) through CMC Microsystems. The mirror plate is composed of two layers of polysilicon and a silicon dioxide layer sandwiched in between. A gold layer is coated on the top to increase reflectivity of the micromirror. The oxide layer is completely sealed by the two polysilicon layers.

![Fig. 2: A SEM picture of the fabricated 2D micromirror](image)

The differential voltage operations of the micromirror are investigated using the model described in Equations (1-3). The electrode driving maps for the X tilt and the Y tilt are shown in Fig. 3 and Fig. 4 respectively.

![Fig. 3: Electrode driving map for the X tilting](image)
Fig. 4: Electrode driving map for the Y tilting

The theoretical angular stability map of the 2D mirror is shown in Fig. 5. The figure indicates that the maximum allowable tilting is 0.95 degrees in X direction and 0.7 degrees in Y direction.

Fig. 5: 2D mirror stability map

The dynamic device properties were simulated using ANSYS. The resonances of the designed mirror were determined as 2.0 kHz for Y tilt and 3.0 KHz for X tilt.

EXPERIMENTAL MEASUREMENTS

The device measurement was performed using the Veeco NT 9100 optical profiler. The system was tested for different combinations of control voltages. The maximum tilting of the device was measured and the experimental data is plotted in Fig. 6. The difference between the theoretical prediction and the experimental reduced stability range is mainly due to the ringing effect of the micromirror from the finite step driving voltages.

Fig. 6: Theoretical vs. practical stability map

To measure the resonant frequencies, a frequency sweep is performed using a sine wave with a phase of 90° (as shown in Fig. 7) and 270°. Peak deflection is detected at 1450Hz. During the experiment, mirror plate is always grounded. Therefore, the force between mirror plate and the bottom electrodes reaches maximal at both positive and negative peak amplitude. The actual mechanical driving frequency is two times the frequency of the signal generator. The experimentally measured resonance frequency is 2.9 kHz for X tilt and 1.8 kHz for Y tilt. From the resonance graphs, the Q factor has been calculated as 33 for the Y-tilt and 28 for the X tilt.

Fig. 7: Frequency sweep with a phase of 90°

To measure the settling time, a step function actuation is applied to the mirror and the mirror deflection is recorded every 100µs. The result is shown in Fig. 8. The measured settling time is approximate 35 ms and the calculated damping ratio is about 0.24.
DISCUSSIONS

The gold layer deposited on top of the structural layers (polysilicon) increases the surface reflectivity and reduces the electrical conductivity of the structure, but it also induces additional stress to the MEMS mirror. Due to the non-uniform residual stresses and thermal mismatching between the metal and the polysilicon layers, the devices fabricated in these processes exhibit significant surface curvatures [11]. The device performance of the multilayer structure is affected by this curvature.

Fig. 9 shows the surface profile of the fabricated micromirror. The micromirror is concave curved and the gap between the mirror plate and bottom electrode is not constant as assumed in the theoretical analysis. The mirror curvature increases the optical interferometric measurement error, which is the main reason why the 2D static measurement data differs from the actual simulation results.

Moreover, material properties taken from the PolyMUMP handbook were used for the theoretical calculation. These material properties are approximations based on sample of PolyMUMP runs [12], and may differ from the real parameters of the fabricated chips. All these factors contribute to the difference between the experimental data and the theoretical calculation.

CONCLUSIONS

In this paper an electrostatically actuated MEMS micromirror was presented. The device has two degree of freedom along X and Y axes and capable of producing 0.7° and 0.6° tilts about X and Y axis respectively. The analytic model was described mathematically and verified with FEA tools. The stability performance of the fabricated device was tested, and dynamic analysis was performed to characterize the 2D micromirror.

REFERENCES


