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Design and Simulation of Electromagnetic Two-dimensional MOEMS Scanning Mirror

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Key words: MOEMS; Scanning mirror; Electromagnetic; FEM simulation

Abstract. This paper presents design methodology, dynamics simulation and fabrication process of a magnetically actuated two-dimensional MOEMS scanning mirror with piezoresistor sensors. In the device, the mirror has two gimbal structures with two integrated driving coils and piezoresistors for the control and measurement of the both tilt angles, respectively. The dynamic model is established and the FEM simulation results show that the resonant frequencies for both directions are 254Hz and 523Hz, respectively. The two-dimensional MOEMS scanning mirror has advantages of tilt angles control and measurement feedback for the both directions.

Introduction

With the rapid development of the micro-optical-electro mechanical systems (MOEMS) technology, the silicon based torsion mirror has broader foreground for optical use, such as scanners and switches [1-2]. At present, most of scanning mirror have been driven by electrostatic, electromagnetic or piezoelectric force. They have a spring structure and are operated on a resonant mode for high-speed scan operation with large deflection [3-5], which have great advantages over the conventional scanning mechanisms with low power consumption, small volume and high frequency. In the field of micro-spacecraft, the scanning mirror is also presented for space target detection and measurement [6]. This requires a two-dimensional scanning mirror for regional scanning and the measurement of deflection angles for target location. For the different driving modes, a very high driving voltage is necessary for the electrostatic force [7], which is not suitable for space application. The piezoelectric materials is not compatible with the silicon based MEMS process [8]. The electromagnetic scanning mirror has a low driving voltage and large driving force [9], but the measurement of deflection angles has not been involved. In this paper, a electromagnetic MOEMS scanning mirror with a two-dimensional structure and integrated motion sensors is presented.

Structure and Principle

Fig. 1 shows a schematic drawing of the electromagnetic two-dimensional MOEMS scanning mirror. The mirror has two gimbal structures, which are supported perpendicularly to each other by torsion beams. Dual-axis movement of the mirror is achieved by the tilt of inner and outer structures. Gold wirings for two driving coils individually formed on the both gimbals and piezoresistors for motion sensors are integrated on the surface of the flexible beam. In order to apply the magnetic field to inner and outer coils simultaneously, the device is placed in two coupled parallel magnetic field by two permanent magnets.

The driving coil on the outer gimbal is used for inducing the mirror to tilt around x-axis while the driving coil on the inner gimbal is used for y-axis. When a electrical current is applied to the coil in the magnetic field, an electromagnetic force is generated. The tilt angle and direction of the gimbal can be controlled by changing the magnitude and direction of the current. Applying the current at the resonant frequency can lead the gimbal vibration with a large deflection angle. Since the tilt of both gimbals can be adjusted independently by the inner and outer driving coils, the incident laser ray to the mirror can be scanned flexibly and two-dimensionally. As the surface stress of the flexible beam is caused by the tilt of the gimbal, by measuring the resistance changes of the piezoresistors for inner and outer flexible beams respectively, the tilt angles of both gimbals can be detected.

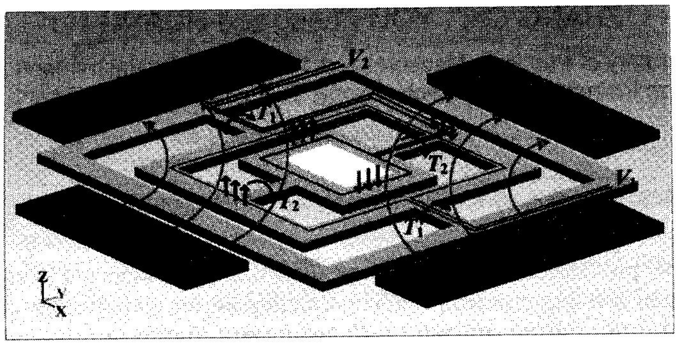

Fig.1 Structure of Two-Dimensional MOEMS Scanning Mirror

Modeling and Simulation

For the tilt of the inner and outer gimbals, each movement is independent from the other. Therefore, the movement equations of the 2-DOF model can be represented as equation (1).

$$I_n\ddot{\theta}_n + C_n\dot{\theta}_n + K_n\theta_n = T_n \tag{1}$$

Where I_n, C_n, K_n, θ_n and T_n represent moment of inertia of the gimbal, damping coefficient, torsional stiffness, tilt angle and driving torque (suffix n denotes 1 or 2 for the inner and outer gimbals), respectively. The resonance frequencies ω_n for each vibration mode are described by equation (2).

$$\omega_n = \sqrt{\frac{K_n}{I_n}} \tag{2}$$

The torque generated by the current is described as equation (3).

$$T_n = i_n B_n l_{1n} l_{2n} N_n \tag{3}$$

Where i_n, B_n, l_{1n}, l_{2n} and N_n represent current, magnetic flux density, length of driving coil parallel to the torsion beam, length of driving coil perpendicular to the torsion beam and number of coil turns, respectively. The magnetic field and the coil are designed to obtain the necessary torque. In the resonant modes, the maximal tilt angles of the two gimbals can be described as equation (4) and (5).

$$\theta_{1-\max} = \frac{N_1 B_1 a_1 b_1}{2K_1\zeta_1} \cdot i_{1-\max} \tag{4}$$

$$\theta_{2-\max} = \frac{N_2 B_2 (a_2 + a_3)(b_2 + b_3)}{8K_2\zeta_2} \cdot i_{2-\max} \tag{5}$$

Where ζ_1 and ζ_2 are the damping ratios, a_n and b_n are the dimensions of the inner and outer gimbals, which is shown in Fig.2. The equations indicate that the maximal tilt angles are proportional to the currents.

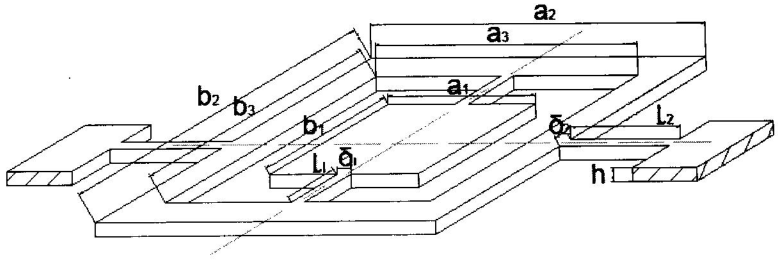

Fig.2 Dimensions of Two-Dimensional MOEMS Scanning Mirror

Tilt angles sensing is based on the piezoresistive effect which has advantages in favorable dynamic characteristics and high sensitivities. The stresses in the longitudinal, transverse and tangential directions of the piezoresistor cause the change of the resistance. The piezoresistive effect in plane is described as equation (6).

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t + \pi_\tau \sigma_\tau \qquad (6)$$

Where σ_l is the longitudinal stress, σ_t is the transverse stress and σ_τ is the tangential stress. π_l is the longitudinal coefficient, π_t is the transverse coefficient and π_τ is the tangential coefficient.

FEM simulation is used for the verification of the structure and modeling with ANSYS software. With the dimension design as shown in Table 1, the silicon material is adopted and the analysis results of low order modal simulation are shown in Fig. 3. The first mode is outer gimbal tilting around x-axis at 254Hz and the second mode is inner gimbal tilting around y-axis at 523Hz when the damping is ignored. The scanning mirror is then analyzed by the harmonic response simulation as shown in Fig. 4. The results indicate that tilting around the x-axis and y-axis with large deflection angles could be achieved in the electromagnetic force at the respective resonant frequencies. Furthermore, the maximal tilt angles are linear to the current. Therefore, the simulation analysis verifies that the design is effective and the modeling is correct.

Table.1. Dimension Design of the Structure

Inner gimbal $a_1 \times b_1$	Outer gimbal $a_2 \times b_2$ (outside)	Outer gimbal $a_3 \times b_3$ (inside)	Flexible beam length L_1, L_2	Flexible beam width δ_1, δ_2	Thickness h	Number of coil turns N_1, N_2
8mm ×6mm	12mm ×13.5mm	10mm ×12mm	3mm	0.1mm	0.1mm	10

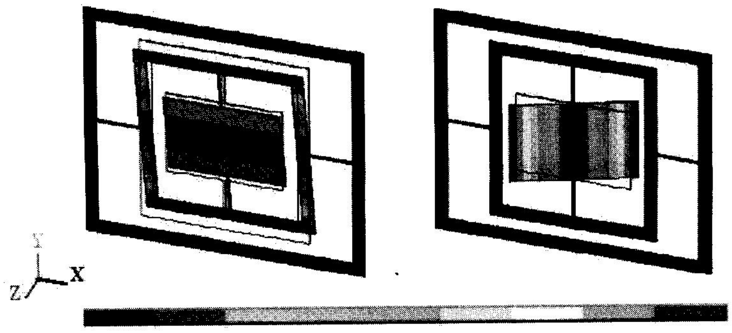

Fig.3. Two Vibration Modes of Scanning Mirror

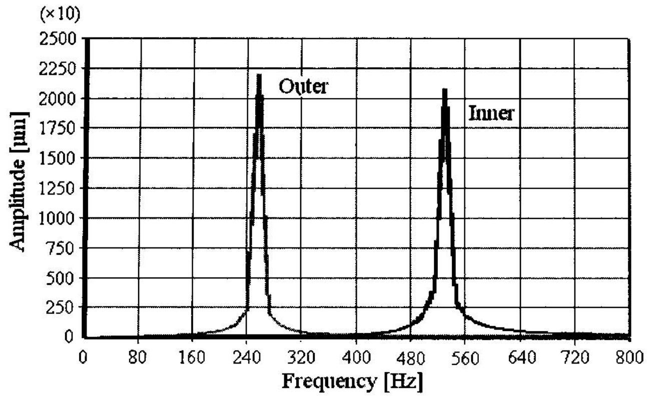

Fig.4. Harmonic Response Simulation of Scanning Mirror

Fabrication Process

The fabrication process flow is shown in Fig.5. The electromagnetic two-dimensional micro scanner is fabricated using a bulk silicon process, starting with an n-type silicon substrate of 300 μm thickness. The surface of the wafer should be covered by an insulation layer of silicon oxide and silicon nitride. In order to obtain the desired p-type piezoresistors with the resistivity $1.1\times10^{-2}\ \Omega\cdot cm$, the dimensions of the piezoresistors are set to 40 μm × 10 μm with 0.5 μm depth and the boron ion implantation density is 8.0×10^{18} ions/cm^2 at the temperature of 1,000°C with 20 minutes duration. After metalization for connection, a seed layer of gold is sputtered on the substrate and the bottom wires are formed on it by photolithography, electroplating and etching. Next an interlayer insulation film of polyimide is covered and the connecting holes are formed by dry etching. By the same way with the bottom wires, the coil is formed and the two metal layers are connected by the etched holes. Finally, the mirror part is plated by gold as a reflective film and the structures are released by backside inductive coupled plasma (ICP) dry etching. After processed in this way, the silicon wafer will be cut into chips by scribing, and packaged together with the permanent magnets.

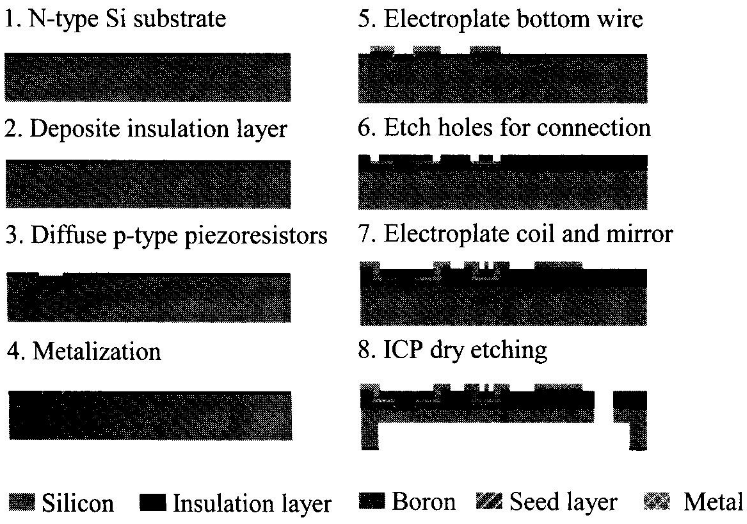

Fig.5. Process Flow

Conclusion

Two-dimensional MOEMS
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Conclusion

Two-dimensional MOEMS scanning mirror is a new kind of deflection scanning device based on MEMS technology, which has great advantages over the conventional scanning mechanisms with small volume, low power consumption and high scanning frequency. The electromagnetic two-dimensional MOEMS scanning mirror is presented and the dynamic model of the 2-DOF system is established. The design principle and simulation of the scanning mirror is implemented successfully with the finite element method. The scanning frequencies for both directions are 254Hz and 523Hz, respectively. It is concluded that the design and modeling of the two-dimensional MOEMS scanning mirror are correct and effective. The fabrication process flow is also proposed with bulk silicon process in this paper. The device has advantages of tilt angles control by driving coils and measurement feedback by piezoresistor sensors, respectively. It has a wide application in the field of space target detection and measurement.

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