特集

2-Dimensional Micro Scanning Mirror Applying 3-DOF Torsionally Coupled Structure Excited by Unidirectional Actuation*

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We have developed a new mechanism of 2-dimensional electrostatic MEMS scanning mirror with ultra high frequency and wide scanning angle. The mechanism has 3-degree of freedom gimbal structure. A unique structure of this mechanism is that the vibration system is excited by only unidirectional actuation by comb actuators. This structure realizes strong operating torque to achieve high frequency and wide scanning angle. The dynamic performance showed resonant frequencies of 40.67kHz and 1.2kHz in the two orthogonal axes. A scanning angle on high frequency was 10.5degrees. Furthermore, the mechanism has linearity in a plot of frequency response, while previous reported comb driven actuators had nonlinear frequency responses.

Key words：MEMS, Scanning mirror, Comb structure, Electrostatic actuator, Vibration system

1. INTRODUCTION

Recently laser scanning systems are commonly used as barcode reader, lidar: (light detection and ranging), etc. To minimize the systems many types of MEMS scanning mirrors are proposed. Actuators of them are mainly categorized into electromagnetic actuators, piezoelectric actuators, and electrostatic actuators.

In our former study, we have developed 2-dimensional torsional mirror excited by piezoelectric actuators [1) 2)]. However, the scanning frequency was low, 510Hz, and 916Hz. In order to increase the frequencies, minimization of the scanner is needed. However the developed scanner has several manually assembled parts such as metal spring, PZT and mirror, which are difficult to be miniaturized.

As electrostatic actuators such as comb actuator are easy to be fabricated by conventional silicon process that is not need a machine assembly process, they are easy to be minimized the structure.

In this study, we have adopted torsionally coupled system excited by only unidirectional actuation and designed a new mechanism. In the mechanism, the unidirectional electrostatic actuator can occupy large area in the limited area of the scanner and generate strong operating force, although conventional 2-dimensional scanners have two actuators having individual areas [3)].

The mechanism has two different torsional resonant frequencies and been designed so that the movement of the electrostatic actuator is small to keep continuous generating force and to achieve high frequency and wide scanning angle. The dynamic performance showed resonant frequencies of 40.67kHz and 1.2kHz on the two orthogonal axes. On top of the ultra high frequency, this scanner has linearity in a plot of frequency response, while the previous studies reported frequencies of less than 20kHz with nonlinear frequency responses [3) 4) 5)].

2. STRUCTURE AND OPARATION PRINCIPLE

The developed micro scanning mirror has a 3-degrees of freedom torsionally coupled system, as shown in **Fig. 1**. It consists of the base, outer gimbal, inner gimbal, and mirror. Operation principles of the 2-deimensional motions are shown in **Fig. 2**. A vibration torque is provided by the comb actuators of the outer gimbal. When the outer gimbal rotate, the inner gimbal and the mirror also rotate. Therefore kinetic momentum moments of the inner gimbal and the mirror change. As a result, the torque is provided to the inner gimbal and the mirror according to the components of torque vector. When the frequency of the applied voltage is closed to the resonant frequency of each axis, 40.67kHz and 1.2kHz, twisting vibrations are excited as shown in the figure.

This structure realizes both small actuator movement and large mirror movement. To enlarge this amplification, we

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have adopted following two features in our scanner structure;

- ●Dense comb actuators are located on the edge of the outer gimbal as far from the center of the vibration as possible.
- ●Small rotational angle of the outer gimbal to keep comb electrodes overlapped for continuous large torque.

The first feature maximizes the torsional moment and the second feature maximizes electrostatic force of the comb-driven actuators.

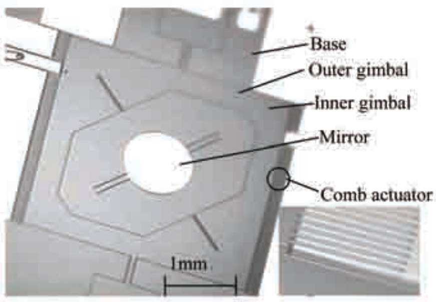

Fig. 1　View of the developed 2-dimensional optical microscanner

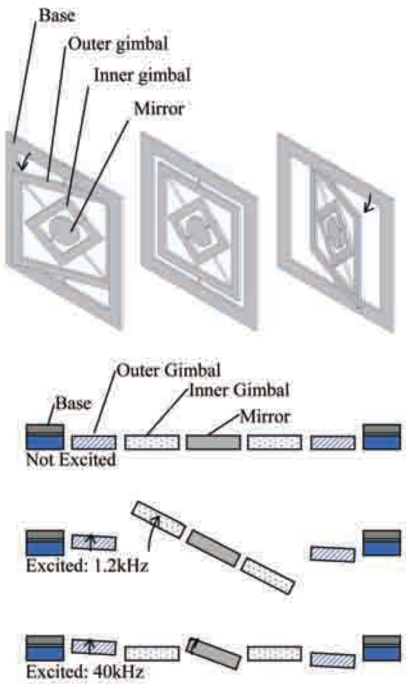

Fig. 2　Operation Principle of the developed 2-dimensional optical microscanner

3.　DESIGN OF THE MECHANISM

When we design a micro scanning mirror applying a vibration system, we have to design the mechanism which meets requirements such as resonant frequencies, amplitudes of vibrations, break strength, etc. We carried out several steps to design the mechanism. At first, we designed a layout sketch through a CAD system, next, derived a momentum equation, at last, simulated with FEM analysis.

Derivation of a momentum equation of a proposed vibration system is too complicated, and have to be considered many factors. So, we adopted a famous ROBOTICS algorithm which is based upon the method published by Luh, Walker, and, Paul in [6].　We used a formula manipulation system as known MAPLE™ and DynaFlexPro™ to operate complex mathematical manipulation. The derived equation is as shown in Eq. (1). To calculate a resonant frequencies and vibration modes, we neglected the damping term, nonlinear term, and torque vector, and calculated eigenvalues, and eigenvectors.

FEM modal analysis is used to design the vibration amplitude ratios among the mirror and two gimbals and to match a resonant frequency to desired frequency as shown in **Fig. 3**. We used ANSYS™ to calculate the dynamics.

$$\mathbf{J}(\mathbf{\Theta})\ddot{\mathbf{\Theta}} + \mathbf{C}\dot{\mathbf{\Theta}} + \mathbf{K}\mathbf{\Theta} + \mathbf{V}(\mathbf{\Theta},\dot{\mathbf{\Theta}}) = \mathbf{T} \qquad (1)$$

where J, C, K, V, and T are inertia, damping, spring constant , nonlinear terms respectively. Each term are matrix form.

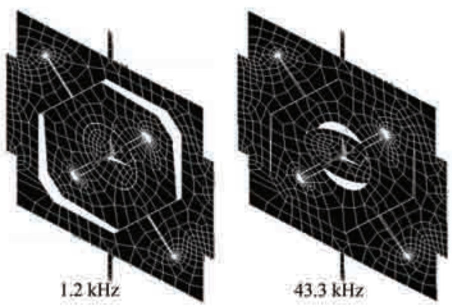

Fig. 3　Calculation result of the FEM modal analysis

4.　FABLICATION PROCESS

The cross section structure of this micro scanning mirror is shown in **Fig. 4**. This structure was fabricated from a 50μm single layer SOI wafer. Deep trench etching process [7] was used to create the scanner, shown in **Fig. 5**. Through backside etching, the gimbals and the mirror are allowed to move freely. Sputter-deposited aluminum films formed on SiO_2 and SOI was used for electrode of drive signal. The aluminum films were formed on the combs of fixed side, and electrostatic force works between the aluminum films on the combs of fixed side and the combs of movable side (SOI).

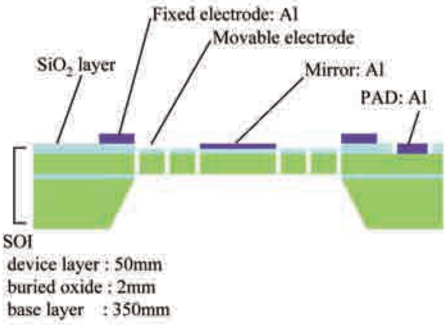

Fig. 4　Cross section structure

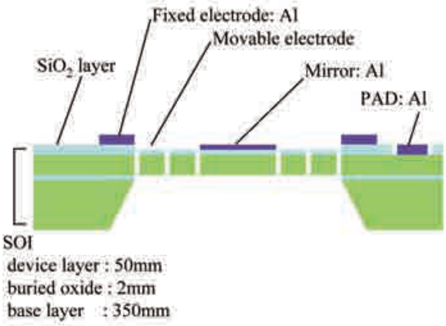

Fig. 5　Scanning electron micrograph of the comb electrode

5. CHARACTARISTICS

Drive circuit

We developed a unique drive circuit to achieve large scanning angles. Because each electrode is isolated electrically, we can apply different signals to each comb. An example of drive circuit and drive signal is shown in **Fig. 6**. In this example, the circuit consists of four function generators, adder, and three amplifiers. The adder mixes two signals of 1.2kHz and 40kHz, and mixed signal is applied to the Al-electrode-A. This signal generates two kinds of motions, the vertical scanning motion and the horizontal scanning motion. The inverted high frequency signal is applied the Al-electrode-B. This signal assists the high frequency motion. The twofold frequency (80kHz) signal is applied the SOI-electrode-C. Because the SOI-electrode has large thickness, it generates large pull-in force that achieves large scanning angle.

Frequency Response

Linearity in a plot of frequency response is observed as shown in **Fig. 7**. We measured the frequency response with Laser Doppler vibrometer (ONO SOKKI LV1200) and Dynamic Signal Analyzer (HP 35670A). We consider that if the inner gimbal and the mirror do not have comb, the vibration systems do not have “electric spring effect”. The property of the linearity causes an easy starting up of the scanning mirror and easy control of the scanning angle.

Scanning Angle

Measured scanning angles of low frequency and high frequency are shown as **Fig. 8**. When we measured scanning angles, we increased the voltage sequentially from the left-Al comb, the right-Al comb, and the SOI comb. The maximum operating voltage of Al-electrode was 160V,and of SOI-electrode was 40V. Although we tried to apply larger voltages, the comb electrodes broke because of a contact between the combs. The maximum scanning angle of the lower frequency and higher frequency was 13degree and 10.5degree. When the drive signal is applied to the SOI electrode, the scanning angles become large compare with the case that only one side Al-electrode is excited. We think the measured scanning angles are small to realize our applications. We believe that the limitation of the scanning motion is caused by an air damping because the speed of the gimbal reaches 30m/s enough to generates damping effect.

Observation of the scanning motion

The scanning motion was tested using a drive signal that has two different signals corresponding to each resonant frequency. We also observed the motion of the mirror and the inner gimbal under microscope with LED pulse light source as shown in **Fig. 9**. We confirmed that, at the low frequency motion, the inner gimbal rotates widely compare with another parts, and, at the high frequency motion, the mirror rotates widely compare with another parts. We confirmed that the motions are realized our innovative design concept.

Scanning image

To confirm the 2-dimensional motion of the mirror, we observed a scanning image using laser light source. An example of 2-dimensional scanning locus is shown in **Fig. 10**. We observed the correct scanning line that is suitable for image detection, such as 2-dimensional bar code, or image generation.

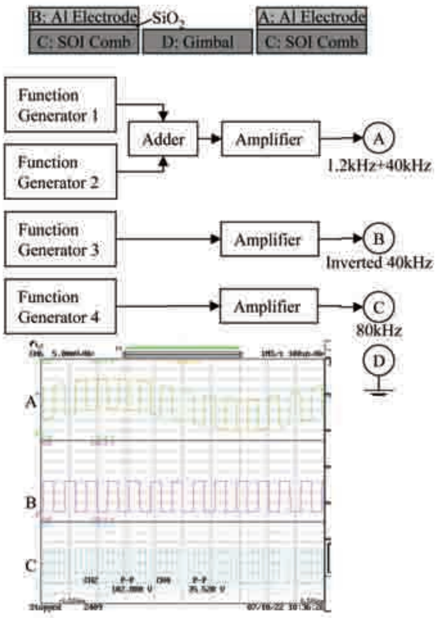

Fig. 6　Drive circuit and drive signals

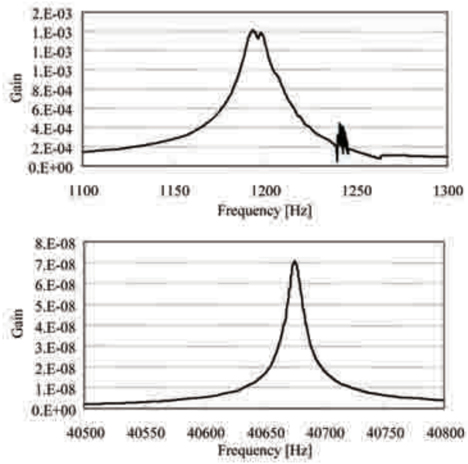

Fig. 7　Frequency Response of lower frequency and higher frequency

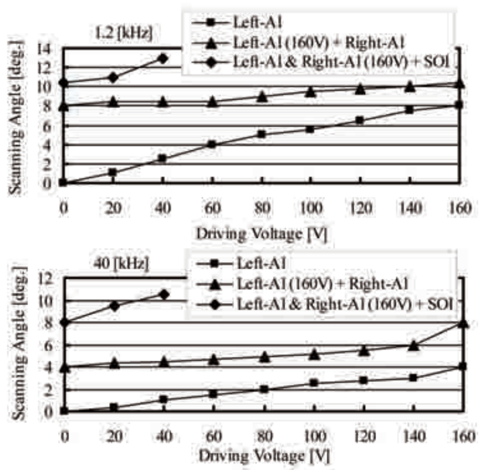

Fig. 8　Optical scanning angle of lower frequency and higher frequency

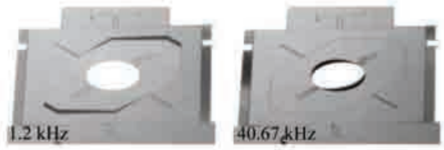

Fig. 9　View of the scanning motion observed under microscope and LED pulse light source

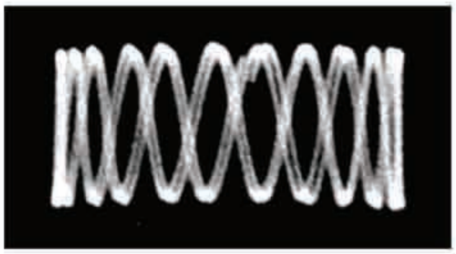

Fig. 10　View of the observed 2-dimensional scanning locus

6. CONCLUSION

A new mechanism of 2-dimensional electrostatic MEMS scanning mirror has been devised. A unique structure of this mechanism is that the vibration system is excited by only unidirectional actuation by comb actuators. This structure realizes strong operating torque to achieve high frequency and wide scanning angle. We will continue to develop this type of scanning mirror to achieve wider scanning angle under much lower driving voltage.

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