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To cite this article: Toshiya Nagasawa et al 2017 Jpn. J. Appl. Phys. 56 06GN12

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Operation of three-dimensional MEMS mirror by single superposed driving signal

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Received December 9, 2016; revised January 19, 2017; accepted February 1, 2017; published online May 18, 2017

We have realized a three-dimensional (3D) operation of a microelectromechanical systems (MEMS) mirror with three resonant modes and a single driving apparatus by a single superposed signal with three frequencies. We fabricated a 3D MEMS mirror with a single pair of beams having three resonant modes (x- and y-axis rotational modes and a z-axis vertical mode). We demonstrated the 3D operation by a single driving apparatus using the Lorentz force. In addition, we have shown that the x- and y-axis rotational angles and z-axis vertical displacement are proportional to the voltage amplitudes of each resonant frequency in the superposed signal, and the proportionality constants for each angle and deformation are approximately determined as 0.10°/V, 0.10°/V, and 70 nm/V, respectively. This result indicates that the mechanical amplitude of each mode is easy to control by the signal amplitude of each resonant frequency in the superposed signal. © 2017 The Japan Society of Applied Physics

1. Introduction

Our objective in this paper is to realize a compact three-dimensional (3D) microelectromechanical systems (MEMS) mirror. To achieve this, we have realized: i) a single pair of supporting beams with three different resonant modes, ii) a single driving apparatus for 3D actuation, and iii) a 3D operation by a single superposed driving signal.

A MEMS mirror has been widely used for laser/light scanning systems such as optical switches,1,2) bar code scanners,3) projection displays,4–6) confocal laser scanning,7,8) and optical coherent tomography.9,10)

Recently, in addition to one- and two-dimensional (1D/2D) MEMS mirrors, a 3D MEMS mirror has been developed for application in an optical phase modulation or a 3D optical projection/imaging.11–12) An optical microsystem using a MEMS mirror can achieve a 3D scanning by two-axis-rotational and one-axis vertical movements or two-axis-rotational and varifocal-mirror movements. 2D/3D MEMS mirrors have usually used a gimbal structure. If we want to achieve a 3D scanning using a gimbal structure only, a triple-nested structure is needed, and the fill-factor must be small.

Therefore, we focused on the realization of a 3D actuation using a single pair of beams, which can contribute to the high fill-factor of the MEMS mirror. In addition, most 2D/3D MEMS mirrors achieve a 2D/3D actuation by using two or three different driving apparatuses. Therefore, we also focused on a single driving apparatus and a single superposed driving signal, which can contribute to a miniaturization of the whole optical system including driving apparatuses. The 3D MEMS mirror with a single pair of beams that is operated by a single driving apparatus and a single superposed driving signal can be realized to implement a compact 3D optical system with a high fill-factor of the mirror region. Such a compact 3D optical system is important to realize a 3D mirror array such as an optical phased array, or a 3D optical system with space limitations, e.g., a 3D projection of a head mounted display or a 3D imaging of endoscope.

Therefore, in this paper, we realize a 3D actuation of a MEMS mirror by a single superposed driving signal. We used a 3D MEMS mirror using a single pair of beams with a high fill-factor. In addition, for further miniaturization of the MEMS mirror, we realize 3D operation of the MEMS mirror by a single driving apparatus and a single superposed driving signal.

2. System design and fabrication

Figure 1 shows an image of the 3D operation by a single superposed signal. (a) Typical operation of a conventional MEMS mirror with gimbal structures using three driving signals for 3D actuation. Three amplifiers and/or three driving apparatuses are usually required. (b) Our 3D MEMS mirror with a single pair of supporting beams is operated by a single driving signal resulting from superposition of three signals of frequencies \( f_x, f_y, f_z \). Each output amplitude \( (\theta_x, \theta_y, \theta_z) \) can be controlled by respective voltage \( (V_x, V_y, V_z) \) in case of a linear system.
possibility for it to be driven by a single signal of superimposing three sinusoidal waves, as shown in Fig. 1(b). The “linearity” of a conventional MEMS mirror means that, for example, the output rotational angle $\theta$ can be determined as $aV_x$ ($a$: proportionality const.) when the input signal is $V_x \sin 2\pi f t$. In this paper, “linearity on superposed signal” means that $\theta_1$ can be expressed as $aV_x$ ($a$: proportionality const.) when the input superposed signal is $V_x \sin 2\pi f t + V_y \sin 2\pi f t + V_z \sin 2\pi f t$. In other words, when the input superposed signal is $V_x \sin 2\pi f t + V_y \sin 2\pi f t + V_z \sin 2\pi f t$, the output $x$- and $y$-axis rotational angles ($\theta_x, \theta_y$) and $z$-axis vertical displacement ($D_z$) must satisfy:

$$
\begin{bmatrix}
\theta_x \\
\theta_y \\
D_z
\end{bmatrix} =
\begin{bmatrix}
a & 0 & 0 \\
0 & \beta & 0 \\
0 & 0 & \gamma
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix}. \quad (1)
$$

Here, $a$, $\beta$, $\gamma$ are the proportionality constants; $V_x$, $V_y$, and $V_z$ are the voltage amplitudes at the resonant frequencies of the $x$- and $y$-axis rotational modes and $z$-axis vertical mode, respectively. Though the linearity on the superposed signal to a single pair of beams is a harder requirement than the standard linearity to a gimbal structure, it can realize an easy control of the output amplitudes $\theta_x$, $\theta_y$, and $D_z$ by the input amplitudes $V_x$, $V_y$, and $V_z$, respectively. Since it also is possible to reduce the number of the amplifiers and operate in 3D by using a single driving apparatus, the linearity on the superposed signal can contribute to a miniaturization of the whole optical system. Therefore, we confirm the linearity on the superposed signal using a fabricated MEMS mirror with a single pair of beams and single driving apparatus.

We fabricated a 3D MEMS mirror with a single pair of beams with a high fill-factor (>80%), as shown in Fig. 2. The design of the beam shape was reported.\(^{22}\) The MEMS mirror has three resonant modes (the $x$- and $y$-axis rotational modes and a $z$-axis vertical mode) at separate frequencies. The fabrication process of the MEMS mirror is shown in Fig. 3.

The MEMS mirror is fabricated from a silicon-on-insulator (SOI) wafer with a 30-µm-thick device layer, a 2-µm-thick box layer, and a 250-µm-thick handle layer. First, 10-nm-thick chromium and 500-nm-thick gold layers are deposited on the surface of the device layer by using the electron beam evaporation and are patterned to the wiring shape. The total resistance of the wiring was 7.8 Ω. Second, the device layer is etched to the mirror shape by inductive coupled plasma reactive ion etching (ICP-RIE) and the handle layer under the MEMS mirror is etched by ICP-RIE. Finally, silicon oxide of the box layer is etched by buffered hydrofluoric acid (BHF).

We used electromagnetic force (the Lorentz force) as the driving force of a single driving apparatus. Most MEMS mirrors are actuated by electromagnetic force,\(^{23–27}\) electrostatic force,\(^{28–31}\) and piezoelectric force\(^{32–36}\) for operation. A force type is not so important, but the ability of the generated force to actuate all modes is important. Figure 4 shows a schematic of a 3D operation by a single driving apparatus. The gold wiring is used to form a single turn coil, and permanent magnets of 320 mT in the surface magnetic flux density are arranged at an angle from the $x$-axis to achieve the magnetic flux having both $x$- and $y$-axis components, as shown in Fig. 4(a). The $x$- and $y$-axis torques and $z$-axis vertical force are generated by the Lorentz force. The $x$-axis torque is generated by the Lorentz force on the wiring parallel to the $x$-axis on the MEMS mirror [Fig. 4(b)]. Similarly, the $y$-axis torque is generated by the Lorentz force on the wiring parts parallel to the $y$-axis on the MEMS mirror.

![Fig. 2. (Color online) (a) Scanning electron microscope (SEM) image of the 3D MEMS mirror. Measurement point a is on the $y$-axis and b is on the $x$-axis. (b) Design of the MEMS mirror with a single pair of beams and wire. The length of beam Q is 1500 µm, the width is 80 µm, and the width of the entire MEMS mirror is 1500 µm. The length of beam P is 400 µm, the width is 15 µm, the gap length between beams P is 25 µm, and the distance between the mirror and beam Q is 200 µm. The wiring widths of the gold wiring are 76 µm on beam Q, 11 µm on beam P, and 100 µm on the mirror region, and the thickness of the gold wiring is 0.5 µm. The thickness of the MEMS mirror is 30 µm.](image)

![Fig. 3. Fabrication process of the 3D MEMS mirror. (a) SOI wafer with a 30-µm-thick device layer, 2-µm-thick box layer, and 250-µm-thick handle layer. (b) Deposition of chromium and gold layers. (c) Patterning of chromium and gold layers by wet-etching. (d) Etching of the device silicon layer by ICP-RIE. (e) Etching of the handle silicon layer by ICP-RIE. (f) Etching of the box layer by BHF.](image)
wirings parts parallel to the x-axis on the mirror. Therefore, the x-axis torque is generated. (c) The y-axis torque is generated by the Lorentz force on the wirings parts parallel to the y-axis on the mirror. (d) The z-axis vertical force is generated by the Lorentz force on beam Q.

[Fig. 4(c)]. In addition, a z-axis vertical force is generated on the wiring parts on beam Q [Fig. 4(d)]. Therefore, the 3D MEMS mirror can be three dimensionally actuated by the single driving apparatus.

We measured the mechanical frequency characteristics of the 3D MEMS mirror using a laser Doppler vibrometer (Polytec MSA-500), as shown in Fig. 5(a), and the mechanical deformation at each resonant frequency of the 3D MEMS mirror is shown in Fig. 5(b). As shown in Fig. 2(a), point a is on the y-axis and point b is on the x-axis. Therefore, point a can be used to measure the deformations of the x-axis rotational and z-axis vertical modes. Point b can be used to measure the deformations of the y-axis rotational and z-axis vertical modes. At 7.43 kHz, which is the resonant frequency of the x-axis rotational mode, a peak appears only at point a, as shown in Fig. 5(b-(i)). Similarly, at 31.96 kHz, which is the resonant frequency of the y-axis rotational mode, a peak appears only at point b, as shown in Fig. 5(b-(ii)). In addition, at 18.35 kHz, which is the frequency of the z-axis vertical mode, peaks appear at both points a and b, as shown in Fig. 5(b-(iii)). Each resonant peak has a sufficiently high Q factor. Therefore, by applying a single superposed driving signal with three resonance frequencies, the MEMS mirror should be driven three-dimensionally, and the output amplitudes $\theta_x$, $\theta_y$, and $\theta_z$ should be controlled by the input amplitudes $V_x$, $V_y$, and $V_z$, respectively.

3. Experimental results and discussion

We confirmed that the 3D MEMS mirror with the three resonant modes can be driven by a single superposed signal, which is a combination of three sinusoidal signals.

We confirmed the 2D laser scanning on a screen by driving the 3D MEMS mirror with a single driving signal. We set the direction of the magnetic flux to $5^\circ$ from the x-axis. The distance between the 3D MEMS mirror and screen is 800 mm.

![Fig. 5. (Color online) (a) Frequency characteristics of the 3D MEMS mirror. The x-axis rotational mode, z-axis vertical mode, and y-axis rotational mode appeared at 7.43, 18.35, and 31.96 kHz, respectively. (b) Deformation images from the measurement at each resonant frequency.

Applied voltage $V_x \sin 2\pi f_x t + V_y \sin 2\pi f_y t + V_z \sin 2\pi f_z t$

<table>
<thead>
<tr>
<th>$V_x$</th>
<th>$V_y$</th>
<th>$V_z$</th>
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</thead>
<tbody>
<tr>
<td>0 V</td>
<td>0 V</td>
<td>0 V</td>
</tr>
<tr>
<td>0.75 V</td>
<td>0.75 V</td>
<td>0.75 V</td>
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<tr>
<td>1.5 V</td>
<td>1.5 V</td>
<td>1.5 V</td>
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</tbody>
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![Fig. 6. (Color online) 2D laser scanning by actuating the 3D MEMS mirror with a single driving signal. We set the direction of the magnetic flux to $5^\circ$ from the x-axis. The distance between the 3D MEMS mirror and screen is 800 mm.](Image)
on the comparison between the images corresponding to different $V_x$ (along the horizontal axis in Fig. 6), the $x$-axis scan lengths are 0, 4, and 8 mm when $V_x$ is 0, 0.75, and 1.5 V, respectively, because the spot size of the laser is 2 mm. These results suggest that the $x$-axis scan length is proportional to $V_x$. In addition, the $y$-axis scan width is not affected by $V_x$.

From these results, we have quantitatively shown the linearity on the superposed signal by determining $\alpha$, $\beta$, and $\gamma$ of Eq. (1). We confirmed that the 3D MEMS mirror with three resonant modes can be driven by a single driving signal resulting from the three signals by measuring the rotational angles and displacement. By using a laser Doppler vibrometer, we determined the rotational angles $\theta_x$ and $\theta_y$ for the $x$- and $y$-axis rotational modes by measuring the displacement at points a and b shown in Fig. 2, and determined the vertical displacement $D_z$ for the $z$-axis vertical mode by measuring the displacement at the center of the MEMS mirror. The measured displacement of the MEMS mirror is the sum of the displacements from the $x$- and $y$-axis rotational modes and $z$-axis vertical mode (Fig. 7). Therefore, we obtained the displacement for each resonance frequency by a fast Fourier transform (FFT). We applied voltage by superposing a sinusoidal wave signal of each resonant frequency, $V = V_x \sin 2\pi f_x t + V_y \sin 2\pi f_y t + V_z \sin 2\pi f_z t$. Figure 7 shows the characteristics of the 3D operation. The $\theta_x$, $\theta_y$, and $D_z$ are the $x$- and $y$-axis rotational angles and $z$-axis vertical displacement at the 3D actuation, respectively.

![Fig. 7. Experimental results for the 3D actuation. The applied voltage $V$ is $V_x \sin 2\pi f_x t + V_y \sin 2\pi f_y t + V_z \sin 2\pi f_z t$. The $\theta_x$, $\theta_y$, and $D_z$ are the $x$- and $y$-axis rotational angles, and $z$-axis vertical displacement at the 3D (1D) actuation, respectively. (a-1) $V_x = 0$ to 1.5 V and $V_y; V_z = 0$ (1D actuation). (a-2) $V_x = 0$ to 1.5 V and $V_y; V_z = 1$ V (3D actuation). (b-1) $V_y = 0$ to 1.5 V and $V_x; V_z = 0$ V. (b-2) $V_y = 0$ to 1.5 V and $V_x; V_z = 1$ V. (c-1) $V_z = 0$ to 1.5 V and $V_x; V_y = 0$ V. (c-2) $V_z = 0$ to 1.5 V and $V_x; V_y = 1$ V.](06GN12-4)
mode have a linearity with respect to the amplitude of the driving signal at each resonance frequency even on the superposed driving signal.

4. Conclusions

We demonstrated that a 3D operation of a MEMS mirror can be achieved by a single superposed driving signal. In addition, we have shown a linearity on the superposed signal of the 3D MEMS mirror system.

A MEMS mirror with three resonant modes and a single driving apparatus can be operated in 3D by a single superposed signal with three frequencies. The three resonant modes are the x- and y-axis rotational modes and z-axis vertical mode. The driving force of the MEMS mirror is obtained from the Lorentz force. We can obtain the driving force in three directions with a single driving operation. Therefore, by a single superposed signal with three resonant frequencies, the MEMS mirror can be driven in 3D. We confirmed the 3D operation of the MEMS mirror and demonstrated that our 3D MEMS mirror has a linearity on the superposed signal. The proportionality constants $\alpha$, $\beta$, and $\gamma$ between the input and output amplitudes were approximately determined as 0.10°/V, 0.10°/V, and 70 nm/V, respectively. This result indicates that the mechanical amplitude of each mode can be controlled by the signal amplitude of each resonant frequency of the superposed driving signal.

Acknowledgments

This work was partly supported by JSPS KAKENHI Grant Number 15H05514. The authors thank the MEXT Nanotechnology Platform Support Project of Waseda University, and the University of Tokyo.

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