

2D Asymmetric Silicon Micro-Mirrors for Ranging Measurements

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Abstract We developed silicon micro-mirrors with two asymmetric axes for ranging measurements using a single external piezoelectric ceramic vibrating element. The 2D asymmetric silicon micro-mirrors were fabricated by using an SOI-MEMS process. The vibration transmissibility of the proposed mirror under a vacuum atmosphere was evaluated by dynamic analysis. We obtained the resonant frequency in the low-speed axis of 23.3 Hz and in the high-speed axis of 556.8 Hz respectively. To prevent a reduction in the amplitude width, we induced a 90° phase shift between the low- and high-speed axes at the resonance frequency. The absolute deformational displacement at 604 Hz was 1/4.04 of the values at 30 Hz, and that at 556.8 Hz was 1/6.48 of the values at 23.3 Hz. The difference between the calculated and experiment values was apparently due to the external vibrating element. A Lissajous pattern projected onto the screen. The scanning angle was a degree of 7.6 (total angle) in the low- and high-speed axis. We subsequently measured the electrostatic field distribution measured using the 2D asymmetric silicon micro-mirrors.

Keywords: 2D asymmetric silicon micro-mirror, ranging measurement, SOI-MEMS, vacuum sealing package, electrostatic field distribution measurement

1. Introduction

Microelectromechanical system (MEMS) scanning mirrors are used in laser projectors, laser scanners, collision-prevention sensors, wearable displays with retinal scan recognition, and electrostatic field distribution measurement (1-4). In the case of 2D silicon scanning micro-mirrors, the resonance frequencies in the low- and high-speed axes have been reported to exceed 500 Hz and 10,000 Hz, respectively (5).

Silicon scanning micro-mirrors have characteristics such as miniaturization, high reliability, and high-speed scanning. In the case of a micro-mirror driven by electrostatic force, the rotation angle of the optical scanner driven by conventional static electricity is limited to the gap between the mirror and substrate, and changing this angle requires a high voltage (1). In the case of a micro-mirror driven by electromagnetic force, although the electromagnetic MEMS optical scanner operates at a low voltage and with a large rotation angle, a magnet and a yoke must be mounted (6). In the case of a micro-mirror driven by piezoelectric force, because the stiffness of torsion increases as the piezoelectric film thickness evaporated due to torsion is increased, the piezoelectric ceramic vibrations are not efficiently transmitted to the torsion. Thus, the magnitude of a vibration turns out to be a small (7). Moreover, the mode of vibration becomes complex. In general, the low-speed axis is driven in non-resonance mode and the high-speed axis is driven in resonance mode. Therefore, the operating current must be high (8).

Recently, an optical beam was electively scanned using a simple asymmetric micro-mirror excited by an external piezoelectric ceramic vibrating element irrespective of the rotation angle and high voltage (9, 10). 2D asymmetric silicon micro-mirrors can be

controlled via the independent resonance frequency of each rotation axis through the use of a single external piezoelectric ceramic vibrating element. The merits of 2D asymmetric silicon micro-mirrors allow the resonance frequencies of the low- and high-speed axes to be controlled via the mode design of the micro-mirrors for vibration.

In the previous study, Asymmetric silicon micro-mirrors are fabricated by the anodic bonding of an ultra-thin silicon film on a glass substrate, followed by the fabrication of ultra-thin silicon MEMS mirror structures by a picosecond-laser micromachining system (10). By vibrating the asymmetric silicon micro-mirror with an external vibrating element, we obtained a horizontal operation of 118 Hz and a vertical operation of 11040 Hz at the resonance frequency. Therefore, 2D asymmetric silicon micro-mirrors can achieve resonance frequencies in the low-speed and high-speed axes of 60 Hz and 15.7 kHz, respectively.

This study aims to develop silicon micro-mirrors with two asymmetrical axes for ranging measurements using a single external piezoelectric ceramic vibrating element. The vibration transmissibility of the proposed mirror under a vacuum atmosphere was evaluated by dynamic analysis. We measured an electrostatic field distribution using the measured 2D asymmetric silicon micro-mirrors for ranging measurements.

2. Design and vacuum-sealing package

2.1 2D asymmetric silicon micro-mirror design

To evaluate the absolute deformational displacement of the characteristic mode, we conducted simulated modal analysis of the resonance frequency and dynamic analysis. The resonance frequency of the 2D asymmetric silicon micro-mirror was evaluated using the IntelliSuite software (IntelliSuite, ver. 8.7).

We designed 2D asymmetric silicon micro-mirrors, as shown in Fig. 1. The 2D asymmetric silicon micro-mirrors were designed to be 5.8 mm long \times 5.8 mm wide \times 15 μ m thick. The scanning mirror was 1.7 mm long \times 1.7 mm wide.

First, we used Blueprint, which is a physical design tool. The 3D model was constructed in IntelliSuite's 3D builder, which is a 3D mesh generator. The frequency analysis was performed by using the ThermoElectroMechanical analysis module. The minimum mesh was 46 μ m long \times 2.5 μ m wide \times 7.5 μ m thick at torsion. The parameters used in the analysis are summarized in Table 1.

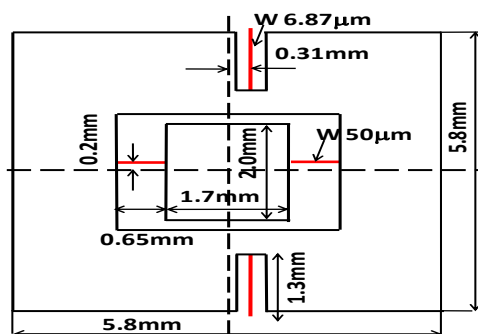


Fig. 1. Layout of a 2D asymmetric silicon micro-mirror.

Table 1. Parameters used for analysis with the IntelliSuite software

Material	Silicon
Young's modulus	160 GPa
Density	2.30 g/cm ³
Poisson's ratio	0.226

In the first stage, we performed the modal analysis using the IntelliSuite software. Fig. 2 shows the results of the modal analysis of the 2D asymmetric silicon micro-mirrors. The resonance frequencies in the low- and high-speed axes, as calculated by the ThermoElectroMechanical module of the IntelliSuite software package, were 30 Hz and 604 Hz, respectively. The results indicate the eigenvalue and mode shape. However, dynamic analysis is necessary to evaluate the absolute deformational displacement of the characteristic mode. The dynamic analysis can indicate the absolute amount of modification although the modal analysis can evaluate the relative spatial relationship of modification.

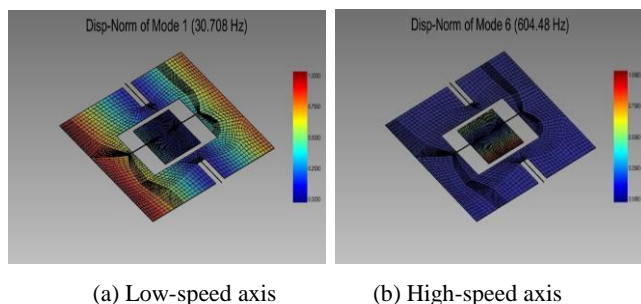


Fig. 2. Modal analysis of 2D asymmetric silicon micro-mirrors.

Fig. 3 shows the model for dynamic analysis of the 2D symmetric silicon micro-mirrors. The sine wave amplitude was generated by a pressure of 0.1 MPa as a function of frequency,

although the mesh size differs from that used in the modal analysis. Fig. 4 shows a plot of the amplitude–frequency characteristics calculated by dynamic analysis. The absolute deformational displacement at 604 Hz was 1/4.04 of the values at 30 Hz.

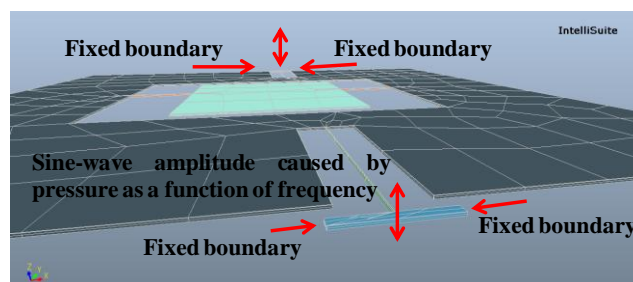


Fig. 3. Model for dynamic analysis of 2D asymmetric silicon micro-mirrors.

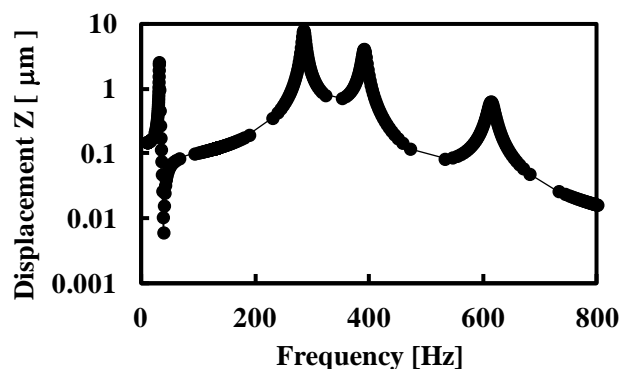


Fig. 4. Vibration transmissibility characteristics calculated by dynamic analysis.

2.2 Vacuum-sealing packaging

2D asymmetric silicon micro-mirrors were fabricated by SOI-MEMS process (9); a photograph of one of the resulting micro-mirrors is shown in Fig. 5 (MEMS CORE). The torsion beam was cut with a picosecond-laser micromachining system (Japan Laser and Time-Bandwidth, Duettino-SHG). For micromachining with a picosecond laser, the 2D asymmetric silicon micro-mirror was placed on a 2D nano-motion stage (Aerotech, ANT130-160), which was driven by motion controlled software (Aerotech, Automation 3200).

After the 2D asymmetric silicon micro-mirror was placed on the piezoelectric ceramic vibrating element, we adhered the 2D asymmetric silicon micro-mirror to the piezoelectric ceramic vibrating element and vacuum-sealing package (KYOCERA). We then vacuum-sealed the package. Fig. 6 shows a photograph of the vacuum-sealed package with the embedded 2D asymmetric silicon micro-mirror.

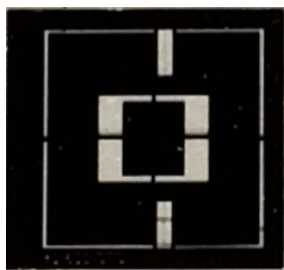


Fig. 5. Photograph of the asymmetric silicon micro-mirror fabricated by the SOI-MEMS process, which is made from the silicon-on-insulator by the semiconductor process.

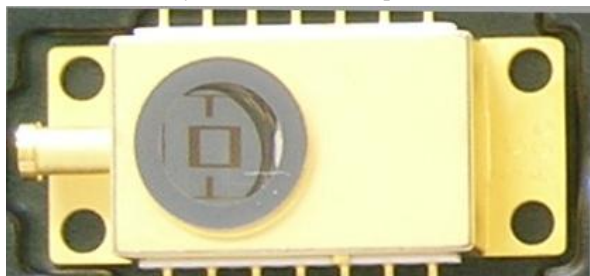


Fig. 6. Photograph of the vacuum-sealed 2D asymmetric silicon micro-mirror.

3. Results

3.1 Scanning characteristics of the 2D asymmetric silicon micro-mirror

Fig. 7 shows a photograph of the experimental setup of the vacuum-sealing package. We obtained the resonant frequency in the low-speed axis of 23.3 Hz and in the high-speed axis of 556.8 Hz respectively. To prevent a reduction in the amplitude width, we induced a 90° phase shift between the low- and high-speed axes at the resonance frequency, as shown in Fig. 8. The absolute deformational displacement at 604 Hz was 1/6.48 of the values at 23.3 Hz. A photograph of the Lissajous pattern used in the experiments projected onto a screen is shown in Fig. 9. The scanning angle was 7.6° (total angle) in the low- and high-speed axes and was limited by the output voltage saturation of the excited instrument in the vacuum-sealing mount.

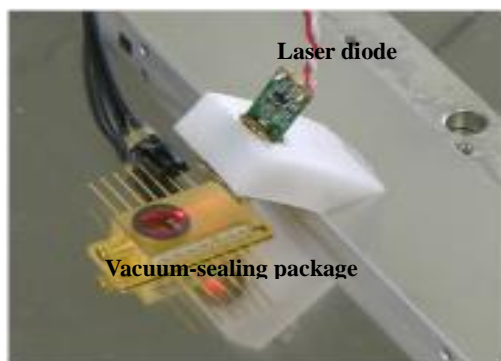


Fig. 7. Experimental setup of the vacuum-sealing package.

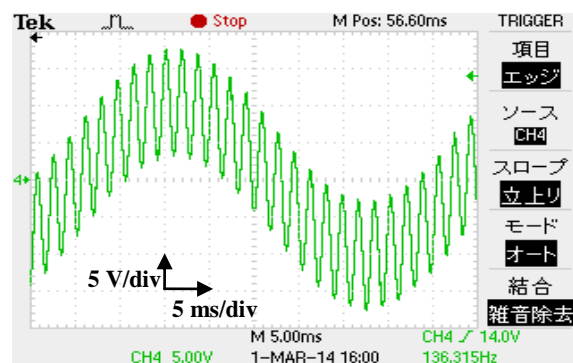


Fig. 8. Digital oscilloscope recording of the drive voltage for the asymmetric silicon micro-mirror shown in Fig. 5 (low frequency: 23.3 Hz, AC 21 Vp-p; high frequency: 556.8 Hz, AC 15 Vp-p).

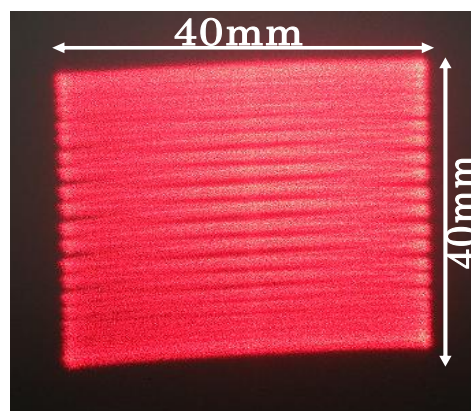


Fig. 9. Photograph of the Lissajous pattern projected onto a screen.

3.2 Electrostatic field distribution measurements

Electrostatic field distribution measurements using a silicon micro-mirror array fabricated by the MEMS process have been presented. The deflection angle of each micro-mirror, which was placed on a spherical surface and was deflected by an electrostatic field, was measured optically using a 2D optical scanner and position-sensitive detector (PSD). The optical scanner is composed of a computer-controlled stepping motor and single-axis MEMS optical scanner. The angle accuracy of the stepping motor was found sufficient. However, the rotation of the stepping motor required a certain amount of time. Therefore, the measurement time was 30 s or more. We consequently attempted to measure the electrostatic field distribution using 2D asymmetric silicon micro-mirrors.

Fig. 10 shows the measurement frame fabricated using a machining device and incorporating a silicon micro-mirror array. Sixteen silicon micro-mirrors were attached to the measurement frame. Four silicon micro-mirrors were scanned by a laser beam, and an electrostatic voltage was applied to one silicon micro-mirror (Sensor 1).

Fig. 11 shows the optical measurement setup. A photograph of a Lissajous pattern projected onto the measurement frame is shown in Fig. 11. A laser beam ($\lambda = 532$ nm, output power 5 mW, Shimadzu, BEAM MATE) was focused on the silicon micro-mirror and scanned two-dimensionally; the beam then irradiated each micro-mirror through a beam splitter and a convex lens. The reflected laser was reflected by the beam splitter and was focused on the PSD (Hamamatsu Photonics, S1880) surface to allow

measurement of the spot position. The horizontal and vertical operations of 23.3 Hz and 556.8 Hz signals, respectively, at the resonance frequency of the asymmetric silicon micro-mirror were suspended by the piezoelectric ceramic vibrating element. Fig. 13 shows the photograph of the Lissajous pattern projected onto the measurement frame.

Fig. 13 shows the PSD output signal (Y), which was measured by scanning a laser beam on a silicon micro-mirror array at Sensor 1 while an electrostatic voltage of 1000 V was applied. Fig. 14 shows the measurement output (Y) at Sensor 1 of the position-sensitive PSD before and after the electrostatic voltage applied. We observed the change of the measurement output (Y) of the PSD by the electrostatic voltage applied.

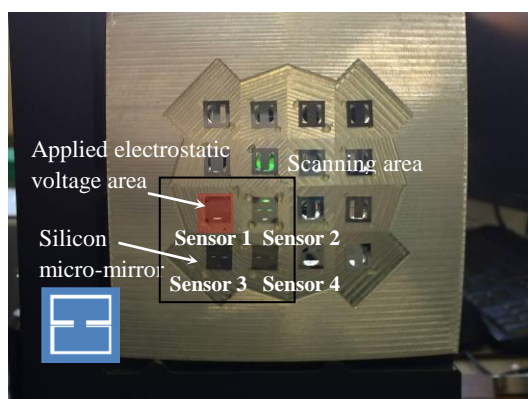


Fig. 10. Measurement frame incorporating a silicon micro-mirror array.

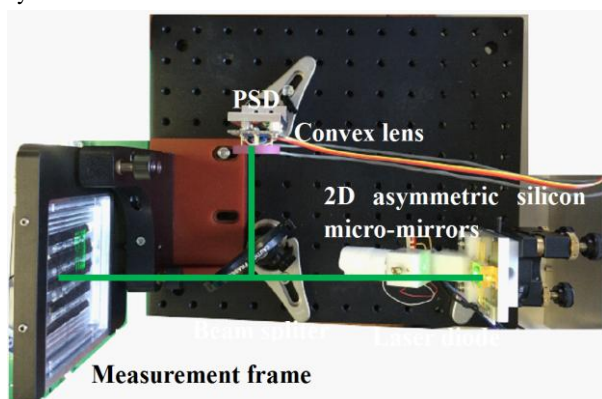


Fig. 11. Photograph of the optical measurement setup.

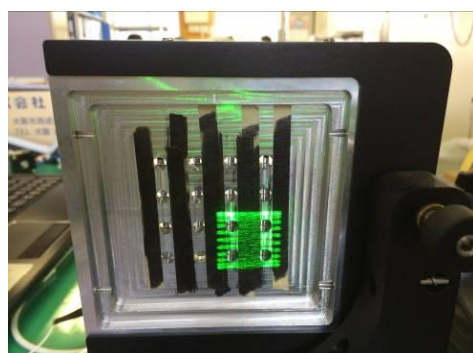


Fig. 12. Photograph of the Lissajous pattern projected onto the measurement frame.

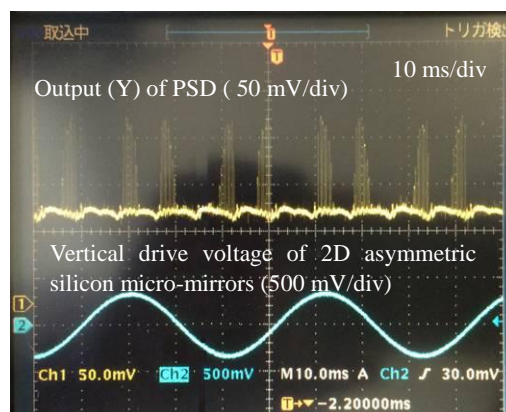


Fig. 13. Photograph of the output signal of the position-sensitive detector (PSD).

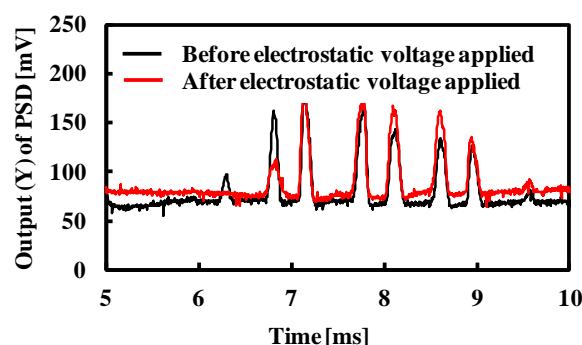


Fig. 14. Measurement output (Y) of the position-sensitive detector (PSD).

4. Discussion

In this study, we developed silicon micro-mirrors with two asymmetric axes for ranging measurements. The vibration transmissibility of the proposed mirror under a vacuum atmosphere was evaluated by dynamic analysis. We measured the electrostatic field distribution measured using our fabricated 2D asymmetric silicon micro-mirrors.

The absolute deformational displacement at 604 Hz was 1/4.04 of the values at 30 Hz, and that at 556.8 Hz was 1/6.48 of the values at 23.3 Hz. The difference between the calculated and experiment values was apparently due to the external vibrating element.

In the case of the 2D silicon scanning micro-mirrors, to prevent a reduction in the amplitude width, which is caused by interference between the low- and high-speed axes vibrations, these axes oscillated in and out of phase with the resonant frequency, respectively (12).

We measured the electrostatic field distribution measured using the 2D asymmetric silicon micro-mirrors, as shown in Figs. 13 and 14. Fig. 15 shows a schematic of the output (Y) of the PSD. The laser beam was scanned in the direction of the arrow from the starting point to the turning point was returned from the turning point to starting point. The laser beam was scanned Sensor 1 four times and Sensor 2 five times. We showed the turn with the notation of 1 to 8. When the electrostatic voltage of 1000 V was applied at Sensor 1, the output of the PSD (Y) changed as shown in Figs. 16. The measurement output (Y) of PSD with the notation of 2, 3, 6, 7 decreased.

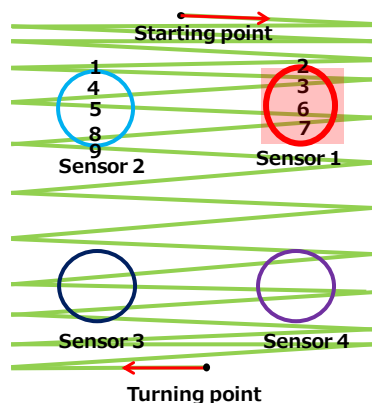
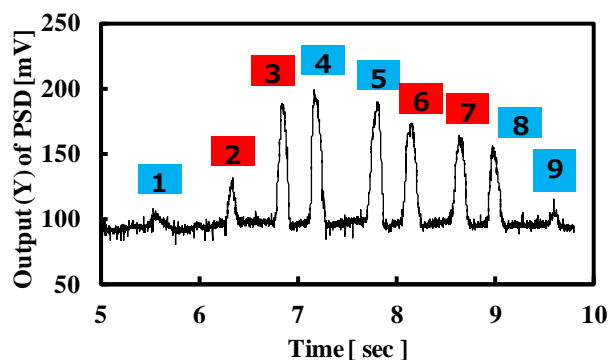
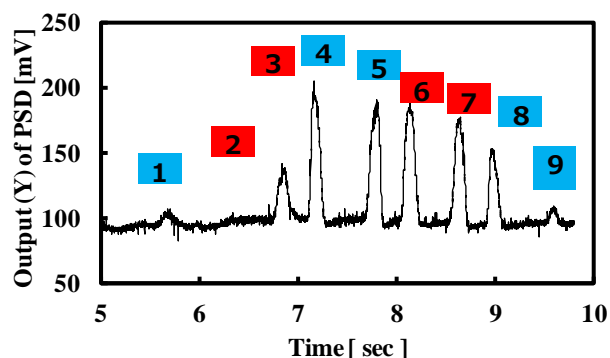


Fig. 15. Schematic of the line scan on the measurement frame.



(a) Before the electrostatic voltage was applied



(b) After the electrostatic voltage was applied

Fig. 16. Measurement output (Y) of the position-sensitive detector (PSD) before and after the electrostatic voltage applied.

5. Conclusions

We developed silicon micro-mirrors with two asymmetric axes for ranging measurements using a single external piezoelectric ceramic vibrating element. 2D asymmetric silicon micro-mirrors were fabricated using an SOI-MEMS process. The vibration transmissibility of the proposed mirror under a vacuum atmosphere was evaluated by dynamic analysis. We obtained the resonant frequency in the low-speed axis of 23.3 Hz and in the high-speed axis of 556.8 Hz respectively. To prevent a reduction in the amplitude width, we induced a 90° phase shift between the low- and high-speed axes at the resonance frequency. The absolute deformational displacement at 604 Hz was 1/4.04 of the values at 30 Hz, and that at 556.8 Hz was 1/6.48 of the values at 23.3 Hz. The difference between the calculated and experiment values was

apparently due to the external vibrating element. A Lissajous pattern projected onto the screen. The scanning angle was a degree of 7.6 (total angle) in the low- and high-speed axis. We subsequently measured the electrostatic field distribution measured using the 2D asymmetric silicon micro-mirrors. 2D asymmetric silicon micro-mirrors may be a useful scanner to realize the resonant frequencies in the low-speed axis of 60 Hz and in high-speed axis of 15.7 kHz respectively.

Acknowledgement

This study was partly supported by the Ministry of Economy, Trade and Industry and Wakayama Industry Promotion Foundation. We thank Dr. Fujimoto and members from the MEMS CORE CO., Ltd. for fabrication the MEMS device. We are also grateful to Dr. Taira and members from the Institute for Molecular Science for a helpful discussion regarding laser microprocessing. The authors would like to thank Enago (www.enago.jp) for the English language review.

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