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Resonant-frequency tuning of angular vertical comb-driven microscanner

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Abstract

The resonant-frequency tuning of a self-aligned angular vertical comb-driven electrostatic microscanner is demonstrated by the electromechanical spring effect. The microscanner is fabricated on a silicon-on-insulator wafer using the plastic deformation of silicon. A tuning electr ode is fabricated to be electrically separated from the actuation electrode to tune the resonant frequency by adjusting the applied direct-current voltage bias. The experimentally obtained maximum resonant-frequency shift was 3.2% when the resonant frequency of 3167 Hz is reduced to 3066 Hz when a tuning voltage of 30 V was applied while maintaining the actuation voltage. The method enables facile frequency tuning without any permanent geometrical modification to the microscanner.

Keywords: Frequency tuning; Micromirror; Microscanner; Electrostatic; Silicon-on-insulator

Introduction

Electrostatic actuators are widely utilized in microelectromechanical systems owing to their various advantages compared to other actuation schemes. Fast response, low power consumption, and large displacement make them suitable for applications such as microscanners and resonators. Furthermore, electrostatic vertical comb-driven actuators are widely adopted because of their large scanning range and high-frequency operation, especially for microscanners. However, it is very difficult to achieve the exact desired resonant frequency for microscanners or oscillators owing to the inevitable dimensional errors existing in the microfabrication processes. Obtaining the exact designed structural dimensions of the microdevice and maintaining the uniformity of the fabricated products are challenging issues. The deviation in the mass or geometrical errors during the microfabrication processes changes the electromechanical characteristics of the microscanner; even small microscale mass deviations or a geometrical error can drastically change the characteristics of the device. Other than the fabrication errors, mechanical fatigue of the torsional springs or changes of operation environments such as temperature and pressure could also vary the resonant frequency of the microscanner during operations. Therefore, feedback control could be adopted to obtain a stable scanning angle during the operation of a microscanner. For the feedback control, an angular displacement sensing element and a resonant frequency tuning element is required.

Because it is very difficult to achieve the exact desired resonant frequency from the fabricated device, a post-fabrication process is generally required to tune the deviated resonant frequency back to the designed value. In order to accomplish this, previous works have increased the movable mass by laser ablation deposition [1], increased the stiffness of the mechanical spring by polysilicon deposition [2], and decreased the stiffness of the in-plane vibrating microstructure by using a focused ion beam [3]. These methods cause permanent modification to the microstructure of the device to adjust the resonant frequency to the desired value.

On the other hand, other studies have been carried out to tune the resonant frequency of the device without permanent structural modifications and therefore offer active and reversible tuning capabilities. Previous efforts to tune the deviated resonant frequency have used the electrostatic spring effect, which is an electrostatic stiffness dependency on the applied voltage [4,5], and the geometry of the capacitors [6-11]. A thermal method that increases the temperature of the device to change the mechanical characteristics of the device to tune the resonant frequency was also introduced [12,13]. These frequency-tuning methods

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allow the device to perform its functions at various resonant frequencies. Although electrostatic vertical comb actuators are widely adopted for light scanning applications, only a few frequency-tuning methods such as inducing a compressive stress on the flexures [14] or using an angle limiter near the torsional spring [15] have been reported.

In this paper, a frequency-tuning method for an electrostatic self-aligned angular vertical comb (AVC)-driven microscanner is described. The AVC-based microscanner generates torsional motion of a micromirror with respect to the axis of rotation for optical scanning. A tuning comb electrode that is electrically separated from the driving comb electrode is designed to tune the resonant frequency. The presented frequency-tuning method is based on the electrostatic spring effect induced by the nonlinear relation between the electrostatic moment and the angular displacement of the microscanner. By independently adjusting the direct-current (dc) bias applied to the tuning comb electrode, the tuning capability was maximized under limited voltage source conditions. The microscanner tested for the resonant-frequency-tuning experiments is fabricated via the plastic deformation of single-crystal silicon, as introduced previously [16].

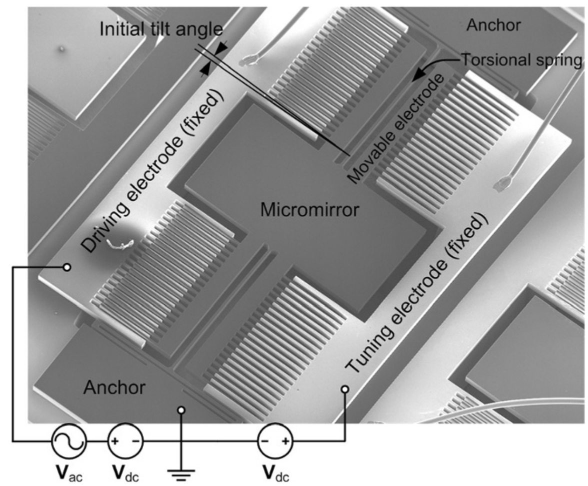

Figure 1 SEM image of the AVC-driven microscanner. The microscanner consists of a rotor, two torsional springs, and two fixed electrodes. The single-crystal silicon torsional springs are plastically deformed such that the rotor including the micromirror and movable comb finger electrode has an initial tilt angle with respect to the stator electrodes. Two electrically isolated fixed electrodes including a driving electrode for actuation and a tuning electrode for tuning of the resonant frequency are symmetrically placed on both sides of the rotor with respect to the torsional springs.

Findings

A scanning electron microscopy (SEM) image of the AVC-driven microscanner for resonant-frequency tuning is shown in Figure 1. The microscanner is fabricated on a silicon-on-insulator (SOI) wafer by utilizing a plastic deformation process [16] in which the moving comb electrode and fixed comb electrode are vertically interdigitated, forming an initial tilt angle. The rotor is initially tilted in order to generate electrostatic force by introducing an unbalanced electrostatic field in the vertical direction when a voltage difference is applied between the fixed and movable electrodes. The fixed and movable comb finger electrodes are defined on a single photomask and subsequently tilted via plastic deformation of the single-crystal silicon. Therefore, the comb fingers are inherently self-aligned. The initial tilt angle between the rotor and the stator is 3.1°. The microscanner consists of a rotor, two torsional springs, and two fixed electrodes. The rotor acts as a movable electrode, which is the countering part of the fixed electrodes, and includes a rectangular micromirror with dimensions of 660 μm × 1200 μm for optical scanning. This rotor is supported by the torsional springs that are connected to the anchors. The fixed driving electrode for actuation and the fixed tuning electrode for resonant-frequency tuning are designed to be electrically isolated and symmetrically placed on both sides of the rotor with respect to the torsional springs. The fixed comb finger electrodes are anchored onto the substrate, which is the handle silicon layer of the SOI wafer. The handle silicon layer below the rotor is completely etched so that the micromirror has enough clearance for its motion. By applying voltage differences between the rotor and the fixed electrodes, the electrostatic moment moves the rotor to find a force-balancing position and therefore induces angular motion of the micromirror.

Figure 2 shows the normalized mechanical and electrostatic moment of the AVC-driven microscanner with respect to the angular displacement. The electrostatic moment (bold black curve) is calculated by a finite element analysis (FEA) using a unit comb electrode-set model to account for the fringing fields. The electrostatic and mechanical moments for the AVC-drive actuator are expressed as

$$M_e=\frac{1}{2}\frac{\partial C}{\partial \theta}V^2$$

$$M_m=k_m\theta$$

where C, θ, V, and k_m are the capacitance, the angular displacement of the rotor with respect to the stator, the applied voltage, and the mechanical stiffness of the microscanner, respectively. As shown in Figure 2, the electrostatic moment of the AVC-driven actuator is highly dependent on the angular position of the rotor with electrostatic stiffness k_e. When

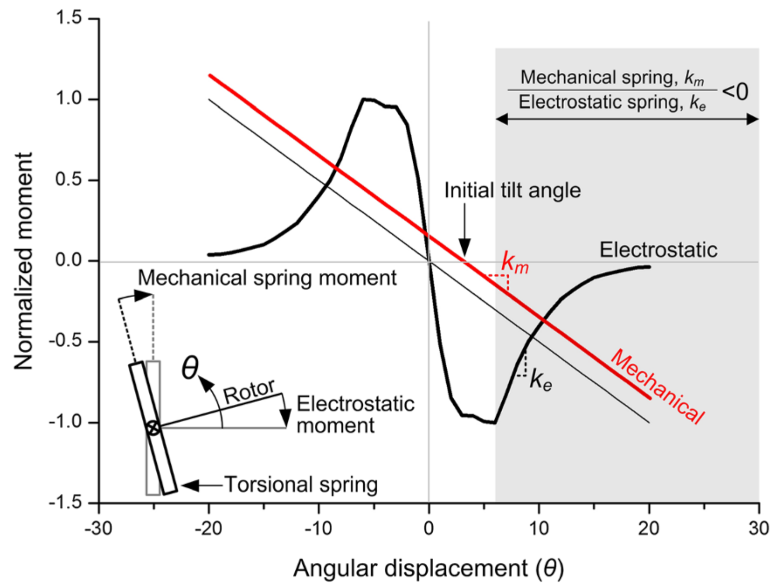

Figure 2 Normalized mechanical and electrostatic moment of the AVC-driven microscanner with respect to the angular displacement. The electrostatic moment (bold black curve) is calculated by FEA, and a unit comb electrode set is used to account for the fringing fields. The mechanical restoring moment of the torsional spring is depicted for the torsional spring with (red line) and without (thin black line) an initial tilt angle.

the angular displacement increases such that the moving and fixed combs begin to disengage, a significant nonlinearity in electrostatic moment occurs with respect to the angular displacement. Furthermore, the electrostatic stiffness also varies with respect to the angular position of the rotor and is proportional to the dc voltage applied to the fixed tuning electrodes. The relationship between the resonant frequency and the stiffness is given as [10]

$$f=\frac{1}{2\pi}\sqrt{\frac{k}{J}}=\frac{1}{2\pi}\sqrt{\frac{k_m+k_e}{J}}=f_0\sqrt{1+\frac{k_e}{k_m}}$$

$$ f=\frac{1}{2\pi}\sqrt{\frac{k}{J}}=\frac{1}{2\pi}\sqrt{\frac{k_m+{k}_e}{J}}={f}_0\sqrt{1+\frac{k_e}{k_m}} $$where k, J, and f_0 are the combined electromechanical stiffness, the moment of inertia, and the un-tuned resonant frequency of the microscanner, respectively. Considering the angular displacement range of the aforementioned normalized electromechanical moment colored in gray in Figure 2, the value of the electrostatic stiffness is negative, and the value of the mechanical stiffness is positive. As a result, the electromechanical stiffness of the AVC-driven microscanner exhibits a spring-softening behavior and reduces the resonant frequency because the electrostatic and mechanical spring constants are in opposite directions.

As illustrated in Figure 1, the experiment was performed by applying a fixed value of the driving voltage to the fixed driving electrode while varying the value of the tuning dc voltage applied to the fixed tuning electrode. The rotor of the microscanner was kept electrically grounded. Figure 3(a) shows the frequency response of the microscanner with a fixed actuation voltage consisting of a 10-V alternating-current (ac) driving voltage on top of a 10-V dc bias ($V_{drive} = 10\ V_{dc} + 10\ V_{ac}$) applied to the driving electrodes. The un-tuned resonant frequency was 3152 Hz when no voltage was applied to the tuning electrodes. The quality factor of the un-tuned microscanner was 112 with a maximum scanning angle of 11°. Subsequently, the tuning voltage was applied, and the tuned resonant frequency was measured. When the tuning voltage of 30 V was applied for the resonant frequency tuning, the quality factor of the microscanner was 108 with a maximum scanning angle of 6.2°.

In Figure 3(b), the tuned resonant frequency is plotted as a function of the dc tuning voltages over a range of 0 V to 30 V. It is clearly observed that the magnitude of the frequency shift is proportional to the applied tuning voltages. The maximum resonant-frequency shift achieved with a tuning voltage of 30 V was 101 Hz (3.2%) from 3167 Hz with a driving voltage consisting of a 10-V ac bias and a 20-V dc bias ($V_{drive} = 20\ V_{dc} + 10\ V_{ac}$). The resonant frequency shifts as a function of the applied tuning dc voltages in the range of 0 V to 30 V. A resonant-frequency shift of 100 Hz from 3158 Hz was achieved with a driving voltage of 20 V_{dc} + 5 V_{ac}. In addition, resonant-frequency shifts of 76 Hz from 3152 Hz and 75 Hz from 3149 Hz were respectively achieved with a driving voltage of 10 V_{dc} + 10 V_{ac} (black squares) and with a driving voltage of 10 V_{dc} + 5 V_{ac} for the un-tuned resonant frequency (green

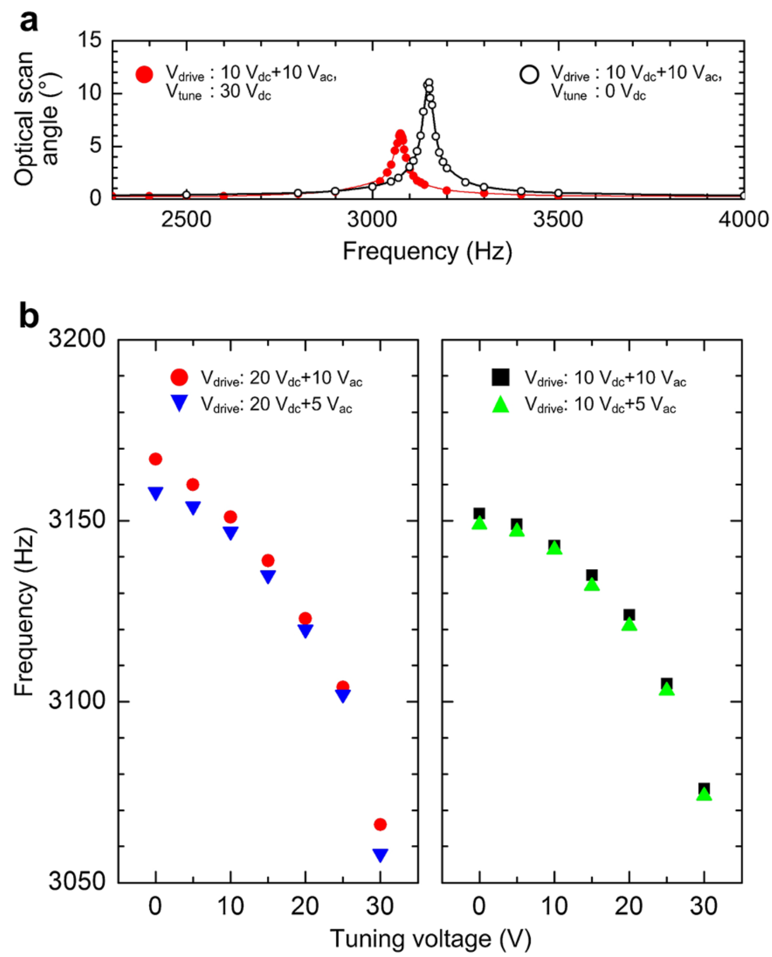

Figure 3 (a) Measured un-tuned and tuned resonant frequencies of the microscanner (3152 Hz and 3076 Hz) with a driving voltage of 10 V_{dc} + 10 V_{ac}. (b) Measured resonant-frequency shift as a function of the applied tuning dc voltages from 0 V to 30 V. The resonant frequency is shifted by 101 Hz from 3167 Hz for the un-tuned resonant frequency with a driving voltage of 20 V_{dc} + 10 V_{ac} (red circles) and by 100 Hz from 3158 Hz with a driving voltage of 20 V_{dc} + 5 V_{ac} (blue inverted triangles). The resonant-frequency shifts of 76 Hz from 3152 Hz and 75 Hz from 3149 Hz were respectively achieved with a driving voltage of 10 V_{dc} + 10 V_{ac} (black squares) and with a driving voltage of 10 V_{dc} + 5 V_{ac} for the un-tuned resonant frequency (green triangles).

triangle). In all cases, the application of the voltage to the tuning electrode reduced the resonant frequency owing to the spring-softening characteristics of the electrostatic spring effect of the given microscanner geometries.

Conclusion

Frequency tuning of an AVC-driven microscanner was demonstrated by utilizing the electromechanical spring effect. The resonant frequency was tuned by applying a dc tuning voltage up to 30 V to the tuning comb electrode with four different driving voltages. A maximum frequency shift of 3.2% was achieved, as the resonant frequency of 3167 Hz was reduced to 3066 Hz when a tuning voltage of 30 V was applied to the tuning comb electrode. Further, the frequency shift of the microscanner was unidirectional. The application of a tuning voltage reduced the resonant frequency because of the spring-softening characteristics of the electromechanical spring effect for the given AVC-driven geometries. By utilizing the electromechanical spring effect of the AVC drive, frequency tuning of the microscanner was achieved without adding any permanent modification to the device structures.

Competing interests
The authors declare no competing financial interests.

Authors' contributions
JK conceived the idea and supervised the project. JK and LL discussed the design and the fabrication process of the microscanner. YE performed the frequency-tuning experiments. JK and YE drafted the manuscript. All authors read and approved the final manuscript.

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