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Vertically supported two-directional comb drive*

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Abstract
A vertically supported comb drive with the feasibility of actuation in two perpendicular directions utilizing electrostatic force from interdigitated comb-shape electrodes has been demonstrated. The prototype microstructures are made of 2 μm thick polysilicon by a standard surface micromachining process. They are vertically lifted after the final sacrificial layer releasing process and are fixed on the substrate with the assistance of micro locking springs and micro hinges. The microstructures can vibrate in the directions either parallel or normal to the comb fingers, depending on the physical setups of the supporting structures and the polarity of driving electrodes. Experimentally, under 10 V dc bias voltage and 10 V ac peak-to-peak driving voltage in air, the prototype structure is found to resonate at the first fundamental mode of 6.8 kHz in the parallel direction. In the direction normal to the surface of the comb fingers, several bands of vibration movements have been observed between 500 Hz and 11.9 kHz due to the strong coupling between the two comb structures. As such, these microresonators using the vertically supported two-directional comb drive might find potential applications in the area of MEMS or MOEMS including optical systems on a chip.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

One promising application for MEMS structures is the possibility of integrating various operational components on a single chip [1]. In the area of MEMS, an electrostatic in-plane comb drive [2] that can move over a substrate plays an important role to actuate microstructures and to detect the capacitance changes. The comb drive generating electrostatic force at an applied voltage is widely used for many applications such as microaccelerometers [3], charge sensors [4], microvibromotors [5] and microgrippers [6]. In the field of MOEMS, researchers have worked on combining basic optical components such as micro Fresnel lenses [7], grating devices [8], etc on a chip by using micro hinges [9] and one critical obstacle has been the difficulty in building up three-dimensional microsystems. The introduction of the micro hinge structure [9] has alleviated the problem by extending the two-dimensional, planar surface-micromachining process to the vertical, third dimension. As a result, several actuators have been constructed to utilize the vertical space and have been demonstrated to generate out-of-plane motions [10–12]. However, difficulty in electrostatic actuation has hindered use of the three-dimensional structures. In addition, other critical issues have also hindered the progress of the surface-micromachined, three-dimensional architecture, including the difficulty in lifting up the devices from their original planar positions, the alignment accuracy of micro components, and the electrical and mechanical interconnections for the lifted microstructures.

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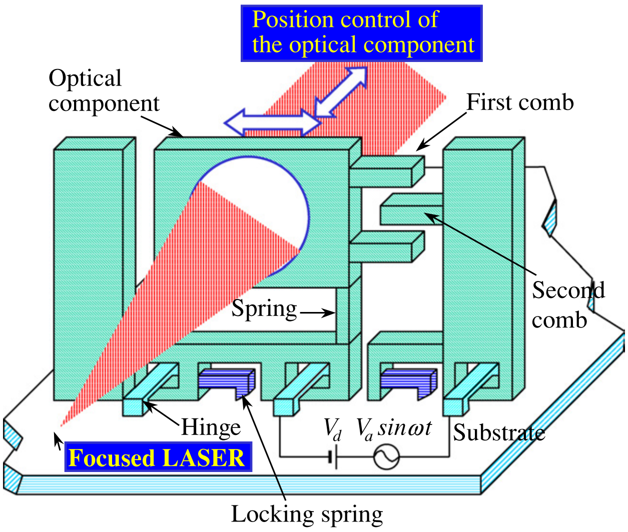
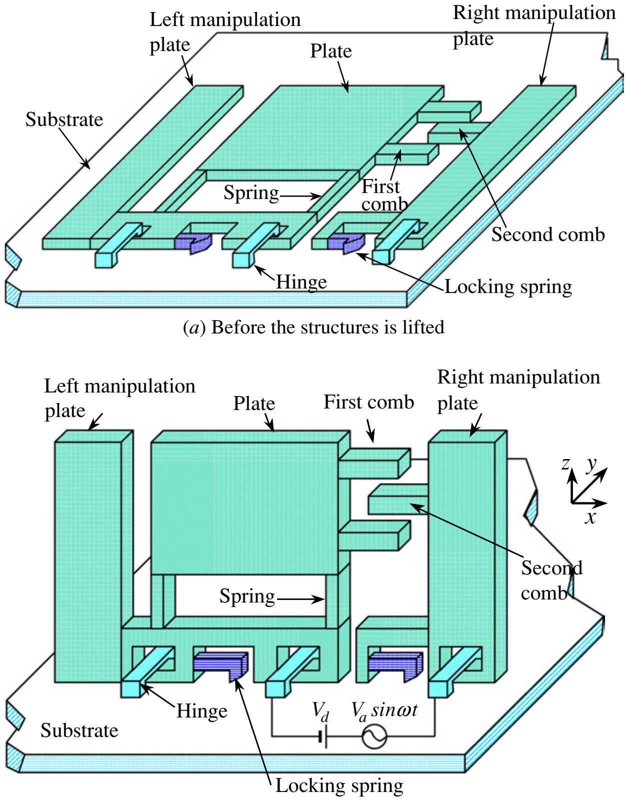


Figure 1. Schematic diagram of an optical system on a chip based on the vertically supported two-directional comb drive. The optical components such as lens or grating can be actuated and positioned by vertically supported comb structures actuated in directions parallel or normal to the comb structures.

This paper provides a vertically supported two-axial comb drive and several unique approaches to address some of these technical challenges, including micro hinge and spring structures to assist critical alignment and reliable mechanical and electrical interconnects.

2. Theory and design

Figure 1 shows the schematic diagram of a potential optical system on a chip based on the vertically supported, two-directional comb drive. The first comb resonator could have an optical component such as a lens while the second comb resonator is used as the stationary structure to provide electrostatic excitation. In order to build this three-dimensional optical microsystem, one can start with the standard surface-micromachining process. Figure 2(*a*) shows the schematic diagram of the vertically supported two-directional microresonator sitting on the substrate before being lifted up. The movable (first) and stationary (second) comb structures are constrained on the substrate by the mechanical hinge structures [9]. The left and right manipulation plates are designed to lift the comb structures to the vertical position by using the mechanical micromanipulator under a probe station. In figure 2(*b*), both comb structures are lifted vertically and fixed by the locking springs that are illustrated in figure 3. These springs are designed to play two important roles at the same time: (1) to supply adequate mechanical force on the hinge to assure good electrical contact between the ground plane and the vertically supported microstructures, and (2) to maintain the designed gap between the two sets of comb fingers after they are raised vertically to avoid electrical short-circuit between the comb fingers. Mechanical springs as shown in figure 3(*a*) with the extrusion design are deformed after the lift process as shown in figure 3(*b*) to provide (1) good electrical contact, (2) mechanical stability and (3) balanced gaps between the two comb sets.



(*a*) Before the structures is lifted

(*b*) After the structures is lifted

Figure 2. Schematic diagram of the vertically supported comb drive: (*a*) structures are fabricated on the substrate by the surface-micromachining process; (*b*) structures are lifted and locking springs (shown in figure 3) are designed to assure good electrical contacts and mechanical stability and to maintain the designed gap between two sets of comb fingers.

Using beam theory, the stiffness, k, and lifting force, F_{lift}, of the locking spring can be obtained with a first-order approximation as [13]:

$$k = \frac{3EI}{l_o^3} \tag{1}$$

$$F_{\text{lift}} = k\delta = \frac{3EI}{l_o^3}\delta \tag{2}$$

where $I = \frac{tw_o^3}{12}$, E, δ, t, l_o and w_o are the moment of inertia of the locking spring, the Young's modulus, the end-point displacement, the structure thickness, the beam length and width of the locking spring, respectively. The stiffness of the locking spring is obtained as 41.5 N m^{-1} from the prototype design data of table 1. Seven and two locking springs are used to support the first and second comb structures of figure 2, respectively, as shown in the SEM (scanning electron microscope) microphoto of figure 6.

In order to have two-directional actuation, the fingers of the first and second combs can be placed to be partially overlapped as shown in figure 4 to generate electrostatic forces in the directions parallel and normal to the surface of the comb fingers. The interfinger gap g is set when we draw the mask for the comb structure. Overlapping width p is made while the comb structures are lifted by using a probe. The energy

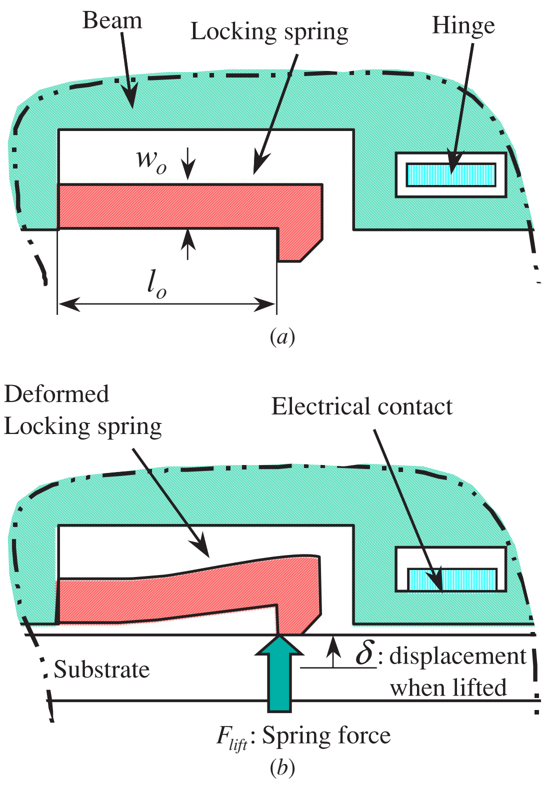


Figure 3. Design of the locking spring to lock the microstructure as well as to provide electrical contacts for the vertically supported structures. (*a*) Before the structure is lifted. (*b*) After the structure is lifted.

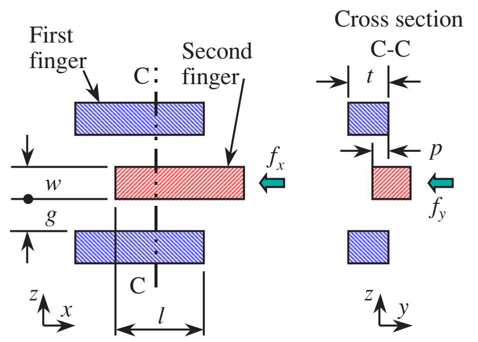


Figure 4. Comb fingers in the x–z and y–z planes. The gap, g, is controlled from the original mask design and the misalignment, p, is constructed during the vertical assembly process to generate the actuation force in the y direction.

Table 1. Designed parameters of the comb drive.

Structure material	Polysilicon
Structure thickness, t	2 μm
Plate size	400 μm × 400 μm
Spring beam	150 μm × 2 μm
Number of finger pairs, n	32
Comb finger dimensions	
Gap, g	3 μm
Finger width, w	3 μm
Overlapping length, l	10 μm
Overlapping width, p	1 μm
Locking spring	
Beam length, l_o	20 μm
Beam width, w_o	2 μm
Displacement after lifted, δ	2.2 μm
Number of locking springs (first comb)	7
Number of locking springs (second comb)	2

method is used to estimate the electrostatic force between the first and second comb structures in the x and y directions. The energy U stored between the capacitance C formed between overlapping comb fingers in figure 4 is obtained as follows:

$$U = \frac{1}{2} C V^2 \tag{3}$$

$$C = \frac{\varepsilon A}{g} = \frac{\varepsilon\,(2pl)}{g} = 2\frac{\varepsilon pl}{g} \tag{4}$$

where l and p are the overlaps of the length and width of the two sets of comb fingers, respectively, and g is the gap between the comb fingers. Using equations (3) and (4), one can obtain the electrostatic forces in the x and y directions:

$$f_x = \frac{\partial U}{\partial l} = \frac{\partial}{\partial l}\left(\frac{\varepsilon pl}{g} V^2\right) = \frac{\varepsilon p}{g} V^2 \tag{5}$$

$$f_y = \frac{\partial U}{\partial p} = \frac{\varepsilon l}{g} V^2. \tag{6}$$

Two forces are compared to show the relative force magnitude:

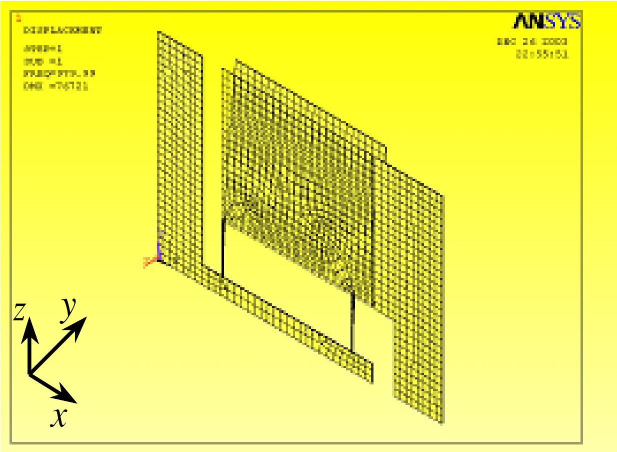
$$\frac{f_y}{f_x} = \frac{l}{p}. \tag{7}$$

It is noted from equation (7) that for $l/p > 1$, the electrostatic force in the y direction is larger than that in the x direction. The electrostatic force in the y direction tends to move the two comb structures slightly to the neutral position when a dc bias is applied. When a dc bias voltage, V_d, and an ac driving voltage, V_a, are applied as shown in figure 2(*b*), the electrostatic forces, F_x and F_y, for n pairs of comb fingers are derived as follows:

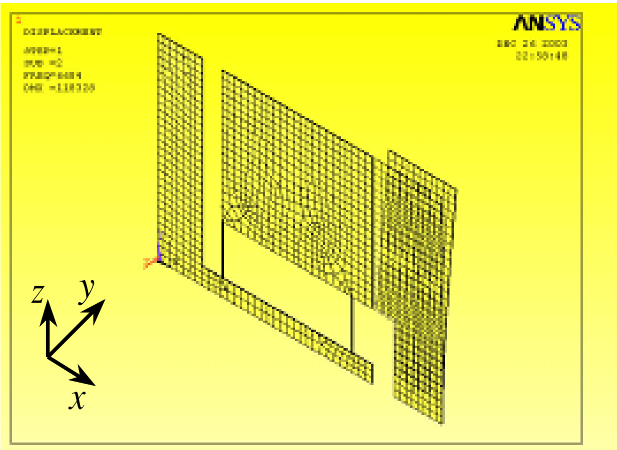
$$\begin{aligned} F_x &= n f_x = n\frac{\varepsilon p}{g}\,(V_\mathrm{d} + V_\mathrm{a}\sin\omega t)^2 \\ &= n\frac{\varepsilon p}{g}\left(V_\mathrm{d}^2 + \frac{V_\mathrm{a}^2}{2} + 2V_\mathrm{d}V_\mathrm{a}\sin\omega t - \frac{V_\mathrm{a}^2}{2}\cos 2\omega t\right) \end{aligned} \tag{8}$$

$$F_y = n f_y = n\frac{\varepsilon l}{g}\left(V_\mathrm{d}^2 + \frac{V_\mathrm{a}^2}{2} + 2V_\mathrm{d}V_\mathrm{a}\sin\omega t - \frac{V_\mathrm{a}^2}{2}\cos 2\omega t\right). \tag{9}$$

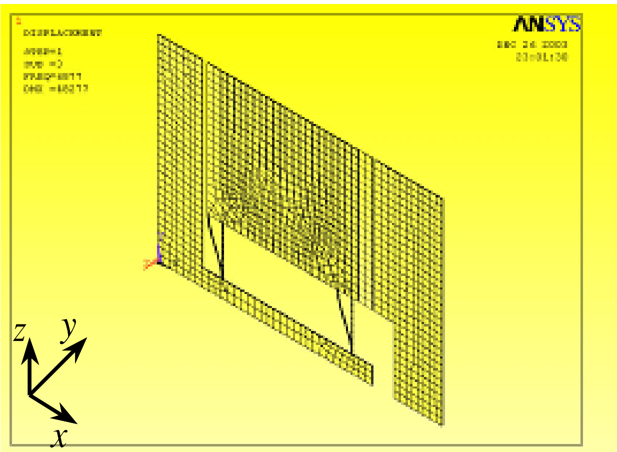
These two forces can excite two-directional motions of the plate. However, it is very difficult to obtain analytic responses corresponding to the forces due to many degrees-of-freedom of the vertically supported microstructure. Modal analysis is used to obtain mode shapes and resonant frequency of the microstructure [14]. Table 1 summarizes the design parameters of a prototype two-dimensional comb drive and ANSYS [15] was used to obtain mode shapes and resonant frequencies. Figures 5(*a*), (*b*) and (*c*) are the first three fundamental modes of the system at the resonant frequencies at 980 Hz, 6.7 kHz and 6.9 kHz, respectively. The first two frequencies as shown in figures 5(*a*) and (*b*) correspond to the first fundamental modes of the first and second combs in the y direction, respectively. Figure 5(*c*) is a mode corresponding to vibration of the first comb in the direction parallel to the



(*a*)



(*b*)



(*c*)

Figure 5. Modal analysis for the prototype device with dimensions listed in table 1. The resonant frequencies corresponding to modes (*a*), (*b*) and (*c*) are 980 Hz, 6.7 kHz, and 6.9 kHz, respectively. (*a*) The first comb structure vibrates in the direction normal to the surface of the comb fingers. (*b*) The second comb structure vibrates in the direction normal to the surface of the comb fingers. (*c*) The first comb structure vibrates in the direction parallel to the comb fingers.

comb fingers. It is expected that the force F_y of equation (9) can actuate the first and second combs in the y direction and

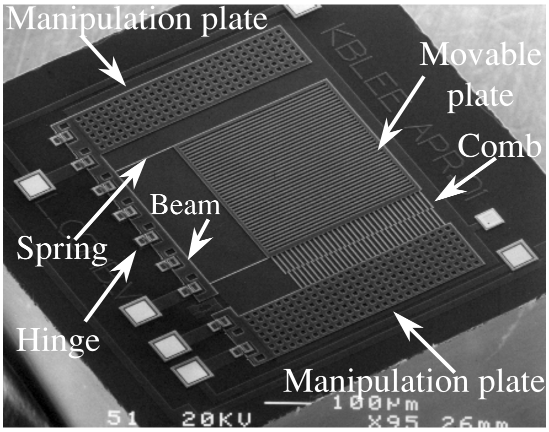


Figure 6. SEM photograph of a vertically supported comb drive by surface micromachining before the microstructures are lifted vertically.

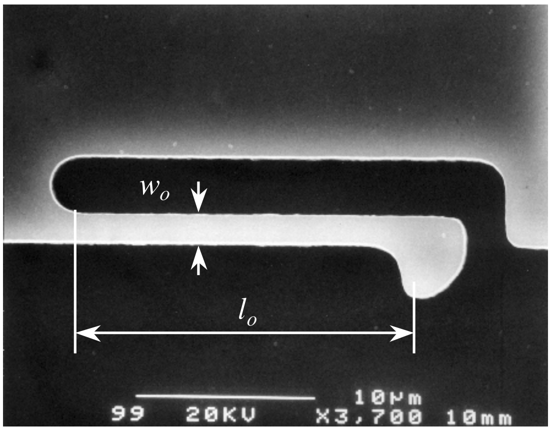


Figure 7. SEM photograph of a locking spring: w_o and l_o are estimated as 1.9 μm and 19 μm.

the force F_x of equation (8) can actuate the first comb in the x direction.

3. Fabrication

The vertically supported microstructures have been fabricated by the standard surface micromachining process [9, 16]. Figure 6 shows the SEM photograph of one released comb drive where the size of the movable plate is 400 μm $\times$ 400 μm and it is connected to the supporting beam structure via two springs. The second comb structure on the right-hand side is attached to the right manipulation plate. Etching holes are designed for the fast release etching process and locking springs and hinges are designed to assist locking structures vertically. Figure 7 shows the SEM photograph of a locking spring of figure 6. The width and length of the locking spring are 1.9 μm and 19 μm, respectively, as defined in equation (1). Figure 8 is the SEM photograph of the lifted comb drive. The left and right manipulation plates are designed to lift comb structures to the vertical position by using the mechanical micromanipulator under a probe station. The micro hinges and locking springs helped position and interconnect the microstructures. The lower left portion of the figure 8 shows the enlarged SEM photograph of a deflected locking spring

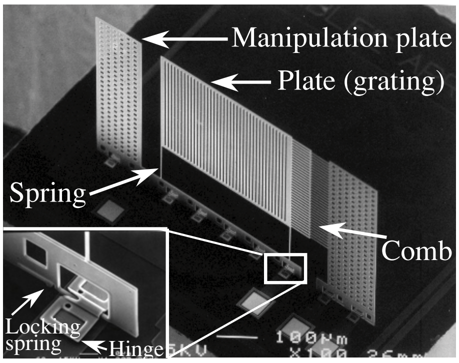
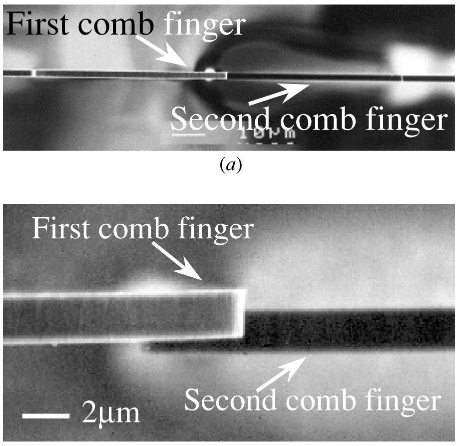


Figure 8. SEM photograph of the comb drive after being lifted from the substrate by using a probe: vertical structures are electrically connected to the contact pads by micro hinges and locking springs.



(*a*)

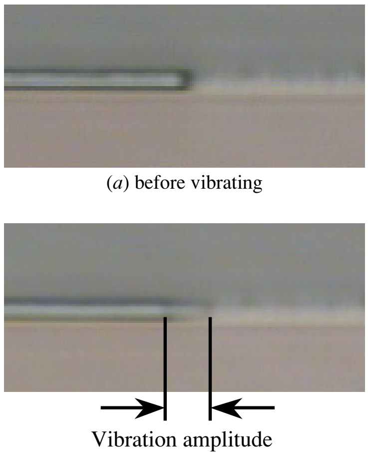
(*b*)

Figure 9. Top view SEM pictures of the lifted resonator structure: (*a*) a good alignment can be achieved after being lifted; (*b*) the comb fingers overlap each other to generate two-directional electrostatic forces.

and a hinge. Seven and two locking springs are used to support the left and right combs, respectively. Figure 9(*a*) is the top view SEM photograph showing that good alignment of two comb structures was achieved. The comb fingers in figure 9(*b*) overlap each other to generate two-directional electrostatic forces as shown in figure 4.

4. Experimental results and discussion

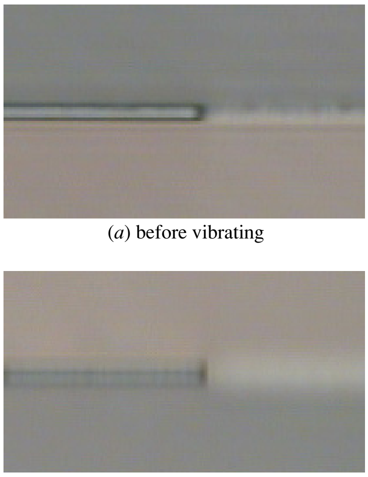
The comb resonator was optically observed to resonate under atmospheric pressure with the 10 V peak-to-peak ac driving voltage, V_a, and 10 V dc bias voltage, V_d. The optical photos in figures 10 and 11 recorded the vibration movement of the vertically-supported microresonator in the directions parallel and normal to the comb fingers, respectively. It is found from figure 10 that the resonant frequency of the first comb structure in the direction parallel to the comb fingers is at 6.8 kHz and the vibration amplitude is 3.0 μm. Figure 11 is an optical photograph of the resonator at 5.7 kHz vibrating in the direction normal to the surface of comb fingers. The vibration amplitude is 4 μm for the first comb structure. Figures 12(*a*), (*b*) and (*c*) show frequency responses of the microresonator in the range of 0–14 kHz. It is noted from



(*a*) before vibrating

(*b*) after vibrating

Figure 10. Optical photographs showing the movement right at the intersection of the two comb structures: (*a*) without excitation and (*b*) with excitation. The resonator is actuated by ac voltage of 10 V_{pp} and dc voltage of 10 V at the resonant frequency of 6.8 kHz. The first (left) comb finger resonates in the direction parallel to the surface of the comb fingers.



(*a*) before vibrating

(*b*) after vibrating

Figure 11. An optical photograph showing the responses of the vertically supported comb drive at a frequency of 5.7 kHz. It clearly demonstrates the feasibility to resonate the structure in the direction normal to the surface of the comb fingers. The resonator is actuated by ac voltage of 10 V_{pp} and dc voltage of 10 V.

figures 12(*a*) and (*b*) that the first and second combs are vibrating in the direction normal to the surface of comb fingers at the same frequencies except 500 Hz. The strong frequency coupling effect as observed experimentally suggests a strong coupling effect between the comb sets and the soft spring stiffness in the *y* direction for both comb structures. On the other hand, figure 12(*c*) shows frequency response of the microresonator in the direction (i.e. *x* direction in figure 2) parallel to the comb fingers. Only one resonance is observed on the first comb set at 6.8 kHz and this is close to the simulation result of 6.9 kHz as shown in figure 5(*c*). However, the resonant frequencies normal to the comb fingers from ANSYS simulation are much higher than those from the experiment. These frequency discrepancies might be due to: (1) torsional stiffness effect of the locking spring, and (2)

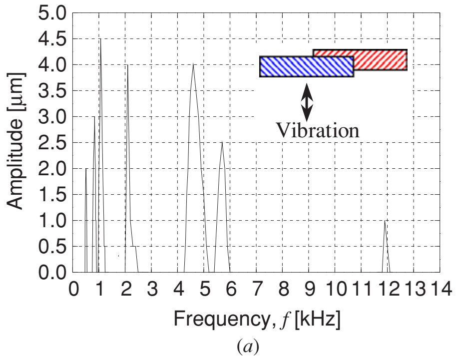


Figure 12. Frequency response: the vibration amplitudes are optically measured under ac driving voltage of 10 V_{pp} and dc bias voltage of 10 V. The optically measured data include 0.3 μm error. (*a*) Response of the first comb structure in the *y* direction. (*b*) Response of the second comb structure in the *y* direction. (*c*) Response of the first comb structure in the *x* direction.

Table 2. Effect of dc bias voltage on resonant frequencies.

V_d (V)	10	15	20
Vertical vibration, f_{5th}[a] (kHz)	4.61	4.60	4.62
Lateral vibration (kHz)	6.82	6.83	6.83

[a] The 5th resonant frequency in figures 12(*a*) and (*b*) is selected to examine the effect of the dc bias voltage on resonant frequency in the *y* direction.

electrical and structural-coupling effect of the first and second comb structures via the substrate. These effects were not considered in the FEM simulation of figure 5, where boundary conditions of the microstructures are assumed to be fixed on the substrate. Table 2 shows the effect of dc bias voltage on resonant frequencies. The resonant frequency in the *x* direction (figure 12(*c*)) and the fifth resonant frequency in the *y* direction (figures 12(*a*) and (*b*)) are selected to examine the

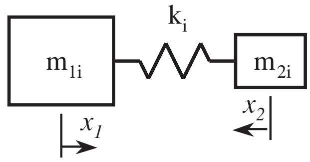


Figure 13. Modal mass and stiffness at the *n*th resonant frequency: vibration modes of complicated structures can be individually separated [14]. The modal analysis also describes that the amplitude of the small mass is larger than that of the large mass.

effect of the dc bias voltage. The resonant frequencies remain at 4.6 kHz in the *y* direction and 6.8 kHz in the *x* direction while the dc bias voltage varies from 10 V to 20 V. These results show that the resonant frequency is not a function of dc bias voltage. It is noted from figures 12(*a*) and (*b*) that the first and second combs are at the resonant frequencies and the vibration amplitude of the first comb is less than that of the second comb. Modal analysis [14] shows that complicated vibration modes are individually separated as shown in figure 13. The modal analysis also describes that the amplitude of the small mass is larger than that of the large mass.

The feasibility to excite the same movable comb structure with several vibration modes or frequencies opens up many possibilities for micro sensing and actuating applications. For example, an optical component such as a grating or a micromirror can be placed on the vertically supported microresonator to be actuated or scanned in two directions normal to each other. This presented structure can be used for sensors such as microgyroscopes, accelerometers, and microphones and even for actuators such as an active lens focusing system.

5. Conclusions

We have successfully demonstrated a new class of vertically supported comb drives that actuate in two perpendicular directions depending on the excitation frequencies. Electrostatic force between a pair of vertically supported combs is used to actuate microstructures in the directions parallel and normal to the comb fingers. The prototype microresonator with locking springs for supporting the comb structures is designed and fabricated by using the surface micromachining technology. Experimental results show that the comb drive has the fundamental mode of resonance at 6.8 kHz in the direction parallel to the comb fingers. In the direction normal to the surface of the comb fingers, several bands of vibration movements have been observed between 500 Hz and 11.9 kHz due to the strong coupling between the two comb structures. Experimental results and a simple analysis show that the amplitude of small mass normal to the comb finger is larger than that of large mass. As such, these comb drives using the vertically supported two-directional comb drive might find potential applications in the area of MEMS or MOEMS including optical systems on a chip.

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