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Coupled electro-mechanical transducers for vertical to horizontal motion translation

Alexandre Poulin, Raphael St-Gelais and Yves-Alain Peter*
Microphotonics Laboratory, Department of Engineering Physics
Ecole Polytechnique de Montreal
Montreal (Quebec), H3C 3A7 CANADA
*yves-alain.peter@polymtl.ca

***Abstract*- This paper reports a Micro-Electro-Mechanical System (MEMS) for vertical to horizontal motion translation. The device, based on coupled electro-mechanical transducers, allows translating an out-of-plane displacement to an in-plane displacement. As a proof of concept, the system was used to tune the cavity length of an optical resonator based on an asymmetric Fabry-Perot (FP) cavity. The monitoring of the translated in-plane motion was done by tracking the spectral position of the FP resonance. We report the translation of a 1.70 µm vertical motion to a 0.57 µm horizontal displacement.**

***Keywords*- vertical to horizontal motion translation, electro-mechanical transducer, Bragg mirrors, optical resonator, sensors**

I. INTRODUCTION

For many MEMS designs, the movement of the structure is restricted to the in-plane (2D) or out-of-plane (1D) domains. It limits the possible designs and therefore narrows the potential applications of many MEMS technologies. Moreover, it tends to make their integration in the environment more complex. This later point is of particular importance for MEMS-based sensors whose integration is critical. In the case of optical MEMS, the in-plane design can simplify the fabrication process and the optical alignment [1]. On the other hand, the out-of-plane design simplifies the integration in the environment allowing large interaction interface with the surroundings [2]. We think that the devices exhibiting three axis of liberty (3D) open the door to significant improvement of actual sensors. It offers a new working dimension which allows gathering benefits from both in-plane and out-of-plane designs in one single device.

The challenge of translating vertical to horizontal motion has been addressed only by few groups. The scratch and drive actuator is one possible approach [3]. This technique allows large displacements and is well adapted for self-assembling MEMS. However, its iterative process is not well suited for sensing applications. A second device, purely mechanical, allows motion translation [4]. Since no electro-mechanical forces are involved, the device is easy to use. However, its working principle involves contact and friction between silicon parts. This may limit the precision and the repeatability of the translated motion. Moreover, the whole mechanical structure is large compared to the load section. The proposed device in this paper is based on coupled electro-mechanical transducers. This approach allows contactless and therefore lossless systems unlike the other developed technologies. It should consequently lead to a more precise and repeatable translated motion. In addition, the coupled electro-mechanical transducers allow tuning device's sensitivity. For a given load, the amplitude of the translated motion is a function of the applied voltage. The dimension of the device is limited by the load patch and not by the motion translating system thus minimizing its size, weight and cost which is often of great importance.

II. WORKING PRINCIPLE

A schematic of the motion translation system is shown in Fig. 1. The device consists in a capacitor with moveable plates. One is attached to a spring ($k_{in\text{-}plane}$) that allows in-plane displacement while the other one is attached to a spring ($k_{out\text{-}of\text{-}plane}$) that allows out-of plane displacement. A voltage source can be connected to the plates in order to charge the capacitor. If no initial voltage is applied there are no electrostatic forces and therefore no interaction between the plates. In that case, the relative movement of the plates has no effect on the system equilibrium.

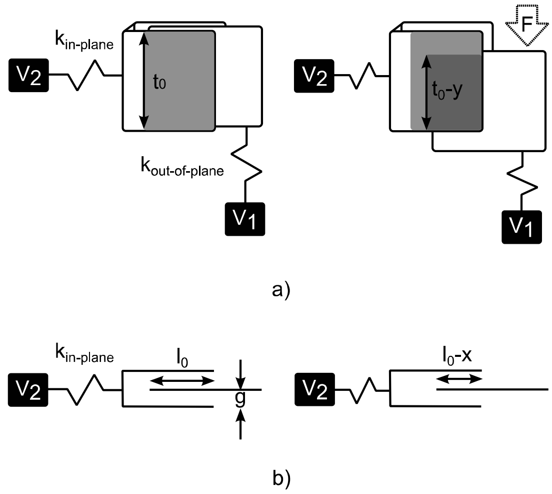

Figure 1. Schematic a) side and b) top view of the coupled electro-mechanical transducers system for vertical to horizontal motion translation.

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However, if an initial voltage V is applied ($V=V_1-V_2$), an electrostatic force will be generated between the plates. They will move toward each other until the system reaches its equilibrium position. This equilibrium will be function of many parameters as shown in Eq. 1.

$$k_{in-plane} \cdot x = \frac{\varepsilon(t_0-y)\cdot N\cdot V^2}{g}. \qquad (1)$$

The parameters are defined in Fig. 1 except for *N* which corresponds to the number of fingers per comb. Interdigited combs capacitor has been used for the device. This type of capacitor exhibits a linear relation between the capacitance and the displacement, therefore allowing higher stability. It can be seen in Eq. 1 that one of the parameters affecting the equilibrium position is the height of the plates overlap area (t_0-y). The in-plane displacement (x) can be expressed in function of the overlap height as shown in Eq. 2.

$$x = (t_0 - y)\cdot \frac{\varepsilon\cdot N\cdot V^2}{k_{in-plane}\cdot g} = (t_0 - y)\cdot K. \qquad (2)$$

This equation places in evidence the vertical to horizontal motion translation capabilities of the proposed system. An out-of-plane force *F* applied on the proper plate will induce a displacement (y) and modifies the overlap area (t_0-y), thus breaking the force equilibrium. In reaction the in-plane position of the plates will rearrange (x). It is interesting to note that the relation between vertical and horizontal displacement is linear. Moreover, the constant of proportionality *K* depends on many variables and can be adjusted both through design (N, $K_{in-plane}$ and g) and operation (*V*) parameters which allows great flexibility.

III. Design and fabrication

The proposed device was specifically developed for sensor applications. Therefore, as a proof of concept, the coupled electro-mechanical transducers system has been implemented in an optical MEMS-sensor design. The sensor consists in an optical resonator which cavity length can be tuned by applying an out-of-plane force. It can be used as a displacement, force, mass or acceleration sensor. This paper however only addresses the motion translation device's behavior. Future work will focus on sensing application of the developed microsystem and study its potential and limitations through sensitivity measurements.

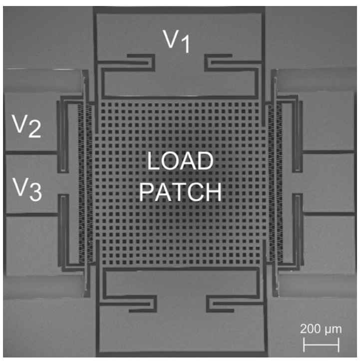

Figure 2. SEM of the fabricated device. The motion translation device allowed the design of a sensor integrating in-plane optics with out-of-plane sensing elements.

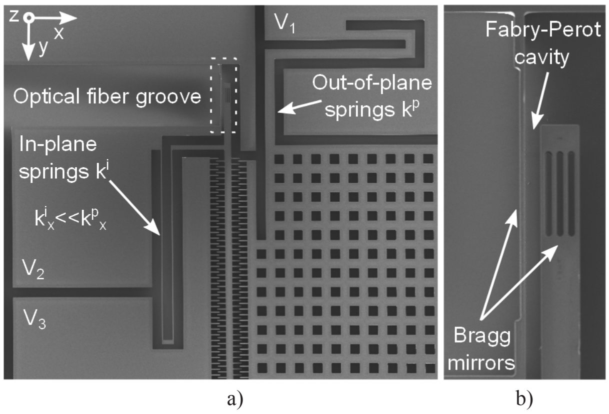

Figure 3. SEM close-up views of the device. a) The electro-mechanical design is clearly visible. The section framed by a dotted line corresponds to the asymmetric FP cavity. b) The details of the asymmetric FP cavity can be seen.

Figure 2 shows a Scanning Electron Microscope (SEM) image of the microfabricated device. The out-of-plane external force can be applied on the load patch whose area is 1 mm^2. The electrodes V_1 and V_2 are used to apply the initial voltage V needed for the coupled electro-mechanical transducers to work. The third electrode V_3 can be used to work in push-pull configuration or to perform capacitive measurements in parallel.

Figure 3 shows two SEM close-up views of the device. A tunable asymmetric Fabry-Perot resonant cavity has been implemented to monitor the in-plane motion. Optical fiber grooves have also been implemented on the device to allow passive-optical alignment and to facilitate the eventual packaging steps. The capacitor is composed of two interdigited combs. One attached to the load patch can move in the *z* direction while the other can move in the *x* direction. The backend mirror of the asymmetric FP cavity is attached to this latter comb. Its translation induces a spectral shift of the resonance peak which can be used to monitor the in-plane motion.

The fabrication process [1] is schematically shown in Figure 4. All mechanical and optical components are structured in one single etching step. The 70 µm thick device layer of a Silicon On Insulator (SOI) substrate is structured by deep reactive ion etching. The movable parts are then released by wet etching in 49% HF. The silicon dioxide sacrificial layer is 2 µm thick.

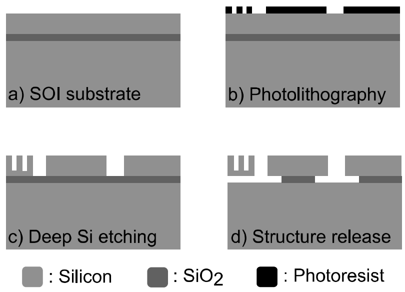

Figure 4. Schematic of the fabrication process. In-plane designs allow to structure optical and mechanical components in one single etch step.

IV. RESULTS

The motion translation capability of the device was experimentally demonstrated. The experimental setup is shown in Fig. 5. The operation voltage *V* was applied using two 3-axis probers connected to a DC voltage source (Kikusui PAB 110-0.6A). The out-of-plane displacement of the load patch was generated using a third 3-axis prober. A flat ended tip was fixed at the prober, centered on the load-patch and aligned perpendicularly to the substrate. It was then actuated vertically to move the load patch down or up. The spectral response of the integrated optical resonator was used to monitor the resulting in-plane displacement. This measurement was done using a broadband source centered at 1550 nm (Newport BBS-430) and an optical spectrum analyser (Agilent 86142A). The broadband source was injected in a single mode fiber SMF-28 and used to interrogate the resonator. The fiber end was cleaved at an angle of 8^o to avoid back reflections from the fiber/air interface. An optical circulator was inserted between the broadband source and the resonator to direct the cavity's reflection spectrum towards the optical spectrum analyser.

The device was tested under different operation voltages and out-of-plane displacements. After each variation of the load patch's vertical position, the cavity's resonance peak position was measured. An example of its spectral response for increasing vertical displacement is shown in fig. 5. The spectral shift toward shorter wavelengths indicates a decrease of the cavity length and is in agreement with the expected device's behavior. The initial 9.3 V working voltage generates an electrostatic force on the movable mirror which increase the cavity's length. The vertical motion of the load patch toward the substrate lowers the overlap area of the combs and therefore lowers the electrostatic force.

The in-plane displacement of the mirror can be extrapolated from the spectral shift observed using an optical model [5] to fit the experimental data. It can be seen from Fig. 6 there is a good correlation between the simulated and the experimental results. It is found that the maximum spectral shift observed of 28 nm corresponds to a 0.57 µm variation of the cavity length (i.e.: horizontal motion). Subsequently, the corresponding out-of-plane

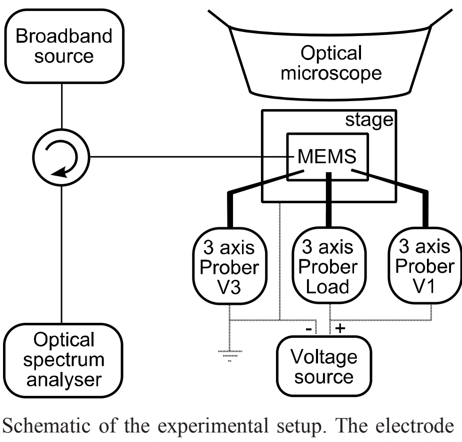

Figure 5. Schematic of the experimental setup. The electrode V_3 and the stage supporting the MEMS are grounded. The electrode V_1 and the flat ended tip used to apply the load are at the same voltage.

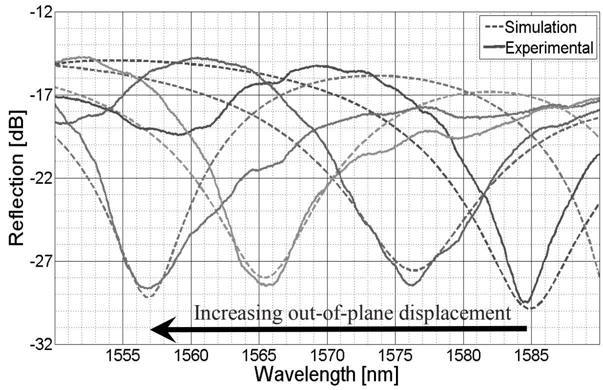

Figure 6. V_1=V_3=0V, V_2=9.3V. Measurements (full lines) and simulations (doted lines) of the cavity spectral response for increasing vertical displacements.

displacement can be calculated using the analytic equations governing the electro-mechanical transducers, taking into account the in-plane displacement, the capacitor parameters and the operation voltage. It appears that the measured 0.57 µm horizontal motion corresponds to the translation of a 1.7 µm vertical displacement of the load patch. The maximum vertical displacement was limited by the thickness of the buried oxide layer (BOX) and not by the height of the combs capacitor. A backside etch behind the load patch area would allow to overcome this limitation and to increase significantly the amplitude range.

The ratio between the out-of-plane and in-plane motion is *K*=2.98. As shown by Eq. 1, the ratio between the amplitude of the vertical and horizontal motions depends on various design and working parameters. Its non-unitary value does not indicate losses in the translation mechanism. The sensitivity of the cavity's resonance peak over a vertical displacement is 16.5 nm/µm. This parameter is more relevant for sensing applications. It depends on the ratio *K* but also on the free spectral range of the optical resonator.

IV. CONCLUSION

A vertical to horizontal motion translation device based on coupled electro-mechanical transducer was proposed. The working principle was exposed and the governing equations were derived. As a proof of concept, the original actuator was implemented in the design of a tunable optical resonator. The microsystem was successfully fabricated and characterised. Experimental results appear to be in good agreement with the theory. A vertical 1.7 µm displacement was translated into a horizontal 0.57 µm motion. The ratio between these values can be adjusted through the design or the working parameters which allow great flexibility. It depends on the combs geometry and the working voltage and could potentially allow motion amplification.

The motion translation device we developed allows to work in 3D and therefore to gather both in-plane and out-of-plane design advantages. The optical microsystem we fabricated requires a single photolithography step, it includes fibre grooves for optical alignment and it exhibits an interaction area of 1mm^2. Consequently, it minimises the fabrication steps, it facilitates the optical alignment, the packaging and the interaction with its environment. For these reasons we think this original actuator is of great interest in the field of sensors. We believe it will help to improve designs and integration of present sensors.

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