Sub-Micron-Thick Electrostatic MEMS Platform for Power Efficient Silicon Photonic Circuits

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***Abstract*—We present the design, fabrication and experimental performance of electrostatic MEMS actuators for tuning silicon photonic components. Two types of electrostatic actuators are presented: an out-of-plane cantilever actuator for a tunable directional coupler and an in-plane comb-drive actuator for a tunable phase shifter. The experimental results show that the MEMS actuators can achieve a static power consumption of <100 nW and a full 2π phase tuning with movement of less than 200 nm.**

I. INTRODUCTION

Silicon photonics is a rapidly advancing field with a number of applications in quantum computing, high-speed telecommunication, sensing, data processing, and active beam forming [1]. Silicon photonics uses silicon waveguides as an optical medium to transmit light on chips. There are two fundamental waveguide-based optical components that are used to control the flow of light: an optical phase shifter and a tunable coupler.

The most common method for tuning such silicon photonic components is the thermal optic effect. This method often employs metal heaters to change the temperature and therefore the refractive index of the waveguide to create a tuning effect. Although it is simple to implement, this method has a high power consumption and is subject to thermal crosstalk between adjacent components [2], which constrains scalability of photonic circuits. Alternatives to the thermo-optic effect, such as piezo-electric effect and phase-change materials, have been proposed [3]. However, these require the incorporation of exotic materials such as lead zirconate titanate thin films, which can complicate the fabrication process. Moreover, phase-change materials haves issues in low durability.

To address these issues, electrostatic MEMS actuators can be used to implement efficient and reliable tunable optical components on a silicon photonics platform. We demonstrated a tunable directional coupler and phase shifter operated by MEMS with a static power consumption of less than 100 nanowatts. In addition, we experimentally demonstrated a tunable optical microring resonator using a combination of a tunable coupler and phase shifter.

II. DESIGN AND METHOD

A. *MEMS implementation on silicon photonics platform*

Standard silicon photonic devices are fabricated on a silicon-on-insulator (SOI) wafer with a 220 nm-thick silicon layer and 2 to 3 μm buried oxide (BOX) layer. The 220 nm-thick silicon layer is used for actuators, and the BOX layer serves as a sacrificial layer for releasing the actuators. Vapor hydrofluoric acid etching is employed to remove the BOX layer, preventing stiction of the actuators. The silicon layer of the SOI wafer is lightly doped for electrical conduction. We have demonstrated two types of electrostatic actuators (cantilever actuator, comb-drive actuator) using this platform and applied them to a tunable coupler and phase shifter.

B. *Out-of-plane cantilever actuator*

Figure 1 depicts a cross-section of our device platform, featuring an electrostatic cantilever actuator (labeled as "MEMS actuator (Cantilever)"). By applying an electrostatic force between the silicon substrate and the cantilever, vertical displacement of the cantilever is precisely controllable. The cantilever's resonant frequency can be tuned by its length, and typically lies in the range of 10 kHz to 1 MHz. The cantilever in this paper has a length of 40 μm, resulting in a resonant frequency of 180 kHz. Additionally, a Cr/Au layer is deposited at the cantilever's hinge to apply prestress, thus defining its initial position. Attached to the end of the actuator is a waveguide with a width of 450 nm and a thickness of 220 nm.

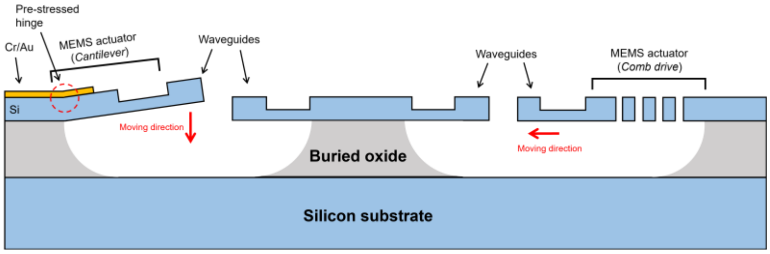

Figure 1. Cross-section view of the wafer platform combines silicon photonics with electrostatic MEMS actuators.

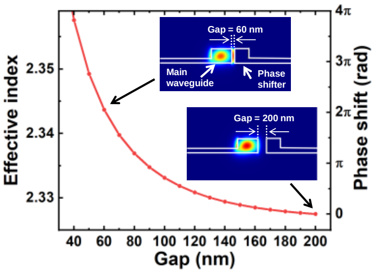

Figure 2. The simulated reponse of the phase shifter. Each inset represents the simulated optical mode profile with 60 and 200 nm gap.

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Upon actuation, the actuator moves towards the waveguide placed on the opposite side, thereby adjusting the optical coupling strength between the two waveguides. The most commonly used wavelength in silicon photonic devices is 1550 nm, where less than 1 µm of displacement is sufficient to achieve full tuning of the tunable coupler. Such small displacement requirements also contribute to the durability of these actuators when compared to conventional thick-silicon based MEMS actuators.

C. *In-plane comb-drive actuator*

We also designed and fabricated in-plane electrostatic comb-drives on our platform (Fig. 1, labeled as "MEMS actuator (Comb-drive)"). The vertical thickness of the actuator is 220 nm, and it has four folded springs with 54 sets of comb-finger pairs. The actuator is able to move more than 200 nm, which is sufficient to use it for the phase shifter tuning, as will be discussed later.

The MEMS phase shifter is a 300 nm-wide and 100 µm-long waveguide, which can be approached close to the main waveguide (450 nm wide) to change the effective index of the main waveguide, thereby creating a phase shifting effect. Figure 2 shows the simulated response of the phase shifter versus the gap between the phase shifter and the main waveguide. The 300 nm waveguide is attached to the in-plane comb-drive actuator, which moves the 300 nm waveguide to precisely control the gap between the 300 nm waveguide and the main waveguide. As shown in the simulation, a movement of less than 200 nm is required to achieve a full 2π phase shift.

III. EXPERIMENTAL RESULTS

Figure 3(a) shows a scanning electron microscopy (SEM) image of the fabricated tunable coupler attached to the cantilever actuator. We placed 2 µm-wide square etch holes for HF vapor to undercut the BOX beneath the cantilever. Figure 3(b) shows an SEM image of the phase shifter attached to the in-plane comb-drive actuator. As depicted in the image, four folded springs are present for mechanical restoring force.

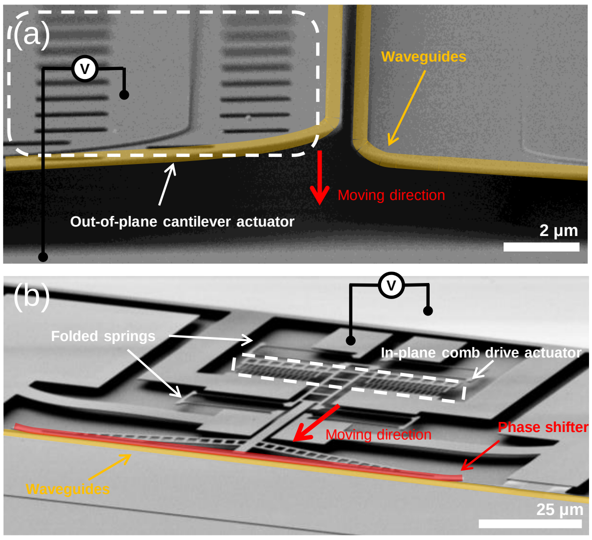

Figure 3. SEM image of fabricated (a) the cantilever actuator with the tunable coupler and (b) the comb-drive actuator with the phase shifter.

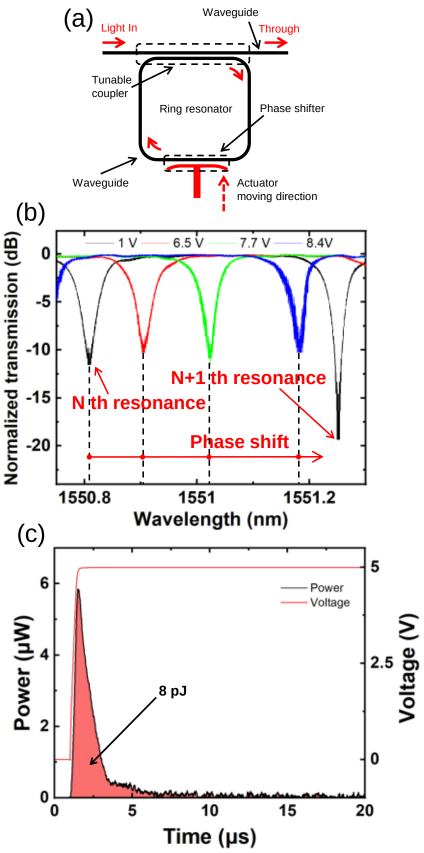

Figure 4. (a) Device configuration of the tunable ring resonaor filter. (b) The measured transimssion spectums of the ring resonator filter with various voltages applied to the phase shifter. (c) The measured electrical power consumption while applying voltage to the phase shifter.

We construct a tunable ring resonator filter by combining the tunable coupler, phase shifter, and a ring resonator (Fig. 4(a)). The tunable coupler tunes the extinction ratio of the ring filter, while the phase shifter tunes the resonance wavelength of the filter. Figure 4(b) shows the experimental data that demonstrates the tuning of the resonance wavelength of the ring filter by the MEMS phase shifter. As evident from the graph, the resonance dip shifts to longer wavelengths as the voltage applied to the phase shifter increases. Figure 4(c) shows the measured electrical power consumption when tuning the phase shifter to 5 V. The energy required to activate the phase shifter is only 8 pJ, and the static power required to maintain the actuator at the location is less than 100 nW, which is five orders of magnitude smaller than thermo-optic phase shifters.

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