New dynamic silicon photonic components enabled by MEMS technology

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ABSTRACT
Silicon photonics is the study and application of integrated optical systems which use silicon as an optical medium, usually by confining light in optical waveguides etched into the surface of silicon-on-insulator (SOI) wafers. The term microelectromechanical systems (MEMS) refers to the technology of mechanics on the microscale actuated by electrostatic actuators. Due to the low power requirements of electrostatic actuation, MEMS components are very power efficient, making them well suited for dense integration and mobile operation. MEMS components are conventionally also implemented in silicon, and MEMS sensors such as accelerometers, gyros, and microphones are now standard in every smartphone. By combining these two successful technologies, new active photonic components with extremely low power consumption can be made. We discuss our recent experimental work on tunable filters, tunable fiber-to-chip couplers, and dynamic waveguide dispersion tuning, enabled by the marriage of silicon MEMS and silicon photonics.

Keywords: MEMS, silicon photonics, tuning, ring resonator, waveguide dispersion, surface grating coupler

1. INTRODUCTION
Microelectromechanical systems (MEMS) refers to the technology combining electricity and mechanics on the microscale. During the past 10 years, MEMS technology has been the driver of innovation within a number of vibrant markets. Modern smart phones and computer gaming consoles, for example, rely on MEMS accelerometers and gyroscopes for engaging and interacting with the user in novel ways. MEMS components are conventionally implemented in silicon, and MEMS sensors such as accelerometers, gyros, and microphones are now standard in every smartphone. These devices use electrostatic actuation, a process in which an applied voltage induces electrostatic parallel-plate forces to trigger a mechanical displacement. Due to the low power requirements of electrostatic actuation, MEMS components are very power efficient, making them well suited for dense integration and mobile operation.

Silicon photonics is the study and application of integrated optical systems which use silicon as an optical medium, usually by confining light in optical waveguides etched into the surface of silicon-on-insulator (SOI) wafers. In recent years, silicon photonics has reached the market with devices such as optical interconnects and NIR spectroscopes, fulfilling its promises of low-cost, reduced size, low power consumption, and high functionality.

Combining these technologies by applying MEMS actuation to silicon photonics, i.e. photonic MEMS, can bring low-power actuation with low optical losses to silicon photonic circuits. Indeed, MEMS and light have already found each other within the field of opto-MEMS, where electrostatic MEMS actuators are used to move reflective, refractive, and diffractive elements in ray-optics systems.1–5 However, our focus within the field of photonic MEMS is on tunable integrated optics, and the particular benefits that MEMS actuation can bring to guided-wave devices on the micro and nanoscales.6–11 In particular, through the manipulation of evanescent fields of guided waves, tunable true time delays and waveguide dispersion can be achieved. Photonic MEMS can thus be an enabling technology for large reconfigurable photonic circuits.12 Here, we discuss our recent experimental work on tunable filters, tunable fiber-to-chip couplers, and dynamic waveguide dispersion tuning, enabled by the marriage of silicon MEMS and silicon photonics.
Figure 1. Cross-sectional illustration of the generic fabrication process employed for silicon photonic MEMS devices. A clean SOI chip (A) is patterned by e-beam lithography followed by timed silicon dry etch (B) to define ridge waveguides. With the resist still on the chip, a second e-beam lithography step, followed by a through silicon dry etch (C), defines the etch holes. After stripping the two resists (D), the structures are released by HF wet oxide under-etch, followed by critical point drying, to define the suspended structures (E). Applied voltage between the silicon substrate and the device layer deflects suspended areas, thereby actuating the photonic structures.

2. FABRICATION

Our devices were fabricated by a very simple SOI-based process, shown in Fig. 1, which consists of two silicon dry etching steps resulting in two heights, and a wet SiO₂ under-etch. The first lithography step defines the silicon beams, ridge waveguides, and the grating couplers. The second lithography step and a wet under-etch define the free-standing cantilevers, which are delimited by fully etched slots, and the free suspended areas are determined by the placement of etch holes.

The fabrication process starts with a clean SOI chip with a 220 nm thick crystalline silicon device layer and 2 μm thick buried oxide (Fig. 1A), which is a standard substrate specification used by the Epixfab silicon photonics foundries. Electron beam patterning of a 50 nm layer of a high-resolution negative electron beam resist (Hydrogen silsesquioxane, HSQ) defines the waveguide patterns, which are then transferred to the device layer by timed dry etch of silicon, resulting in ridge waveguide structures with 110 nm height on a 110 nm thick silicon slab (Fig. 1B). The patterned HSQ remains on the chip for the next lithography step. In order to define the free-standing cantilever, a 200 nm thick layer of positive e-beam resist (ZEP7000) was patterned after alignment to the existing structures. The subsequent through dry etch of silicon was then defined by the superposition of the two e-beam masks (Fig. 1C). This allows the creation of a self-aligned etched slot in the center of a waveguide, defined by the high resolution HSQ patterning of the first lithography step. After stripping the two resists (Fig. 1D), the patterned cantilever was released via a 50% HF wet oxide etch, followed by critical point drying (CPD, Fig. 1E).

3. TUNABLE PHASE SHIFTERS AND FILTERS

Most applications of tunable phase shifters and filters require a large number of densely packed devices with low cross-talk, and MEMS can provide this due to its low actuation power consumption. Parallel plate MEMS actuation of a free-standing cantilever that contains a suspended waveguide changes the waveguide geometry. This affects the effective refractive index of the guided optical mode, resulting in a phase shift. We demonstrated low-power MEMS tunable phase-shifting-based filters fabricated by our simple SOI-based process (Fig. 2). We use an integrated electrostatic actuator to perturb the evanescent field of a silicon ring resonator and shift its resonance wavelength. Light couples from the input waveguide into the ring waveguide, half of which is encircled by a static silicon rim separated by a through etched slot. A suspended cantilever is formed by the slot and
Figure 2. (a) We demonstrated a low-power MEMS tunable add-drop filter fabricated by a simple SOI-based process. (b) SEM of the MEMS tunable ring resonator add-drop filter. (c) FEM eigenmode simulations show the effect of vertical displacement of the ring resonator waveguide in relation to the static silicon rim on the effective mode index. Electrostatic actuation with a voltage \( V \) results in downward movement of the waveguide, which thus translates into redshift of the resonance wavelength of the ring resonator as the waveguide approaches the static rim, and a blueshift as the waveguide moves away from it. (d) and (e) SEM images of tunable rings with reduced radii for increased FSR. The left panels show rings in initial state, and the right panels show rings that have been collapsed to the underlying substrate by pull-in.

As shown in Table 1, for a ring with a radius of 80 \( \mu m \) the maximum measured resonance shift (tuning range) was 1000 pm, and the maximum linear tuning rate was \(-62 \text{ pm/V}\) (Fig. 3(b)), which is the highest value reported for electrostatically tuned ring resonator based add-drop filters. We observe an average free spectral range of 1176 pm (148 GHz), which varies by less than 1 pm over the full tuning range, and an average bandwidth of 160 pm (20 GHz), which at 1544 nm equates to a \( Q \) of \( 10^4 \). Compared to other MEMS actuated rings,\(^9\) our device presents a comparable bandwidth and a more than fourfold increase in tuning range and tuning rate.

### 4. TUNABLE WAVEGUIDE DISPERSION

An effective strategy to tune the dispersion of a waveguide is to change its geometry. We designed a ring resonator with low anomalous dispersion, with a cantilever designed for large dispersion tuning.\(^{18}\) With such a device, we
Figure 3. (a) Transmission spectra at the through and drop ports of the device in Fig. 2 (b). The right panel shows an enlarged view of the shaded area in the left panel, illustrating the movement of the spectra under actuation voltages between 0 and 21.5 V. The saturation of the line color decreases with voltage. (b) Resonance shift of the MEMS tunable add-drop filter, under actuation voltages from 0 to 21.5 V. The data is from the drop port spectra and averaged over the 15 resonances shown in (a). The device presents a maximum resonance shift of 530 pm with a linear tuning rate of 7.6 GHz/V (-62 pm/V) for actuation voltages between 12 and 21.5 V.

Table 1. Measured performance of our MEMS tunable ring resonators.

<table>
<thead>
<tr>
<th>Radius [µm]</th>
<th>Q</th>
<th>FSR [nm]</th>
<th>Tuning range [pm]</th>
<th>Tuning rate [pm/V]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>16200</td>
<td>1.24</td>
<td>1000</td>
<td>-36</td>
<td>Through port only</td>
</tr>
<tr>
<td>80</td>
<td>10000</td>
<td>1.24</td>
<td>530</td>
<td>-62</td>
<td>Add-drop ports</td>
</tr>
<tr>
<td>20</td>
<td>12000</td>
<td>5</td>
<td>122</td>
<td>-17</td>
<td>Through port only</td>
</tr>
</tbody>
</table>

demonstrated dynamic tuning of waveguide dispersion.

Our resonator consists of a suspended silicon waveguide ring of 10 µm radius (480 × 220 nm cross-section) surrounded, with a separation of 100 nm, by a waveguide rim (220 × 220 nm). The waveguide rim is part of a suspended cantilever, and the ring waveguide is attached by a silicon slab to a bus waveguide, leaving the ring coupling unaffected by actuation. Application of a voltage difference between the cantilever and the substrate displaces vertically the waveguide rim and changes the waveguide geometry. Waveguide simulations using an eigenmode solver show the effect of displacement of the waveguide rim on the waveguide quasi-TE mode group index and the dispersion coefficient (Fig. 4(a)).

A SEM of our device is shown in Fig. 4(b). From the measured ring resonator FSRs, in the wavelength range between 1.46 and 1.58 µm, we calculate the waveguide group index (Fig. 4(c)), the dispersion coefficient (Fig. 4(d)), and the group velocity dispersion (GVD). Our results show an 800 ps/nm/km tuning of the dispersion coefficient, i.e. from 1500 to 2300 ps/nm/km, which, in combination with our measured GVD values from −1.9 to −3 ps²/m, are in the range of static dispersion-engineered waveguides enabling phase matching and efficient silicon nonlinear optics.19

5. TUNABLE GRATING COUPLER

Our tunable grating coupler consists of an SOI cantilever containing a silicon photonic grating tuned by parallel-plate actuation.20 This changes the diffraction pattern in the grating, which changes the light distribution in the grating and allows tuning of the alignment optimum in one direction. A schematic of the tunable grating coupler is shown in 5(a).
Figure 4. a) Eigenmode simulations of our waveguide cross-section show the effect of the displacement of the rim due to tuning voltage $V$ on the quasi-TE mode field distribution. b) Colored SEM of our device showing the cantilever (green), ring and bus waveguide (purple), and rim (orange). c) Measured group index tuning with increasing voltage, with a linear fit. d) Measured tuning of the dispersion coefficient, showing the fit to our simulations.

For characterization, the device consists of a straight silicon waveguide with a static input grating in one end, and our dynamic grating at the output end. The gratings were designed for TE transmission at a wavelength of 1550 nm, low back-reflection, and coupling into a standard telecom optical fiber tilted 10 degrees with respect to the chip normal. Figure 5(b) shows an SEM image of our device, showing the direction along which the output fiber was linearly scanned under a range of actuation voltages. We use TE polarized laser light at 1549 nm and 350 $\mu$W as input, and measured the output power for a range of fiber positions and actuation voltages. The actuation voltage was applied using a soft probe needle connected to a voltage source, and grounding the chip substrate.

We achieved up to 6 $\mu$m displacement of the optimum coupling position under voltage actuation up to 6 V (See Fig. 5(d)), which correlates to our simulations (Fig. 5(c)). The device returned to its initial state and remained functional after removal of the actuation voltage. Figure 5(e) shows our measured linear tuning rate of $-1.6 \mu$m/V under actuation voltage ranging from 2 to 6 V.

6. CONCLUSIONS

We have discussed our recent experimental work on tunable filters, tunable fiber-to-chip couplers, and dynamic waveguide dispersion tuning, enabled by the marriage of silicon MEMS and silicon photonics. We have demonstrated MEMS tunable photonic ring resonator add-drop filters with a low static power drain, good optical performance, and a high tuning rate. Moreover, using MEMS, we can reconfigure the waveguide geometry to demonstrate dynamic dispersion tuning of 800 ps/nm/km in a silicon photonic ring resonator waveguide with a low, anomalous dispersion, with applications in nonlinear optics. Finally, we have experimentally demonstrated the first MEMS tunable grating coupler for post-assembly optimization of fiber-to-chip light coupling, able to compensate for the typical drift caused by glued fiber connections or assembly misalignment of up to 3 $\mu$m in one direction.21 by using standard 5 V CMOS voltage levels. Our results show the potential of silicon photonic MEMS technology for enabling densely integrated reconfigurable silicon photonic systems.
Figure 5. (a) A MEMS tunable photonic grating for post-assembly optimization of fiber-to-chip light coupling. Parallel-plate actuation of the suspended grating shifts the position of the emitted light to optimize coupling. (b) SEM image of our MEMS tunable grating coupler. (c) Simulated and (d) measured optical power coupled into an optical fiber scanning linearly along the dashed arrow in (b) for actuation voltages up to 6 V. Our results show a displacement of the optimum coupling position up to 6 µm, with (e) a linear tuning rate of −1.6 µm/V.

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