Large-scale silicon photonic switches with movable directional couplers

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Fast optical circuit switches (OCSs) with high port count offer reconfigurable bandwidth in optical networks and have the potential to significantly increase the performance and efficiency of modern datacenters. In this paper, we report on a new type of integrated OCS that combines silicon photonics with MEMS actuation. The switch is built on a 50 × 50 passive crossbar network with very low optical loss (0.04 dB/crossing). Efficient switching is achieved by a pair of directional couplers with moving waveguides and an actuation voltage of 14 V. 2500 MEMS-actuated directional coupler switches have been integrated with the crossbar network to form a strictly nonblocking 50 × 50 OCS on a 9 mm × 9 mm chip. The measured switching time is 2.5 μs, and the extinction ratio is 26 dB. To our knowledge, this is the largest silicon photonic switch reported to date. The switch architecture is highly scalable because the light travels through only one active switching element, regardless of the size of the switch.

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1. INTRODUCTION

Optical circuit switches (OCSs) are essential building blocks in optical communication networks, enabling dynamic reconfiguration of the optical network. In past decades, various OCSs have been presented, including 2D MEMS optical switches [1–3] or 3D MEMS optical cross connects (OXC,s) [4–7]. Such systems offer high port counts, including systems exceeding 100 × 100 input and output ports, and low insertion loss, typically less than 2 dB for any given optical connection. They offer a typical response time in the range of milliseconds. Recent studies have suggested that fast OCSs with microsecond switching time can significantly increase the performance and efficiency of datacenter networks [8,9]. Promising candidates for such fast OCSs are based on silicon photonics technology. Recently, silicon photonic switches have been reported exhibiting micro/nanosecond response time, exploiting thermal tuning [10–13] or carrier injection [14,15] methods. Since silicon photonics technology leverages complementary-metal-oxide-semiconductor (CMOS) manufacturing process technology, it is conducive to high-density integration, potentially including CMOS driving circuits [16,17]. To date, however, the maximum port count for silicon photonics-based switches has been limited to 8 × 8 [10,12,17]. While silicon photonics-based switches utilizing thermal or free-carrier effects offer fast switching, their efficiency is limited due to the weak perturbation of the refractive index. Moving waveguides with MEMS actuators [18–26] allow a much stronger optical effect: 100% switching can be achieved by moving the waveguides over very short distances. This opens up new switch architectures that are inherently scalable. Though silicon photonic devices with moving waveguides have been reported previously [27,28], to date the switch size has currently been to 2 × 6 [29,30]. This paper reports on a new type of MEMS silicon photonic switch built on a low-loss crossbar network. A total of 2500 switching elements has been integrated monolithically to constitute a full 50 × 50 OCS on a die area of 9 mm × 9 mm, with a switching voltage of 14 V and a switching time of 2.5 μs.

2. SWITCH DESIGN

A. Switch Architecture

Figure 1(a) shows the schematic of the switch architecture. The crossing waveguides form the backbone of a low-loss optical crossbar network, which is architecturally similar to the free-space 2D MEMS switches [31] but now integrated on silicon with much higher density. It is essential that the waveguide crossing have very low optical loss. The presented design exhibits a loss of 0.015 dB/crossing. Light couples in and out of the waveguides through grating couplers. Within each unit cell, there is a pair of switchable directional couplers with moving waveguides. Depending on the position of the moving waveguides, there are two switching states [Fig. 1(a) right]. In the through state, light propagates to the next unit cell without interruption. In the drop state, the directional couplers are “switched on” by moving the waveguides downward with electrostatic actuation. The input light is coupled to the...
orthogonal waveguide through two directional couplers. A strictly nonblocking $N \times N$ switch can be realized in this manner. A salient feature of the switch is its scalability: light is switched only once through the directional couplers. There is no cumulative switching loss.

**B. Switch Unit Cell**

Figure 1(b) depicts the details of a switch unit cell. There are two movable directional couplers controlling the light path. Each directional coupler consists of a stationary and a movable waveguide. The movable waveguide is attached to a MEMS cantilever, which controls the position of the movable waveguide precisely by voltage through electrostatic actuation. The stationary waveguides are anchored at the crossing point. To minimize the transition loss from the fully released waveguide to the anchored waveguide, the oxide underneath the waveguide is tapered to reduce reflection at the discontinuity.

**C. Movable Directional Coupler**

The directional coupler consists of two fully etched waveguides. Upon releasing, both waveguides are suspended in air. The width and the thickness of the waveguides are 350 and 220 nm, respectively. The length of the coupling region is 11.9 $\mu$m, and the gap between two waveguides is 250 nm. The coupling between the two waveguides is controlled by adjusting the vertical offset. Figures 2(a) and 2(b) show the $H_y$ field profile of the movable directional coupler with vertical offset of 0 and 1000 nm, respectively. Without offset, light is effectively coupled from the in-port to the drop-port through a pair of directional couplers. With a vertical offset of 1000 nm, the two waveguides do not couple, and the light remains in the input waveguide and continues to the through-port. Figure 2(c) shows the simulated transmission of the movable directional coupler versus the vertical offset. The transmission characteristics show that an extinction ratio of
25 dB is achievable for the drop-port with only 1000 nm offset. The small offset requirement allows for fast actuation of the switch.

**D. Ultra-Low-Loss Waveguide Crossing**

Because there are 2N-2 crossings in the longest path, the insertion loss of the waveguide crossing needs to be minimized. The main loss mechanism is optical scattering at the intersection. Several structures were used to minimize loss. First, we transitioned the strip waveguide to ridge waveguide. Second, we employed multimode interference (MMI) structures to focus light at the crossing. Third, we inserted waveguide tapers before and after the MMI. The length of the MMI region and the taper section was 13.5 μm [Fig. 3; see inset]. To reduce loss further, we used a multimode interference (MMI) structure to focus light at the center of the crossing (Fig. 3; see inset). To reduce loss further, a waveguide taper was inserted before and after the MMI. The thicknesses of the core and the cladding layer of the ridge waveguide are 220 and 150 nm, respectively. The width of the MMI region was 2 μm. To optimize the design, we varied the lengths of the MMI region and the taper section using a time-domain simulation tool. The optimal design has a taper length of 3.5 μm and an MMI region length of 13.5 μm [Fig. 3]. The insertion loss per crossing was 0.015 dB, and the crosstalk between the orthogonal ports was 66 dB. For a 50 × 50 crossbar network, the longest light path had 98 waveguide crossings, corresponding to an insertion loss of 1.47 dB.

**E. Electrostatic MEMS Cantilever Actuator**

Figure 1(c) shows a cross-sectional view of the electrostatic actuator, which controls the vertical offset of the movable directional couplers. The actuator is capacitive type, and thus there is no power consumption when holding the switch in the ON state. The cantilever was bent upward by the tensile stress of the metal coating [32]. The amount of bending can be controlled by adjusting the thickness of the metal and the length of the metal coating on the suspended part of the cantilever. With 5 nm of Cr and 30 nm of Au and a coated length of 6 μm, the initial displacement of the cantilever tip is 1.5 μm, which is sufficient to keep the coupler in the OFF state. A capacitive cantilever beam model was used to design the actuator. The thickness of the cantilever was 220 nm, which is the thickness of the Si device layer of the silicon-on-insulator (SOI) wafer. The gap between the cantilever and the substrate was 3 μm, which was defined by the thickness of the buried oxide (BOX) of the SOI wafer. The length of the cantilever was chosen to be 40 μm for low voltage and high-speed actuation. The resonance frequency [33] and the pull-in voltage [34] of the cantilever were calculated using the following equations:

\[ f_{\text{res}} = \frac{3.52}{2\pi} \sqrt{\frac{E t^3}{12 \rho l^4}} \]  

(1)

\[ V_{\text{pull-in}} = \frac{3E t^3 z_0^3}{10\varepsilon_0 T^3} \]  

(2)

where \( E \) and \( \rho \) are the Young’s modulus and density of Si, \( t \) and \( l \) are the thickness and length of the cantilever, and \( z_0 \) is the gap between the cantilever and the substrate. For our actuator design, \( E = 150 \text{ GPa}, \rho = 2.32 \text{ g \cdot cm}^{-3}, \text{ } t = 220 \text{ nm}, \text{ } l = 40 \text{ μm}, \text{ } \) and \( z_0 = 3 \text{ μm} \). The resonance frequency and the pull-in voltage were calculated to be 179 kHz and 24 V, respectively.

**3. EXPERIMENTS**

**A. Fabrication**

The switch was fabricated using a process similar to that of standard silicon photonics process on 150 mm SOI wafers, consisting of a 220 nm device layer and 3 μm BOX. Three lithography steps were performed at wafer scale using a 248 nm deep UV stepper.
All waveguides and MEMS actuators were defined by two etching steps: a partial etch with 70 nm depth and a full etch through the 220 nm SOI layer. The shallow etch was used to pattern the waveguide crossings, ridge waveguides, waveguide tapers, and grating couplers. The full etch delineated the movable directional couplers and MEMS actuators. A metal lift-off process deposited Cr/Au on part of the MEMS actuator to introduce stress-induced bending as well as the electrical contact pad. After fabrication, we used HF vapor etching to release the movable directional couplers and the MEMS actuators. Figure 4 shows the scanning electron micrographs (SEMs) of the 50 × 50 switch. The size of a unit cell is 160 μm × 160 μm, and the size of the whole chip, which includes 2500 (50 × 50) unit cells and grating couplers, is 9 mm × 9 mm. The bending of the cantilever beam is clearly visible in Figs. 4(b) and 4(c).

B. Voltage Transfer Curve of Switch

We tested the individual switches by applying a voltage between the cantilever and the substrate. Figure 5 shows the optical transmission at the drop- and through-ports versus applied voltage. Optimal switching (drop state) was near 14 V, where the optical power transmitted to the drop-port was maximum, while the optical power transmitted to the through-port was minimum. The extinction ratios were 26 and 25 dB for the drop- and through-ports, respectively. At 14 V, the deformation of the waveguide due to the electrostatic interaction with the fixed waveguides was calculated to be 10 nm. For voltages higher than 14 V, the remaining power in the through-port increases again because the movable waveguide moves below the plane of the stationary waveguide.

C. Spectral Response of Switch

Figure 6 shows the spectral response of the switch unit cell for the drop state. Both simulation and experiment show a maximum

![Fig. 4. SEM images of fabricated switch chip.](image)

![Fig. 5. Measured voltage transfer curve of switch unit cell.](image)

![Fig. 6. Switch unit cell spectral response (at drop state).](image)
extinction ratio between the drop-port and the through-port near a wavelength of 1550 nm. The measured extinction ratio between drop-port and through-port at 1550 nm was 22 dB. The discrepancy between the simulation and the measurement is attributed to the fabrication imperfection of the waveguide dimensions. The –20 dB bandwidth of the through-port is measured to be 13 nm, which is typical of standard directional couplers. Broadband designs such as [15] can potentially be used to enlarge the switching bandwidth.

D. Time Response of Switch

Figure 7 shows the measured time response of the switch. The rise time (to 90% power) and the fall time (to 10% power) were 2.5 and 3.8 µs, respectively. Ringing was not significant due to air damping of the MEMS cantilever. The ringing can be suppressed by using a two-stage voltage waveform as reported in [35]. The response time of the switch can be reduced further by using stiffer springs in the MEMS actuators but at the expense of higher switching voltage.

E. Insertion Loss of Switch

We measured the insertion loss of different optical paths in the 50 × 50 switch to study the path-dependence loss. Due to the fabrication variation, the average width of the waveguides in the movable directional coupler was 430 nm. The loss of the waveguide crossing was characterized by test structures with 20, 50, and 90 cascaded crossings. The measured loss of 0.04 dB/crossing is slightly higher than the theoretical prediction of 0.015 dB, but is still very low. The loss of the through state was 0.253 dB, which is primarily due to the propagation loss of the waveguide. The loss of the drop state is 2.47 dB, which includes the losses of two movable directional couplers. A salient feature of the switch is that the light signals only go through the drop-state loss for any switch configuration; therefore, the drop-state loss is not cumulative, unlike other silicon photonic switches based on cascaded 2 × 2 Mach–Zehnder switches. The theoretical insertion loss of the directional couplers is ideally 0 dB. Here, the measured loss is mainly due to the deviation of the waveguide dimensions and, therefore, the effective coupling length. This can be greatly suppressed with better dimensional control in advanced foundries. In addition, the propagation loss of the waveguides can be reduced further with more advanced fabrication processes. The insertion loss of the through state should be comparable to the waveguide crossing loss [36,37]. The optical insertion loss of the longest path is 27.5 dB. Potentially, the maximum insertion loss of the 50 × 50 switch could be reduced to 4 dB (0.04 dB × 98 + drop-state loss), or even lower if the crossing loss can be further reduced.

4. CONCLUSION

We designed, fabricated, and characterized a 50 × 50 MEMS-actuated silicon photonic switch. 2500 (50 × 50) switch unit cells were monolithically integrated on a 9 mm × 9 mm chip. To our knowledge, this is the largest (highest port count) silicon photonic switch to date. Movable directional couplers with electrostatic MEMS actuators enabled fast (2.5 µs response time) and high extinction ratio (26 dB for drop-port) optical switching. The switch architecture is highly scalable. With further reduction of waveguide propagation loss, switches with dimensions greater than 100 × 100 can be realized with an insertion loss of just a few decibels.

See Supplement 1 for supporting content.

REFERENCES