Monolithic 50x50 MEMS Silicon Photonic Switches with Microsecond Response Time

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Abstract: We report on 50x50 MEMS-actuated silicon photonic switches with 16V switching voltage and microsecond switching time. 2,500 MEMS cantilever 1x2 waveguide switches have been integrated on 9mmx9mm chips.

OCIS codes: (130.4815) Optical switching devices; (250.5300) Photonic integrated circuits

1. Introduction

Fast optical circuit switches (OCS) can deliver reconfigurable bandwidth in datacenter networks, augmenting electronic packaging switching and offering potential cost saving and performance improvement [1,2]. 3D MEMS-based OCS has been used in datacenter-scalable streaming systems [2]. However, its slow switching time (10-100ms) limits its use to highly aggregated traffic or applications with high traffic stability. Faster, microsecond-scale OCS will allow orders of magnitude faster reconfiguration time of the control plane [1]. Recently, a CMOS-integrated silicon photonic switch with nanosecond switching time has been reported, however, the switch size is limited to 4x4 and 8x8 [3].

In this paper, we report on a monolithic 50x50 silicon photonic matrix switch with MEMS actuation. The switch has high density (160μmx160μm/cell), and a fast switching time is 2.4μs. The maximum optical loss is 23.7dB (0.039dB/cell + 3.7dB switching). The switching voltage is 16V, and there is no power consumption except during switching. To our knowledge, this is the largest monolithic OCS reported to date.

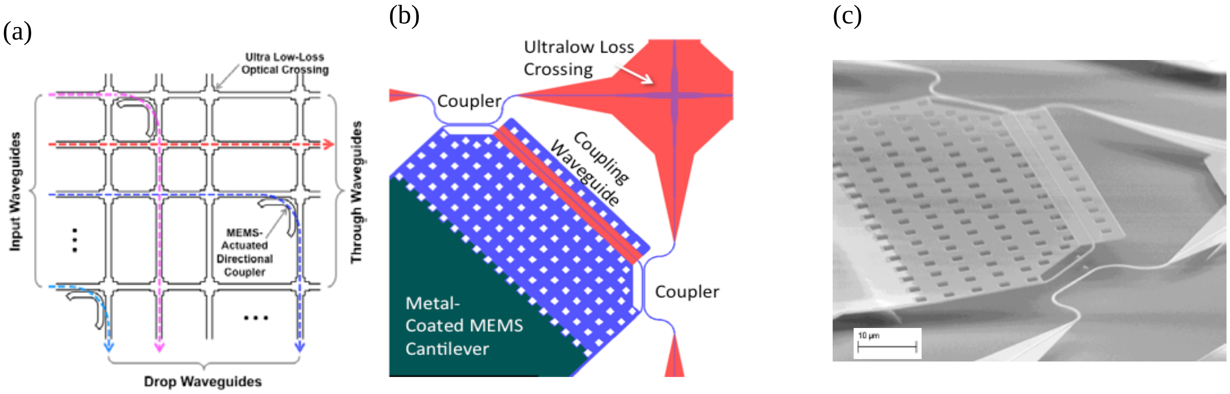

Fig.1. (a) Schematic of the optical matrix switch. (b) Detailed structure of a 1x2 switching cell. (c) SEM of a fabricated unit switching cell showing suspended directional couplers and MEMS cantilever actuator.

2. Silicon Photonic Switch Design and Simulation Results

The schematic of the switch is shown in Fig. 1a. The input and output waveguides form an orthogonal grid with a pitch of 160μm on a silicon photonics platform with 220nm-thick silicon-on-insulator (SOI). We use 500nm wide ridge waveguides for both input and output. Without actuation, light stays in the input waveguide and reach the "Through" port. Since the optical signals go through a large number of waveguide crossing, the loss must be minimized to reduce insertion loss. We optimize the loss performance using a multi-mode interference (MMI) section with 2μm width and 13.5μm length (Fig.2a). Light is focused at the center of the crossing and therefore experience minimum scattering from the crossing. Finite-difference time-domain (FDTD) simulations predict an optical insertion loss as low as 0.015dB per crossing (Fig.2b), and crosstalk is less than -60dB. The ideal insertion loss of the longest path (100 crossing) is only 1.5dB.

Light can be switched from any input waveguide to any selected output waveguide by moving a pair of directional couplers near the waveguide crossing, as shown in Fig.1b. Light is first coupled to the intermediate waveguide on the actuator by the first directional coupler, and then to the output waveguide by the second coupler.

To increase the coupling efficiency and to allow for release (free suspension) of the movable waveguide, the ridge waveguides are tapered to fully etched waveguides with a width of 350nm. With a spacing of 250nm, the coupler length is only 10µm. Since narrow strip waveguide has higher loss due to optical scattering at the Si-air interface, ridge waveguides are used to connect the switch cells. The switch is in the normally OFF state, with the cantilever bent upward by the stress of coated metal (Cr/Au) [4]. The simulated optical transmission versus vertical offset (MEMS displacement) is shown in Fig.2c. Thanks to the high refractive index contrast in silicon photonics, a displacement of 1µm will produce complete switching with an extinction ratio greater than 30dB.

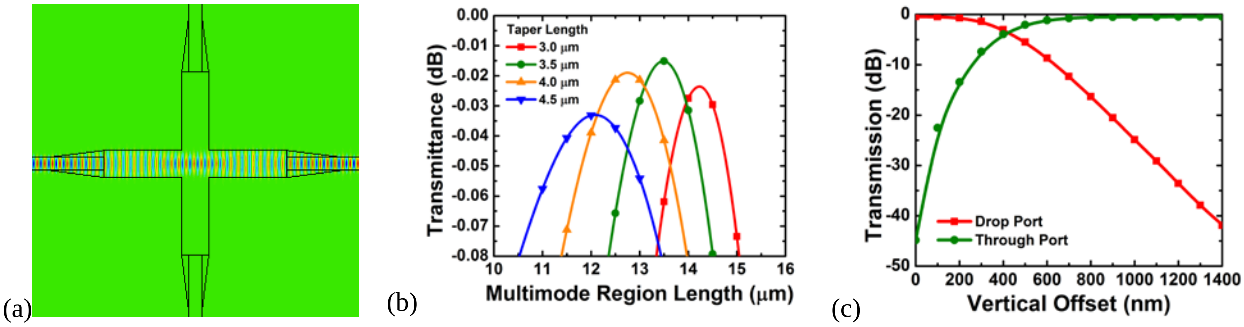

Fig.2. (a) FDTD simulation of low-loss optical waveguide crossing. (b) Transmission spectra of MMI waveguide crossing. The minimum loss is 0.015dB/crossing. (c) Simulated switch transfer curve as a function of the vertical offset between the fixed waveguides and movable directional couplers.

3. Switch Fabrication

The switch is fabricated using the standard silicon photonics technology at Berkeley Marvell Nanolab. The ridge waveguides and the grating couplers are first partially etched to a depth of 150nm. Then the directional couplers and release holes for MEMS cantilevers are fully etched through. Cr/Au (10nm/30nm) is coated on part of the cantilever by evaporation. Lastly, the chip is released in vapor HF. The fully etched waveguides will be completely suspended, and anchored by the large slab area of the ridge waveguides. Upon release, the tip of the cantilever is bent upward to about 2µm above the input/output waveguides. The cantilever is 45µm long and 90µm wide. The lengths of the cantilevers are defined by the release holes (2µm x 2µm area with 3um spacing). The unit switch cell has an area of 160µm x 160µm, and the total chip area including all input/output grating couplers are 9mm x 9mm.

The scanning electron micrograph (SEM) of the release chip is shown in Fig.3a. Fig. 3b shows the close-up view of the bent cantilever and displaced directional couplers. Fig.3c shows the details of the waveguide crossing. Note that the buried oxide here is also tapered to minimize the optical reflection. The large slab area of the crossing also serves as the anchor of the suspended waveguides.

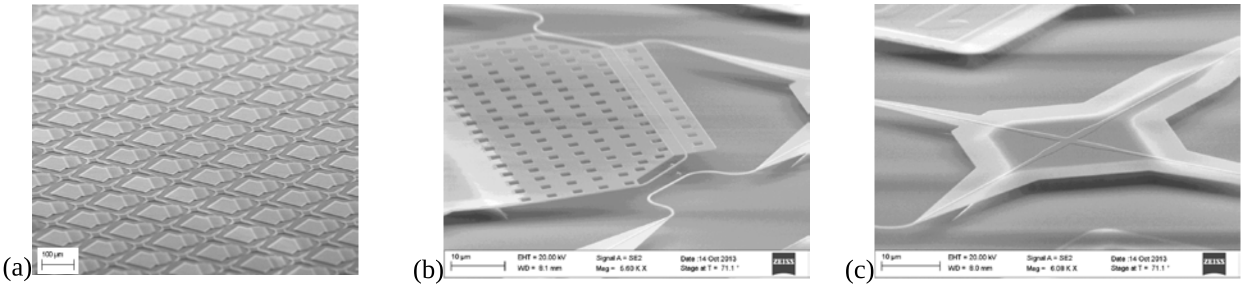

Fig.3. SEMs of the fabricated MEMS silicon photonic switch: (a) large area view. (b) Close-up of a single switching cell showing the suspended waveguides and MEMS cantilver actuator. (c) Low-loss MMI waveguide crossing. Note the buried oxide underneath the silicon slab is tapered to minimize optical reflection and scattering loss.

3. Experimental results

Light is coupled to the switch chip through grating couplers using a 1x24 array of angle-polished fiber array. The fiber coupling loss is characterized using two pairs of waveguide-connected grating couplers. The grating coupler is not optimized, and current coupling loss is about 6dB. The waveguide crossing loss is measured by test structures with a variable number of crossings (Fig.4a). The measured loss is 0.039dB/crossing. Though this is higher than our theoretical value (0.015dB/crossing), the loss is still quite low. The optical loss per unit cell, which includes the losses of two ridge-to-strip waveguide tapers and one waveguide crossing, is measured to be 0.2dB. For our 50x50 OCS, the longest path with 50+50 = 100 cells has 20dB insertion loss. The average insertion loss is 12dB (not including grating couplers), the cross talk is less than -54dB, and the extinction ratio is higher than 30dB.

Switching is tested by applying a voltage between the cantilever and the substrate. The measured transmission of the Through and Drop ports are shown in Fig.4b. As the voltage approaches 14V, we start to observe light in the Drop port. At 16V, maximum light is switched to the Drop port with an insertion loss of 3.7dB. The residue light in the Through port is less than -12.5dB. The dynamic response of the switch is measured by applying a square-wave at 30kHz repetition frequency. The frequency response is obtained by Fourier transforming the temporal response, as shown in Fib.4c. The resonance frequency is 0.414MHz, corresponding to a switching time of 2.4µs. Because the optical coupling is very sensitive to the waveguide separation, the time domain response exhibits some ringing. The ringing can be suppressed by feedforward control signal consisting of two voltage steps [5].

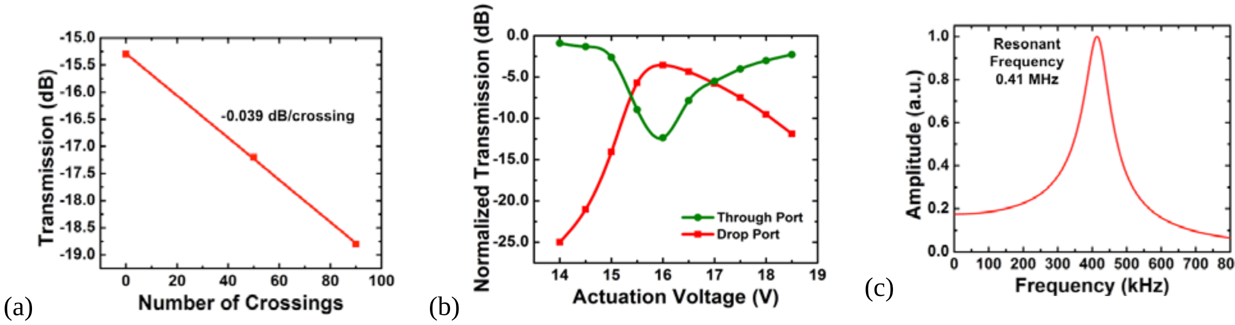

Fig.4. (a) Measured optical transmission versus the number of waveguide crossing. A loss of 0.039dB/crossing was measured. (b) Measured switching characteristics of the MEMS silicon photonic switch. Switching voltage of 16V and a switching loss of 3.7dB are measured. (c) Measured frequency response of the switch. The resonance frequency of 0.41MHz corresponds to a switching time of 2.4 µs.

4. Conclusion

We have designed and fabricated a monolithic 50x50 MEMS silicon photonic switch. The switch has 50 input ports, 50 Through ports, and 50 Drop ports, and a total of 2,500 MEMS cantilever switches. A switching voltage of 16V is achieved, with optical insertion loss of a single switching element measured to be 3.7dB. Crosstalk is below 54dB. The maximum insertion loss is 23.7dB (20dB loss for passing through 100 cells plus 3.7dB switching loss). Our theoretical simulation shows that the optical insertion loss can be reduced to below 6dB with improved fabrication process. The switch is extremely compact. The area of the 50x50 chip is only 9mm x 9mm, with a unit cell (1x2 switch) area of 160µm x 160µm. Leveraging on silicon photonics technology, the switch can be mass-produced at low cost (only 3 photomasks for the current process). The switch has a resonance frequency of 0.41MHz (~ 2.4µs switching time). The reported switch has applications for fast optical circuit switch in datacenter networks.

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