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ABSTRACT
We report on monolithically integrated wavelength cross-connects (WXCs) on an enhanced silicon photonic platform with integrated micro-electro-mechanical-system (MEMS) actuators. An 8 × 8 WXC with 8 wavelength channels comprising 16 echelle gratings and 512 silicon photonic MEMS switches is integrated on a 9.7 mm × 6.7 mm silicon chip. The WXC inherits the fundamental advantages of silicon photonic MEMS space switches, including low loss, broad optical bandwidth, large fabrication tolerance, and simple digital control. The WXC exhibits a low crosstalk of −30 dB, a submicrosecond switching time of 0.7 μs, and on-chip optical insertion losses varying from 8.8 dB to 16.4 dB. To our knowledge, it is the largest channel capacity (64 channels = 8 ports × 8 wavelengths) integrated WXC ever reported.

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I. INTRODUCTION
Wavelength-selective switches (WSSs) and wavelength cross-connects (WXCs) are widely used to route individual wavelengths in wavelength-division-multiplexing (WDM) networks. They also allow adding or dropping of signals in reconfigurable optical add/drop multiplexers (ROADMs).1–4 WXCs can be implemented by deploying WSSs based on the route-and-select architecture or combining wavelength (de)multiplexers and space switches (SSs). For the former approach, WSSs are realized with free-space optics utilizing liquid crystal on silicon (LCOS) spatial light modulators (SLMs) or digital micromirror devices (DMDs).5 The latter approach is based on integrated planar lightwave circuits (PLCs) technology.6 Hybrid approaches have been also reported in which arrayed waveguide gratings (AWGs) are implemented on PLCs as the wavelength (de)multiplexers and SLMs or 3D micro-electro-mechanical-system (MEMS) switches are employed as the space switches.7–9 As the port counts and the number of wavelength channels scale up, the size, weight, and cost of WXCs grow rapidly. Traditionally, the WXCs and ROADMs are deployed in core and metropolitan networks. Recently, there has been increasing interest in using WXCs to facilitate the scaling of data center networks.10,11 Fully integrated WXCs with reduced size and cost are desirable for data center applications. Furthermore, faster switching time enables dynamic provisioning of wavelengths for flow control.

Silicon photonics is a promising platform to integrate many optical components on a small chip at low cost using advanced complementary metal-oxide-semiconductor (CMOS) foundries.12–14 Previously, a 1 × 2 WSS with 16 wavelength channels using foldback AWGs,15 a 4 × 8 WXC with 12 wavelength channels using AWGs and ring resonators,16 and an 8 × 4 WXC with 2 wavelength channels using feedback-controlled ring resonators have been demonstrated. However, the ring resonators and phase shifters used in these WXCs are prone to fabrication variations and ambient temperature changes. Thermo-optic tuning was used to compensate for these variations, leading to a complex control scheme with high
power consumption. The scalability of the WXC was also limited by the optical loss and crosstalk.

Silicon photonic MEMS is the hybrid of silicon photonics and MEMS technologies.\textsuperscript{17–21} MEMS enables physical movement of silicon waveguides, which provides effective switching of broadband optical signals with unprecedented loss, crosstalk, and extinction ratio. Using MEMS-actuated vertical adiabatic couplers, we have demonstrated 64 × 64 and 240 × 240 silicon photonic switches.\textsuperscript{20,21} The advantages of silicon photonic MEMS are also favorable for large-scale WXCs.

In this paper, we will describe the design, fabrication, and characterization of a fully integrated WXC with echelle grating multiplexers/demultiplexers and silicon photonic MEMS space switches. As a proof of concept, we have experimentally demonstrated an 8 × 8 WXC with 8 wavelength channels. We measured on-chip optical insertion losses of 8.8–16.4 dB, a switching time of 0.7 μs, and crosstalk below –30 dB. The WXC has simple digital control and does not have static power consumption.

II. ARCHITECTURE AND DESIGN

Figure 1(a) shows the architecture of an N × N WXC with M wavelength channels. The WXC has N input and N output ports, N wavelength demultiplexers and N multiplexers, and M arrays of N × N space switches, where M is the number of wavelengths. The wavelengths are first separated by demultiplexers and routed to the corresponding space switch dedicated to each wavelength. The switched wavelengths are combined by multiplexers and routed to the output ports. Figure 1(b) depicts our experimental prototype of the 8 × 8 WXC with 8 wavelength channels (N = 8, M = 8). It has 16 grating couplers (8 input ports and 8 output ports), 16 echelle gratings (8 demultiplexers and 8 multiplexers), and 8 arrays of 8 × 8 silicon photonic MEMS switches. The waveguides are highlighted with different colors to show the routing path of each wavelength.

We designed the echelle gratings to separate 8 wavelength channels (λ₁, λ₂, …, λ₈) from 1490 nm to 1560 nm with a channel spacing of 10 nm based on the Rowland configuration.\textsuperscript{32} The designed echelle gratings have a Rowland radius of 120 μm, a grating period of 4.4 μm, and an output waveguide spacing of 3.3 μm. The input and output waveguides are 2-μm-wide. The second order distributed Bragg reflectors (DBRs) with a period of 400 nm and a duty cycle of 50% were used at the reflection facets of the gratings to enhance the performance.\textsuperscript{23} The simulated reflectivity of the DBR facet is 91%, vs 20% reflectivity of the etched Si facet. In the layout shown in Fig. 1(b), each signal path experiences different number of crossings, depending on the wavelength and the input and output ports. Wavelength λᵢ from input Iᵢ passes through (8 − w) × (x − 1) + (w − 1) × (8 − x) crossings between the demultiplexer and the switch. Similarly, λᵢ passes through (8 − w) × (y − 1) + (w − 1) × (8 − y) crossings between the switch and the multiplexer. The total number of crossings of the 8 × 8 WXC varies from 0 to 98. Therefore, it is essential to reduce the crossing loss. We employed multimode interference (MMI) crossings with a simulated insertion loss of 0.011 dB/crossing, which had been also used in our previous silicon photonic switches.\textsuperscript{20,21} It should be pointed out that the horizontal and vertical waveguides of the crossing here have different wavelengths, which is unique to WXC. To minimize the crossing losses for both wavelengths, we designed the crossing with different multimode region lengths for the horizontal and vertical waveguides. Figure 2 shows the calculated center wavelengths of MMI crossings vs multimode region lengths. It varies linearly with a slope of dλ/dl = −4.88 nm/100 nm. Based on this calculation, the MMI crossings were optimized to have insertion losses as low as 0.01 dB for all wavelength channels.

For the space switches, we utilized 8 blocks of 8 × 8 silicon photonic MEMS switches. It has been shown that silicon photonic MEMS switches are highly scalable, owing to their low insertion loss and low crosstalk.\textsuperscript{20,21} The small footprint of the switch unit cell (110 μm × 110 μm) enables high density integration of large-scale switches. The MEMS-actuated vertical adiabatic coupler switch offers broadband operation covering L, S, and C communication bands, simple digital control, and high energy

![FIG. 1. (a) Schematic of the wavelength cross-connect architecture. (b) Illustration of the silicon photonic wavelength cross-connect with 8 input ports (Iᵢ), 8 output ports (Oᵢ), and 8 channel wavelengths (λᵢ). The waveguides are highlighted with different colors for different channel wavelengths.](image-url)
efficiency without static power consumption, which are favorable for large-scale switches and WXC. A total of 512 switch cells (8 arrays of $8 \times 8$ switches) were integrated in our WXC. Unlike the MMI crossings with asymmetric lengths in the routing paths, symmetric MMI crossings were used in the switch arrays as each $8 \times 8$ array operates with a designated wavelength.

III. FABRICATION AND CHARACTERIZATION

The designed WXC were fabricated in a commercial 200-mm CMOS foundry at TSI semiconductors. The $8 \times 8$ WXC with 8 wavelength channels are monolithically integrated on a 220-nm silicon-on-insulator (SOI) chip with an area of 9.7 mm $\times$ 6.7 mm.
the same chip. Figure 4 shows the measured transmission spectra of the echelle grating normalized to the reference from a back-to-back grating coupler pair. The on-chip loss of the central channel is 2.1 dB with a crosstalk of −20 dB. The loss variation over the channels is 1.3 dB. The measured peak wavelengths of the WDM channels are 1493 nm, 1503 nm, 1513 nm, 1524 nm, 1534 nm, 1544 nm, 1554 nm, and 1564 nm, which are well matched to the designed wavelengths with only 3–4 nm shift.

The switching characteristic of the WXC was investigated by addressing MEMS actuators in the space switch cells. Figure 5(a) shows the transfer curve of a representative switch cell. The transfer characteristic exhibits a digital switching behavior with an ON voltage ($V_{\text{ON}}$) of $\sim 40$ V and an OFF voltage ($V_{\text{OFF}}$) of $\sim 27$ V. The extinction ratio over 40 dB was achieved by the MEMS switching mechanism. Figure 5(b) shows the distribution of $V_{\text{ON}}$ measured from all 512 switch cells. The average $V_{\text{ON}}$ was measured to be 39.6 V with the standard deviation of 2.3 V. Although there exist small variations of the switching voltages, the bistable switching characteristic of the MEMS switch enables simple digital control without customized bias for individual switching cells. From the temporal response measurement, submicrosecond switching was confirmed as in our previous silicon photonic MEMS switches. The ON and OFF switching times were measured to be 0.7 $\mu$s and 0.3 $\mu$s, respectively, as shown in Fig. 6.

The full transmission spectra through the echelle gratings, the MMI crossings, and the MEMS switches were measured between the input ports and the output ports. Figure 7 shows the representative transmission spectra from the input port $I_n$ to the output port $O_n$ when the corresponding switching cell (n, n) of all switch arrays is turned on (n = 1, 2, …, 8). For example, the red curves ($\lambda_8$) in the plot are the measured $I_1$-$O_1$, $I_2$-$O_2$, …, and $I_8$-$O_8$ transmissions when the switching cells (1, 1), (2, 2), …, and (8, 8) of the $\lambda_8$ switch array are on, respectively. For each channel wavelength, signals of different paths ($I_n$-$O_n$) passed through the different input and output echelle gratings. The measured spectra show slight peak wavelength shifts within 2 nm and confirm the echelle gratings with a good uniformity. The measured crosstalks for the central channels are better than −40 dB, which are currently limited by the noise floor of our photodetector. It is expected that the worst-case crosstalk is still lower than −30 dB when all 8 channels are utilized. Note that the curved noise floors are due to the normalization to the grating coupler reference.
The insertion loss of the WXC depends on the number of crossings and the length of routing waveguides of the selected input/output ($I_x$ and $O_y$) and wavelength ($\lambda_z$). To characterize the insertion loss, we measured the transmissions of all possible configurations and plotted as a function of the number of crossings in Fig. 8(a). The measured on-chip losses of the device vary from 8.8 dB to 16.4 dB. The loss increases with the number of crossings at a rate of 0.06 dB/crossing. This loss is higher than the simulation (0.01 dB/crossing), most likely due to the additional propagation imperfection. In addition, the small wavelength shifts in echelle grating (de)multiplexers may also contribute to the extra crossing loss. The loss distributions of each wavelength are plotted in Fig. 8(b). Due to the routing scheme of the device, the center wavelength has the least variation in the number of crossings (42–56). Consequently, its optical loss has a tight distribution around 10 dB.

FIG. 8. (a) Measured on-chip loss vs number of crossings in the path. (b) Loss distributions of each wavelength channel.

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