Large-Scale High-Speed Photonic Switches Fabricated on Silicon-Based Photonic Platforms

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Abstract: Large-scale high-speed photonic switches were demonstrated on silicon-on-insulator and thin-film Lithium Niobate platforms, respectively. Ultra-low-loss spot-size-converter, grating coupler, waveguide crossing, and high-speed switch unit are developed, as well as an integrated 128 × 128 switch.

1. Introduction

With the rapid developments of modern ICT technologies, low-power-consumption and high-speed optical routing are highly demanded to build the internal optical networks in datacenters and high performance computers. However, the optical routings are currently realized with MEMS based optical switches [1,2] or electrical switches based on optic-electric-optic conversions, due to the lack of low-loss and high-speed photonic switches. Therefore, researches are requested to reduce the insertion loss [3] and switching time of photonic switches [4]. On the other hand, silicon based integrated photonic devices are promising in constructing large-scale photonic switches [5-7], whereas the chip insertion loss is remained as an unsolved issue and the switching speed is not fast enough to support network packet switching. Therefore, in order to solve these two problems, we focus our researches on developing large-scale switches and their key units, including low-loss fiber coupling spot-size converters (SSCs), grating couplers (GCs), waveguide crossings, and low-loss, fast, and high efficiency switch units. The studies are based on silicon-on-insulator (SOI) and thin-film Lithium Niobate (TFLN) platforms, which have advantages in realizing high density integrated switches and ultra-fast switches for various applications, respectively. All demonstrated SOI device are based on CMOS compatible or commercial silicon photonic processes, while TFLN devices are fabricated with UV-lithography processes, which can be directly used to fabricate integrated large-scale photonic switches.

2. Devices and Experiments

2.1. Fiber coupling spot-size-converters and grating couplers

Fiber coupling loss might be the biggest problem for integrated photonic chips and photonic switches to be applied. SSCs and GCs for fiber coupling were both studied in our investigations. Edge-coupling SSCs are prepared to receive lights with unknown polarizations after propagating in fibers and should be polarization insensitive. Avoiding the mechanical unreliability of cantilever type SSCs, we demonstrated SSCs using SiN tapers as the SSC second core to raise up the light mode field coupled from tapered SOI waveguide. The SSC fabricated with commercial 180nm node silicon photonic processes reaches TE and TM coupling losses of about 1.3dB coupling with a 9 μm MFD (mode field diameter) SMF in measurements.

On the other hand, vertical coupling GCs are prepared for chip output coupling owing to that light polarizations in chip are usually fixed to TE mode. By combining an apodized structure optimized with our fast directional optimization method and interleaved etch realized with a layout strategy involving an extended mask to avoid alignment errors in multi-etching processes, the GC coupling efficiency was measured to be −2.2 dB at 1549nm wavelength with a 3 dB bandwidth of 47 nm [8]. Moreover, O-band GCs were designed with novel gradient index-matching subwavelength structures to reduce the leakage loss and mode mismatch. The coupling efficiency of GCs implemented with trapezoidal subwavelength gratings and apodization was measured to be -1.72 dB. It is the lowest reported loss of single-step etched GCs in the O-band with a minimum feature size of 120 nm, which is the typical minimum feature size in 130 nm commercial silicon photonic processes.

2.2. Waveguide crossings

In large-scale photonic switches, waveguide crossings have the largest number and introduce more losses. Considering device quantity and fabrication complexity, we developed 2D planar crossings for smaller switches and 3D bridge crossings for larger-scale switches, respectively. By implementing parabolic inverted tapers inside, a planar waveguide crossing having a compact footprint of 18 × 18 μm^2 was measured with an insertion loss of 8 mdB [9], which is the lowest reported loss for planar silicon waveguide crossings operating in the O-band, along with a low crosstalk below -40 dB over a 40 nm wavelength range. Subsequently, a 3D bridge crossing consisting of SiN-Si bridge crossing and SiN-Si parabolic interlayer coupling structure was fabricated. The 3D bridge crossings exhibit ultra-low propagation loss (< 1.5 mdB) and crosstalk (< −56 dB). The interlayer transition loss is less than 0.1dB across the O-band, which is the lowest value reported for SiN-Si interlayer transition structure.

2.3. Switch units

Switch units are basic elements to construct large-scale switches. Electro-optical controlling MZI switch units are selected in our research for supporting high-speed wide bandwidth switching. The units based on SOI platform are developed toward multiple directions: high-speed, low-power, and low loss for various demands. As shown in Fig. 1, these devices exhibit short switching time (< 2 ns), low loss (< 0.8 dB), and low switching power (< 0.35 mW). The results indicate that SOI switches may be used for applications requesting compact device footprint and below-GHz switching operation.

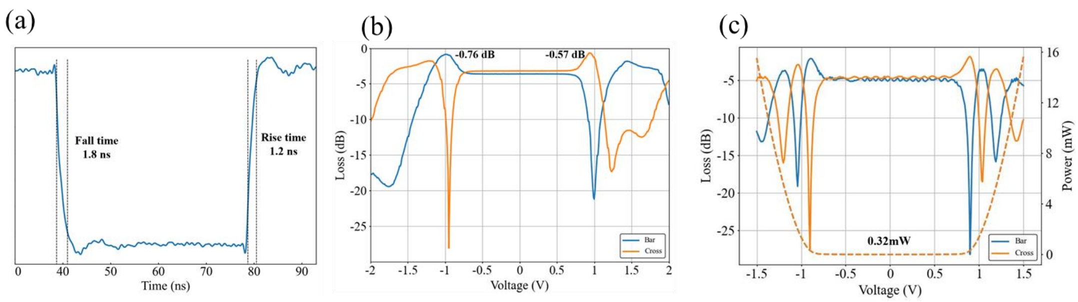

Fig. 1. Measurement results of SOI MZI switch units: (a) high-speed: < 2 ns; (b) low loss: < 0.8 dB; (c) low power consumption: < 0.35 mW.

Recently, TFLN has attracted attentions owing to its fast modulation and low propagation loss. However, there are less reports on TFLN switches, due to its low modulation efficiency and large device footprint. We start our research of TFLN switch on improving its modulation efficiency to shorten its MZI phase-shift arms, as shown in Fig. 2. First, a high TFLN modulation efficiency of 1.41 V·cm (half-wave voltage-length product) was measured by implementing high ε (relative permittivity) material composite cladding to enhance the electric field strength in waveguides and its overlap with optical fields. Subsequently, the modulation efficiency was improved to 1.24 V·cm by introducing optical isolation trenches beside phase-shifters to enhance optical field confinement and shorten the distance between driving electrodes. The measured device modulation speeds are 40 GHz. These designs can be used to shorten MZI phase-shifters and realize future high-density integration of high-speed large-scale photonic switches. TFLN switches are promising in building ultra-fast photonic switches for applications that device size and integration density are not strictly limited.

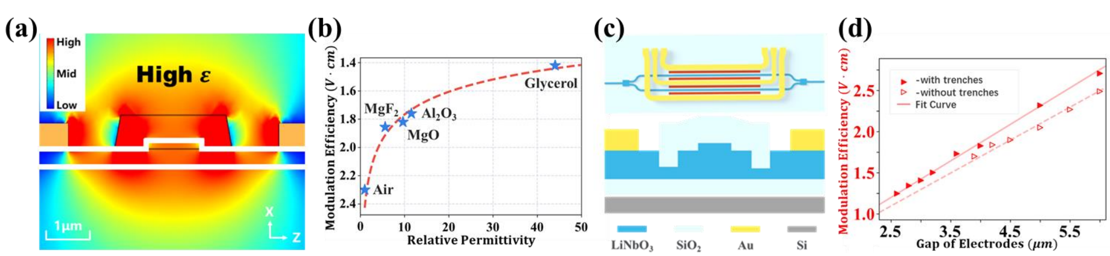

Fig. 2. (a) Simulated z component of microwave field distribution of TFLN phase shifter (cross-sectional view) with high ε material cladding. (b) Measured modulation efficiencies with phase-shifter claddings made of different materials. (c) Schematic and cross-sectional view of phase-shifter with optical isolation trenches. (d) Measured modulation efficiencies of devices with and without optical isolation trenches.

2.4. Large-scale photonic switches

Using commercial silicon photonic processes, we fabricated EO and thermo-optical (TO) controlling 128 × 128 switches, respectively. As shown in Fig. 3, the 128 × 128 EO switches show a chip footprint of 16.7 × 28.8 mm^2. The device is presently under system testing.

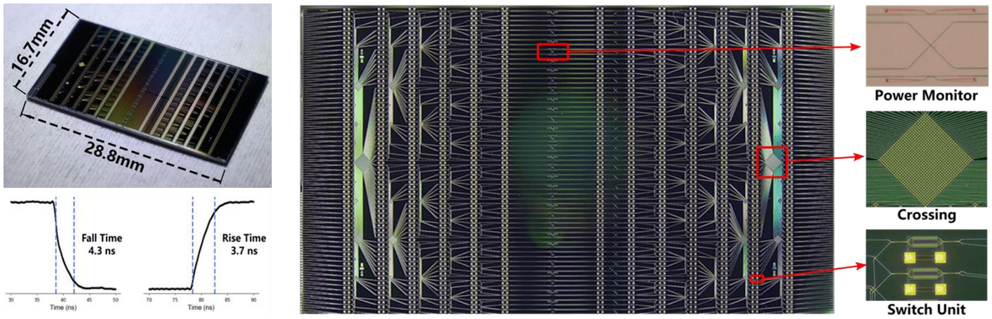

Fig. 3. 128 × 128 EO switches fabricated with commercial silicon photonic processes on SOI substrate, microscopy view of switch chip and measured switching time of its switch unit.

3. Conclusions

By focusing our research on switch key devices of fiber coupling SSCs and GCs, waveguide crossings, and low-loss, high-speed and low-power switch units, as well as integrated large-scale switches, we demonstrated technical improvements on reducing loss and increasing modulation efficiencies with novel designing concepts. We demonstrated mechanical stable none-cantilever type SSCs having TE and TM SMF-coupling losses of around 1.3dB, 1.72-dB-loss grating couplers, 8-mdB-loss planar crossings, ~1.5-mdB-loss 3D bridge crossings, and SOI MZI switch units with short switching time (< 2 ns), low loss (< 0.8 dB), and low switching power (< 0.35 mW). Moreover, we demonstrated TFLN devices with high modulation efficiencies of 1.41 V·cm and 1.24 V·cm by add composite cladding and isolate trenches on their MZI phase-shifters, which indicate the possibilities to fabricate compact fast TFLN switches. Finally, we demonstrate an integrated 128 × 128 large-scale EO switch fabricated with commercial silicon photonic processes on SOI substrates. The results indicate the promising future to construct low-loss large-scale SOI switches and ultra-fast TFLN switches for wide switch applications.

4. References

[1] T. J. Seok, et al., "Large-scale broadband digital silicon photonic switches with vertical adiabatic couplers," Optica 3, 64-70 (2016).
[2] T. J. Seok, et al., "Wafer-scale silicon photonic switches beyond die size limit," Optica 6, 490-494 (2019).
[3] Moriwaki O, et al., "Fast Switching of 84 μs for Silica-based PLC Switch," In Optical Fiber Communication Conference, (Optica Publishing Group, San Diego,2020), pp. Th3B-5.
[4] Dupuis, et al., "An 8× 8 silicon photonic switch module with nanosecond-scale reconfigurability," In Optical Fiber Communication Conference, (Optica Pub mlishing Group, Washington,2020), pp. Th4A.6.
[5] K. Suzuki et al., "Low-Loss, Low-Crosstalk, and Large-Scale Silicon Photonics Switch," In Optical Fiber Communication Conference, (Optica Publishing Group, San Diego, 2019), pp. M3B.2.
[6] L. Qiao, et al., "16x16 Non-blocking Silicon Electro-optic Switch Based on Mach-Zehnder Interferometers", In Optical Fiber Communication Conference, (Optica Publishing Group, Anaheim, 2016), pp. Th1C.2.
[7] R. Konoike, et al., "Polarization-insensitive low-crosstalk 8 × 8 silicon photonics switch with 9 × 13.5 cm2 control board," In 2020 European Conference on Optical Communications, (IEEE, Brussels, 2020), pp. We2C-6.
[8] X. Luo, et al., " High-efficiency grating coupler based on fast directional optimization and robust layout strategy in 130 nm CMOS process," Optics Letters 47, 1622-1625 (2022).
[9] L. Han, et al., " Ultralow-loss waveguide crossing for photonic integrated circuits by using inverted tapers," Optics Express 30, 6738-6745 (2022).