Calibration-free 6 × 6 Mach–Zehnder switch for Optical network-on-chip

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***Abstract*— We have proposed and implemented a calibration-free 2×2 Mach-Zehnder switch (MZS) and a calibration-free 6×6 MZS array, featuring an excess loss of ~2.5 dB and an extinction ratio >20 dB across the C-band without any calibration.**

Keywords—Mach–Zehnder switch, calibration-free, silicon photonics

I. Introduction

The demand for increased datacenter capacity has led to the adoption of photonic interconnect technologies in system architecture. Optical network-on-chip (ONoC) has emerged as a promising solution that offers higher bandwidth and lower power consumption than electrical interconnects, making it highly desirable for high-performance multi-core processors. In cluster Mesh ONoCs or 3D ONoCs, 6-port optical switches are crucial for connecting two cores to a single router [1-3]. Silicon photonics technology has shown promise for large-scale integration of photonic switch networks. However, the performance of switches depends on the selection of topology, which has a significant impact on interconnect connectivity, crosstalk suppression, and switch scalability. Non-blocking Benes switch fabrics have received the most attention, as they require fewer switch cells for scaling up N × N Mach-Zehnder switches (MZSs). Conventional MZS cell designs are prone to size variations during fabrication, leading to random phase errors that require compensated power consumption, extra heating power, and on-chip feedback control schemes. Recently, widened waveguides beyond single mode have been proposed [4], reducing the random phase imbalance of 2 × 2 MZS and considerably reducing compensation power consumption and excess loss.

We optimized tapered Euler S-bends to suppress high-order modes in our 2 × 2 MZS, resulting in reduced phase error and increased extinction ratio. The calibration-free switch has an excess loss of about <1 dB and extinction ratios of >21 dB across C-band without calibration. We also demonstrated a non-blocking 6 × 6 MZS with optimized Spanke-Benes topology, which features low excess loss (~2.5 dB) and high extinction ratio (~20 dB) in the C-band, even without calibration.

II. Design

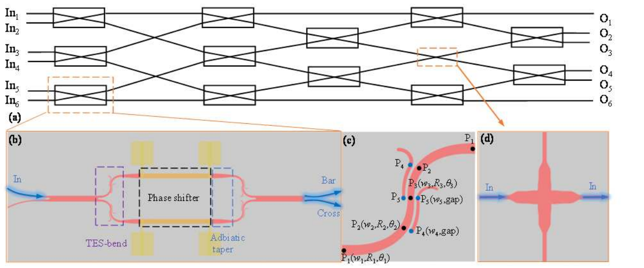

Fig. 1. (a) Schematic of the 6 × 6 MZS. (b) 2 × 2 calibration-free MZS. (c) TES-bend with bent-ADC mode filter. (d) Crossings.

The proposed non-blocking calibration-free 6 × 6 MZS is designed for transverse electric (TE) polarization. Figure 1(a) shows the schematic configuration of the proposed 6 × 6 MZS based on optimized Spanke-Benes topology, which consists of 12 calibration-free 2 × 2 MZS cells and 3 crossings. The element 2 × 2 MZS is consist of two identical 2 × 2 MMI couplers and two arm waveguides, as illustrated in Fig. 1(b). To realize TO switching, the waveguide arms are integrated with TiN micro-heaters. Each arm waveguide is composed of a 2μm-width and 30μm-length phase-shifter, two 10μm-length adiabatic nonlinear tapers, and two tapered Euler S-bends (TES-bends). The TES-bend consists of two identical 90° Euler-bends, which is determined by the radius, local angle, and waveguide widths of P_1 to P_3, as illustrated in our previous work [4]. To further filter out the residual high-order modes (mainly TE_1) from MMI and TES-bends, mode filters based on bent asymmetric directional couplers (ADCs) are introduced, as shown in Fig. 1(c). According to coupling-mode theory, the higher-mode in TES-bend evolves to TE_0 mode in the narrow waveguide, which evidently suppresses the TE_1 mode transmission. The specific parameters of TES-bend are given in Table 1. Figure 1 (d) shows the schematic configuration of the crossings based on 1 × 1 varied-width MMIs [5].

Table 1. The specific parameters of TES-bend. (μm)

R_1	R_2	R_3	θ_1	θ_2	θ_3	w_1	w_2	w_3	gap	w_4	w_5
12	3	10	0	60	90	0.9	0.67	0.5	0.2	0.3	0.22

III. FABRICATION AND MEASUREMENTS

The proposed 2×2 MZS and 6×6 MZS were fabricated on a SOI wafer with a 220-nm-thick top-silicon layer and a 2-μm-thick buried-oxide (BOX) layer using standard 180-nm silicon photonics foundry processes. Figure 2(a) shows the microscope image of the fabricated device. Characterized the fabricated 2×2 MZSs for excess loss and random phase imbalance. Figure 2(b) shows the measured transmissions at the cross/bar port for a representative MZS when sweeping the heater power Q from 0 to 80 mW. It can be find that the compensation power consumption is 1.3mW. Therefore, the random phase imbalance between the two MZS arms was calculated to be 0.06π. The effectiveness of calibration-free operation is additionally confirmed by analyzing the transmission spectra obtained in the calibration-free state, as depicted in Figure 2(c). The fabricated MZS has a low excess loss of < 1 dB and a high extinction ratio of >21 dB across the C-band without calibration. Furthermore, we also measured the transmission spectra of MZS in the ON ($Q = Q_0+Q_\pi$) and OFF ($Q = Q_0$) states, as shown in Fig. 2(d). The extinction ratio of > 26 dB and excess loss < 0.9 dB across the C-band. Overall, the proposed device features low excess loss, high extinction ratio, and random phase imbalance compensation, making it suitable for mass manufacturing in state-of-the-art silicon photonics foundries.

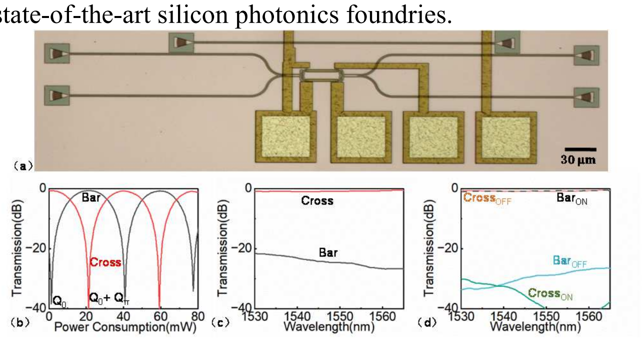

Fig. 2. (a) Optical microscope image of the fabricated 2 × 2 MZS; (b) Measured transmissions at the cross/bar ports for 1550 nm when sweeping the heating power Q from 0 to 80 mW. (c) Measured transmissions at the cross/bar ports of the present MZS without extra heating power (Q = 0). (d) Measured transmissions at the cross/bar ports of the present MZS operating at the Off/On (cross/bar) states.

The 6 × 6 MZSs is composed of 12 elements of 2 × 2 MZI switches and Figure 3(a) shows the microscope image of the fabricated device. By changing the heating power from 0 to Q_0+Q_π, the MZI is switched between "cross" and "bar" states, denoted as "0" and "1," respectively. The transmission spectra of T_{ij} at output port O_j from input port I_i were measured to validate the calibration-free 6 × 6 MZSs, as shown in Fig. 3(b). The on-chip insertion loss is ~2.5 dB, and the extinction ratio for all ports is >20 dB across the wavelength range from 1530 nm to 1565 nm at the (000|000|00|00|00) state without any calibration for 12 MZSs. The calibration-free feature of the device greatly simplifies the calibration processes, especially for N × N MZSs that have a large number of 2 × 2 MZSs, and significantly reduces the power consumption for phase-imbalance compensation. The transmission spectra of the 6 × 6 switch at the (111|111|11|11|11) state are shown in Fig. 3(c). In this state, the signals from input ports I_1~ I_6 are routed to output ports O_1, O_4, O_2, O_5, O_3, and O_6, respectively, with low excess losses of < 2.5dB and high extinction ratios of >23 dB, which is similar to the calibration-free states.

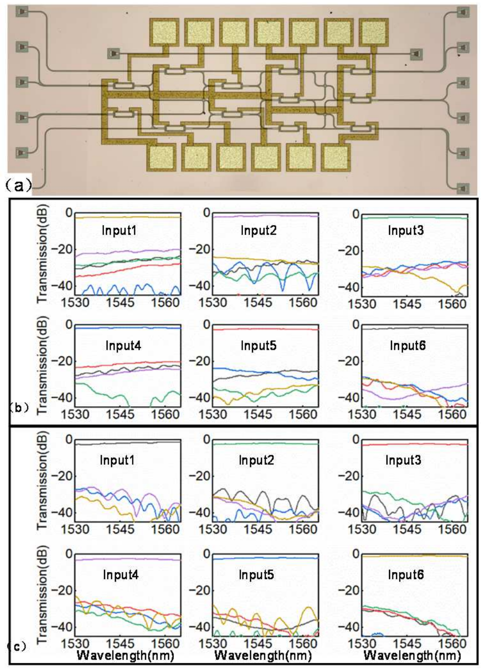

Fig. 3. (a) Microscope image of fabricated 6 × 6 switch chip. (b) Measured transmission spectra T_{ij} at (000|000|00|00|00) state. (c) Measured transmission spectra of 6 × 6 MZS at (111|111|11|11|11) state.

IV. CONCLUSION

We have proposed an optimized calibration-free 2 × 2 MZS that is suitable for mass manufacturing in state-of-the-art silicon photonics foundries. By particularly adjusting the MZI arm waveguides and incorporating TES-bends, the phase imbalance can be significantly reduced, resulting in a 2 × 2 MZS with high extinction ratios >21 dB and low excess loss <1dB across the C-band, even without calibration. Additionally, we have demonstrated a calibration-free 6 × 6 MZS based on the proposed 2 × 2 MZSs with optimized Spanke-Benes topology. The measurement results show that the 6 × 6 MZS has an excess loss of about 2.5 dB and extinction ratio ~20 dB across the C-band without any calibration.

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