Fabrication-Tolerant High-Speed 5-bit Silicon Optical True Time Delay Line In the O-band

Ziheng Ni[1, 3], Yixuan Wang[1, 3], Liangjun Lu[1, 2,*], Yuanbin Liu[1], Jianping Chen[1, 2] and Linjie Zhou[1, 2]

[1]State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

[2]SJTU-Pinghu Institute of Intelligent Optoelectronics, Pinghu, 314200, China

[3]These authors contributed equally.

**luliangjun@sjtu.edu.cn*

Abstract: We demonstrated a high-speed 5-bit silicon optical true time delay line based on fabrication-tolerant electro-optic push-pull optical switches, which shows a lower phase deviation and a lower insertion loss compared with the conventional design.

1. Introduction

Optical beamforming networks (OBFNs) utilizing optical true time delay lines (OTTDLs) to realize microwave phase shift offer significant advantages including ultra-wide bandwidth, low loss, and immunity to electromagnetic interference [1]. Fast reconfiguration time of several nanoseconds is highly demanded for various applications, such as target detection and tracking, mobile communications, etc. Besides, due to the low fiber dispersion in the O-band, it is promising to combine OBFNs with analog radio-over-fiber systems [2]. Therefore, fast-tunable OTTDLs working in the O-band is the key component. With the rapid development of silicon photonic technologies, silicon-integrated microwave photonic beamformers offer significant advantages in terms of size, weight, and power (SWaP) reduction [3]. Among various structures, OTTDLs composed of cascaded optical switches have been widely used [4]. However, free-carrier absorption in the fast electro-optic (EO) switching not only increases insertion loss but also the crosstalk. In addition, imperfect fabrication induces random phase errors in the optical switches, which induces more complex calibration for large-scale OBFNs.

In this paper, we devise a novel push-pull EO Mach-Zehnder interferometer (MZI) switch with a three-section waveguide design to reduce the random phase variation. A fabrication-tolerant silicon 5-bit OTTDL with high switching speed in the O-band is demonstrated using the proposed switches. To the best of our knowledge, this is the first demonstration of a fast OTTDL in the O-band.

2. Device Design

Figure 1(a) shows the schematic structure of the proposed fabrication-tolerant EO push-pull switch element. To realize EO switching based on the silicon PIN diodes, the arm waveguides of the MZI are transitioned to ridge waveguides with linear tapers. To reduce the crosstalk induced by free-carrier absorption, we set the initial phase difference between the two arms to π/2, and thus only π/2-phase shift is required for either of the EO phase shifters to realize fast switching between the cross and the bar states. Each arm waveguide is made of three ridge waveguide sections with different widths (w_1, w_2, and w_3) connected by two linear tapers to introduce a π/2 phase shift. The length differences of the three ridge waveguides between the two arms are ΔL_1, ΔL_2, and ΔL_3, respectively. With the following two equations satisfied, the two arms have an initial π/2 phase difference:

$$\Delta L_1 + \Delta L_2 + \Delta L_3 = 0 \tag{1}$$

$$n_{eff\,1} \cdot \Delta L_1 + n_{eff\,2} \cdot \Delta L_2 + n_{eff\,3} \cdot \Delta L_3 = \lambda / 4 \tag{2}$$

where n_{effi} (i=1, 2, 3) is the effective index of the three ridge waveguides, and λ is the wavelength in the vacuum. To reduce the influence of fabrication-induced width deviation on the phase difference between the two arms, we introduce another equation:

$$\partial n_{eff} / \partial w\Big|_{w=w_1} \cdot \Delta L_1 + \partial n_{eff} / \partial w\Big|_{w=w_2} \cdot \Delta L_2 + \partial n_{eff} / \partial w\Big|_{w=w_3} \cdot \Delta L_3 = 0 \tag{3}$$

which indicates the gradient of the phase difference with respect to the waveguide width is zero.

Figures 1(b) and (c) show the simulated TE_0 mode effective refractive index and $\partial n_{eff}/\partial w$ of the ridge waveguide with the width varying from 0.4 to 3 μm at the 1310 nm wavelength. We can obtain multiple sets of solutions for the widths and length differences that approximately satisfy Eqs. (1)-(3) based on the enumeration method. To maximize the operation bandwidth of the switch, we further employ Eq. (4) to minimize the wavelength-dependent phase difference between the two arms in the wavelength range from λ_1 = 1280 nm to λ_2 = 1340 nm:

$$\Delta\varphi = \left|\Delta\phi_{\lambda=\lambda_1} - \Delta\phi_{\lambda=\lambda_2}\right| \tag{4}$$

where $\Delta\phi$ is the phase difference between the two arms. We select the one with the minimal phase change within the wavelength range as the design parameters.

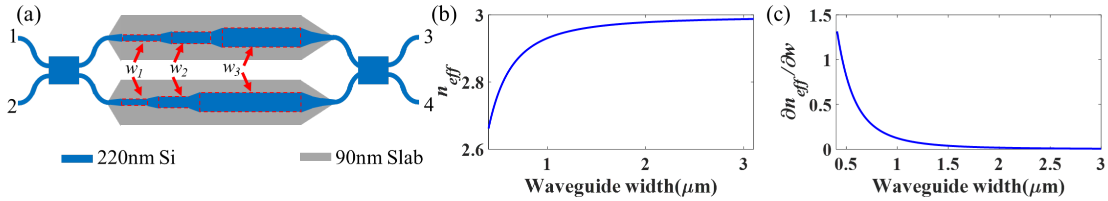

Fig. 1. (a) Schematic of the proposed switch element. (b, c) Simulated (b) n_{eff} and (c) $\partial n_{eff}/\partial w$ of the ridge waveguide at the 1310 nm wavelength.

Figure 2(a) shows the schematic of the OTTDL. It is composed of two stages: a 5-bit switchable tunable delay line at the front and a continuously tunable delay line at the end. In this work, we only characterized the discretely tunable delay line part from Out1 of the OTTDL. The delay step is designed as Δt = 10.13 ps, so the maximum delay is 314.03 ps. The delay waveguides are designed as 2-μm-wide ridge waveguides to reduce the transmission loss and delay errors induced by fabrication deviation [5]. The 5-bit switchable delay line consists of 6 optical switches based on the proposed fabrication-tolerant design. A TiN microheater is integrated on one of the arms for thermo-optic (TO) phase shift, while two PIN-diode-based phase shifters are integrated in both two arms for push-pull EO tuning. By applying a negative or a positive voltage to ports 5 and 6, only one of the PIN-diode-based phase shifters is turned on, enabling push-pull switching. We also insert two variable optical attenuators (VOAs) based on PIN diodes after each pair of the delay waveguides for delay state calibration and crosstalk suppression. To verify the effectiveness of our design, we also designed and fabricated a similar switchable tunable OTTDL but based on conventional 2×2 MZIs with a waveguide width of 0.5 μm for both two arms. Figure 2(b) shows the microscope image of the fabricated chip consisting of these two OTTDLs.

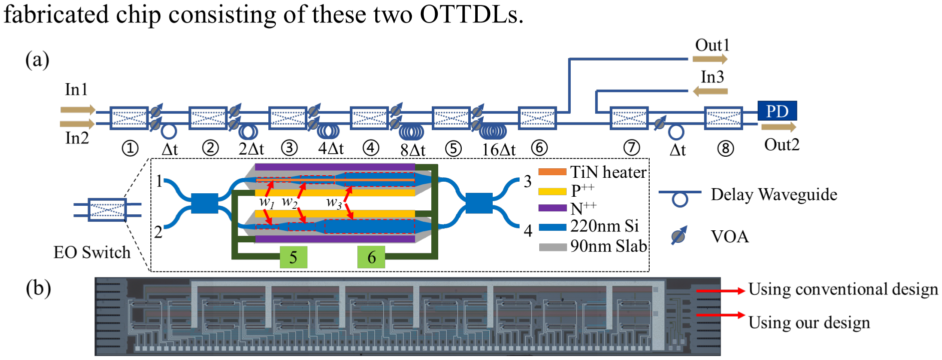

Fig. 2. (a) Schematic of the OTTDL. (b) Microscope image of the fabricated chip.

3. Experimental Results

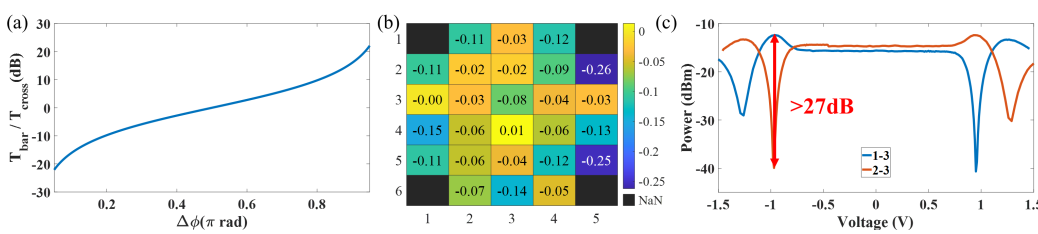

Fig. 3. (a) Transmission ratio (T_{bar}/T_{cross}) between the bar port and the cross port of the switch. (b) Wafer-level test results of the phase difference deviation (π rad) from π/2 for the proposed switch element. (c) Transmission of the switch under the push-pull tuning.

To validate the performance of the proposed fabrication-tolerant optical switch, wafer-level testing was conducted. The initial phase difference of the switch was extracted from the relation between the T_{bar}/T_{cross} ratio and the phase difference as shown in Fig. 3(a). Figure 3(b) shows the measured phased deviation from π/2 of all 26 dies in a passive wafer (without PIN diodes). Except for the devices at the edges of the wafer, the phase differences are almost close to π/2, which validates the high fabrication tolerance of our design. Figure 3(c) shows the measured transmission of paths 1-3 and 2-3 of the MZI switch when the voltage is only applied to the EO phase shifters. The electrical switching voltages for the cross and the bar states are both close to 0.96 V. The extinction ratio is > 27 dB, which is higher than the traditional EO switches by tuning only one phase shifter.

Figures 4(a) and (b) show the normalized optical power curve under various thermal tuning powers on each switch when the other switches are in the bar state for the proposed fabrication-tolerant OTTDL and the conventional OTTDL. The extracted initial phase variation among the 6 MZI switches is ~0.5π for the conventional OTTDL, which is reduced to only ~0.17π for our proposed OTTDL. Figures 4(c) and (d) show the output optical power curves under various voltages on the two EO phase shifters of each switch in both of the OTTDLs. To be noted, TO phase shifters are tuned to adjust the phase difference to π/2 for both OTTDLs in the test. For our proposed device, the electrical switching voltages for the cross and bar states are all near 0.96 V with a variation of 0.03 V. In contrast, the electrical driving voltages range from 0.927 V to 0.978 V for the conventional switches, which also verifies the uniformity of our design. Figure 4(e) shows the measured transmission spectra of the longest delay paths of the two delay lines when VOAs are on and off, respectively. Since our fabrication-tolerant optical switches have a wider waveguide width which reduces the transmission loss, the fiber-to-fiber insertion loss of our proposed OTTDL is only 8.3 dB at the 1300 nm wavelength, which is ~2.54 dB lower than the traditional design. Besides, when the VOAs are turned off, there are more significant ripples appear in the spectrum for the conventional design. Therefore, we further used the VOAs to suppress the crosstalk from the switches. The loss variation of the proposed OTTDL is less than 0.3 dB for all the delay states at the 1300 nm wavelength. Figure 4(f) shows the measured group delay responses of all 32 delay states of the proposed OTTDL when the VOAs are turned on. The delay error is less than 0.25 ps and the delay fluctuation is less than 0.73 ps over the frequency range of 8~43.5 GHz.

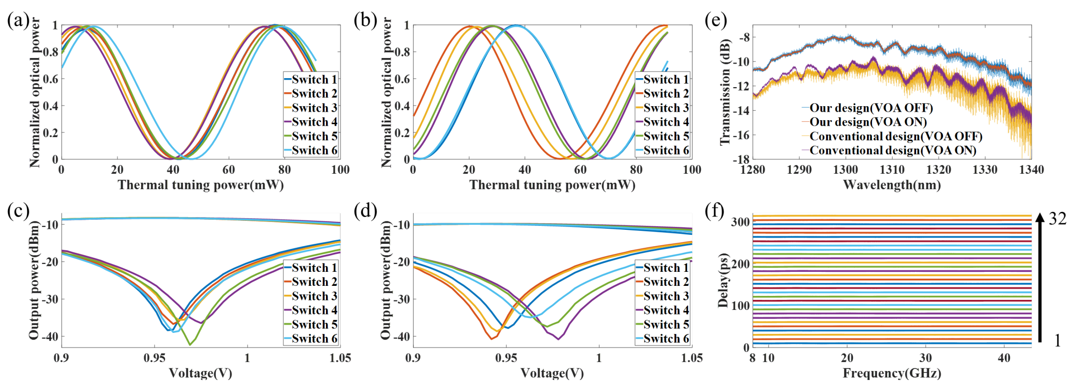

Fig. 4. (a, b) Normalized optical power curves under various thermal tuning powers in (a) the proposed OTTDL and (b) the conventional design. (c, d) Output optical power curves under various voltages of two EO phase shifters of each switch in (c) the proposed OTTDL and (d) the conventional design. (e) Measured transmission spectra of the longest delay path for both OTTDLs. (f) Measured group delay responses of all the 32 delay states of the fabrication-tolerant OTTDL when VOAs are turned on.

4. Conclusion

We proposed a push-pull EO switch element for fast-tunable OTTDLs in the O-band with high fabrication tolerance. With the three-section waveguide design, a π/2 phase difference is introduced between the two arms. Wafer-level test results show a low phase deviation of ~0.1π for most of the measured dies in the passive wafer. In the case of the 5-bit OTTDL, the initial phase variation is only ~0.17π, which is 1/3 of that in the conventional design. Besides, our proposed OTTDL has a low fiber-to-fiber insertion loss of 8.3 dB at the 1300 nm wavelength and a delay tuning range of 0-313.9 ps. The high-performance fabrication-tolerant OTTDLs are promising for applications in fast beamforming in the future.

References

[1] S. Pan et al., "Microwave Photonic Radars," J. Lightwave Technol. 38(19), 5450-5484 (2020).
[2] N. Taengnoi et al., "Coherent O-band Transmission of 4×25 GBd DP-16QAM Channels Over a 50 km BDFA-Equipped Link," in Proc. OFC 2023, Th3F.5.
[3] C. Zhu et al., "Silicon integrated microwave photonic beamformer," Optica 7(9), 1162-1170 (2020).
[4] S. Idres et al., "Optical Binary Switched Delay Line based on Low Loss," in Proc. OFC 2022, Th1D.2.
[5] Z. Ni et al., "Silicon-Integrated 8-Channel 6-bit Tunable Optical True-Time Delay Lines with High Switching Speed and Low Loss," in Proc. MWP 2023.