Fast-response, energy-efficient thermo-optic silicon phase shifter based on non-Hermitian engineering

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Abstract: We present a fast response, energy-efficient thermo-optic silicon phase shifter based on Non-Hermitian engineering. A 729 kHz bandwidth and an 11.3 mW π-phase-shift (Pπ) power consumption are demonstrated at 1550 nm wavelength.

1. Introduction

Phase shifters are among the fundamental building blocks for integrated photonics. They enable active control of many complicated on-chip systems, including optical computing [1], integrated spectrometers [2, 3], and optical switches [4, 5]. Phase shifter based on thermal-optic (TO) effect is intensively investigated due to its low-loss and easy-to-fabrication compared with other kinds of phase shifters [6]. However, the heating electrodes always introduce optical loss into the phase shifter, which prevents further reducing the gap between the waveguide and the metal heater. The large gap inevitably impedes heat conduction, leading to high power consumption [7]. For a conventional TO phase shifter, a trade-off between optical loss and heating efficiency is inevitable. Air trench or organic material has been introduced in attempts to reduce the heat dissipation but at the cost of speed [8].

Recent explorations of Non-Hermitian photonics based on parity-time-symmetry offer a novel approach to device engineering [9]. In this paper, we propose a Non-Hermitian engineered TO phase shifter, leveraging the loss from the metallic heater to broke the parity-time-symmetry and achieve a fast response and high efficiency. Asymmetric Mach-Zehnder interferometer (aMZI) is used to experimentally verify the improvement of modulation performance. The characterization results show the rise time and fall time of 0.464 and 0.496 µs, respectively, corresponding to a bandwidth of 729 kHz, and a π- phase-shift (Pπ) power consumption of 11.3 mW.

2. Design

The schematic and the cross-section of the non-Hermitian engineered phase shifter are shown in Fig. 1(a) and (b), respectively. The whole phase shifter is based on an asymmetrical direction coupler (aDC) configuration, of which the two waveguides are 220 nm thick, and the left and right waveguides are 500 nm and 300 nm wide, respectively. Here, the left wide waveguide is for light propagation and the right Si region is a thin waveguide with a metallic heater on top. There is a 70 nm thick silicon slab between the two waveguides to increase the coupling and help heat conduction from the right waveguide to the left one. Conventional design requires the gap between the metallic heater and the waveguide to be larger than 1.5 µm to avoid the excess loss from the metal. This restriction greatly limits the energy efficiency and the dynamic response. However, using the non-Hermitian theory, for our aDC case, when properly design the ratio between the coupling strength and the loss in the right thin waveguide beyond the exception point (EP), shown in Fig. 1(c), the propagation mode in the left waveguide, shown in Fig. 1(e), could experience a counterintuitive loss enhanced transmission, namely higher loss from the right waveguide could actually reduce the propagation loss of the mode in the left waveguide. We thus choose 150 nm thick gold on top of the thin waveguide as our heater to introduce higher loss to guarantee the device operate in the region beyond the EP. After that, we optimize the gap to further reduce the loss of the left guiding mode. When the gap is larger than 300 nm, the metal-induced loss on the propagation mode is about 0.3 dB/cm as shown in Fig. 1(d). Considering our phase shifter is only 100 µm long and the insertion loss is negligible in this case, we thus set the gap to 300 nm for fast response. The optimized phase shift has a theoretical π-phase-shift power of 7.9 mW. The corresponding simulated temperature distribution is plotted in Fig. 1(f).

We designed and fabricated an asymmetrical TO modulator in MZI configuration with the heater on one arm. Fig. 2 is the optical image of the MZI modulator. A 50:50 Y-junction splits the input light into two arms. The upper waveguide run near the metal heater and the heating length is about 100 µm. As a result, the light wave of different wavelengths traveling through two arms of MZI has different phases, results in the constructive/destructive interference at the output 50:50 Y-junction. When the heating power is applied, the interference dips will shift. To avoid the scattering loss caused by abrupt waveguide section changing, we add a taper between the 500 nm wide strip waveguide and the phase shifter, as shown in the inset of Fig. 2.

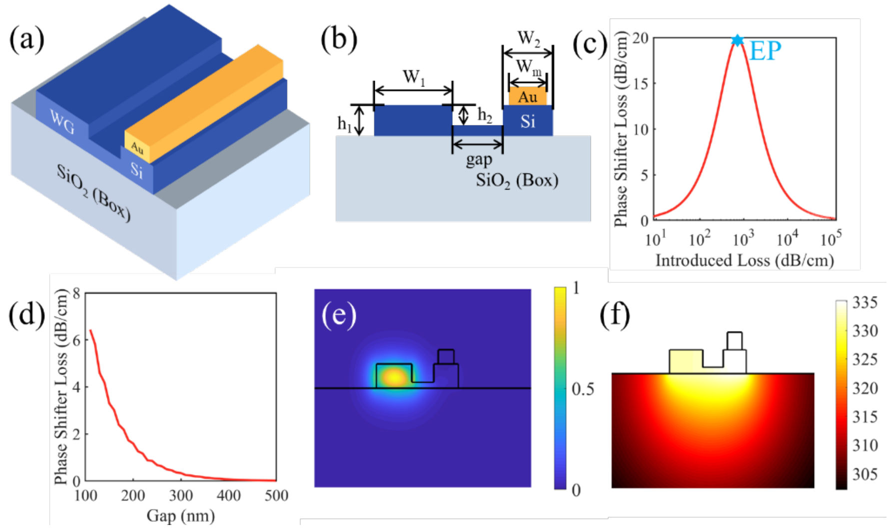

Fig. 1. Schematic (a) and cross-section view (b) of the proposed phase shifter. W_1=500 nm, W_2=300 nm, W_m=300 nm, *gap*=300 nm, h_1=220 nm, h_2=150 nm. Calculated loss of the proposed phase shifter under different introduced losses on the right thin waveguide (c) and different gaps (d). (e) Simulated optical mode profile inside the phase shifter. (f) Simulated temperature distribution of the phase shifter at a driving power of 7.9 mW.

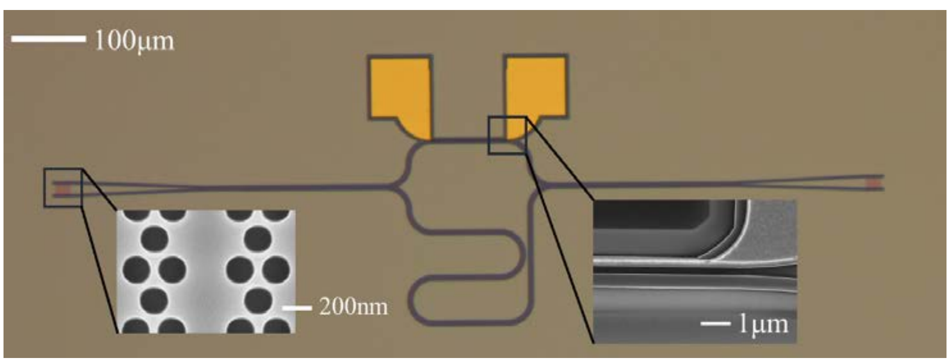

Fig. 2. Optical image of the aMZI. Inset shows the zoom-in SEM images of the photonic crystal grating coupler (left) and the phase shifter (right).

3. Results

Switching power characterization: For static measurement, optical signal from an amplified spontaneous emission source (Thorlabs ASE730) goes through a polarization controller and grating (inset of Fig. 2) coupled into our device. The output light is also grating coupled out and send to an optical spectrum analyzer (YOKOGAWA AQ6376). An adjustable power supply is used to apply driving voltage and monitor the current flow. The interference dips shift of the device can be obtained. Fig. 3(a) shows the normalized output spectra, which are calculated by subtracting the MZI output from the reference waveguide. The insertion loss of the phase shifter is less than 1 dB, the extinction ratio (ER) is about 18 dB, and the free spectra range (FSR) for the asymmetric MZI is 1.072 nm. When applying different heating powers, and the spectra blue shift. The energy efficiency can be calculated by linear fitting the interference dips shift under different driving voltages, which is shown in Fig. 3(b). The energy efficiency η is 0.0473 nm/mW. With energy efficiency and FSR, the Pπ (Pπ=FSR/2/η) is calculated to be 11.3 mW. This result is slightly higher than our simulation which is about 7.9 mW, which is probably caused by an inferior attachment of the metal heater.

Dynamic characterization: C-band narrow-linewidth tunable laser (Keysight 8164B) is employed to fix the wavelength at 1550.7 nm. The output light from the grating coupler is sent to a photodetector (Thorlabs PDA10CF-EC), and the modulated signal is recorded by an oscilloscope. In this way, we obtain the rise and fall time. The dynamic response of the MZI modulator was characterized in time domain. Fig. 3(c) shows the input voltage signal and the measured output signal from the photodetector when the modulation frequency is 100 kHz and the duty cycle of 50%. The 10%-90% rise time and 90%-10% fall time are 0.464 and 0.496 μs, respectively, corresponding to 729 kHz, which is among the fastest TO modulators ever reported. For ease of comparison, a figure-of-merit (FOM) could be defined as $1/(P\pi\cdot\tau)$, in which $P\pi$ is the π-phase-shift power and τ is the response time (choose the longer τ if the rise time and fall time are not identical as the longer response time limits the dynamic performance). The FOM of our device is calculated to be 0.178 $mW^{-1}\mu s^{-1}$.

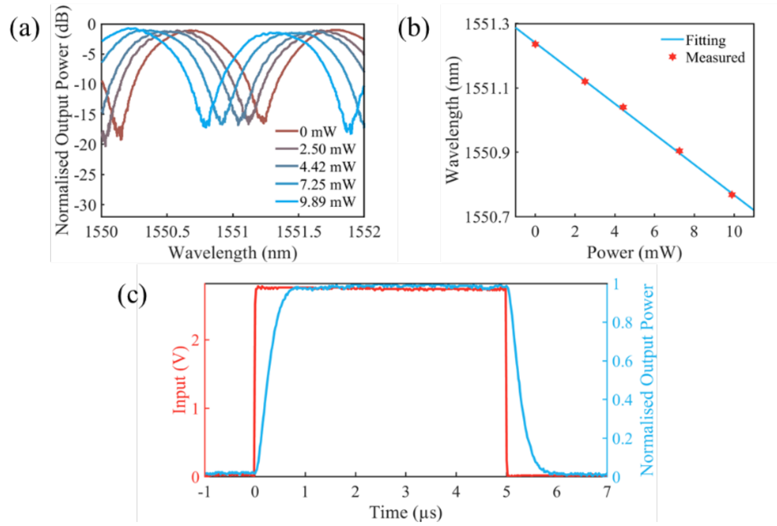

Fig. 3. (a) Normalized output power from the aMZI under different driving powers. (b) The wavelength shifts of the interference dip of the modulator with the heating power. (c) Dynamic response of the aMZI.

4. Conclusion

In conclusion, we applied non-Hermitian engineering on a TO phase shifter to bring the speed of the device to a sub-μs level. The MZI configuration device shows the rise time and the fall time to be 0.464 μs and 0.496 μs, corresponding to a bandwidth of 729 kHz, which is among the fastest TO modulators ever reported. Pπ for this device is down to 11.3 mW. A FOM of 0.178 $mW^{-1}\mu s^{-1}$ is achieved, which is also among the highest FOM ever reported. By applying our approach to other types of phase shifters, such as resonators, suspended phase shifters, et al., we can further reduce Pπ to a sub-mW level.

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