A compact 2×2 optical gate using a silicon photonic MEMS dual-drive directional coupler

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ABSTRACT

Reconfigurable optical gates control power and phase in programmable photonic circuits. However, state-of-the-art optical gates are power-hungry due to using heaters and large due to using Mach-Zehnder Interferometers. Here, we demonstrate a compact low-power optical gate based on a silicon photonic MEMS dual-drive directional coupler.

Keywords: Silicon photonics, MEMS, photonic MEMS, optical gates, programmable photonics

1. INTRODUCTION

Programmable photonic circuits are emerging as a versatile optical processing platform for microwave photonics, quantum information processing, and machine learning.[1] A 2×2 analog gate is the fundamental building block for such programmable photonic circuits, providing control over both power coupling ($0 - 100\%$) and phase delay (2π) from any input to any output. These devices typically employ a balanced Mach-Zehnder Interferometer (MZI) with a phase shifter in each arm. Thermal phase shifters fulfill the 2π requirement with <0.5 dB insertion loss but consume over a mW of driving power per device.[2] Alternatively, MEMS phase shifters can provide similar optical performance with essentially no static power consumption,[3,4] but the additional fabrication complexity has limited their adoption. In both cases, using multiple discrete components for a single optical gate results in longer optical lengths, and the insertion losses add up. Perez-Lopez et al. demonstrated an MZI-free optical gate based on a single tunable dual-drive directional coupler (DDDC) using two heaters.[5] Still, the device consumes over 100 mW and requires mm-long coupling sections to provide sufficient asymmetric effective index tuning. Here, we demonstrate a compact 2×2 optical gate using a single tunable directional coupler with dual MEMS actuation to control both power and phase. The two MEMS actuators tune the effective indices of the suspended waveguides without any crosstalk, enabling large tuning of the index difference with a short coupler length of 50 µm. We have implemented the MEMS-based optical gates on IMEC's silicon photonics foundry platform iSiPP50G with only a few post-processing steps. We show independent tuning of phase and power coupling. The demonstrated compact MEMS device can significantly increase the density of optical gates in programmable photonic circuits while decreasing their power consumption.

2. DESIGN

Our compact silicon photonic MEMS optical gate is presented in Fig. 2. The device comprises two symmetric suspended waveguides anchored to each side of the MEMS opening and two movable comb-drive actuators symmetrically placed on each side of the two waveguides. The actuators can tune the effective indices of the suspended waveguides by moving a slender silicon perturber within the evanescent field of the waveguide cores. The electromechanical design of the comb-drive actuators is similar to our previous work on a silicon photonic MEMS phase shifter.[6] The device is, therefore, a directional coupler, where the effective indices of the two

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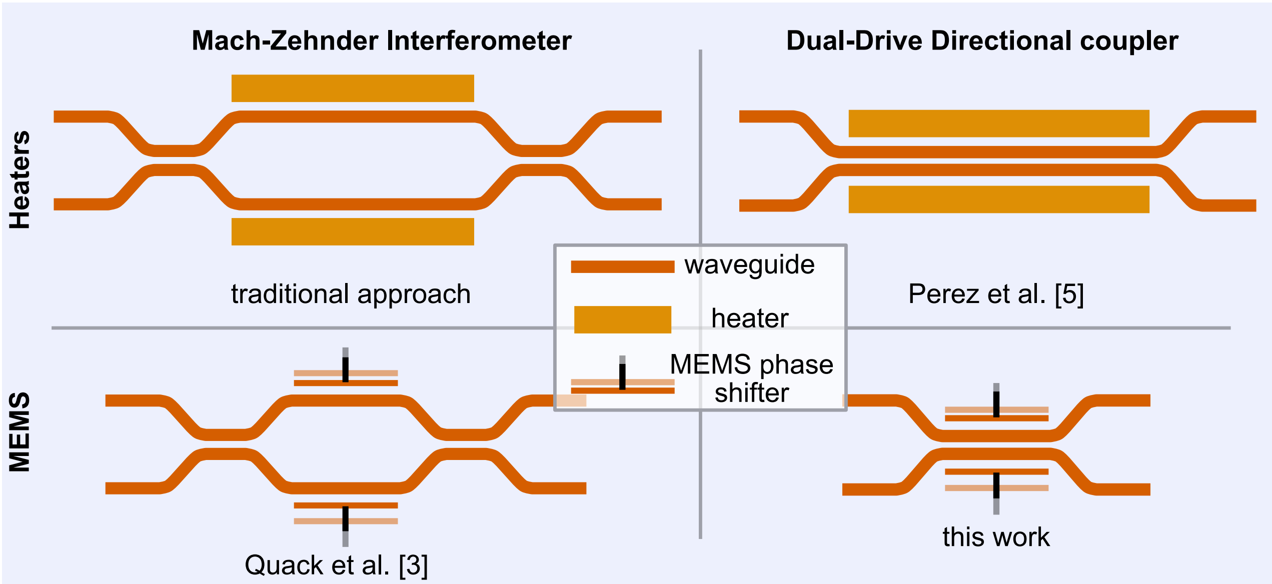

Figure 1. Overview of 2×2 analog optical gates for programmable silicon photonic circuits. Mach-Zehnder-Interferometers offer broadband operation but require multiple sub-components, thus increasing optical length, wafer footprint, and light losses. Dual-drive directional couplers are compact but narrowband. Heaters are well-established but power-hungry, while MEMS consume very little power but are not available yet in foundries.

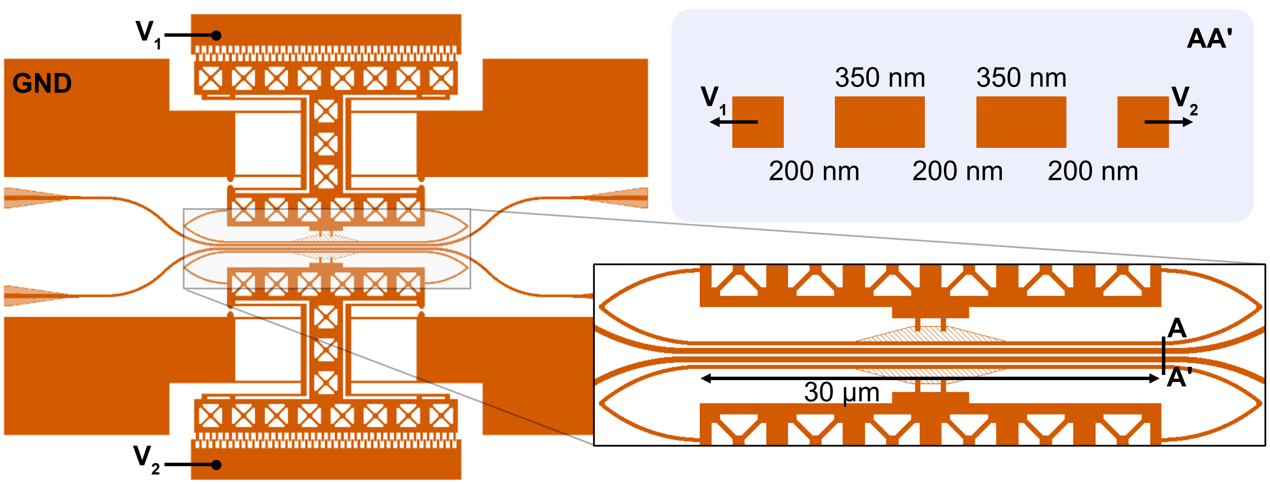

Figure 2. Design of our silicon photonics MEMS dual-drive directional coupler (DDDC). The device is built around two symmetric suspended waveguides anchored to each side and two movable MEMS comb-drive actuators symmetrically placed on each side of the two waveguides. The actuators can tune the effective indices of the suspended waveguides by moving a slender silicon perturber within the evanescent field of the waveguide cores. The inset shows a cross-section through the perturbers and waveguides.

coupled waveguides can be independently tuned. The device can either provide a phase shift, a change in power coupling, or both, depending on the configuration of the two actuators.

We note that the maximum optical power that can be transferred decreases as the directional coupler asymmetry increases.[7] This translates into an optical insertion loss that depends on the actuation, which is undesirable. A trade-off between asymmetry and acceptable variable loss has to be reached. Moreover, the coupling coefficient varies with wavelength due to the dispersion of the directional coupler.

3. FABRICATION

We implemented the devices on the silicon photonics platform iSiPP50G from IMEC; see sketch cross-section in Fig. 3(a). All the design and layout were done using the standard Process Design Kit (PDK) provided by the foundry, and no modifications to the process flow were done to implement the photonic MEMS optical gates. However, the platform does not include MEMS processing. For the release of the MEMS components, we performed three main post-processing steps: (i) bHF etching to remove the planarization oxide above the MEMS, (ii) Atomic Layer Deposition (ALD) and patterning of alumina, and (iii) vHF etching of the sacrificial BOX layer to release the MEMS components.[3] The final cross-section is sketched in Fig. 3(b).

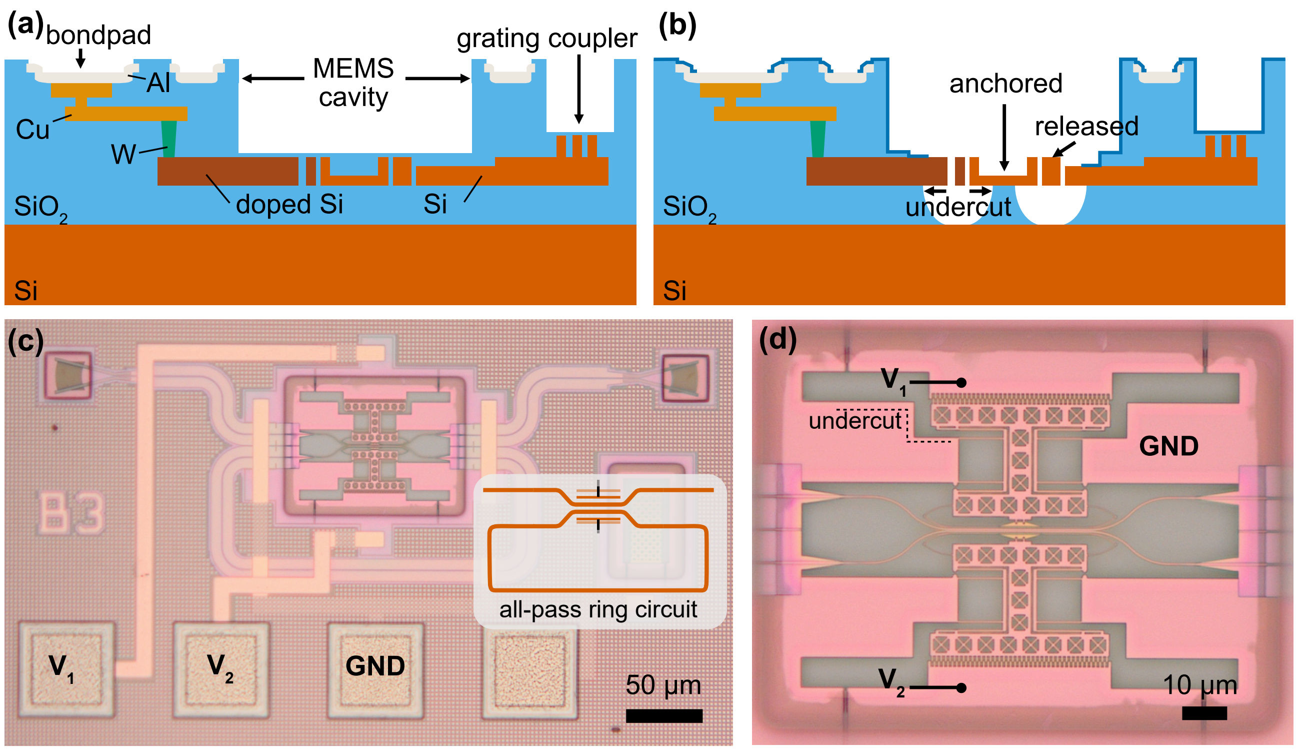

Figure 3. Implementation of the device on IMEC's iSiPP50g platform. (a) Device sketch cross-section after foundry processing. (b) Device sketch cross-section after vHF release. (c) An optical microscope top view of the device, tested as a coupler to an all-pass ring resonator. (d) Zoom-in top microscope view of the fabricated device.

We used standard PDK waveguides and grating couplers from the platform to design simple all-pass ring resonators as a testing circuit; see Fig. 3(c). Only the MEMS component uses suspended waveguides, while the test circuit uses oxide-clad strip waveguides. The comb-drive electrodes and the suspended waveguides are connected to bond pads using doped silicon and low-resistance metal layers.

4. MEASUREMENTS

The characterization results are presented in Fig. 4. The optical spectrum displays interference fringes corresponding to the optical length of the ring resonator circuit. The extinction ratio of the fringes varies from 0 dB to more than 30 dB over the measured wavelength range, corresponding to the wavelength-dependent coupling ratio of the directional coupler. By applying a voltage bias to either pad 1, pad 2, or both pads simultaneously, the extinction ratio and position of individual peaks can be tuned. If we look at the full spectrum, the extinction ratio distribution shifts to shorter wavelengths, confirming a change in the coupling coefficient over a large wavelength range. The individual voltage biases also result in a small phase shift, measured as a resonance shift using the ring resonator circuit. A two-dimensional mapping of the voltage biases over the full wavelength range

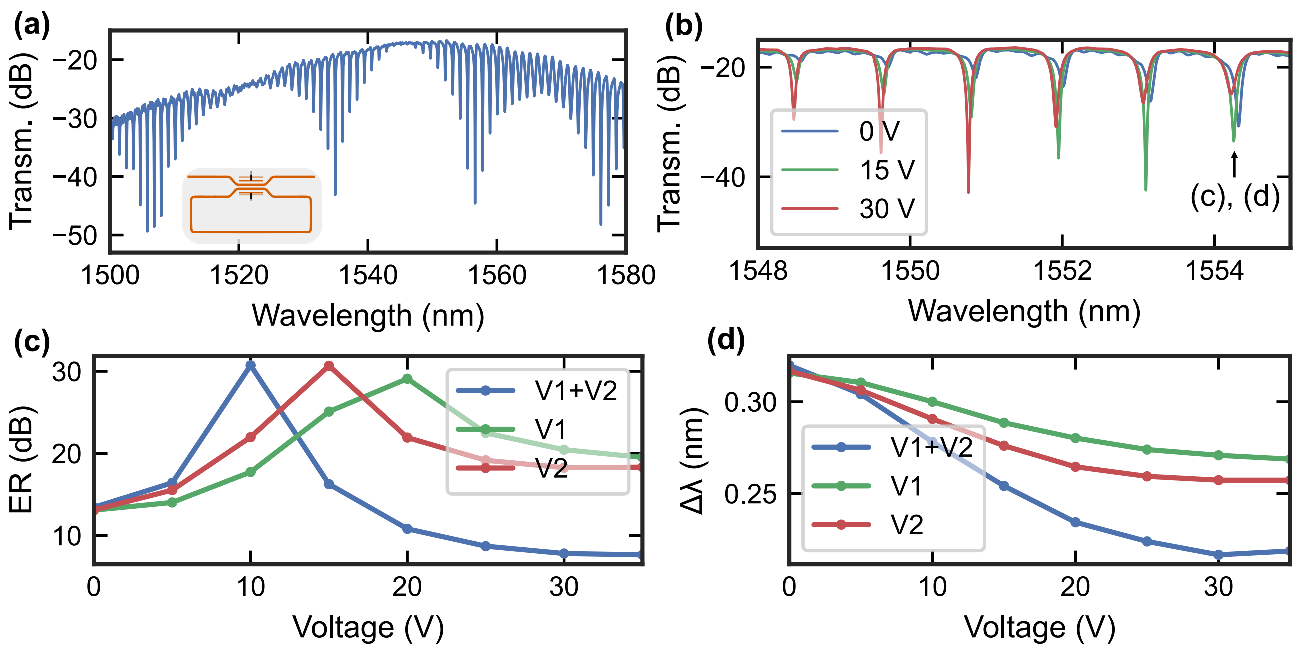

Figure 4. Measurement results for the MEMS DDDC tested as a tunable all-pass ring resonator. (a) Passive transmission of the circuit over the wavelength range 1500 to 1580 nm. (b) Example of tuning of the optical transmission for multiple resonances. The biases were applied to both pads simultaneously. (c) Extinction ratio and (d) resonance shift at a wavelength of 1550 nm with biases V_1, V_2, and simultaneous $V_1 + V_2$ up to 35 V.

would be needed to characterize the optical gate fully. Unfortunately, such multi-dimensional characterization requires long and automated measurements, and we could not obtain such a map for the measured device.

5. CONCLUSIONS

We have presented a compact photonic MEMS 2×2 optical gate for programmable photonic circuits. The optical gate is compact because it uses a single tunable coupler instead of the conventional MZIs composed of two passive splitters and two active phase shifters. It still provides independent tuning over the phase and power coupling using two MEMS actuators to independently tune each suspended waveguide's effective index. We implemented the devices on a silicon photonics foundry platform and experimentally demonstrated phase shifting and power coupling. However, additional measurements and design improvements are needed to demonstrate independent $0 - 100\%$ power coupling tuning and 2π phase shift, both needed for a fully functional 2×2 analog gate. Still, the proposed device can benefit photonic circuits by significantly reducing the circuit footprint at the cost of optical bandwidth.

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REFERENCES

[1] Bogaerts, W., Pérez, D., Capmany, J., Miller, D. A. B., Poon, J., Englund, D., Morichetti, F., and Melloni, A., "Programmable photonic circuits," *Nature* **586**, 207–216 (Oct. 2020). Number: 7828 Publisher: Nature Publishing Group.

[2] Liu, S., Feng, J., Tian, Y., Zhao, H., Jin, L., Ouyang, B., Zhu, J., and Guo, J., "Thermo-optic phase shifters based on silicon-on-insulator platform: state-of-the-art and a review," *Frontiers of Optoelectronics* **15**, 9 (Apr. 2022).

[3] Quack, N., Takabayashi, A. Y., Sattari, H., Edinger, P., Jo, G., Bleiker, S. J., Errando-Herranz, C., Gylfason, K. B., Niklaus, F., Khan, U., Verheyen, P., Mallik, A. K., Lee, J. S., Jezzini, M., Zand, I., Morrissey, P., Antony, C., O'Brien, P., and Bogaerts, W., "Integrated silicon photonic MEMS," *Microsystems & Nanoengineering* **9**, 27 (Mar. 2023).

[4] Kim, D. U., Park, Y. J., Kim, D. Y., Jeong, Y., Lim, M. G., Hong, M. S., Her, M. J., Rah, Y., Choi, D. J., Han, S., and Yu, K., "Programmable photonic arrays based on microelectromechanical elements with femtowatt-level standby power consumption," *Nature Photonics* **17**, 1089–1096 (Dec. 2023). Number: 12 Publisher: Nature Publishing Group.

[5] Pérez-López, D., Gutierrez, A. M., Sánchez, E., DasMahapatra, P., and Capmany, J., "Integrated photonic tunable basic units using dual-drive directional couplers," *Optics Express* **27**, 38071–38086 (Dec. 2019). Publisher: Optica Publishing Group.

[6] Edinger, P., Takabayashi, A. Y., Errando-Herranz, C., Khan, U., Sattari, H., Verheyen, P., Bogaerts, W., Quack, N., and Gylfason, K. B., "Silicon photonic microelectromechanical phase shifters for scalable programmable photonics," *Optics Letters* **46**, 5671–5674 (Nov. 2021).

[7] Chrostowski, L. and Hochberg, M., [*Silicon Photonics Design: From Devices to Systems*], Cambridge University Press, Cambridge (2015).