Microdisk-Based Full Adders for Optical Computing in Silicon Photonics

Zhoufeng Ying [1], Zheng Wang [1, 2], Zheng Zhao [1], Shounak Dhar [1], David Z. Pan[1], Richard Soref [3] and Ray T. Chen[1, 2, 4*]
[1]Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78712, USA
[2]Materials Science and Engineering Program, Texas Materials Institute, The University of Texas at Austin, Austin, Texas 78712, USA
[3]Department of Engineering, University of Massachusetts Boston, Boston, Massachusetts 02125, USA
[4]Omega Optics, Inc., 8500 Shoal Creek Blvd., Bldg. 4, Suite 200, Austin, TX 78757, USA.
**e-mail address: chenrt@austin.utexas.edu*

Abstract: We experimentally demonstrate a two-bit thermal-optic ripple-carry full adder based on microdisk resonators in silicon photonics with the advantages of large bandwidth, low power consumption, and high scalability, paving the way to future optical computing.

OCIS codes: (200.4660) Optical logic; (250.3750) Optical logic devices; (130.3120) Integrated optics devices

1. Introduction

Due to the projected saturation of Moore's law as well as the drastically increasing trend of bandwidth with lower power consumption, silicon photonics has emerged as one of the most promising alternatives that has attracted a lasting interest due to the accessibility and maturity of ultra-compact passive and active integrated photonic components [1]. Electro-optic logic gates and modules [2], as the building blocks of optical computing, have gained intensive attention recently with various compact optical components, such as electro-optic switches or modulators [3], interconnects [4,5] and photodetectors. Several silicon-based optical logic devices have been proposed and demonstrated experimentally, showing the potential for realizing future chip-based high-speed and low-power consumption optical computing [6].

We propose a new design of an electro-optic (EO) full adder on the silicon-on-insulator (SOI) platform, where each carry bit ripples to the next full adder directly through single-mode optical waveguides. Thus, the electrical latency caused by the relatively low speed of on-chip electrons can be drastically reduced. Every bit of this full adder utilizes two silicon microdisk resonators. To demonstrate the proposed architecture, a two-bit thermal-optical (TO) full adder is experimentally demonstrated as a proof of concept with some computation functions demonstrated.

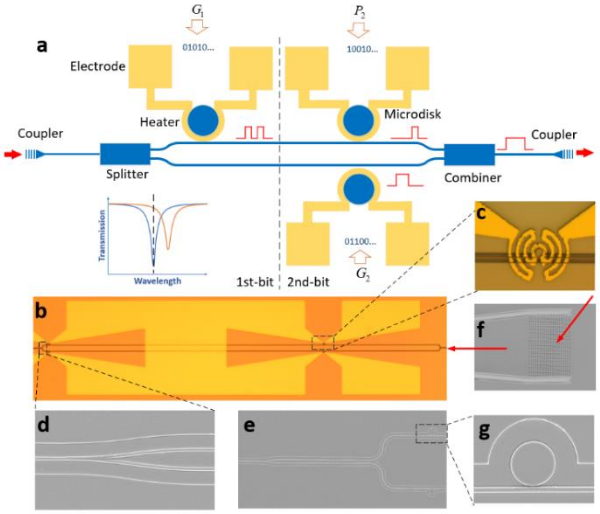
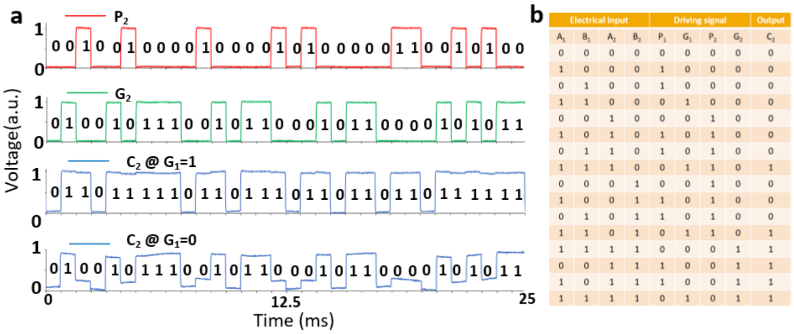


Fig 1. (a) Schematic diagram of a two-bit full adder. The inset shows that the induced resonance shift generates the optical "1" and "0". (b-c) Microscope photograph of the two-bit TO full adder and zoom-in pictures of metallic heaters. (d-g) The SEM pictures of the splitter/combiner, the combination of splitter and modulators, the grating coupler, and a microdisk with a radius of 2.5 µm.

2. TO full adders

The theory and simulation results have been discussed in [7]. Here in experiment, microdisk modulators with small footprint and low power dispassion are adopted as the EO modulators for our proposed full adders for computation so as to achieve a compact, high-speed and low-power-consumption (power/bit) EO carry-ripple full adder [3]. Figure 1 shows the schematic diagram and experimental figures of a two-bit TO full adder. First, the light is coupled into the



Electrical input				Driving signal				Output
A_1	B_1	A_2	B_2	P_1	G_1	P_2	G_2	C_2
0	0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0	0
0	1	0	0	1	0	0	0	0
1	1	0	0	0	1	0	0	0
0	0	1	0	0	0	1	0	0
1	0	1	0	1	0	1	0	0
0	1	1	0	1	0	1	0	0
1	1	1	0	0	1	1	0	1
0	0	0	1	0	0	1	0	0
1	0	0	1	1	0	1	0	0
0	1	0	1	1	0	1	0	0
1	1	0	1	0	1	1	0	1
1	1	1	1	0	0	0	1	1
0	0	1	1	1	0	0	1	1
1	0	1	1	1	0	0	1	1
1	1	1	1	0	1	0	1	1

Fig 2. (a) Experimental results of the two-bit TO full adder. (b) Truth table for a two-bit full adder.

full adder through a grating coupler and then split into two parts, serving as the targeted λ for the first and second bit, respectively. After being modulated by several microdisks, light beams from two arms will merge through a combiner to generate the final carry signal. All these operands are applied simultaneously. The operating wavelength is set at the center of the resonance spectrum of these unbiased microdisks, generating an optical "0" at "0" electrical input, as shown in the inset in Fig .1(a). When one applies electrical currents into the modulators, these resonance spectra will redshift due to the thermo-optic effect of silicon and therefore let the light go through to generate the optical "1". The two-bit full adder was fabricated on a silicon-on-insulator (SOI) platform, as shown in Fig .1(b). The waveguide is 450 nm in width and 220 nm in height. Gold micro-heaters have the thickness of 140nm with a separation layer of 1.5 µm SiO2 between heaters and waveguides. All the microdisks including a redundant one called the backup microdisk have radii of 2.5 µm with a gap of 100 nm between the microdisk and the bus waveguide. The quality factors of these microdisks are ~2×104. An amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA) were first used to align all the wavelengths of three microdisks. After the alignment, the source was switched to a tunable laser. The light beam was fed into the chip through grating couplers and then coupled out to a photodetector which was connected to an oscilloscope. Finally, pseudorandom non-return-to-zero (NRZ) sequences were applied independently to these EO modulators which function as the logic gates. The results of the device operating at 2.56 kbs-1 are shown in Fig. 2. All these input digital signals, as well as the sum signals, can be derived from the these carry signals simultaneously by electrical circuits, for example, a field-programmable gate array (FPGA), or integrated CMOS circuits [8]. Figure 2(a) shows the results for the final carry signal at different combinations of inputs, which turned out to be completely consistent with the truth table listed in Fig .2(b).

In conclusion, we proposed a microdisk-resonator-based carry-ripple EO full adder, which utilizes optical components to replace the conventional electrical parts in the critical path to transfer carry signals from one bit to the next. Since the latency of this EO full adder does not accumulate due to the small propagation delay for light on a chip, it will pave the way for the future high-speed optical computing systems. At last, a TO full adder is demonstrated to prove the feasibility and validity.

3. Reference

1. H. Subbaraman, X. Xu, A. Hosseini, X. Zhang, Y. Zhang, D. Kwong, and R. T. Chen, "Recent advances in silicon-based passive and active optical interconnects," Opt. Express **23**, 2487 (2015).
2. R. Soref, J. Guo, and G. Sun, "Low-energy MOS depletion modulators in silicon-on-insulator micro-donut resonators coupled to bus waveguides," Opt. Express **19**, 18122 (2011).
3. E. Timurdogan, C. M. Sorace-Agaskar, J. Sun, E. Shah Hosseini, A. Biberman, and M. R. Watts, "An ultralow power athermal silicon modulator," Nat. Commun. **5**, 4008 (2014).
4. Z. Ying, G. Wang, X. Zhang, Y. Huang, H. P. Ho, and Y. Zhang, "Ultracompact TE-Pass Polarizer Based on a Hybrid Plasmonic Waveguide," IEEE Photonics Technol. Lett. **27**, 201–204 (2015).
5. Z. Ying, G. Wang, X. Zhang, H. Ho, and Y. Huang, "Ultracompact and broadband polarization beam splitter based on polarization-dependent critical guiding condition," Opt. Lett. **40**, 2134 (2015).
6. L. Zhang, J. Ding, Y. Tian, R. Ji, L. Yang, H. Chen, P. Zhou, Y. Lu, W. Zhu, and R. Min, "Electro-optic directed logic circuit based on microring resonators for XOR/XNOR operations," Opt. Express **20**, 11605 (2012).
7. Z. Ying, Z. Wang, S. Dhar, Z. Zhao, and D. Z. Pan, "On-chip Microring Resonator Based Eletro-optic Full Adder for Optical Computing," in *CLEO* (2017), pp. 4–5.
8. C. Sun, M. T. Wade, Y. Lee, J. S. Orcutt, L. Alloatti, M. S. Georgas, A. S. Waterman, J. M. Shainline, R. R. Avizienis, S. Lin, B. R. Moss, R. Kumar, F. Pavanello, A. H. Atabaki, H. M. Cook, A. J. Ou, J. C. Leu, Y.-H. Chen, K. Asanović, R. J. Ram, M. A. Popović, and V. M. Stojanović, "Single-chip microprocessor that communicates directly using light," Nature **528**, 534–538 (2015).

The authors acknowledge the Multidisciplinary University Research Initiative (MURI) program through the Air Force Office of Scientific Research (AFOSR), contract No.FA 9550-17-1-0071 , monitored by Dr. Gernot S. Pomrenke.