Large-Scale Integrated Silicon Photonic Circuits for Optical Phased Arrays

Jie Sun,[1] Ami Yaacobi,[1] Erman Timurdogan,[1] Zhan Su,[1] David B. Cole,[1] Ehsan shah Hosseini,[1]
Michele Moresco,[1] Gerald Leake,[2] Douglas Coolbaugh,[2] and Michael R. Watts [1]
[1]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA 02139
[2]College of Nanoscale Science and Engineering, University at Albany, Albany, NY, USA 12203
Author e-mail address: sunjie@mit.edu

Abstract: We present several optical phased arrays enabled by state-of-the-art large-scale silicon photonic integration which could find potential applications in optical switching, optical communications, light detection and ranging, and holography.

OCIS codes: (130.3120) Integrated Optical Devices; (250.5300) Photonic Integrated Circuits.

1. Introduction

Silicon photonic technology, being inherently compatible with Complementary Metal-Oxide-Semiconductor (CMOS) fabrication techniques, lends itself to large-scale photonic integration. While a variety of high-performance silicon photonic devices have been demonstrated over the past two decades, it is now possible and increasingly desirable to integrate these otherwise discrete optical components to form functional large-scale silicon photonic systems [1]. Successful silicon photonic integration not only greatly reduces the form factor of current optical systems such as the optical transceivers [2] and the optical switch fabrics [3], but also enables optical systems that would not even be possible with bulk optics, such as the large-scale optical phased arrays [4].

Here we present several large-scale integrated optical phased arrays based on silicon photonic circuits, including a uniform 8×8 array and an apodized 8×8 array [5] for optical beam steering, a 64×64 holographic phased array representing the largest silicon photonic circuit to date, and a 1×16 array that demonstrates the widest 51° beam steering angle [6]. These demonstrations of optical phased arrays hold promise for future applications in free-space optical switching, optical communication, light detection and ranging (LIDAR), holography, etc.; moreover, as the largest silicon photonic circuits, they suggest that photonic integration in silicon at the same level as microelectronics is indeed possible and the time for large-scale silicon photonic circuitry has truly arrived.

2. Large-scale optical phased arrays

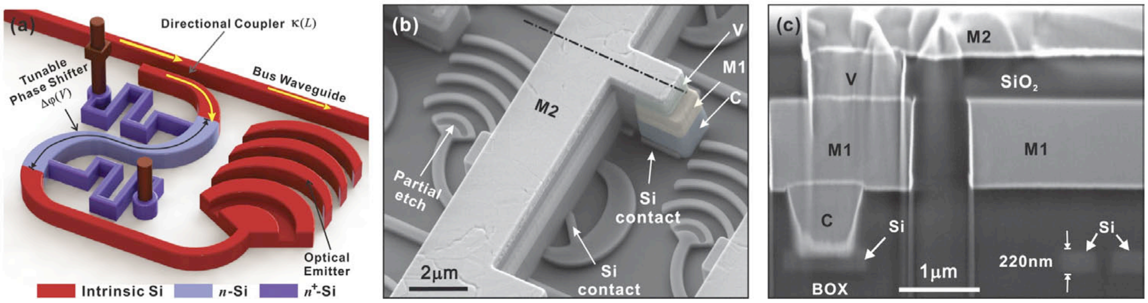
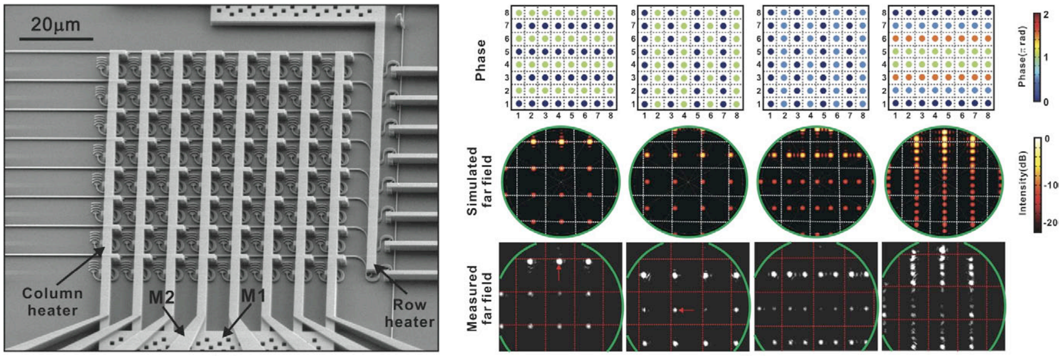


Figure 1. (a) A schematic of the phased array unit cell containing a directional coupler, a tunable phase shifter, and an efficient light emitter. (b) A scanning-electron micrograph (SEM) of the fabricated unit cell with a compact size of 9μm×9μm. (c) A cross-section of the fabricated device, which was cut by focused ion-beam along the dash-dot line in (b).

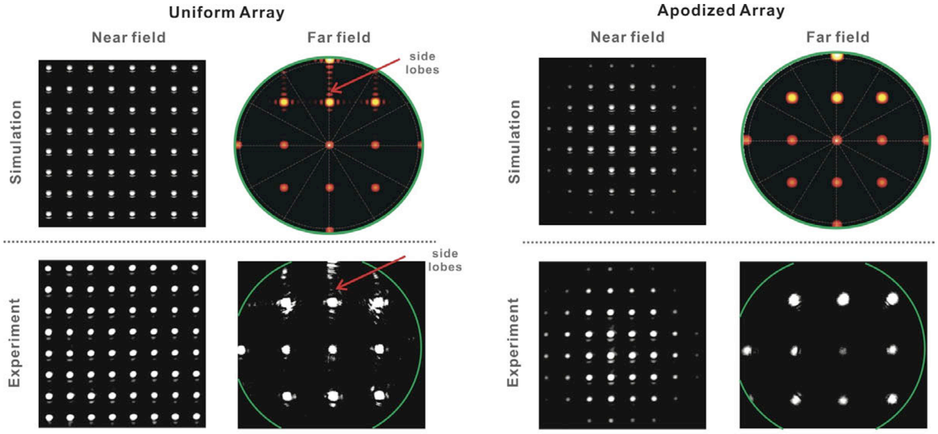
Optical phased arrays have been studied for decades on various optical platforms and most recently using integrated silicon photonics [7]. Compared with all previous integrated optical phased arrays, the uniqueness of our phased array lies in the ability to form a compact unit cell as the fundamental building block, as shown schematically in Fig. 1(a). By making use of robust photonic design and the state-of-the-art CMOS fabrication techniques, a directional coupler that couples out arbitrary amount of optical power from the bus waveguide, a thermo-optic phase shifter that can achieve 2π tunable phase shift over a propagation distance of just a few wavelengths [8], and a high-efficiency grating-based light emitter, are tightly integrated in an ultra-compact 9μm×9μm unit cell (Fig. 1). The device was fabricated in a standard CMOS foundry on 300-mm silicon-on-insulator (SOI) wafers at 65-nm technology node using four dopings (n, n^+, p, and p^+) and four electrical interconnections (C: silicon contact, V: contact via, M1: metal 1, and M2: metal2), as shown in Fig. 1(b) and 1(c).



(a) (b)

Figure 2. (a) An SEM of the fabricated 8×8 silicon photonic phased array. (b) The generated far-field beam can be steered in vertical and horizontal directions, and can be split into two and four beams, by applying voltages on the array accordingly.

The optical phased array was formed by periodically placing the unit cells in two dimensions (2D) and electrically connecting them, as shown in Fig. 2(a) where an 8×8 silicon photonic phased array was fabricated. In a uniform phased array, the directional couplers in the unit cells are adjusted in such a way that each unit cell receives the same amount of power to light up uniformly across the array in the near field and project a focused beam in the far field, as shown in Fig. 3(a). Multiple interference orders are generated in the far field since the antenna spacing (9μm) is a multiple of the operating wavelength (1.55μm). It is seen in Fig. 2(a) that the phase shifters in the same column are electrically connected together so as to avoid complicated electrical wiring. By applying voltages on the tunable phase shifters in the columns and rows, the near-field phase can be dynamically reconfigured to control the beam in the far field accordingly. As shown in Fig. 2(b), the phased array can steer the optical beam by 12° in two dimensions and can even generate additional beams. The electrically controlled beam steering can find immediate applications in LIDAR, free-space optical switching, optical micromanipulations, etc.



(a) (b)

Figure 3. (a) Simulated and measured near field and far field of a uniform phased array. (b) Simulated and measured near field and far field of a Gaussian-apodized phased array to eliminate the side lobes in the far field.

Although most of the optical phased arrays demonstrated to date have a uniform near-field emission, it generates undesired sidelobes in the far field, as shown in Fig. 3(a). This problem can be overcome by apodization to create a slowly varying intensity distribution in the near field so that the sidelobes in the far-field beam can be suppressed, according to the Fourier transform relation between the near and far field. As shown in Fig. 3(b), a Gaussian-shaped apodization is applied in the near field by adjusting the directional couplers accordingly, generating a Gaussian-shaped beam in the far field without sidelobes. In addition, the generated beam can also be actively steered by the phase shifters. The ability to arbitrarily engineering the intensity and phase of the near-field emission can be used to generate arbitrary optical beamforms in the far field.

While 2D phased arrays have the ability to steer the beam in two dimensions, it is challenging to reduce the antenna spacing for wide-angle beam steering. However, in a 1D phased array as shown in Fig. 4(a) where long gratings are used as optical antennas to confine light in the horizontal direction and the array confines and steers light in the vertical direction, wide-angle steering can be realized since the gratings can be placed as close as 2μm. As shown in Fig. 4(b), 51° beam steering has been achieved with an estimated steering speed up to 5×10^{6} °/s [6].

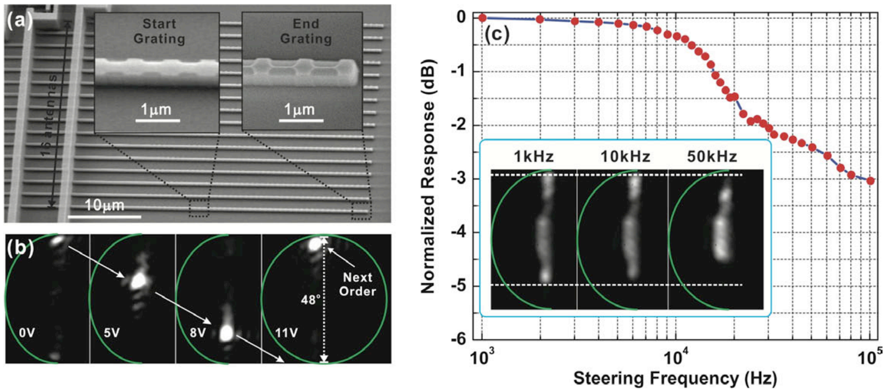


Figure 4. (a) An SEM of the fabricated 1×16 phased array. (b) 51° beam steering was achieved. (c) Beam steering speed was measured by driving the array with a sinusoidal signal at different frequencies.

Although relatively small phased arrays have been shown above, there is no limitation to extend to much larger arrays by placing more unit cells in the array, which is a unique advantage of our phased array architecture enabled by the compact unit cell. With large-scale phased arrays consisting of thousands of unit cells, new possibilities can be enabled by the phased array. For example, by setting the phase of a large number of optical emitters, the interference of these emitters can create sophisticated, predesigned, holographic patterns in the far field. Figure 5(a) shows the near-field emission from a 64×64 phased array, where the uniform emission from all of the 4,096 optical emitters are seen, highlighting the robustness of the photonic design and the accuracy of the CMOS fabrication techniques. Moreover, all of the 4,096 emitters are aligned in phase to create the holographic MIT-logo in the far field, as shown in Fig. 5(b). Figure 5(c) shows the far field of another 32×32 array with a different pattern. Note that the required phase shift here was fabricated in the waveguide without electrical tunability, limited by the electrical wiring. However, tunable holographic phased arrays can be achieved in the future with the aide of CMOS digital circuitry directly integrated with the photonics, capable of generating reconfigurable patterns in the far field.

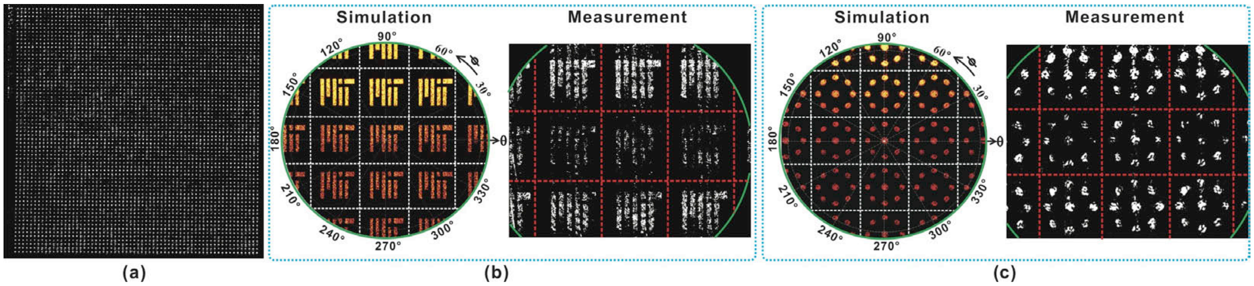


Figure 5. (a) Uniform near-field emission of a 64×64 phased array. (b) Simulated and measured far field of the 64×64 array, creating an MIT-logo. (c) Simulated and measured far field of a 32×32 array with a different pattern.

3. Conclusions

We present in this paper several integrated silicon photonic circuits for optical phased arrays. The demonstrated phased arrays by themself can find many applications such as free-space optical switching, LIDAR, optical manipulation, and even holography; moreover, as the largest silicon photonic circuit demonstrated to date with more than 4,096 functional components, it confirms the viability of large-scale silicon photonic integration. A growing number of large-scale silicon photonic integrated systems can be expected in the near future with increased integration level and enhanced functionality for a wide range of applications in communication and beyond.

This work was supported by DARPA under the E-PHI and SWEEPER projects, grant no. HR0011-12-2-0007.

4. References

[1] T. Baehr-Jones, *et al*, “Myths and rumours of silicon photonics,” Nature Photonics **6**, pp. 206-208, 2012.

[2] X. Zheng, *et al*, “Ultra-low power arrayed CMOS silicon photonic transceivers for an 80 Gbps WDM optical link,” in Optical Fiber Communication Conference (OFC) 2011, paper PDPA1.

[3] L. Chen, *et al*, “Compact, low-loss and low-power 8×8 broadband silicon optical switch,” Opt. Express **20**, pp. 18977-18985 (2012).

[4] J. Sun, *et al*, “Large-scale nanophotonic phased array,” Nature **493**, pp. 195–199, 2013.

[5] J. Sun, *et al*, “Two-dimensional apodized silicon photonic phased arrays,” Opt. Lett. **39**, pp. 367-370, 2014.

[6] A. Yaacobi, *et al*, “Integrated phased array for wide-angle beam steering,” Opt. Lett., submitted.

[7] J. K. Doylend, *et al*, “Two-dimensional free-space beam steering with an optical phased array on silicon-on-insulator,” Opt. Exp. **19**, pp. 21595–21604, 2011.

[8] M. Watts, *et al*, “Adiabatic thermo-optic Mach-Zehnder switch,” Opt. Lett. 38, 733-735 (2013).