

# On chip wide angle beam steering

Ami Yaacobi<sup>1</sup>, Jie Sun<sup>1</sup>, Michele Moresco<sup>1</sup>, Gerald Leake<sup>2</sup>, Douglas Coolbaugh<sup>2</sup>, and Michael R. Watts<sup>1</sup>

<sup>1</sup>Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA 02139

<sup>2</sup>College of Nanoscale Science and Engineering, University at Albany, Albany, NY, USA 12203

[mwatts@mit.edu](mailto:mwatts@mit.edu)

**Abstract:** We demonstrate an on-chip optical phased array fabricated in a CMOS compatible process with continuous, fast (100 kHz), wide-angle (51°) beam-steering that is suitable for applications such as low-cost lidar systems.

**OCIS codes:** (140.3300) Laser beam shaping; (110.5100) Phased-array imaging systems; (010.3640) Lidar

## 1. Introduction

On-chip optical phased arrays have been widely investigated in the last few years [1-3] with applications in many fields including holographic video displays, optical communication systems, and low cost light detection and ranging (lidar) systems. In particular, low cost chip-scale lidars can in principle dramatically enhance accident avoidance systems in the automotive industry and are key components for autonomous vehicles. However, lidar systems require beams, features that are challenging for on-chip phased arrays. While two-dimensional beam steering is usually not required, high-speed continuous beam steering is often necessary. Moreover, for greater power efficiency, large scan angles, and low crosstalk between different ports, a large angle between the different optical orders represents a critical requirement. And, despite the substantial progress in optical phased arrays, to date, current phased arrays can only steer across a maximum of ~28°, whereas, for example autonomous vehicle applications require scan angles exceeding 45-degrees.

Here, we propose and demonstrate the first high-speed, low-power and wide-scan-angle optical phased array. The approach utilizes directly integrated thermo-optic phase shifters [4, 5] to provide the high-speed steering in a small footprint and with low power consumption. Fig. 1a and 1b show the design and a Scanning Electron Microscope (SEM) image of the phase shifter. A cascaded phase shifting architecture (Fig. 1c) enables a steering frequency equal to the phase shifter cutoff and further reduces power consumption. We demonstrate here a phased array steerable over the whole 51° beam spacing with 10.6 V signal, average power consumption of ~13 mW/antenna and 3 dB cutoff steering speed of 100 kHz.

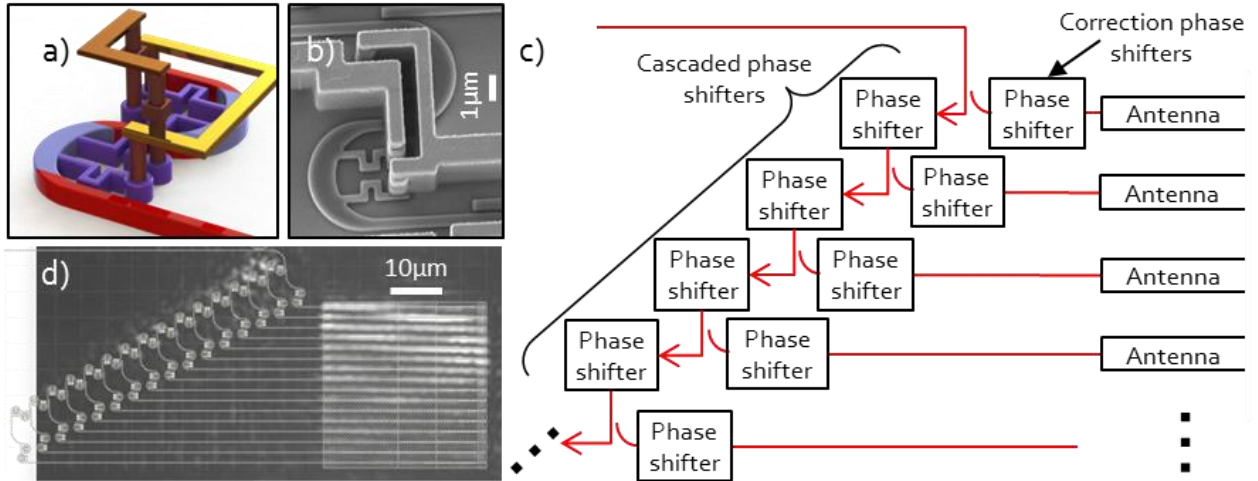


Fig. 1. Phased array design: (a) Design and (b) SEM image of the phase shifter, (c) architecture of the phased array showing the cascade phase shifting, and (d) an IR image of the array output superimposed on a sketch of the array.

## 2. Theory and design

The relation between the beam spacing  $\Theta$  and unit cell size  $d$  is given by  $\sin(\Theta) = \lambda/d$ , where  $\lambda$  is the laser wavelength. Using sixteen, 32 μm long, grating based antennas with a 2 μm pitch, we create a 32 μm x 32 μm aperture with a 51° beam spacing in the lateral dimension and no additional beams in the longitudinal dimension. The array and its near field infrared (NIR) output can be seen in Fig. 1d. Finite-Difference Time-Domain simulations were used to determine the grating strength along the emitter and minimize aberrations to ensure a

collimated beam. The grating strength was modified along the antenna in order to create a constant intensity across the array length.

Phase shifting was achieved using the thermo-optic effect in silicon. The use of an S-shaped waveguide allowed both a longer phase-shifter length in a small space and electrical contact to be made to the inner side of the curves with minimal losses through the use of an adiabatic bend [4, 5]. An optical path of length  $\sim 1.5 \mu\text{m}$ , average width of  $\sim 0.75 \mu\text{m}$  and thickness of  $0.22 \mu\text{m}$ , lightly doped at a level  $1.5 \times 10^{18} \text{ cm}^{-3}$ , yields a total resistance of  $\sim 8 \text{ K}\Omega$  per curve. The two curves, connected in parallel, in each phase-shifter create heating of around  $500^\circ\text{C}$  and change the Si refractive index by  $\sim 3.2$  percent. Comsol<sup>TM</sup> simulations show that this temperature shift applies not only to the resistor area, but flows quickly along the waveguide, thus enabling higher and more efficient phase shifting.

### 3. Results and discussion

Fig. 2a shows the resulting far field beam, captured with an InGaAs camera, as it is steered over the whole beam spacing. The images were taken through a NA=0.45 lens. This lens shows an angular radius of only  $24^\circ$  and, therefore, cannot show more than one beam at a time. However, it can still clearly be seen that at 11 V the next order shows up where the main beam was at 0 V bias. The white circles in the images show the lens numerical aperture.

In order to measure the frequency response of the system, we looked at frequencies higher than the inverse integration time used to capture these images. This setting enables us to see the steering as a steady line (Fig. 2b) where the steering amplitude is the line length. Applying higher frequencies, we measure the normalized frequency response of the array by comparing the steering angle with the steering angle at low frequency (Fig 2c). This test was run with a sinusoidal signal, and we found the 3 dB cutoff operation speed to be  $\sim 100 \text{ kHz}$ .

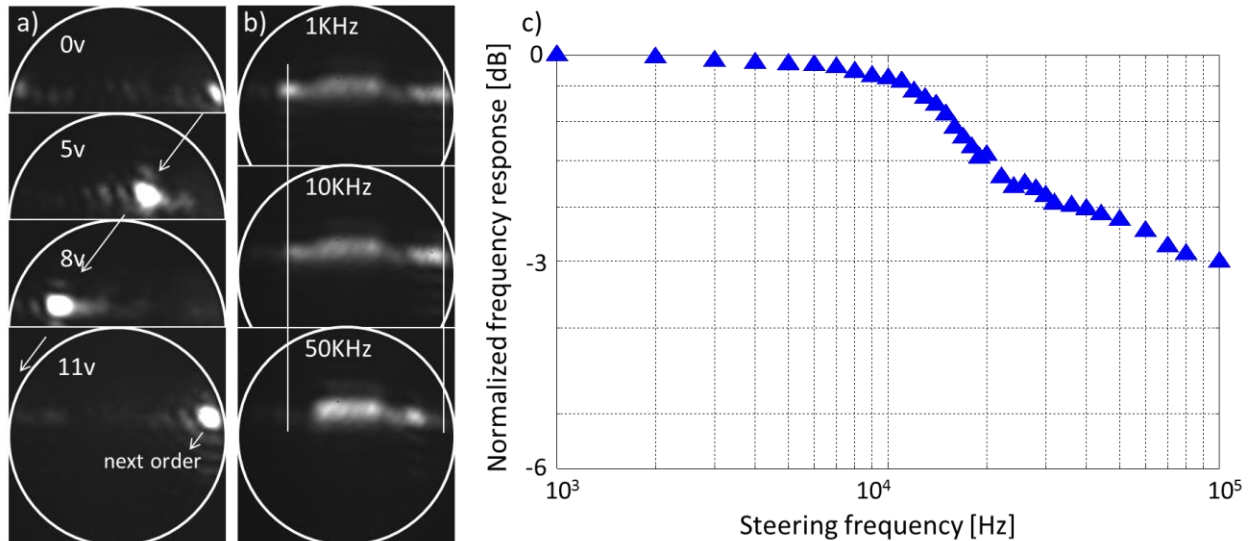


Fig. 2. Far field images of (a) steady steering, (b) high speed steering and (c) normalized frequency response of the phased array. The white circles in the images show the 0.4 numerical aperture of the lens ( $24^\circ$  in radius).

In conclusion, we demonstrate the first high-speed and wide-angle ( $51^\circ$ ) silicon photonic optical phased array. This one-dimensional phased-array provides continuous beam steering with high-speed steering suitable for lidar applications. Importantly, this phased array was fabricated in a standard 300 mm CMOS fabrication facility using a custom silicon photonics process. As such, the device can be efficiently mass produced and serve numerous applications including the important space of automotive accident avoidance technologies.

This work was supported by Toyota Central R&D Labs., Inc. (TCRDL) and by the Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office's (MTO) EPHI program, grant no. HR0011-12-2-0007.

### 4. References

- [1] J. Sun, E. Timurdogan, A. Yaacobi, E. S. Hosseini and M. R. Watts, "Large-scale nanophotonic phased array," *Nature* **493**, 195–199 (2013).
- [2] J. K. Doylend\*, M. J. R. Heck, J. T. Bovington, J. D. Peters, L. A. Coldren, and J. E. Bowers, "Two-dimensional free-space beam steering with an optical phased array on silicon-on-insulator," *Optics Express*, **19**, 22, 21595-21604 (2011).
- [3] N. Hamdam, K. V. Acoleyen, and R. Baets. "Beam steering for wireless optical links based on an optical phased array in silicon," *annals of telecommunications* **68**.1-2, 57-62 (2013).
- [4] M. R. Watts, J. Sun, C. DeRose, D. C. Trotter, R. W. Young, and G. N. Nielson2, "Adiabatic thermo-optic Mach-Zehnder switch," *Optics Letters*, **38**, 5, 733-735 (2013).
- [5] M. R. Watts, "Adiabatic microring resonators," *Optics Letters*, **35**, 19, 3231-3233 (2010).