Fresnel-Lens-Inspired Focusing Phased Arrays for Optical Trapping Applications

Jelena Notaros[1,*], Christopher V. Poulton[1,3], Manan Raval[1], Matthew J. Byrd[1], Douglas Coolbaugh[2], and Michael R. Watts[1]

[1] *Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2] *College of Nanoscale Science and Engineering, University at Albany, Albany, New York 12203, USA*
[3] *Currently with Analog Photonics, 1 Marina Park Drive, Boston, Massachusetts 02210, USA*
[*] *notaros@mit.edu*

Abstract: An integrated optical phased array which focuses radiated light in one dimension to a tightly confined spot in the near field is demonstrated for the first time and proposed for chip-scale optical trapping applications.

OCIS codes: (250.5300) Photonic integrated circuits; (130.3120) Integrated optics devices; (350.4855) Optical tweezers or optical manipulation.

1. Introduction to Optical Trapping and Focusing Phased Arrays

Optical trapping and tweezing – the manipulation of particles using optical forces – has many applications ranging from biological characterization to trapped-ion quantum computing [1,2]. While optical trapping using bulk optics is a well established technique, recent work has turned towards integrating optical trapping using on-chip devices such as photonic crystal nanocavities [3] and plasmonic nanoantennas [4]. However, many of these systems are fundamentally limited to passive trapping demonstrations within microns of the chip surface. Dynamic and wide-angle integrated tweezing at millimeter scales – especially advantageous for in-vivo applications [2] – has not been demonstrated.

Integrated optical phased arrays, which manipulate and dynamically steer light at 200 MHz rates [5] with large aperture sizes [6], provide one possible approach to scaling and arbitrary tweezing of optical traps. However, current phased array demonstrations have focused on systems which form and steer beams or project arbitrary radiation patterns in the far field [5,6]. Since optical forces are formed due to intensity gradients, optical trapping requires a system with a tightly-focused spot in the near field of the array. In this paper, the first Fresnel-lens-inspired 1D-focusing passive integrated optical phased array is demonstrated. The system focuses light down to a 13 μm spot in one dimension 5 mm above the chip. A CMOS-compatible platform is leveraged for natural scaling to an active demonstration.

2. Focusing Phased Array Theory

A phased array is a system comprised of an array of antennas that are fed with controlled phases and amplitudes to generate arbitrary radiation patterns. If the phase front fed into the array is linear, the array creates a steerable, diffracting beam in the far field of the array as shown in Fig. 1c. In contrast, if a "lens-like" hyperbola phase is applied, the array will focus light into a tightly-confined spot in the near field above the array as shown in Fig. 1d–e. This focusing phase is given by

$$\Phi_n = \frac{2\pi}{\lambda}\left(\sqrt{f^2 + d^2\left(N/2 - 1/2\right)^2} - \sqrt{f^2 + d^2\left(N/2 - n - 1/2\right)^2}\right), \tag{1}$$

where Φ_n is the phase applied to the nth antenna, λ is the free-space wavelength, f is the desired focal height, d is the antenna pitch, and N is the total number of antennas in the array. Similarly to a Fresnel lens, Φ_n can be encoded modulo 2π as shown in Fig. 1b.

For potential applications, a valuable figure of merit of a focusing array is the power full-width half-maximum (FWHM) of the resulting spot at the desired focal height. Similar to bulk lenses, this spot size depends on the aperture size of the array and the focal height. For example, for a 128 antenna array with 4 μm antenna pitch at 1550 nm as simulated in Fig. 1d–e, the FWHM is found to be 13 μm and 40 μm for focal heights of 5 mm and 15 mm, respectively.

3. System Architecture, Implementation, and Experimental Data

As a proof of concept, a passive 1D-focusing phased array is designed and fabricated in a CMOS-compatible foundry process at CNSE SUNY using a silicon-nitride 1D-tree architecture as shown in Fig. 1a [6]. A 7-layer multi-mode

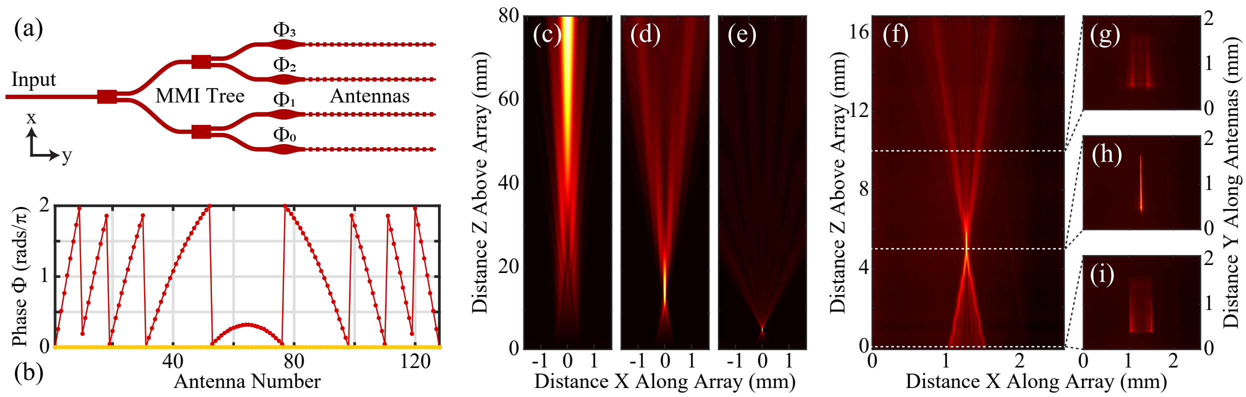

Fig. 1. (a) Schematic of a focusing phased array with two MMI splitting layers. (b) Feeding phase profile for a standard non-focusing phased array (yellow) and a 5 mm focal height focusing phased array (red). Simulated array-factor intensity above the chip for a (c) non-focusing, (d) 15 mm focal height, and (e) 5 mm focal height array. (f) Measured intensity above the chip for a 5 mm focal height phased array with top-down intensity shown (i) in the plane of the chip, (h) at the focal plane, and (g) above the focal plane. Phase profiles, simulated intensity, and measured intensity are shown for an array with 7 MMI splitting layers and 4 μm antenna pitch.

interference (MMI) splitter tree is used to evenly distribute the input power to 128 waveguide arms with a final pitch of 4 μm. On each arm, a phase bump structure is placed which imparts a static phase delay dependent on the width of the bump. The width of each bump is chosen so that the correct phase profile for focusing at 5 mm above the chip is applied. Finally, a 1.2 mm-long grating-based antenna is placed on each arm to create a 0.5 mm $\times$ 1.2 mm aperture size. The antennas are designed to radiate upwards and exponentially along the antenna length.

To characterize the fabricated array, an optical system is used to image the plane of the chip onto an InGaAs IR camera. The system height is then progressively scanned and top-down views of the intensity at varying heights above the chip are recorded. The resulting cross-sectional intensity as a function of the distance above the chip and three top-down views are shown in Fig. 1f–i. In the plane of the chip (Fig. 1i), the full aperture is illuminated by the antennas; as the system scans to the expected focal plane 5 mm above the chip (Fig. 1h), the light is tightly-focused in one dimension; finally, above the focal plane (Fig. 1g), the light is, once again, diffracted out. Additionally, a focal spot size with FWHM of 13 μm is measured at the desired focal height of 5 mm, matching the simulated results in Fig. 1e.

4. Conclusions, Anticipated Applications, and Future Outlook

This work presents the first demonstration of an integrated optical phased array which focuses radiated light to a tightly-confined spot in the near field. An array with 128 antennas, 4 μm pitch, and 0.5 mm $\times$ 1.2 mm aperture size is demonstrated to focus light to a 13 μm spot at a 5 mm focal height. The system has important applications ranging from optical trapping for biological characterization and trapped-ion quantum computing to chip-scale lithography.

Since the array is fabricated in a CMOS-compatible platform, it is naturally scalable to an active arbitrarily-tunable system through interfacing with active silicon-based phase shifters [5]. Additionally, using numerical methods and synthesis algorithms [7], two-dimensional focusing can be achieved by appropriately chirping the period and varying the perturbation strength of the antennas in the array. Finally, the demonstration can be scaled to larger aperture sizes to further reduce the focus spot size and enable larger focal heights [6].

This work was supported by the Defense Advanced Research Projects Agency (DARPA) E-PHI program (Grant No. HR0011-12-2-0007) and a National Science Foundation Graduate Research Fellowship (Grant No. 1122374).

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