Large-Scale Optical Phased Arrays Enabled by Silicon Photonics

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Abstract: The largest (up to 64×64) optical phased arrays to date are demonstrated with silicon photonics, including passive arrays generating intricate far-field patterns and an active array for dynamic beam steering and shaping.

OCIS codes: (130.3120) Integrated Optics Devices; (280.5110) Phased-array Radar

1. Introduction

Optical phased arrays are seen as an enabling technology for a broad range of applications such as Laser Detection And Ranging (LADAR), optical free-space communication, holographic displays, optical tweezers, and biomedical sensing. With the aide of the Complementary Metal-Oxide-Semiconductor (CMOS) technology, optical phased arrays hold promise for large-scale integration of a large number of optical antennas in a silicon chip which is essential for these applications. Although integrated optical phased arrays have been well studied [1,2], all of the demonstrations to date are limited to 1-dimensional (1-D) or small-scale 2-dimensional (2-D) arrays containing no more than 16 antennas.

Recently we proposed an approach to achieve large-scale optical phased arrays using the state-of-the-art silicon photonic technology [3]. Here we present the work in detail along with some new results. Two passive phased arrays, 64×64 and 32×32, are shown to create complex holographic images, as well as an 8×8 active phased array that is capable of dynamically steering and shaping the optical beams through thermo-optical tuning of the antenna phase, representing the largest and most complex optical phased arrays demonstrated to date.

2. Passive Phased Array

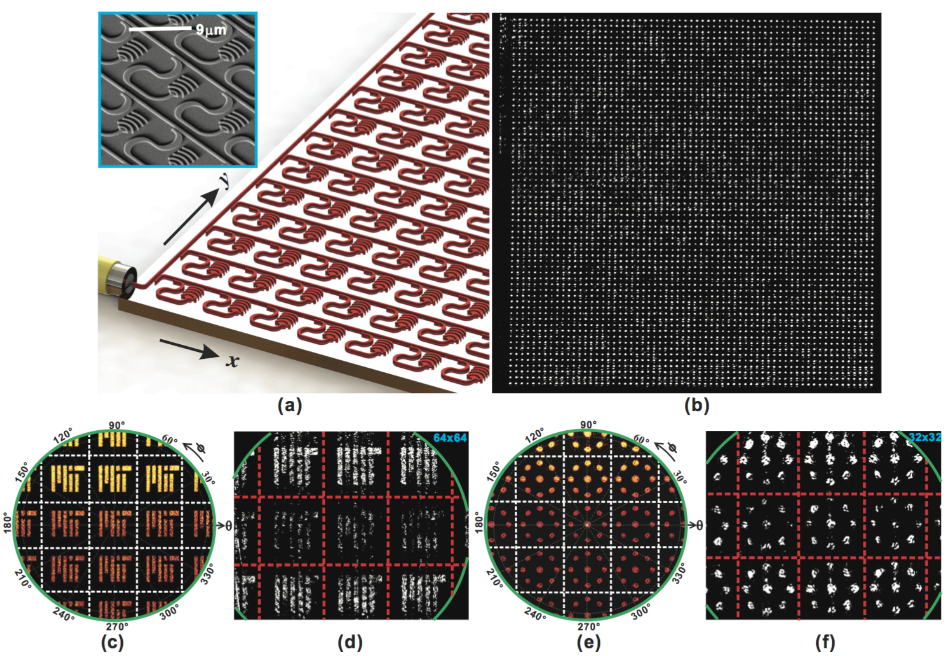

Fig. 1. Passive phased arrays. (a) A schematic of the large-scale optical phased array. Inset, a scanning electron micrograph (SEM) of a part of the phased array fabricated with the state-of-the-art CMOS technology. (b) Near-field emission of a 64×64 phased array. (c) Simulated and (d) measured far-field interference pattern of a 64×64 phased array to generate an MIT-logo. (e) Simulated and (f) measured far-field interference pattern of a 32×32 phased array to generate multiple beams. The white/red lines separate the interference orders, while the green circle depicts the edge of the objective lens (same in Fig. 2).

Figure 1(a) shows the structure of an *N*×*N* optical phased array. An optical input at 1.55μm is coupled from a fiber to a silicon bus waveguide which is then coupled to *N* silicon row waveguides. Light in each row waveguide is then coupled to *N* unit cells. The coupling efficiency is varied by accurately adjusting the length of each directional coupler so as to have each unit cell emit the same optical power, as shown by Fig. 1(b) where uniform near-field emission is observed from 4,096 optical nanoantennas in a 64×64 array. Each unit cell contains an efficient silicon grating emitter as an optical nanoantenna and a waveguide delay line to precisely allocate the desired optical phase to each emitter. By assigning each antenna unit in the phased array with a specific optical phase which could be calculated by the Gerchberg-Saxon algorithm [4], complex holographic interference patterns can be achieved in the far field, as shown in Fig. 1(d) where an MIT-logo is created and in Fig. 1(f) where a pattern with 9 beams aligned in a concentric way is generated. Figure 1(c) and 1(e) show the corresponding simulated patterns. The simulations agree well with the measured results, confirming the robustness of the design and reliability of the CMOS fabrication. Multiple interference orders are seen, a consequence of a larger antenna spacing (9μm×9μm) compared to the wavelength used. This unique ability to generate arbitrary far-field patterns enabled by the large-scale phased array and the state-of-the-art CMOS technology could find potential applications in optical beam shaping, optical space division multiplexing, and optical tweezers.

3. Active Phased Array

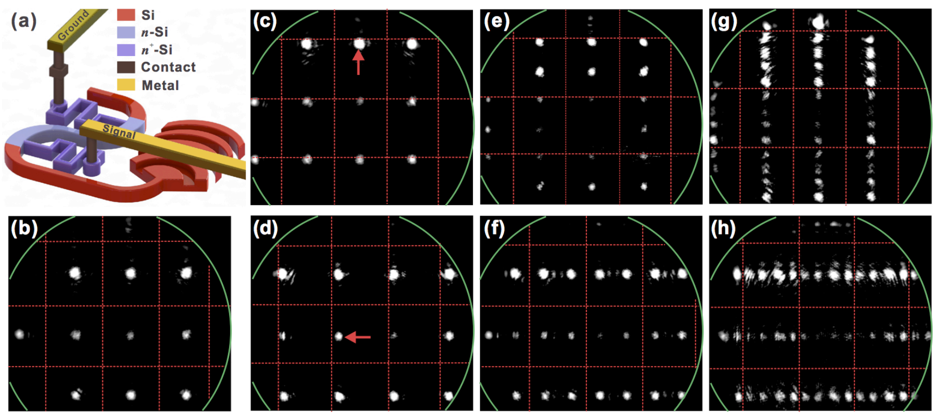

Fig. 2. An active optical phased array. (a) A schematic of an active antenna unit with thermo-optic phase tunability. Measured far-field patterns of an active 8×8 phased array (b) where no voltage is applied, the beam is steered in the (c) vertical and (d) horizontal, the beam is split into two in the (e) vertical and (f) horizontal, and into four in the (g) vertical and (h) horizontal.

Although many applications could be found in passive phased arrays, active phased arrays are more appealing where active phase tunability is added to each antenna unit to project dynamic patterns in the far field. The phase tunability in the proposed phased array is achieved by an integrated thermo-optic silicon heater in each antenna unit by slightly doping the silicon waveguide to form a resistor [5], as shown in Fig. 2(a). By applying voltages on the heater, the phase of the optical emission from each nanoantenna can be tuned from 0 to 2π. Figures 2(b)-(h) show versatile far-field patterns generated by an 8×8 phased array by applying different voltage configurations to the phased array, where the focused optical beam (Fig. 2(b)) can be steered (Fig. 2(c) and (d)), split into 2 beams (Fig. 2(e) and (f)), and into 4 beams in both directions. In spite of the smaller scale of the active phased array compared to the passive demonstrations which is limited by the electrical connectivity in our fabrication process, this 8×8 active phased array still represents the largest 2D active phased array demonstrated to date, and is seen as an enabling technology to applications such as LADAR, optical switching, optical coherence tomography (OCT), etc. With the aide of a CMOS circuitry to address and control the voltage applied to each antenna unit, the active phased array can be extended well beyond the current 8×8 case to include thousands or even million of antennas so as to dynamically project complex 3D images in the far field, a possible pathway to a truly 3D holographic display.

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4. References

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