Optical Beamform Engineering Using Phase and Amplitude Coded Nanophotonic Antenna Arrays

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Abstract: A novel method to generate optical beams using on-chip silicon nanophotonic antenna arrays with engineered phase and amplitude is demonstrated. An 8×8 nanophotonic phased array to generate and manipulate Gaussian beams is shown.

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

1. Introduction

The generation and manipulation of optical beams with arbitrary phase and amplitude distributions has long been pursued as an enabling technology for applications ranging from optical communication [1] to optical tweezers [2]. To this end, versatile approaches, mainly in the form of free-space optics, have been demonstrated from liquid crystals to metasurfaces [3]. To generate truly arbitrary optical beam-formations, both the amplitude and phase of the optical field need to be simultaneously engineered, a task that is extremely challenging with free-space approaches. Silicon photonic circuits, on the contrary, are capable of accurately manipulating both the optical power distribution and phase progression with minute changes to the waveguide geometry or length in tightly-confined silicon waveguides, an enormous advantage for optical beamform engineering when combined with waveguide-to-freespace light converters such as optical nanoantennas.

Recently, we demonstrated a large-scale silicon photonic phased array where the near-field phase can be engineered to generate far-field radiation with desired optical intensity patterns [4]. Here we show that using a similar phased array technique, not only the phase but also amplitude of the near-field optical emission can be accurately tailored to create arbitrary optical beam-formations with desired amplitude and phase profiles in the far field. Moreover, taking advantage of the tunability of silicon photonic devices, the generated beam can be actively manipulated, a feature of particular interest to applications such as laser detection and ranging (LADAR) and optical tweezers.

2. Device Design and Experiment

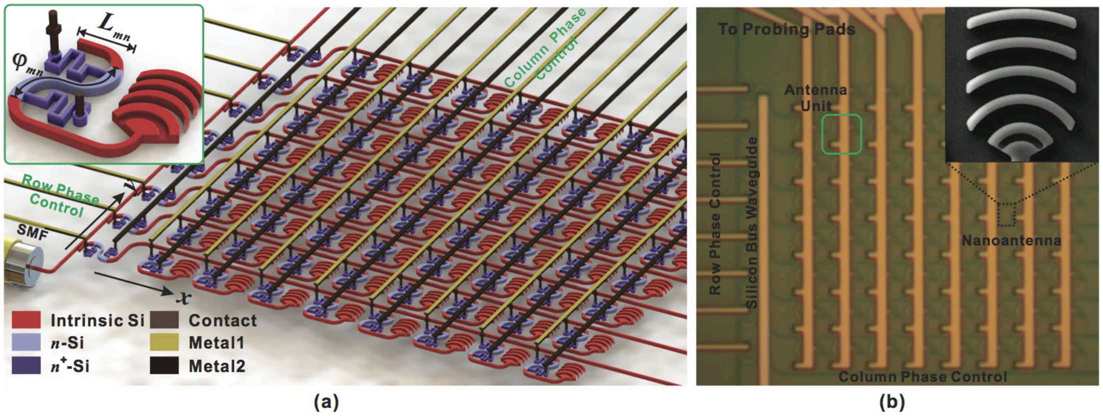

Fig. 1. (a) A schematic of an 8 × 8 integrated antenna array with active phase tunability provided by integrated silicon heaters. Inset: an active antenna unit whose emission amplitude is tailored by coupling length L_{mn} and phase adjusted by φ_{mn}. (b) An optical image of the fabricated 8 × 8 array. Inset: a scanning electron micrograph of the dielectric nanoantenna.

As an example of arbitrary beamform generation, an 8×8 silicon photonic antenna array was designed, as schematically shown in Fig. 1(a), to create an optical beamform in the far field with a Gaussian-shaped amplitude and uniform phase profile. The Fourier transform relation between the near field (antenna array) and far field (beamform) indicates that, in order to generate certain beamform with specific amplitude and phase profile in the far field, corresponding amplitude pattern and phase distribution have to be created in the near field at the antenna array. The required amplitude profile of the antenna array, which also has a Gaussian shape according to the Fourier relation, is achieved by adjusting the coupling length L_{mn} of the 72 directional couplers in the antenna array to accurately deliver the required optical power to each of the 64 nanoantennas. The corresponding phase profile, which is uniform across all of the antennas, is obtained through the 64 optical waveguide delay lines in each antenna unit, each of which provides a phase shift φ_{mn}. The antenna unit measures 9µm×9µm, including an embedded thermo-optic tunable phase shifter formed by doping the silicon waveguide, as shown in the inset of Fig. 1(a). The proposed antenna array with designed emission amplitude and phase profile was fabricated on a silicon-on-insulator (SOI) wafer in a 300-mm complimentary metal-oxide-semiconductor (CMOS) foundry. Figure 1(b) shows the fabricated antenna array. Figure 2(a) shows the simulated and measured near-field emission from the fabricated 8×8 antenna array, with the designed Gaussian-shaped intensity profile. Figure 2(b) shows the simulated and measured far-field beam-formation generated by the fabricated antenna array, where an optical beam-formation with Gaussian-shaped amplitude is created, as designed. The excellent agreement between simulation and measurement confirms the accuracy of the design and the reliability of the fabrication. Furthermore, by adjusting the voltages applied on the 72 integrated silicon heaters, the near-field optical phase emitted from the 8×8 nanoantennas can be thermally tuned, resulting in dynamic beamform manipulation in the far field, as shown by Fig. 2(c)-(f), where the generated single Gaussian-shaped optical beam is steered (Fig. 2(c)), split into 2 beams (Fig. 2(d) and 2(e)) and into 4 beams (Fig. 2(f)). This dynamic beam manipulation capability is essential in optical tweezers to trap and move small objects with optical beams.

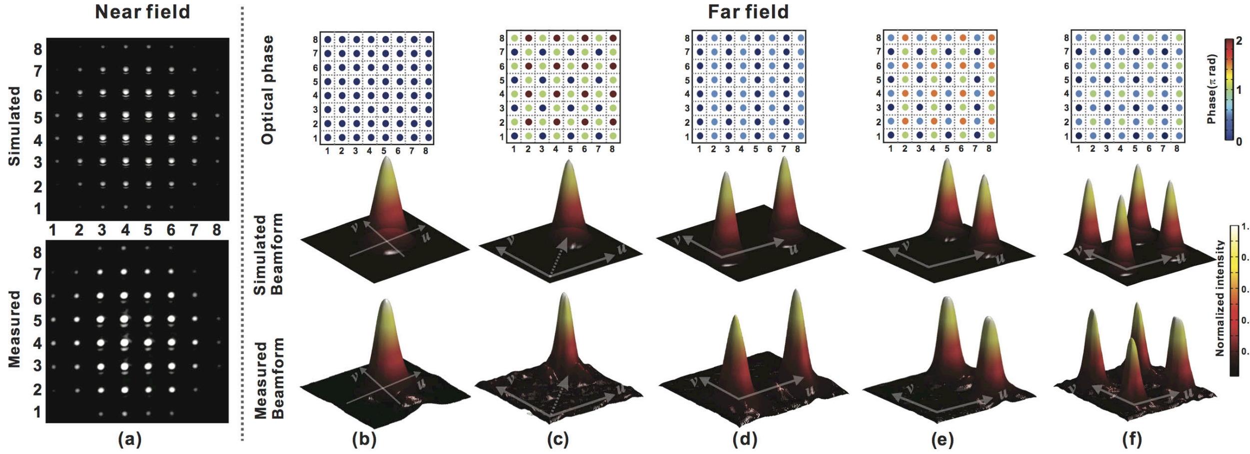

Fig. 2. (a) Simulated (upper) and measured (lower) near-field emission from the fabricated 8×8 antenna array. (b) The designed beamform with Gaussian-shaped amplitude is generated in the far field. Dynamic manipulation of the generated optical beam through phase tuning: the beam is (c) steered, (d)-(e) split into 2 beams in two orthogonal directions, and (f) split into 4 beams. *u* and *v* stand for the far-field axis. The first row shows the corresponding near-field phase profiles, while the second and third row show the simulated and measured beamforms, respectively. The measurements are in good agreement with simulations.

3. Conclusions

In this work, a novel method to generate and manipulate arbitrary optical beamform using phase and amplitude coded silicon photonic antenna array is proposed and demonstrated for the first time by simultaneously engineering the amplitude and phase profile of the near-field emission. Although a relatively small-scale array - yet the largest-scale of its kind demonstrated to date - is demonstrated in this work, it is straightforward to extend to a much larger scale to generate more complex optical beam-formations with high resolution, as an enabling technique for a broad range of applications from optical freespace communication to biomedical sensing and optical tweezers. Furthermore, combined with the demonstrated tunable silicon phase shifters and variable optical attenuators, both the optical phase and amplitude of the near-field emission can be actively tuned to realize a truly reconfigurable optical arbitrary beamform generator with the proposed integrated antenna array.

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4. References

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