Generating and Identifying Optical Orbital Angular Momentum with Silicon Photonic Circuits

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Abstract: We demonstrate a fully integrated silicon photonic circuit capable of generating light carrying optical orbital angular momentum. Experimentally, orbital angular momentum wavefronts are identified by interfering with another on-chip generated Gaussian beam.
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1. Introduction

Optical vortices, whose phase profile has an angular dependence $\exp(j \cdot l \cdot \theta)$, carry an orbital angular momentum (OAM) $l\hbar$ per photon where θ is the azimuthal angle with respect to the beam axis and the integer l represents different OAM states. Besides its application in quantum information for high-dimensional entanglement [2], OAM has recently drawn significant attention for a wide range of classical applications such as high-capacity optical communications [3,4] and optical micromanipulations [5].

While free-space optical components such as spiral phase plates and spatial light modulators are generally used to generate OAM beams, the alternative integrated solutions are of great interest for device miniaturization, enhanced stability, and the possibility to integrate with other on-chip photonic components and functionalities. To this end, large-scale silicon photonic integrated circuits (PICs), which have recently shown remarkable accuracy in controlling the optical phase [6], are particularly well suited to generate OAM beams [4]. Here we present silicon photonic integrated circuits to create optical beams with different OAM states. In addition, to identify these OAM states, the wavefront of the generated light is visualized by interfering with a Gaussian beam generated on the same chip, as an example of integrating conventional free-space optical systems onto a compact silicon chip using PICs.

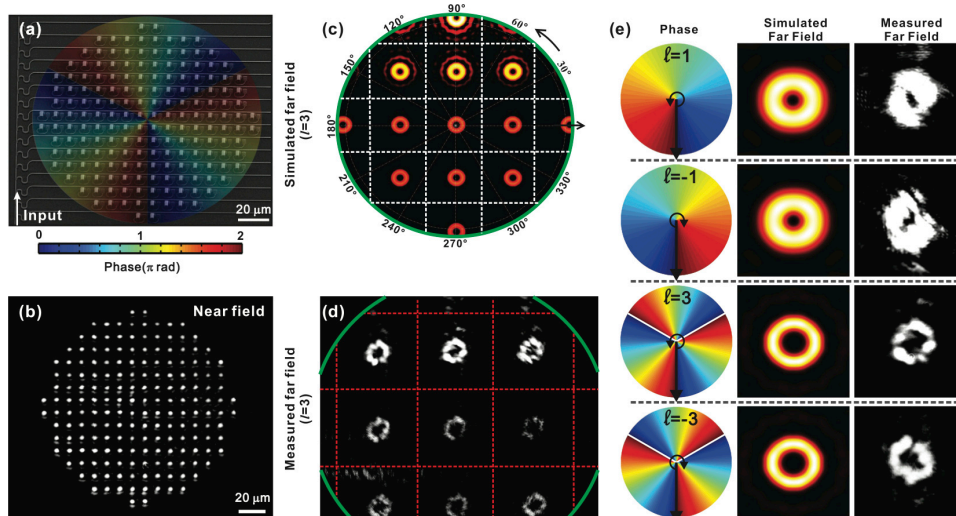## 2. Device Design and Characterization

Figure 1. (a) An SEM of the fabricated integrated photonic circuit coded with angular phase profile to generate OAM with $l = 3$. (b) Measured near-field emission. (c) Simulated and (d) measured far-field pattern with $l = 3$. (e) OAMs with $l = \pm1$ and ±3 are generated (only one of the interference orders is shown in the far field).

Figure 1(a) shows a scanning-electron micrograph (SEM) of the fabricated silicon PIC, which is essentially an optical phased array in which the emitting phase of each optical antenna depends on its azimuthal angle θ, as shown in Fig. 1(a) where a phase profile $\exp(j \cdot l \cdot \theta)$ is coded to generate an OAM with $l = 3$. Unlike conventional phased arrays where a rectangular layout is used, the 180 optical antennas here are placed within a circle to reflect the circular symmetry of the OAM beam. Figure 1(b) shows the measured near field where uniform emission across

all of the 180 optical emitters was observed. The measured far field is shown in Fig. 1(d), agreeing well with the simulation in Fig. 1(c). Multiple interference orders are seen in the far field since the antenna spacing (9μm) is a multiple of the optical wavelength (1.55μm). The multiple OAM beams can be used, for example, to optically trap and rotate multiple particles simultaneously [5]. By coding the array with different phase profiles, optical beams with different OAM states ($l = \pm 1$ and ± 3) were also generated (Fig. 3(e)). All of the generated far-field beams have zero intensity in the center, representing a phase singularity which is the signature of optical vortices.

To identify these OAM states, interference with a Gaussian reference beam is usually used to reveal the helical wavefront of the OAM beam, which is carried out exclusively with free-space interference systems in all previous work [3,5]. It can, however, be realized on a silicon chip since the Gaussian beam can also be generated with PICs [7]. As shown in Fig. 2(a), an OAM phased array (in the red circle) is superimposed with a larger array (32×32) that generates a co-propagating Gaussian beam, creating the signature helical (or 'corkscrew-shaped') interference patterns in the far field, which reveals the corresponding OAM states, as shown in Fig. 2(b).
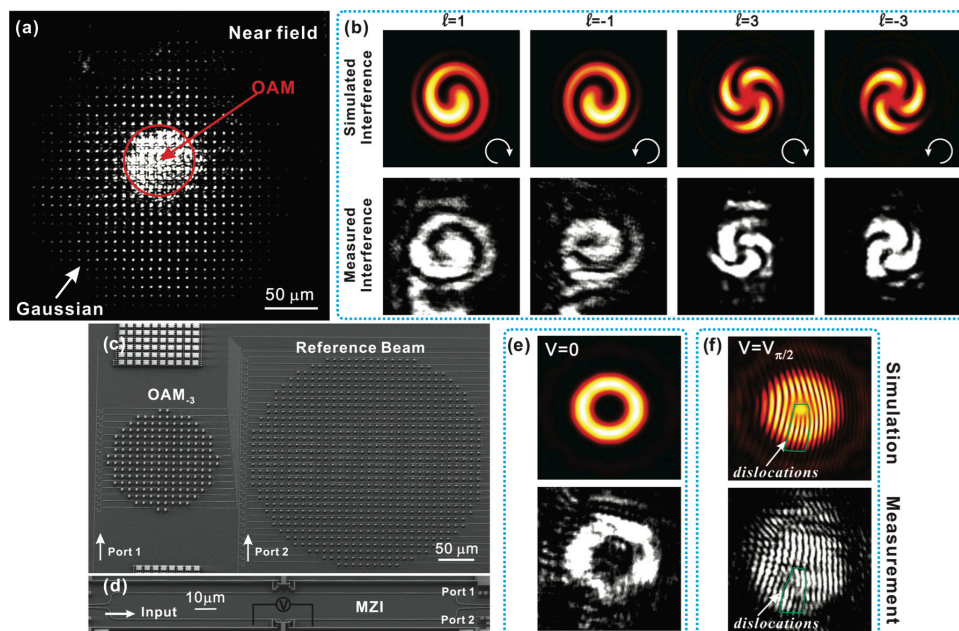

Figure 2. (a) Measured near field of an OAM array (in the red circle) superimposed with a Gaussian array. (b) Measured far-field patterns of OAM arrays ($l = \pm 1$ and ± 3) superimposed with a Gaussian array. (c) SEM of an OAM array and a Gaussian array placed side by side to create oblique interference. (d) The integrated MZI to balance the power of the two arrays. (e) The OAM beam only when $V = 0$, and (f) the interference pattern when $V = V_{\pi/2}$ was applied to equalize the power of two arrays.

In addition to the co-propagating interference, when the two arrays are placed side by side (Fig. 2(c)) so that the OAM and the Gaussian beam interfere at an angle in the far field, an interference pattern with $|l| + 1$ dislocated fringes were generated, as shown in Fig. 2(f). Note that an on-chip Mach-Zehnder Interferometer (Fig. 2(d)) was also integrated on the chip to control the interference condition. When the voltage on one of the balanced arms is 0, only the OAM array lights up, creating a typical OAM beam in the far field (Fig. 2(e)); and when $V = V_{\pi/2}$, the OAM beam and the reference beam are balanced in power to create the predicted interference pattern (Fig. 2f).

In conclusion, we have demonstrated silicon photonic circuits to generate OAM beams. Moreover, the conventional free-space interference system was fully integrated on a silicon chip to identify the OAM states, as an example of replacing conventional bulk optical systems with PICs, a goal of photonic integration.

3. References

[1] M. Padget, et al, "Light's orbital angular momentum," Phys. Today **57,** 35 (2004).
[2] R. Fickler, et al, "Quantum entanglement of high angular momenta," Science **338,** pp. 640-643 (2012).
[3] N. Bozinovic, et al, "Terabit-scale orbital angular momentum mode division multiplexing in fibers," Science **340,** pp. 1545-1548 (2013).
[4] T. Su, et al, "Demonstration of free space coherent optical communication using integrated silicon photonic orbital angular momentum devices," Opt. Express **20,** pp. 9396-9402 (2012).
[5] J. Curtis, et al, "Structure of optical vortices," Phys. Rev. Lett. **90,** 13 (2003).
[6] J. Sun, et al, "Large-scale nanophotonic phased array," Nature **493,** pp. 195-199 (2013).
[7] J. Sun, et al, "Two-dimensional apodized silicon photonic phased array," Opt. Lett. **39,** pp. 367-370 (2014).