Integrated Continuously Tunable Optical Orbital Angular Momentum Generator

Jie Sun,[1] Ami Yaacobi,[1] Michele Moresco,[1] Douglas Coolbaugh,[2] and Michael R. Watts[1]
[1]*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA 02139*
[2]*College of Nanoscale Science and Engineering, University at Albany, Albany, NY, USA 12203*
sunjie@mit.edu mwatts@mit.edu

Abstract: We present the first demonstration of generating light carrying continuously tunable optical orbital angular momentum using a compact integrated silicon photonic circuit and a single electrical control.

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1. Introduction

The optical vortex, or the twisted light, has angular phase dependence ($E \sim \exp(j \cdot l \cdot \theta)$, where θ is the azimuthal angle with respect to the beam axis), and carries an optical orbital angular momentum (OAM) $l \cdot \hbar$ per photon, where $\hbar$ is the reduced Plank constant and l is called the topological charge [1]. Optical OAM finds a wide range of applications from quantum information [2] to high-capacity optical communication [3] to optical micromanipulation [4] and sensing [5]. The unique advantage of using optical OAM in these applications relies, to a large extent, on the use of multiple different OAM states. Therefore, it is desirable to have a device that is able to generate light with freely adjustable OAM state, preferably in an integrated form for large-scale integration.

While prior demonstrations have produced different OAM states by coupling to different ports on an otherwise passive chip [6] or by adjusting the operating wavelength [7], no continuously tunable OAM generator has previously been demonstrated. Here we present the first demonstration of a compact integrated silicon photonic circuit to generate continuously tunable OAM states with both integer and non-integer l-numbers. The compactness and flexibility of the device and its compatibility with CMOS processing hold promise for integration with other silicon photonic components for wide-ranging applications.

2. Device Design and Experimental Results

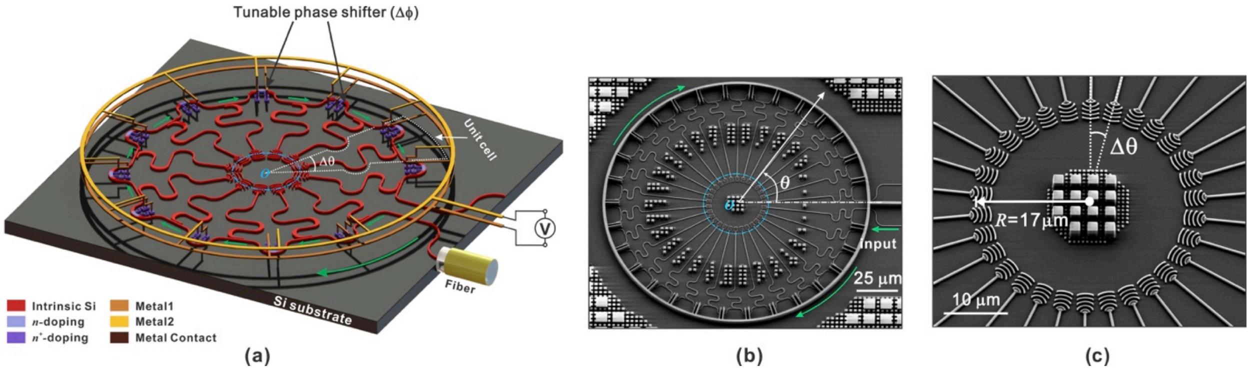

Figure 1. (a) A schematic of the silicon photonic circuit to generate continuously tunable optical OAM. (b) A scanning-electron micrograph (SEM) of the fabricated silicon photonic circuit. (c) An SEM of the 30 optical emitters in the center of the circle.

Figure 1(a) shows a schematic of the silicon photonic circuit. Light is launched from an optical fiber to the silicon bus waveguide that forms an open circle. Light in the bus waveguide sequentially couples into N optical emitters as it travels clockwise in the loop. The emitters are placed in the center of the circle with angular separation $\Delta\theta$. The phase difference of adjacent emitters, due to the phase delay of light traveling between two coupling points in the bus waveguide, is $\Delta\phi$. As a result, the optical field emitted by the emitters has a linear phase dependence on the angular position θ, e.g., $E \sim \exp(j \cdot l \cdot \theta)$, where $l = \Delta\phi/\Delta\theta$. Therefore, the optical emission constructed by these emitters resembles that of an optical vortex whose OAM state l is determined by the phase delay $\Delta\phi$. Further, as shown in Fig. 1(a), the phase delay $\Delta\phi$ is thermo-optically tuned by a silicon heater directly integrated in the bus waveguide between two coupling points so that the OAM state l can be continuously adjusted. Figure 1(b) shows the fabricated silicon photonic circuit using a 300-mm CMOS compatible silicon photonic process with 65-nm technology node. The number of emitters is $N = 30$ here as shown in Fig. 1(c). The optical emitters and thermo-optic tunable phase shifters have a similar design to those used in [8]. Note that here it is crucial for the tunable phase shifters to have a low insertion loss since they are cascaded in the bus waveguide and the loss in each phase shifter will be accumulated to the last emitter.

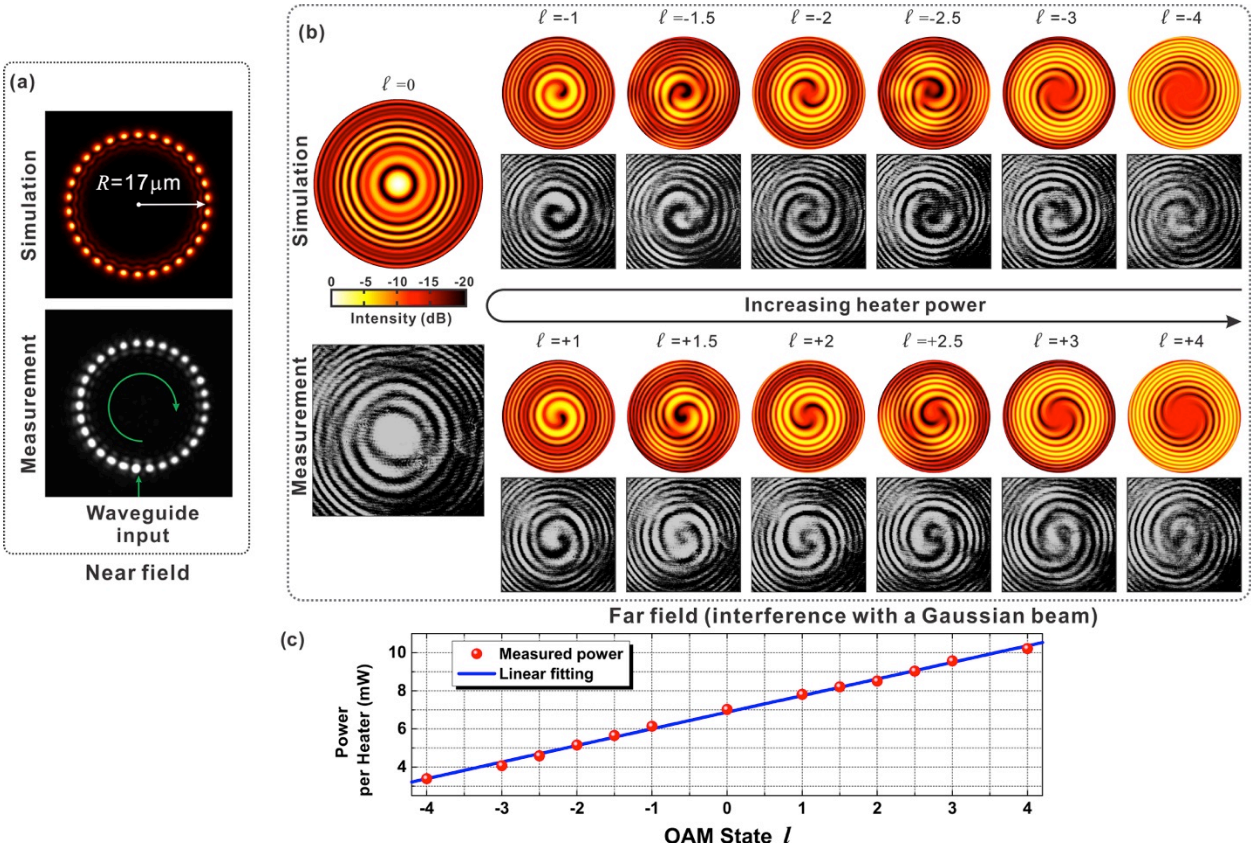

Figure 2. (a) The simulated and measured near-field emission from the 30 optical emitters in the photonic circuit. (b) The interference pattern of the generated optical vortex beam with a Gaussian beam. Applying a single voltage on the phase shifters, the OAM state (indicated by the number and direction of the spiral arms of the interference pattern) was continuously tuned from $l = -4$ to $l = +4$ with both integer and non-integer OAM states. (c) The measured heating power at different OAM state.

Transverse-electrically (TE) polarized light at 1470nm was coupled into the fabricated silicon photonic circuit. All of the 30 emitters were uniformed excited (Fig. 2(a)), showing very low insertion loss in the phase shifters. In the far field, the generated optical vortex beam was combined with a Gaussian beam to create the spiral-shaped interference pattern from which the OAM state can be distinguished by the number and direction of the spiral arms [1]. As shown in Fig. 2(b), by applying a single electrical control on the phase shifters, the OAM state of the generated optical vortex beam can be tuned from $l = -4$ to $l = +4$. Moreover, since the phase delay $\Delta\phi$ can be continuously adjusted, the l-number can be freely tuned to realize both integer OAM states and non-integer states (e.g. $l = \pm 1.5$ and $l = \pm 2.5$ in Fig. 2(b)), the first of its kind that can find important applications such as quantum information and optical manipulation.

In conclusion, we proposed and demonstrated the first silicon photonic integrated circuit to generate optical vortex beam with well-defined and continuously tunable (both integer and non-integer) OAM state using a single electrical control. This compact OAM generator, with the promise to integrate with other on-chip silicon photonic components, opens up new opportunities in many applications such as optical communication and sensing.

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3. References

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