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Optical vortex splitter using topological edge state waveguide

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Abstract

We realized an Si-based optical vortex splitter using topological edge state waveguides. The device consists of several kinds of topological edge state waveguides having C_6 symmetric Si/SiO_2 nanoholes arranged in honeycomb lattice, and it can change the branching ratio of the optical vortices propagating in the circuit by arbitrarily setting the photonic structure in the device. The device was actually fabricated on SOI wafer and, as a result, the output ratio between two ports of the device changed from +4.6dB to -6.2dB, which tendency agreed with our theoretical calculation.

1. Introduction

Since the optical vortex can carry information on the helical cycle of the wave front, it is attracting attention as a key technology for high-capacity transmission [1]. However, conventional optical circuits that are widely used in optical communication system never have high affinity with optical vortices because waveguide devices in the optical circuit operate only with TE/TM mode light. Therefore, by replacing a part of the conventional optical circuit with a topological photonics system, we aim to realizing various controls of optical vortex signal in the photonic integrated circuit (TPICs: Topological Photonic Integrated Circuits).

A honeycomb lattice structure having dielectric components with C_6 symmetry is promising for controlling the optical vortex in the optical circuit [2]. The topological edge states generated at the interface between the trivial and the topological photonic structures allow optical vortex mode propagation [3, 4]. In this situation, a splitter for optical vortices having the same role as Y-splitters or directional couplers for the conventional optical circuits is strongly desired. In this paper, we investigated Si-based optical vortex splitter using topological edge state waveguides from theoretical and experimental aspects.

2. Operation principle and design of optical vortex splitter

Figure 1 illustrates the schematic of proposed optical vortex splitter using the $\mathbb{Z}2$ topological photonic phase. The device has five domains, namely, the two trivial photonic domains, two topological photonic domains, and a variable photonic domain (domain X). Here, we consider controlling the intensity ratio of the optical vortex signal emitted from port 1 and 2 by arranging a suitable photonic structure in the domain X.

Figure 2(a) shows a photonic structure we used in simulation. It consists of a Si core layer with a film thickness of 220 nm sandwiched between a 1.5 µm-thick SiO_2 cladding and an air cladding. Figure 2(b) shows band diagram for each photonic structure calculated by using Plane Wave Expansion (PWE) method. In simulation, a period of the honeycomb lattice was fixed to 800 nm, and the distance R from the center of the honeycomb lattice to the center of the nanohole, and the length L of one side of the nanohole were used as parameters for analysis. The typical band diagram for a

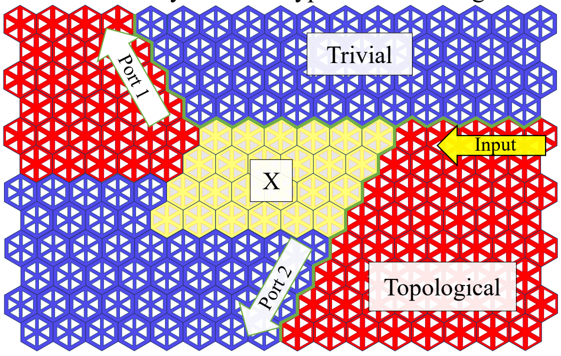


Fig. 1 Schematic of optical vortex splitter using topological edge state waveguides. The red and blue domains have topological and trivial structures, respectively.

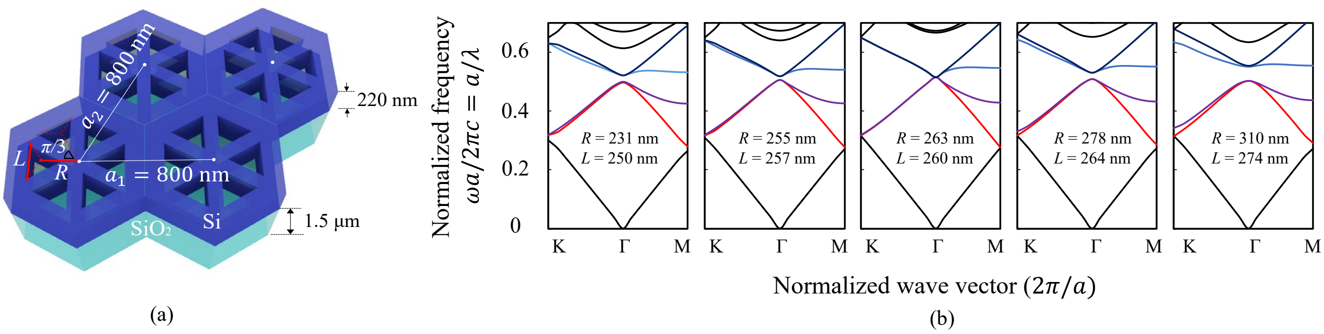
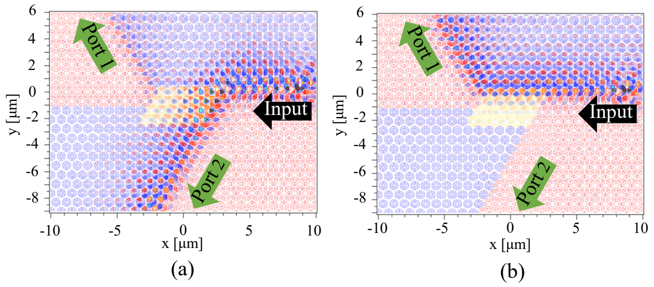


Fig. 2 (a) Photonic structure used in simulation. (b) Band diagram for each photonic structure calculated by using Plane Wave Expansion (PWE) method.



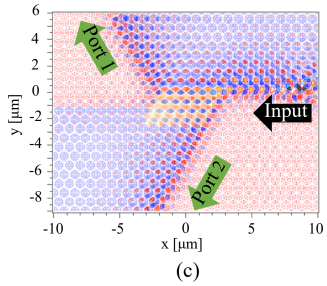


Fig. 3 Propagation characteristics of the optical vortex beam splitter (a) Trivial photonic structure (*R* = 231 nm, *L* = 250 nm), (b) topological photonic structure (*R* = 310 nm, *L* = 274 nm), and (c) zero-bandgap photonic structure (*R* = 263 nm, *L* = 260 nm) placed in the splitter domain.

trivial/topological photonic structure was obtained at (*R*, *L*) = (231, 250)/(310, 274). Assuming that these structures are arranged in the domain of trivial and topological domains of Fig. 1, it is necessary to place a photonic structure having a band diagram between these two in the domain X. Figure 2(b) also shows an example of these band diagrams. As a result, increasing *R* and *L* caused a transition from a trivial system to a topological one. Here, both *R* and *L* were changed so that the center frequency of the bandgap would always be nearly equivalent to the wavelength of the input light (= 1550 nm), thereby ensuring that this device does not cause changes to the optical vortex mode.

Using the photonic structure designed above, we analyzed transmission characteristics of the optical vortex beam splitter. Figure 3 shows propagation characteristics of the device calculated by the 3-dimensional FDTD method. In this analysis, we assumed that the domain X comprises 4 × 6 = 24 unit cells. When the trivial photonic structure or topological photonic structure was arranged in the domain X, the input was directly connected to each output port through a topological edge state waveguide (Figs. 3(a)(b)). When a zero-bandgap photonic structure—where all electromagnetic modes are degenerated in the center of the Brillouin zone—was arranged in the splitter domain, the intensity ratio of the optical vortex signal emitted from port 1 and 2 approached 1:1 (Fig. 3(c)).

3. Fabrication and evaluation of optical vortex splitter

Based on the design described in Section 2, we actually fabricated an optical vortex splitter and measured characteristics of the device. First, ZEP520A (film thickness: 500 nm) was coated onto a SOI substrate (Si core thickness: 220 nm, BOX thickness: 3 μm). After that, a device pattern was formed by electron-beam lithography and inductively coupled plasma reactive ion etching (ICP-RIE) with CF_4-SF_6 mixed gas (mixing ratio 8:1). Figure 4 shows scanning electron microscope (SEM) images of the fabricated device. In this experiment, *R* of the trivial/topological photonic structure was set to 231/310 nm.

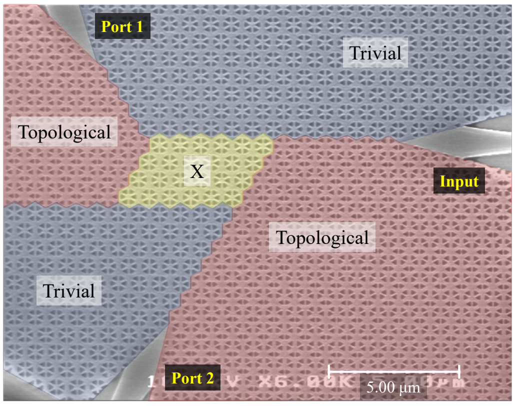


Fig. 4 Colored SEM image of fabricated device.

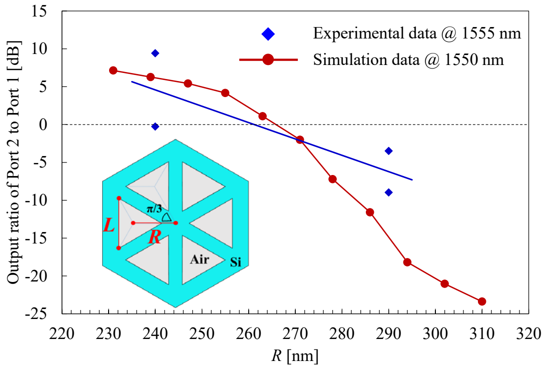


Fig. 5 Output ratio between two ports of fabricated device as a function of dimensions of photonic structure placed in domain X.

We measured the propagation characteristics of the device for 1550-nm-band incident light. Figure 5 shows the output ratio (port 1/port 2) of the device as a function of dimensions of the photonic structure placed in domain X (the simulation results are also plotted). According to the simulation results, as *R* of the photonic structure arranged in the domain X is increased, the output intensity of port 1 is suppressed, and the output intensity of port 2 gradually increases. As an initial experiment to confirm this, we fabricated two kinds of devices in which a trivial-like photonic structure (*R* = 240 nm) and a topological-like photonic structure (*R* = 290 nm) were arranged in the domain X, respectively. As a result, the output intensity ratio changed from +4.6dB to -6.2dB. By changing the photonic structure arranged in the domain X, optical vortex transmission to either port 1 or port 2 became dominant. In the future, we aim to continuously change the output intensity ratio by finely changing the photonic structure arranged in the domain X.

Acknowledgment

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