Topological nanophotonics for integrated devices

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Abstract *We will show our recent works of topological nanophotonics in silicon-on-insulator platform, including topological routing in valley photonic crystals and on-chip filtering based on topological corner states. These results are promising for the development of topologically-protected integrated devices at telecommunication wavelength.*

Introduction

The development of nanophotonic integrated devices in silicon-on-insulator (SOI) platform can potentially improve the capabilities of modern information-processing systems by replacing some of their electrical counterparts[1]. To implement novel integrated devices, one of the fundamental principles is the complex light manipulation at nanoscale. Photonic crystal (PC) slab provides a useful tool to manipulate light waves in silicon photonic integrated circuits (PICs), through finely engineering some defects in a precise location of the PC slab. Recently, the discovery of topological photonics[2-4] provides a new degree of freedom to control the flow of light, which is an advanced platform to experimentally explore a variety of topological crystalline phases that are difficult to implement in atomic scale. Also, the development of topological photonics at nanoscale (i.e. topological nanophotonics) gives a new paradigm to design novel devices in PICs. In topological nanophotonics, the intrinsic guided/localized mode will be totally predictable by investigating the bulk topology, regardless of the local region of PC slab. In other words, the guided/localized modes will be induced by the global feature of topological bulk states, so that one can apply the simple “topology” language to achieve intrinsic guided/localized mode with GLOBAL method.

To develop topological physics into integrated photonic system, one of primary factors is that design should be compatible with low-absorption semiconductor materials. Recent development of all-dielectric topological photonic crystals, e.g. by breaking spatial-inversion symmetry[5-9] or by deforming the sublattices of unit cell[10-16], paves an extensive way to achieve high-performance topological nanophotonic devices in PICs. For example, to retrieve topological valley phase, a general method is to break spatial-inversion symmetry for accessing opposite Berry curvature profiles near Brillouin zone corners, i.e. K and K’ valley. The topological valley phase below light cone ensures high-efficient light confinement in the plane of chip, such that photonic valley degree of freedom (DOF) naturally makes a balance between in-plane robustness and out-of-plane radiation. This is a crucial condition to design topological integrated photonic structures.

Topological routing in valley photonic crystals

Advanced in nanofabrication techniques, precise manufacture of the inversion-symmetry-broken nanophotonic structures is easy to implement nowadays. To do this, we design the VPC structures on SOI wafers with 220-nm-thickness silicon layers[8]. A bearded-stack interface is constructed by using two VPCs with opposite valley Chern index. Thus the propagating light inside the topological bandgap will smoothly detour by 120º bending (60º sharp corner). The valley-dependent topological edge states operate below the light cone so that the photonic crystal slab can strongly confine the propagating waves in the plane of chip. Benefit from near-quarter-wavelength periodicity, our VPC can develop a high-performance topological photonic device with a compact feature size. Based on the bearded-stack interface, we have fabricated flat-, Z- and Ω-shape topological channels. The measured results of these three devices show the flat-top high-transmittance spectra with relatively large bandwidth, even for sharp-bend geometry.

Unidirectional coupling of topological edge states shows many promising applications in light manipulation, e.g. selectively routing the light path. Here the mechanism and performance of unidirectional coupling between VPC waveguides and chiral dipole emitters is analyzed[17]. In two types of bearded- and zigzag-stack VPC waveguides (VPCWs), both analytical derivation and numerical calculations show that the directionality distributions by full-wave simulations are consistent with the Stokes parameter profiles of eigenmode. The strategy of bearded VPCW can relax the bias error of frequency and source location, so that it is easier to obtain high-efficiency unidirectional coupling

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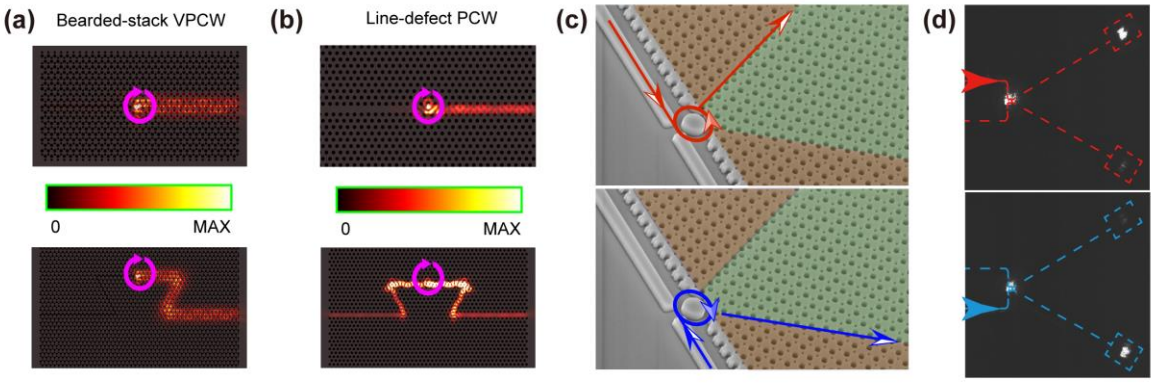

Fig. 1: Analysis of unidirectional coupling with robustly optical transport and experimental demonstration of photonic routing at telecommunication wavelength.

than that of zigzag interface. In addition, such topological-protected unidirectional coupling is proved that can support robust transport against sharp-bending interface, as shown in Figs. 1(a) and 1(b). In experiment, we aim to develop an all-optical strategy, for unidirectional excitation of the valley-chirality locking edge states in the SOI platform[8]. We have experimentally demonstrated on-chip topological photonic routing. Such routing effect is based on the topological chiral channel of VPC. With introducing a subwavelength microdisk to serve as phase vortex generator, the valley-chirality-locked edge state is selectively excited (Fig. 1c). Thus the photonic valley-chirality locking property and topological routing effect were experimentally verified by far-field microscope images, as shown in Fig. 1(d).

Furthermore, we will show another type of topological integrated photonic waveguide based on bilayer photonic crystal slabs[18]. Note that each layer of all-dielectric layered photonic topological insulators (PTIs) can be considered as VPC slab. The introduction of layer pseudospin offers more dispersion engineering capability, leading to the layer-polarized and layer-mixed photonic topological insulators. Their phase transition is demonstrated with a model Hamiltonian by considering the nonzero interlayer coupling. For one, layer-direction locking behavior of layer-polarized photonic topological insulators results in the selective light refraction. For another, high transmission is observed in the bilayer domain wall between two layer-mixed photonic topological insulators, even when a large defect is introduced.

On-chip filtering based on topological corner states

Recently, the corner state in second-order topological photonic crystal (SOTPC) renders a global method to achieve intrinsic cavity mode. Based on III-V semiconductor materials, the SOTPC slab has been extensively explored for light-matter interaction. Here we will show an intuitively exploration of such topological corner state under in-plane excitation in silicon PICs, as well as discuss the promising application for on-chip filters.

In theory, the second-order topological structure is designed by a dielectric-vein PC, whose unit cell consists of four square-holes clusters in silicon background. When we shrunken/expand the clusters to the center/corner of unit cell, the topologically trivial/nontrivial phase can be achieved with zero/nonzero bulk polarization. Consider a 90-deg-bend interface constructed by shrunken (green) and expanded (orange) PCs as shown in Fig. 2(a), the corner state will be induced by the differences of bulk polarizations. The square holes (side length 2s = 266nm) are arranged in square lattice with the periodicity of a = 430nm. To confirm the corner state in simulation, we calculate the resonant mode distributions at real space. Fig. 2(b) gives the H_z field patterns at resonant wavelength (λ = 1400.515 nm) for $z = 0$ and $y = 0$ planes, respectively. In this cavity mode, the calculated Q factor is about 9000, while the mode volume is $V_m = 0.366(\lambda/n_{si})^3$.

In experiment, a cross-coupled cavity based on SOTPC bend interface was designed on free-standing silicon membrane (the refractive index of silicon is n_{Si} = 3.464) with 220-nm thickness. Some edge rectangular holes of the interface are filled with silicon to form a line-defect photonic crystal waveguide (PCW). This cross-coupled cavity design enables us to experimentally “see” the topological corner states on PC slab. SEM images of fabricated samples for bulk crystal, flat interface and cross-coupled cavity are respectively shown in Fig. 2(c). The shrunken/expanded PCs are labelled as green/orange false color. Fig. 2(d) shows the measured transmission spectra of bulk crystal (black), flat interface (orange) and cross-coupled interface (green) samples, which is normalized by the transmission spectra of a strip Si waveguide. In the low-transmission region of bulk crystal and flat interface, the spectrum of cross-coupled cavity has a sharp resonant peak near 1383 nm, in correspondence with corner state. This sharp peak means the cross-coupled cavity works as a narrow band filter. The light is transmitted only for wavelength near the resonant mode of the cavity (corner state). Light from the input PCW can couple into the cavity by exciting the corner state, and then the cavity in turn coupled to the output PCW. Based on coupled-mode theory and Lorentz fitting, we experimentally evaluate the resonant wavelength λ_C = 1383.108 nm, the bandwidth of the resonant peak $\Delta\lambda_C$ = 0.411 nm, the in-plane coupling quality factor Q_w = 5688 and the out-of-plane radiative quality factor Q_r = 8233 (also can be considered as the intrinsic Q of corner state). Fig. 2(e) gives the far-field microscope images of cross-coupled cavity excited at λ = 1383.033 nm. It confirms that we do indeed observe the in-plane localized mode around the corner of bend interface, i.e. the topological corner state. These results quantitatively confirm that we have successfully obtained a high-Q cavity mode based on the topological corner state, with a promising application for transmission cavity filters.

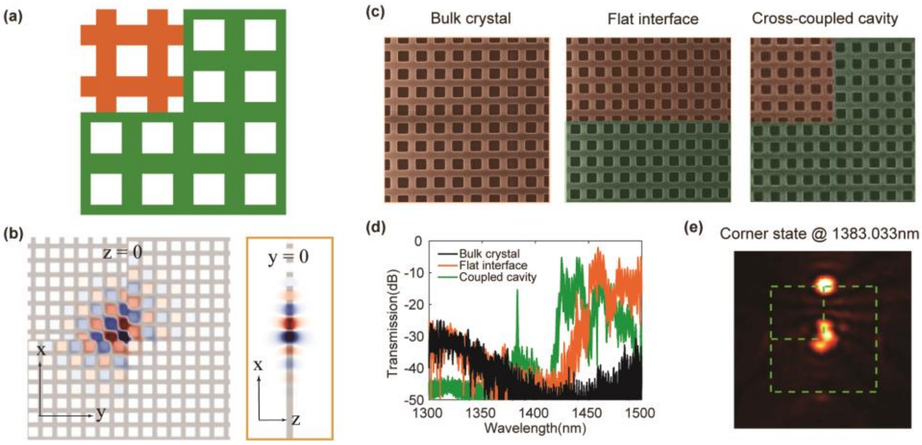

Fig. 2: (a) Schematic illustration of a bend interface constructed by shrunken (green) and expanded (orange) photonic crystals. (b) Hz field patterns of corner states for the z-center and y-center planes at resonant wavelength (λ=1400.515nm). (c) Scanning-electron-microscope images of fabricated samples. (d) Measured transmission spectra of bulk crystal (black), flat interface (orange) and cross-coupled cavity (green) samples. (e) Far-field images of corner states in cross-coupled cavity sample via optical microscope system at resonant wavelength (λ=1383.033nm).

Conclusions

In summary, we have successfully applied different type of topological phases to manipulate the flow of light in silicon-on-insulator platform with global method. Topological robust transport and topological photonic routing are experimentally demonstrated and confirmed at telecommunication wavelength. A cross-coupled photonic crystal cavity based on second-order topology has been implemented to observe topological corner state and to characterize on-chip filtering features. The emerging field of topological nanophotonics opens up an alternative route towards the discovery of fundamentally novel states of light and some promising applications. These works show a prototype of on-chip photonic devices and photonic analogues of quantum information processing based on topological nanophotonic modes.

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