A topologically protected optical filter based on a silicon photonic nanobeam cavity

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***Abstract*—We propose and experimentally demonstrate a novel optical filter based on a bus waveguide side-coupled to a topological photonic nanobeam cavity. The measured extinction ratio is 15.25 dB, and the intrinsic quality factor is 2914.**

Keywords—optical filter, topological photonics, nanobeam cavity

I. Introduction

In the past decades, silicon photonics has attracted great attention in the fields of optical communication systems and data centers, due to its compatibility with complementary metal oxide semiconductor (CMOS) process and its possibility of integrating various optical devices in one chip [1]. Silicon optical filters are widely used in wavelength division multiplexing systems and spectrum sensing systems [2,3]. To date, many designs have been proposed, including those based on Mach-Zehnder interferometers (MZIs) [4], microring resonators (MRRs) [5], photonic crystal cavities [6], etc. However, they have the disadvantages of large footprints and/or low fabrication tolerance. Recently, one-dimensional (1D) topological photonic crystal (TPC) nanobeam cavity has received much attention for its compact footprint, high quality factor and distinctive topology protection feature **Error! Reference source not found.**. In such structures, a zero-dimensional interface state is formed between two one-dimensional (1D) photonic crystals with different topological invariants. The emergence of the interface state is related to the nontrivial Zak phase [8], which leads to strong robustness against fabrication imperfections.

In this work, we propose and experimentally demonstrate a compact optical filter based on a bus waveguide side-coupled to a 1D TPC nanobeam cavity. The extinction ratio of the device is measured to be 15.25 dB while the intrinsic quality factor is 2914. The existence of the cavity mode is robust against the deformation of the shape of the nanoholes composing the nanobeam cavity.

II. Structure and Design

The schematic diagram of our proposed optical filter is shown in Fig. 1. It is composed of a bus waveguide in the proximity of a 1D TPC nanobeam cavity. Two different 1D TPCs are interfaced at x = 0, forming the nanobeam cavity. They have the same band structure but different geometric (Zak) phase. The TPCs are formed by a nanobeam waveguide with the width w_2 = 484 nm and the period of the unit cells a = 400 nm. Each unit cell contains two elliptical holes of equal major axis length d_2 = 304 nm. The half lengths of the minor axes of two elliptical holes are r_1 = 60 nm and r_2 = 40 nm, respectively. The purple and yellow boxes encircle the typical unit cells of two TPCs. Due to the inversion symmetry of the unit cells, the geometric (Zak) phase is quantized to either 0 or π. The existence of an interface state can thus be guaranteed by the difference of the Zak phase between two TPCs. The bus waveguide has a width of w_1 = 350 nm, and the gap between the bus waveguide and the nanobeam cavity is chosen to be d_1 = 510 nm. The whole device is built on a silicon-on-insulator (SOI) wafer with a 220-nm-thick top silicon layer, a 3-μm-thick buried oxide layer and a 1-μm-thick silica upper cladding layer.

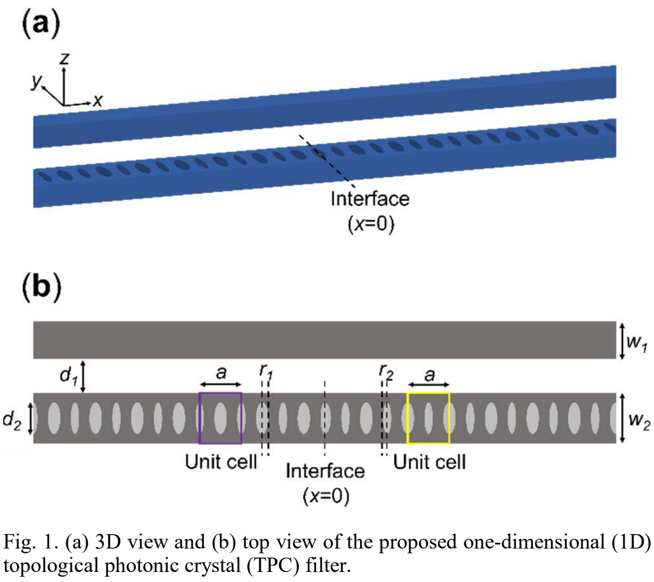

Fig. 1. (a) 3D view and (b) top view of the proposed one-dimensional (1D) topological photonic crystal (TPC) filter.

Fig. 2(a) displays the band diagrams of the photonic crystals whose unit cells are shown in the purple and yellow boxes in Fig. 1(b). The first bandgap ranges from 189.15 THz to 197 THz, which corresponds to a wavelength range of 1523 nm - 1586 nm. The TPCs composed of these two kinds of unit cells share the same band structure, as shown in Fig. 2(a). The associated mode profiles of the two lowest bands at the band edges exchange for two TPCs [see the insets of Fig. 2(a)], manifesting the presence of band inversion.

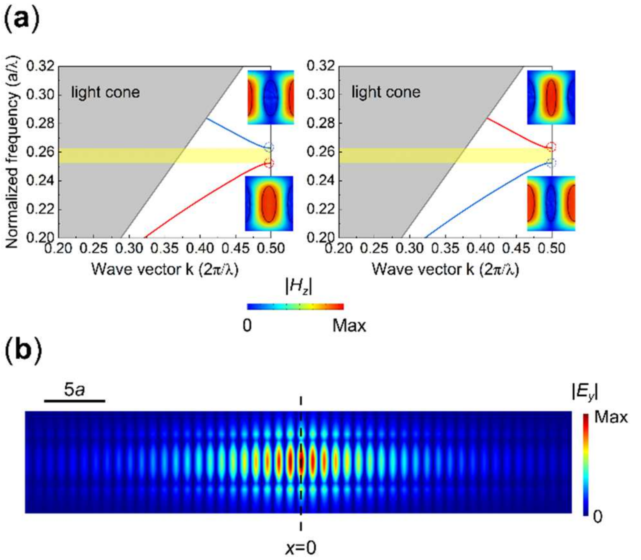

Fig. 2. (a) Band diagrams of the photonic crystals with the unit cells encircled by the purple and yellow boxes. The insets show the magnetic field intensity of the Bloch modes at the band edges. (b) Electric field ($|E_y|$) distribution of the defect mode in the TPC nanobeam cavity.

The electric field $|E_y|$ profile of the resonant mode is simulated by the 3D finite difference time domain (FDTD) methods and shown in Fig. 2(b). The optical power is concentrated in a small area around the interface with a mode volume of about 2.05 $(\lambda/n)^3$, which proves the existence of a single cavity mode at the interface.

III. Device Fabrication And Measurement

The designed device was fabricated on a SOI wafer with a 220-nm-thick top silicon layer on a 3-µm-thick buried oxide layer. The device was patterned by e-beam lithography (EBL, Vistec EBPG 5200$^+$) and etched by inductively coupled plasma etching (ICP, SPTS DRIE-I). A 1-µm-thick silica cladding layer was deposited upon the device by plasma-enhanced chemical vapor deposition (PECVD, Oxford Plasmalab System 100). The scanning electron microscope (SEM, Zeiss Ultra Plus) image of the nanobeam is presented in Fig. 3. The footprint of the device is 1.4 µm × 48.4 µm. As we can see, the elliptical holes are imperfect in shape. However, as long as the TPC bandgap remains open, the hole shape has little impact on the existence of the defect mode.

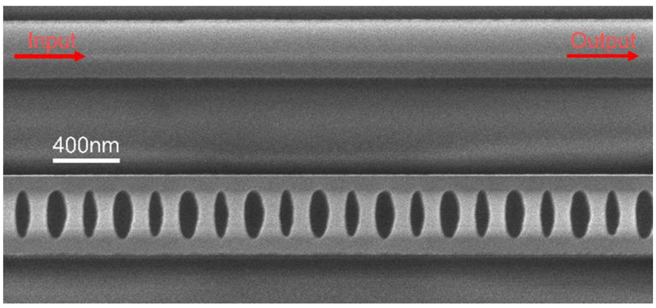

Fig. 3 SEM image of the fabricated TPC nanobeam filter.

The performance of the fabricated device was characterized using a tunable laser (Santec TSL-770) and a photodetector (Santec MPM-210). In the measurements, the TE-polarized light in the wavelength range of 1500 nm - 1600 nm was coupled into and out of the silicon chip by grating couplers. The transmission spectra of the 1D TPC filter are shown in Fig. 4. The extinction ratio of the device is 15.25 dB with almost negligible insertion losses at the wavelengths we concern. Due to the inevitable fabrication errors, the resonance wavelength (λ = 1534.58 nm) is blue-shifted from the designed value (λ = 1550 nm). By fitting the resonance dip to a Lorentzian curve, the intrinsic quality factor and the loaded quality factor are estimated to be 2914 and 1712, respectively.

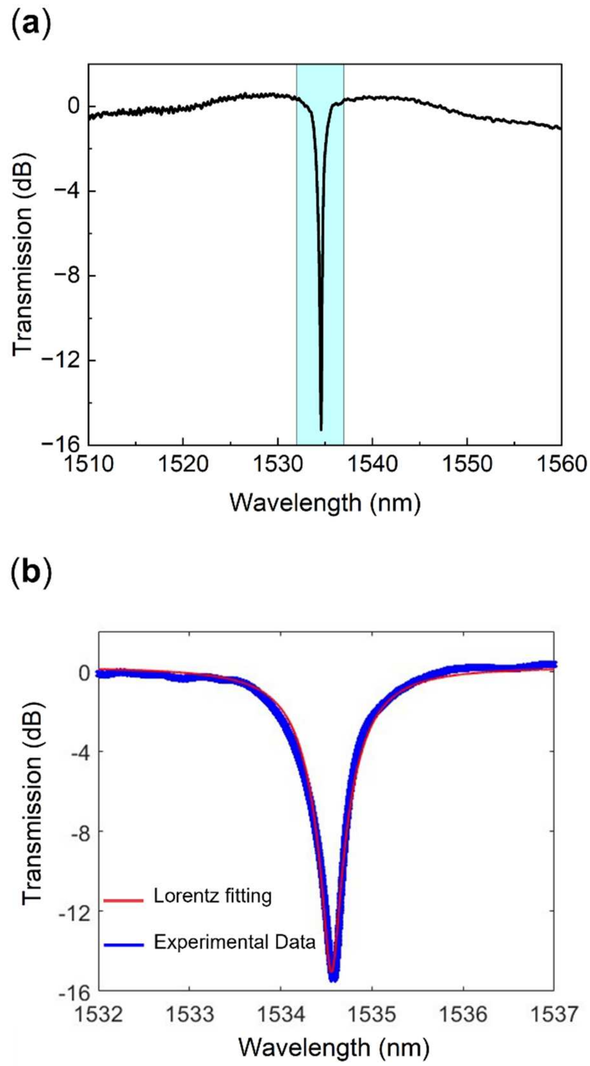

Fig. 4. (a) Transmission spectra of the fabricated 1D TPC nanobeam filter. (b) Zoom-in spectrum and Lorentz fitting of the resonance dip in the blue shaded area in (a).

IV. Conclusion

In summary, we have proposed and experimentally demonstrated a novel optical filter which consists of a bus waveguide side-coupled to a TPC nanobeam cavity. A zero-dimensional interface state is formed at the junction of two 1D photonic crystals. Despite the fabrication errors, the topological design can ensure the existence of the defect mode as far as the bandgap remains opened. The single mode filter was fabricated on a SOI wafer with a small footprint of 1.4 µm × 48.4 µm. The extinction ratio, intrinsic quality factor, and loaded quality factor are 15.25 dB, 2914, and 1712, respectively.

ACKNOWLEDGMENT

This work was supported in part by National Key Research and Development Program of China (2019YFB2203503), and National Natural Science Foundation of China (62035016, 62105200, 61835008, 61860206001).

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