Topologically Protected Entangled Biphoton States in High-order Topological Insulators

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Abstract: We demonstrate different structures of high-order topological insulators supporting topologically protected biphoton states and theoretically explained that the photon pairs generated from the four-wave mixing (FWM) process are continuous frequency entangled. © 2023 The Author(s)

1. Introduction

Due to their distinctive edge states and transport characteristics, topological insulators have received much theoretical and experimental research. Topological features can provide robustness for the transport of quantum entangled states, which can be applied to many frontiers. Potential applications of topology in quantum communication include topological quantum sources [1], topologically protected entanglement [2, 3], and topological protection of quantum interference [4].

In this study, second-order topological photonic crystals with entangled biphoton states are implemented. The topological edge states show robustness against the sharp bends and structural defects in the two dimensional (2D) photonic generalization of the Su-Schrieffer-Heeger (SSH) model. Furthermore, the quantum entanglement between signal and idler photon pairs produced by the four-wave mixing (FWM) process is elucidated.

2. Topological photonic crystals

Photonic crystal (PC) band configurations provide platforms for studying various topological features. Here we consider a scheme of 2D photonic crystals based on a silicon nitride (Si_3N_4) topological waveguide with mirror symmetries as shown in Fig.1(a). There are four identical dielectric rods in each square unit cell with lattice constant a = 700 nm. The location and size of dielectric rods are denoted by l_x, l_y, and r as illustrated by the zoom-in structure. PC1 and PC2 are isotropic with l_x=l_y=a/8 and l_x=l_y=3a/8, respectively. The simulation result of the field distribution when PC1 and PC2 have a right-angle-shaped interface is shown in Fig. 1(b), indicating the topological protection characteristics. Fig. 1(c) shows the calculated dispersion at the interface between PC1 and PC2. The dark green area indicates the topological bandgap (~6.0THz) from 183THz to 189THz. To investigate the characteristics of the interface between different PCs, we also construct an anisotropic PC3 with l_x=a/8, l_y=3a/8 whose unit cell structure is shown in Fig.1(d). The topological bandgap in the interface between PC1 and PC3 is calculated as 12.0THz (183THz ~ 195THz).

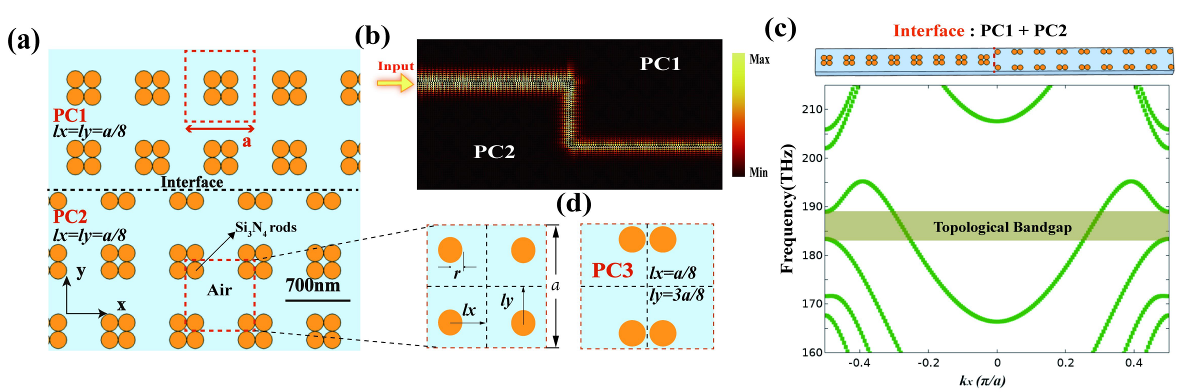

Fig. 1. (a) A scheme of topological PCs with the zoom-in structure of a unit cell. (b) Simulated field distribution in the right-angle-shaped interface composed of PC1 and PC2 at 188THz. (c) Corresponding band structure at the interface between PC1 and PC2. (d) The unit cell structure of anisotropic PC3.

3. Topological protection of entangled biphoton states

The spectral correlations between signal and idler photons generated by spontaneous FWM are illustrated by the joint spectral amplitude (JSA) in Fig. 2(a). We employ Schmidt decomposition to testify the separability of the JSA, the result of the normalized Schmidt coefficient is plotted in Fig. 2(b). The presence of more than one nonzero Schmidt coefficient reveals the continuous frequency entanglement of photon pairs produced by the FWM process at the interface between PC1 and PC2. The entangled photon pairs propagating along the interface are topologically protected, showing robustness against right-angle bends and structure imperfections.

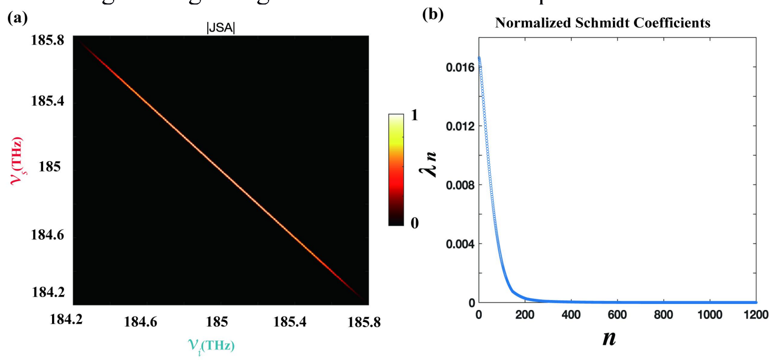

Fig. 2. Simulation results of the interface between PC1 and PC2. (a) JSA of photon pairs generated from the FWM process. The frequencies are denoted as ν_s(signal) and ν_i (idler) in the picture. (b) Normalized Schmidt coefficients of photon pairs.

We further investigated the topological edge states of the box-shaped combined structure (PC1 outside and PC2 inside). The existence of topological edge states in the box-shaped structures is clarified as illustrated in Fig. 3. The results show that the propagation boundary of the entangled photon pair can be further selectively controlled by changing the frequency. We also get similar results in the box-shaped structure consisting of PC1 and PC3.

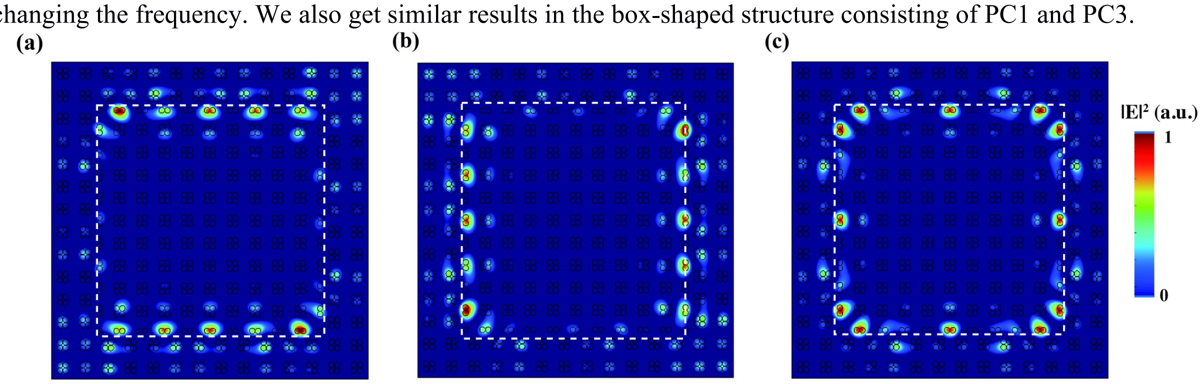

Fig. 3. Schematics of the box-shaped combined structure. The white dashed lines label the boundary between two different PC (PC1 outside and PC2 inside). Different sets of degenerate edge states (DESs) are obtained with different frequencies. The frequency of (a) and (b) is 184.9 THz and the frequency of (c) is 184.1 THz.

4. Conclusion

We showed a platform based on second-order photonic crystals that integrates topological photonic systems with entangled biphoton states. The continuous frequency entanglement of the photon pairs generated from FWM is clarified. Further, we verify the existence of topological boundaries in the box-shaped structures and propose that the control and selection of the propagation boundary of entangled photons can be realized in this combined structure.

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References

[1] Mittal, Sunil, et al. "Tunable quantum interference using a topological source of indistinguishable photon pairs." Nature Photonics **15** 842-548(2021).
[2] Jiang, Zhen, et al. "Topologically protected energy-time entangled biphoton states in photonic crystals." Journal of Physics D: Applied Physics **55** 315104 (2022).
[3] Jiang, Zhen, et al., "Topological protection of continuous frequency entangled biphoton states." Nanophotonics **10** 4019-4026 (2021).
[4] Nie, Wei, et al. "Topologically protected quantum coherence in a super atom." Physical Review Letters **124** 023603 (2020).