Four-wave Mixing Interaction in a Topological Resonator

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Abstract: We demonstrate a topological resonator implementing the four-wave mixing interaction based on valley photonic crystals. The topologically protected spontaneous four-wave mixing process in the topological resonator is numerically manipulated.

1. Introduction

Quantum topological photonics paves a new way for exploiting the topological protection into the field of quantum optics. Due to the one-way transport and robustness against structural imperfections, topological edge states seem to be prospective paradigms for conducting topological devices. Most recently, comprehensive researches revealing the topologically protected nonlinear interactions were implemented theoretically and experimentally [1,2]. As a result of the topological nature, these nonlinear interactions show robustness against disorders and structural imperfections. Besides, the concepts of topological phases have also been exploited in quantum systems, including a topological quantum source [3], topological single quantum emitters [4] and even topologically protected quantum entanglement [5].

Here we demonstrate a topological resonator supporting the nonlinear four-wave mixing (FWM) process in the photonic system. The valley kink states propagating along the topological interface are observed in valley photonic crystals emulating the quantum valley Hall (QVH) effect. We calculate the dispersion relation of the kink states and supported cavity modes in the resonator.

2. Topological resonators

Topological resonators are practical platforms for manipulating topologically protected nonlinear interactions. Here we propose a whisper-gallery topological resonator implementing the quantum valley Hall (QVH) effect. As shown in Fig. 1 (a), A triangular ring-resonator is designed by silicon-based valley photonic crystals (VPCs), where a topological waveguide is used to couple the pump into the cavity. The topological valley kink states are supported along the interface between two different VPCs referring to as VPC_1 and VPC_2. With the excitation of the pump, A degenerate FWM process emerges along the topological interface, two pump photons at the frequency of ω_p are annihilated, while a pair of photons (namely the signal (ω_s) and idler (ω_i)) are produced. The degenerate FWM process should satisfy the relations: $2\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$ and $2k_p = k_s + k_i$, where k_p, k_s and k_i are wavevectors of the pump, signal, and idler respectively. When the frequencies of the pump, signal, and idler are overlapped with the resonator modes of topological cavity, the edge states can be coupled into the cavity.

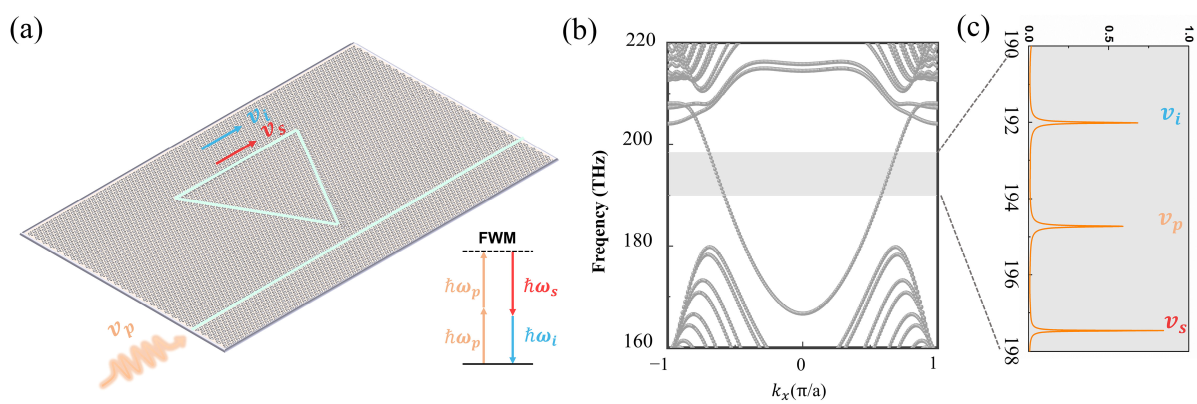

Fig. 1. (a) A scheme of a whisper-gallery topological resonator. (b)Dispersion relation of VPCs. (c) linear spectrum of energy inside the topological resonator.

To study the underlying properties of topological valley kink states, we calculate the dispersion relation of VPCs composed of VPC_1 and VPC_2. As depicted in Fig. 1(b), the result reveals that a pair of kink states appears inside the photonic bandgap. As a result of the QVH effect, the propagating directions of kink states are locked to different valleys. Consequently, the edge states inside the photonic bandgap are topologically protected. In order to support more resonator modes with kink states, a large photonic bandgap is designed with tunning the parameters of photonic crystals. For a degenerate FWM process, the frequencies of the pump, signal and idler should match with the potential resonator modes of the topological cavity. Hence, we simulated the linear spectrum of energy inside the topological resonator, as illustrated in Fig. 1(c). There exist several energy peaks at the resonant wavelengths of the topological resonator within the deserved bandwidth, which implies that the three kink states can efficiently couple into the whisper-gallery resonator through the gap between the topological waveguide and the resonator. The resonance frequencies are 192.0, 194.7 and 197.4 THz respectively, with the free spectrum range (FSR) of 2.7 THz. Thanks to the linear dispersion slopes of valley kink states, these resonance modes have the same propagating direction inside the cavity. Specifically, these resonance modes are topologically protected because the frequencies are localized inside the topological bandgap.

3. Nonlinear FWM interaction

To get insight into the nonlinear processes in the ring-resonator, we numerically simulate the electric field profiles of the FWM process in the proposed whisper-gallery topological resonator. A right-handed circularly polarized source is set to emulate valley kink states propagating along the topological interface. To match the resonance frequencies of the ring-resonator, the frequencies of the FWM process are considered as $\upsilon_p = 192.0$ THz, $\upsilon_s = 194.7$ THz and $\upsilon_i = 197.4$ THz respectively. As shown in Fig. 2, the cavity modes are all excited at the frequencies of the pump, signal and idler. Noticeably, there is no input for the idler, therefore, the excitation of mode at the idler frequency is the consequence of the FWM interaction due to the third-order nonlinear susceptibility tensor $\chi^{(3)}$ of silicon. As expected, the cavity states of the pump, signal and idler show robustness against sharp bends, clarifying the topological protection of the FWM process.

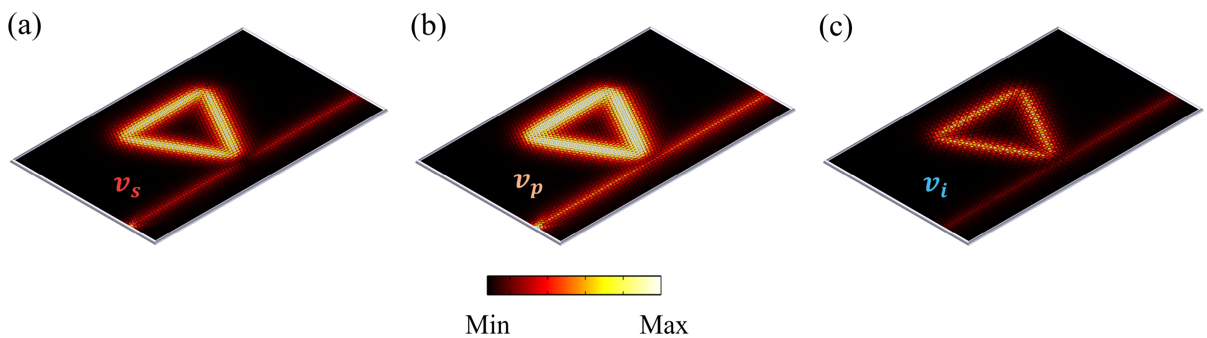

Fig. 2. Topologically protected FWM process in the topological resonator. Field profiles of the topological edge states at the frequencies of (a) the pump ($\upsilon_p = 192.0$ THz), (b) signal $\upsilon_s = 194.7$ THz) and (c) idler $\upsilon_i = 197.4$ THz respectively.

4. Conclusion

Topological nonlinear optics has attracted attention in recent years. Here, we demonstrate a photonic-crystal based topological resonator implementing the FWM interaction. The linear dispersion relations of topological kink states in valley photonic crystals are exploited. We numerically simulate the nonlinear spontaneous FWM process in the topological resonator. Our proposal may give rise to novel on-chip topological nonlinear optical devices.

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References

[1] M. S. Kirsch, Y. Zhang, M. Kremer et al. Nonlinear second-order photonic topological insulators. a *Nature Physics* vol. 17, p. 995–1000 2021.
[2] J. W. You, Z. Lan & N. C. Panoiu. Four-wave mixing of topological edge plasmons in graphene metasurfaces. *Science advances,* vol. 6, p. eaaz3910, 2020.
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[5] Z. Jiang, Y. Ding, C. Xi, G. He & C. Jiang. Topological protection of continuous frequency entangled biphoton states. *Nanophotonics,* vol. 10, p. 4019–4026, 2021.

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Abstract

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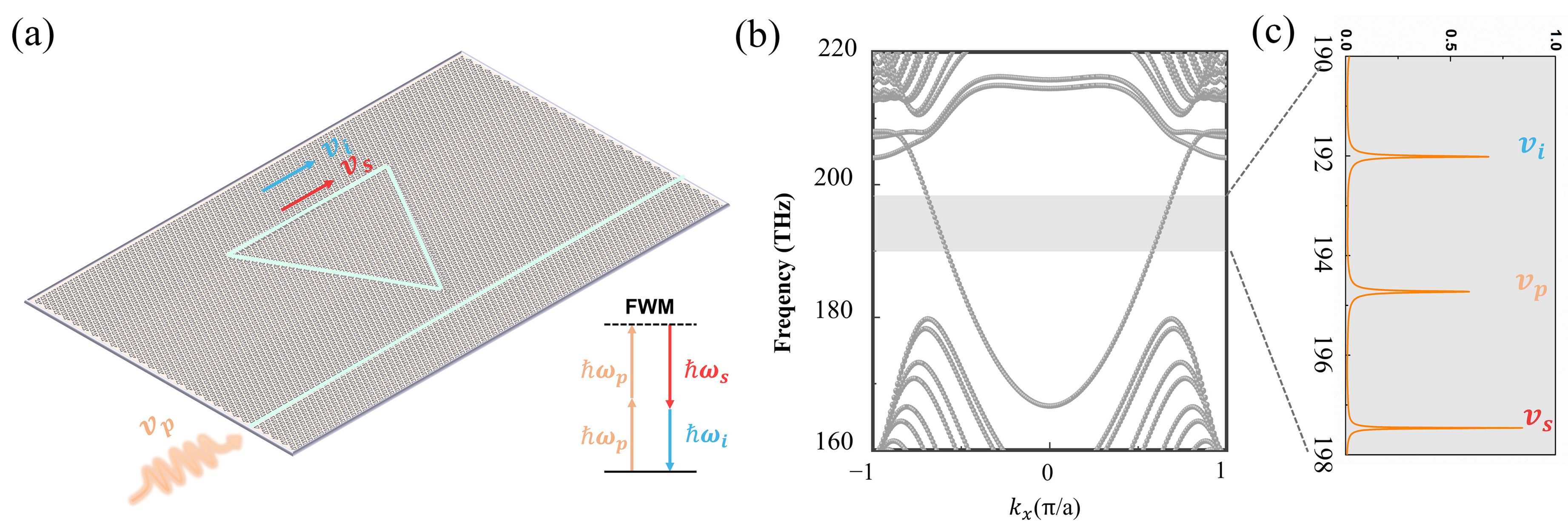

Fig.1 A scheme of a whisper-gallery topological resonator.

3. Nonlinear FWM interaction

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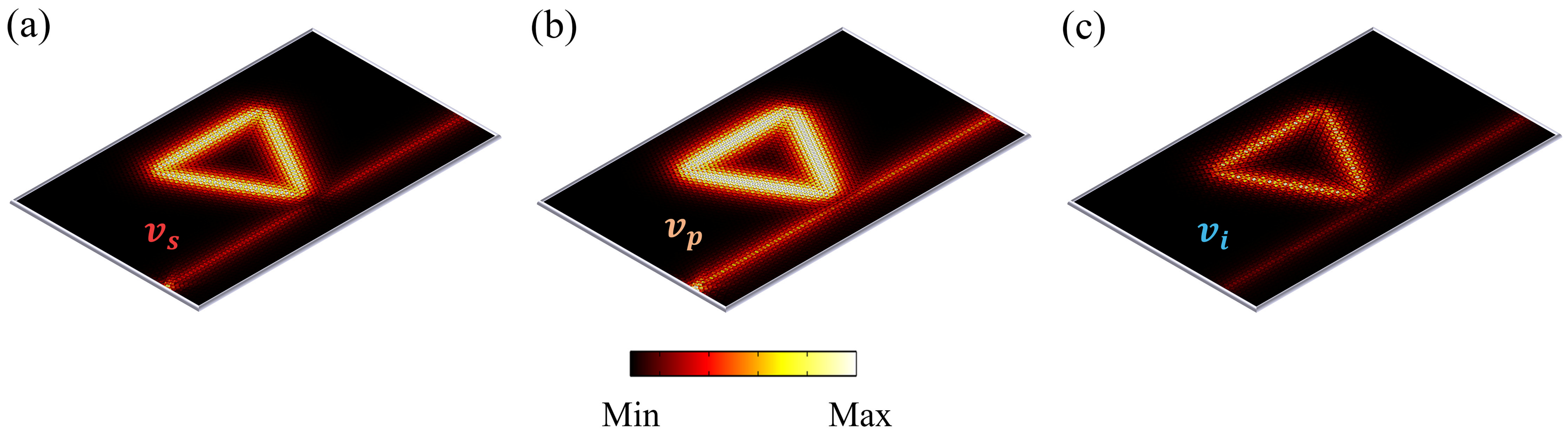

Fig.2 Topologically protected FWM process in the topological resonator.

References

[1] M. S. Kirsch, Y. Zhang, M. Kremer et al. Nonlinear second-order photonic topological insulators. Nature Physics 17, 995–1000, 2021.

[2] J. W. You, Z. Lan & N. C. Panoiu. Four-wave mixing of topological edge plasmons in graphene metasurfaces. Science advances, 6, eaaz3910, 2020.

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