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Cavity Quantum Electrodynamics with Second-Order Topological Corner State

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Topological photonics provides a new paradigm in studying cavity quantum electrodynamics with robustness to disorder. In this work, the coupling between single quantum dots and the second-order topological corner state are demonstrated. Based on the second-order topological corner state, a topological photonic crystal cavity is designed and fabricated into GaAs slabs with quantum dots embedded. The coexistence of corner state and edge state with high quality factor close to 2000 is observed. The enhancement of photoluminescence intensity and emission rate are both observed when the quantum dot is on resonance with the corner state. This result enables the application of topology into cavity quantum electrodynamics, offering an approach to topological devices for quantum information processing.

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1. Introduction

Cavity quantum electrodynamics (CQED) studies the interaction between photons and quantum emitters, including the strong and weak coupling regime, which has widespread applications.[1–3] For instance, CQED systems are widely proposed for the realization of quantum information processing.[4] Especially, the weak coupling can greatly enhance the spontaneous emission rate of quantum emitters,[5–7] which can be used to optimize the photonic devices, such as high-efficiency single photon source,[8–10] ultra-fast qubit gate,[11,12] and low-threshold laser.[13] Up to now, solid-state CQED experiments have been implemented in a wide range of photonic nanocavities, including whispering gallery modes,[14] Anderson-localized modes,[15] and photonic crystal (PhC) cavities,[16–20] with coupled two-level systems. These photonic nanocavities are optimized for high quality factor (Q) and small mode volume to enhance the coupling strength, and they are always strongly affected by defects and disorders introduced by fabrication imperfections, environment perturbations, etc. The emerging field of topological photonics provides a new paradigm to solve the problem, offering an approach to the development of photonic devices with robustness to defects and disorders.

So far, the application of topology in optics has been investigated in many areas,[21–44] such as one-way waveguide[28–34] and topological lasers,[35–42] which are mainly in the classical domain. The combination of topology with quantum regime will bring more interesting phenomena and physics.[45–49] Especially, the coupling between quantum emitters and topologically protected state will exhibit robust strong light-matter interaction, enabling a topological quantum optics interface.[50,51] For example, the coupling to topological edge state enables the robust chiral emission of quantum dots (QDs).[50] More importantly, the coupling to topological nanocavity will have more widespread applications in development of photonic devices and quantum optics devices for quantum information with built-in protection, which has not been demonstrated. To investigate CQED with topological state, both high-quality topological nanocavity and a good matching with quantum emitters are required. Recently, a new class of higher-order topological insulators have been proposed and experimentally demonstrated in different systems,[52–74] including 2D PhC slab where 0D topological corner state has been

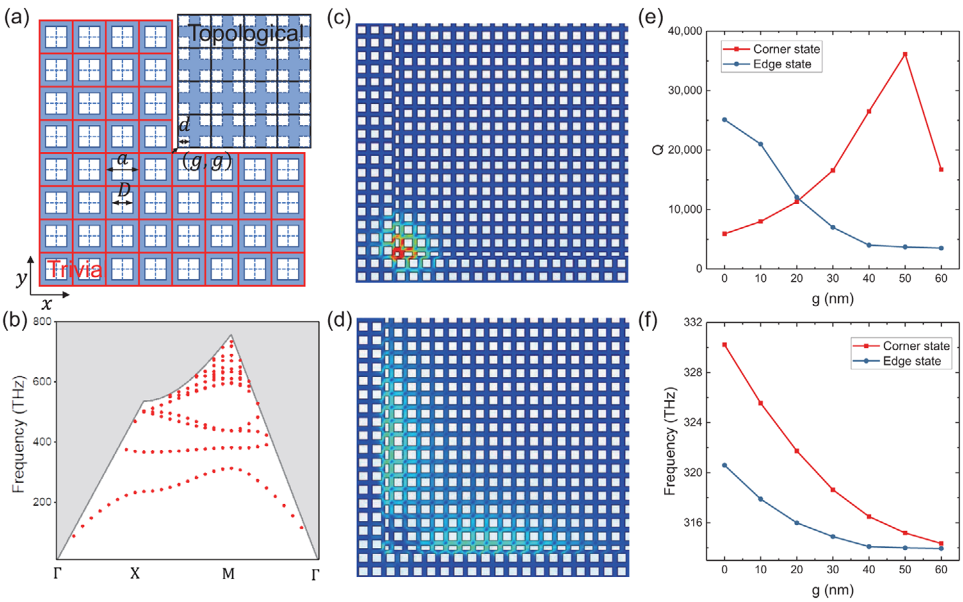

Figure 1. a) Schematic of the 2D topological PhC cavity in a square shape with square air holes with length of D ($d = D/2$). Unit cells with red (black) outline correspond to trivial (topological) PhC. The topological PhC is shifted away from the corner by (g, g) to optimize Q of the corner state. b) Bulk band structure of the 2D PhC slab with $a = 280$ nm, $D = 0.64a$, and $t = 150$ nm. Electric field profile of c) topological corner state at 321.11 THz and d) topological edge state at 314.8 THz with $g = 20$ nm. e) Q and f) frequency of corner state and edge state with different g.

observed.[54,55] This high-order topological state provides an ideal platform to design topological nanocavity for the investigation of CQED.

In this work, we report on the coupling between the second-order topological corner state and single QDs. Based on the generalized 2D Su–Schrieffer–Heeger (SSH) model, a topological PhC cavity is designed and fabricated into GaAs slab with QDs embedded. The Q is optimized by shifting the non-trivial PhC away from the corner. The existence of topological corner and edge states with high Q are observed by photoluminescence (PL) spectra. The emission intensity of single QD coupled to the corner state is enhanced by a factor of about 4, and the emission rate is enhanced by a factor of 1.3. Our results demonstrate the potential of the application of topology into CQED, enabling the development of quantum information processing.

2. Design and Optimization of Topological Corner State

Previous investigations have shown that the 0D corner state can exist in the 2D topological insulators protected by the quantized bulk quadrupole polarization[60–65] or quantized edge dipole polarization,[52–55] which is related to the 2D Zak phase, $\theta^{\text{Zak}} = (\theta_x, \theta_y)$ defined as

$$\theta_i = \int \mathrm{d}k_x \mathrm{d}k_y Tr[A_i(k_x, k_y)] \tag{1}$$

where $i = x$ or y and $A_i(k_x, k_y)$ is the Berry connection.[75] Many recent works[54,55] have shown that the Wannier-type 0D corner state, which is induced by the non-trivial edge dipole polarization, can be easily realized in the optical system by combing two different photonic crystals with distinct topologies but identical band gap. In this case, we design a topological nanocavity in the 2D PhC slab based on such 0D corner state, as shown in **Figure 1**a. The cavity consists of two topologically distinct PhC slabs in square shape with the same period a and thickness of t, which are distinguished by different colors of the outline. It is clearly shown that the four sub-squares in unit cell with the black (red) outline are far away from (adjacent to) each other, corresponding to a topological (trivial) phase with the 2D Zak phase being $\theta^{\text{Zak}} = (\pi, \pi)$ ((0,0)).[54,55] Additionally, due to the same period and size of the structures, these two PhC slabs share the common band structure, as presented in Figure 1b. By suitably combing the two topologically distinct PhC slabs, the quantized edge dipole polarizations along x- and y-axis can induce the 0D corner state in the band gap, and the related edge states get opened. Figure 1c,d shows the electric field profiles of the corner and edge states. In contrast to the dispersive distribution of 1D edge state, the corner state is tightly localized at the intersection of two types of PhC slab, which has a much smaller mode volume.

In addition to a small mode volume, the high Q is also important for the coupling between quantum emitters and nanocavity. The Q of corner state is optimized by slightly shifting the topological PhC away from the corner by (g, g), as shown in Figure 1a. In that case, Q of corner state first increases and then decreases with increasing g, whereas Q of edge states decrease monotonically, as shown in Figure 1e. When $g = 20$ nm, the Q of corner state and one of edge states are comparable with the magnitude of 10^4. However, their mode volumes show a big difference, about $0.23(\lambda/n)^3$ for the corner state and $6.59(\lambda/n)^3$ for the edge state, where λ is the resonant wavelength of the cavity and n is the refractive index of GaAs. Meanwhile, the corner state and edge state show redshift with increasing g, as shown in Figure 1f. Detailed calculations and discussions about Q and mode volume are

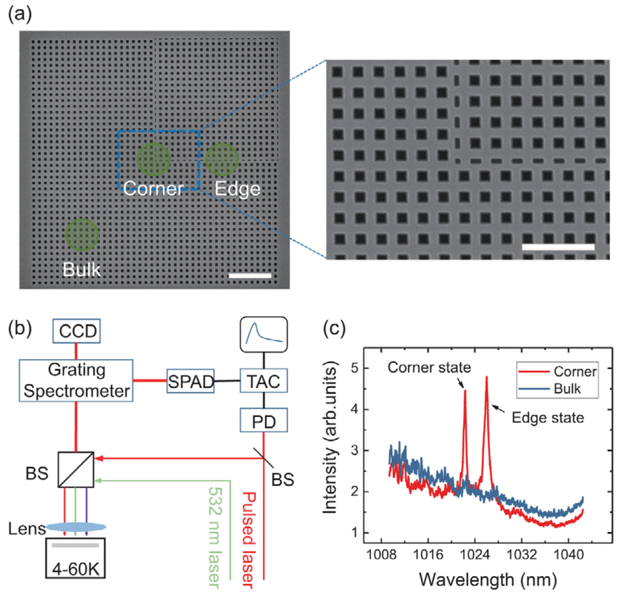

Figure 2. a) SEM image of a fabricated topological cavity with a scale bar of 2 μm. The inset shows an enlarged image of the blue area with a scale bar of 1 μm, indicating the location of the corner state. The different excitation positions are represented by green areas. b) Schematics of measurement setup for PL measurement and time-resolved PL spectroscopy. c) PL spectra collected from different positions of the cavity (a = 285 nm, D = 0.61a, and g = 30 nm) with a pump power of 350 μW. The red (blue) line is the PL spectrum collected from the corner (bulk PhC). The two peaks are identified as corner state and edge state as the arrows indicated.

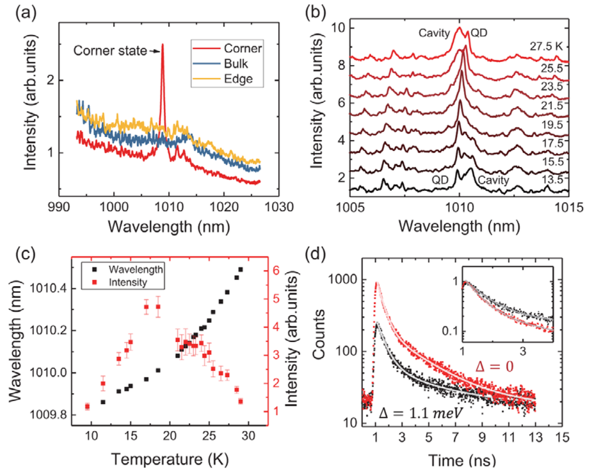

Figure 3. a) PL spectra collected when a topological cavity with a = 280 nm and g = 20 nm is excited at different positions. The corner state is identified. b) PL spectra collected when the QDs are tuned across the corner state by temperature. The spectra are shifted for clarity. c) Fitted intensity and wavelength of the QD indicated in (b). d) Decay curves for QD tuned on resonance and off resonance with the corner state. Inset shows the normalized decay curves. The black (red) squares are the experimental results with a detuning $\Delta = 1.1$ meV ($\Delta = 0$). The fitted results are represented by the grey lines.

shown in Supporting Information. Since the designed topological nanocavity has such high Q and small mode volume, it can be used for the investigation of CQED.

3. Experimental Results

We fabricate the designed topological PhC cavities with different geometric parameters into a 150-nm-thick GaAs slab using electron beam lithography followed by inductively coupled plasma and wet etching process. The GaAs slab is grown by molecular beam epitaxy and contains a single layer of InGaAs QDs at the center. The density of QDs is about 30 μm^{-2}, which is low enough to investigate the coupling between single QDs and topological cavity. The scanning electron microscope (SEM) image of a fabricated cavity is shown in **Figure 2a**. The inset is an enlarged SEM image around the location of the corner state. The fabricated square air holes are not perfect because of fabrication imperfection. However, the corner state can still exist with the slight shape perturbation, as long as there is no topological phase transition happens.

Then we perform the confocal micro-PL measurement at low temperature using a liquid helium flow cryostat as shown in Figure 2b. The topological cavity is excited by a continuous laser with wavelength of 532 nm. The PL signal is collected by a grating spectrometer and detected with a liquid-nitrogen-cooled charge coupled device camera with a spectral resolution of 60 μeV. Figure 2c shows the collected PL spectra when the cavity with g = 30 nm is excited at different positions of the PhC slab with high excitation power, which are indicated in Figure 2a. Two peaks are observed in the PL spectrum when excited around the corner (red line in Figure 2c) whereas disappear in the bulk (blue line in Figure 2c). According to the electric field profiles (Figure 1c,d), the edge state will also be excited besides the corner state when the laser is focused at the corner. Furthermore, the energy difference between the edge state and corner state will decrease with increasing g, enabling the observation of edge state close to the corner state in the spectrum. So the two peaks originate from the corner state and edge state. Thereinto, the PL peak with short wavelength is identified as the corner state whereas the peak with long wavelength is the edge state. The Q of the corner state and the edge state are about 1900 and 1200, respectively. The coexistence of corner and edge state with high Q provides a new platform to integrate the waveguide and cavity on a single chip.

In order to resolve single QD lines and therefore investigate the interaction between QD and corner state, we pump the sample at low-excitation power about tens of μW. The stronger pump power compared with other CQED experiments[16,17,19,20] may result from more defects in the samples. We tune the single QD lines across the corner state by temperature, and the corner state with linewidth about 730 μeV is identified by the PL spectra (as shown in **Figure 3a**). The absence of peak from the edge state may result from the low Q-factor induced by the fabrication imperfection. Figure 3b shows the PL spectra while the QD is tuned across the corner state by temperature. A crossing behavior with an obvious enhancement is observed, suggesting the cavity-QD system is in the Purcell regime. The intensity and wavelength fitted with Lorentz lineshape are shown in Figure 3c. The intensity of the QD is enhanced by a factor of about 4 on resonance with the corner state.

The Purcell enhancement is further studied by means of time-resolved PL spectroscopy. The schematic of measurement setup is shown in Figure 2b. The pulsed laser centered at 750 nm with a repetition rate of 82.5 MHz is used. It is split to two beams by a beam splitter (BS). One is used for excitation of the QDs; the other is used as synchronization signal detected by a photodiode (PD). The PL signals are filtered by the grating monochromator with a resolution less than 100 μeV then detected by a single-photon avalanche diode (SPAD). The time differences between photon detection events and synchronization pulses provided by the laser are transformed to electrical signals by a time-to-amplitude converter (TAC), which give the decay curve of the QD in topological cavity.

We measured the decay curves for the QD tuned on resonance (red points) and off resonance (black points) with the corner state, as shown in Figure 3d. From the inset, it can be clearly seen that the QD decays faster when on resonance. The curves can be well fitted by a biexponential decay function with fast and slow decay components. When the QD is off resonance (black), the fast and slow decay lifetime of QD are about 0.62 ns and 3.85 ns. On resonance (red), they are 0.48 and 3.00 ns, respectively. Both fast and slow decay components are changed, so they could be attributed to the two fine-structure components of neutral exciton.[76] The fast and slow decay rate are both enhanced by a factor of about 1.3, which are due to the Purcell effect. Here, limited by the weak enhancement, we did not take the lifetime of other QDs in positions without patterning the cavity as a reference. However, the Purcell enhancement can be extracted by comparison of the two decay curves with zero detuning, and detuning that is much larger than the linewidth of cavity mode.[7,15] In the coupling system between QD and cavity, the off-resonant coupling assisted by acoustic phonons generally exists and strongly depends on temperature and detuning.[76] Unfortunately, it is difficult to estimate its influence in our system since both temperature and detuning are changed during the measurement. Even though the effect of phonons is not taken into consideration, the enhancement of PL intensity and the emission rate sufficiently demonstrate the weak coupling between the QD and the corner state. The weak enhancement may result from spatial misalignment and polarization mismatch between QD and corner state. With better spatial and polarization matching, for example, with QDs embedded in the position with the strongest electric field which is around the smallest square at the corner (See Figure S3, Supporting Information), the coupling strength can be improved.

4. Conclusion

In conclusion, we have demonstrated a CQED system with second-order topological corner state. We designed and fabricated the topological PhC cavity based on 0D topological corner state. The coexistence of edge state and corner state with Q about 10^3 is observed. The Purcell enhancement of single QD on resonance with the corner state is demonstrated by means of PL spectra and time-resolved PL spectroscopy. The Q of corner state can be further optimized by changing the position and size of the air holes without changing the topology, therefore making the realization of the strong coupling regime in such a cavity-QD regime possible. Our results provide a new platform to investigate CQED combined with topology, offering an approach to topological devices for quantum information processing. Additionally, the coexistence of edge state and corner state with high Q may enable the integration of topological cavity and waveguide on a single chip, with potential applications in the realization of quantum photonic internet.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

cavity quantum electrodynamics, Purcell enhancement, topological corner state, topological photonics

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