Absorption Reduction of Large Purcell Enhancement Enabled by Topological State-Led Mode Coupling

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We propose the mechanism of edge state-led mode coupling under topological protection; i.e., localized surface plasmons almost do not have any influence on the edge state, while the edge state greatly changes the local field distribution of surface plasmons. Based on this mechanism, in the well-designed topological photonic structure containing a resonant plasmon nanoantenna, an obvious absorption reduction in the spontaneous emission spectra appears due to the near-field deformation around the antenna induced by the edge state. Because a plasmon antenna with ultrasmall mode volume provides large Purcell enhancement and simultaneously the photonic crystal guides almost all scattering light into its edge state, the rate of nonscattering single photons reaches more than $10^4\gamma_0$. This topological state-led mode coupling mechanism and induced absorption reduction, which are based on topological protection, will have a profound effect on the study of composite topological photonic structures and related micro- and nanoscale cavity quantum electrodynamics. Also, nonscattering large Purcell enhancement will provide practical use for on-chip quantum light sources, such as single-photon sources and nanolasers.

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By introducing the quantum Hall effect into optics, topological photonics becomes an important branch in micro- and nanophotonics [1–4]. Topological states are some specific optical modes existing between the optical bands, expressed by topological invariants in the reciprocal space [5–7]. Thus, those micro- and nanostructures with energy bands and gaps, such as photonic crystals [8], coupled-resonator arrays [9], and synthetic dimension spatial-modal lattices [10], are good candidates to realize topological properties. Topological states, generally referring to edge states or interface states, are characterized as the nonscattering propagation of photons and immunity to a wide class of impurities and defects, i.e., topological protection [6,7]. These features allow one to fabricate various micro- and nanophotonic devices, including topological lasers [11–13], nonscattering sharp bent waveguides [14,15], and topological quantum light [16]. Recently, topological protection was utilized in on-chip quantum information processing, such as robust transport of entangled photons [17], protection of biphoton states [18], and topological phase transition in single-photon dynamics [19]. The enhancement and suppression of spontaneous emission in the transition of type-I and type-II photonic Weyl systems are studied [20]; however, introducing topological protection into the Purcell enhancement has not been reported yet.

A micro- or nanoscale single-photon source is an indispensable building block in on-chip quantum information processing [21,22]. Utilizing local field enhancement or high density of optical modes of photonic structures to improve the spontaneous emission of a single emitter is one of the key principles of realizing single-photon emission. Typical micro- and nanostructures include whispering guided resonators [23], multilayered structures [24,25], photonic crystals (PCs) [26–28], and plasmon nanostructures [29–31]. Owing to possessing an ultrasmall optical mode volume, plasmon nanostructures can provide large Purcell enhancement [29–31]. However, their scattering and absorption are two barriers when guiding these single photons into other devices. To solve the problem of scattering, gap surface plasmon structures are proposed by combining two advantages of effectively collecting scattering light and inducing large Purcell enhancement at the nanoscale gap [32–34]. However, their collecting efficiency is not very high. The final part guided into other on-chip devices is very low, and this stray light will severely affect the performance of neighboring devices, which prevents them from being used in a high-quality single-photon source.

In this Letter, we propose a specific topological photonic structure, i.e., a 1D topological PC containing a resonant

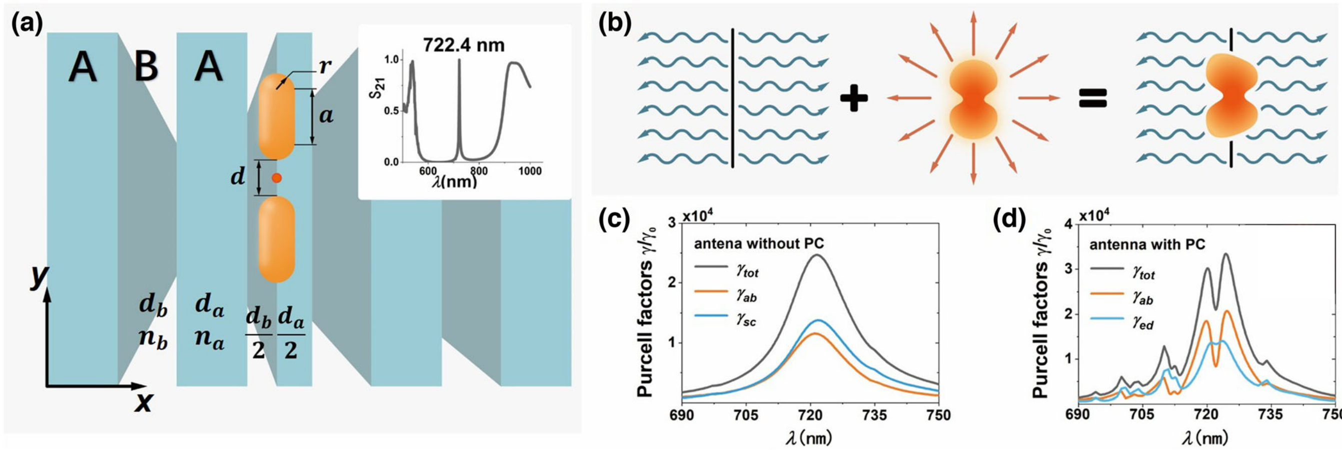

FIG. 1. (a) Schematic diagram of topological structure composed of a 1D topological PC, a silver nanoantenna, and a quantum emitter. The inset in (a) is its transmission spectrum. (b) Schematic diagram of the edge state-led mode coupling mechanism. Purcell factors at the gap center of the nanoantenna (c) without and (d) with a topological PC as a function of λ. Here, the parameters of the silver nanoantenna are $r = 7$ nm, $a = 24.5$ nm, and $d = 10$ nm.

nanoantenna [Fig. 1(a)]. Under the condition of topological protection, we first reveal the edge state-led coupling mechanism; namely, surface plasmons of the antenna almost do not have any influence on the edge state, while the edge state greatly changes the pattern of the local field around the antenna. Based on this mechanism, an obvious absorption reduction in the spontaneous emission spectra is obtained due to the near-field deformation around the antenna induced by the edge state. By embedding an antenna into the topological PC, a strong local field near the antenna leads to a large Purcell enhancement, while the edge state can make almost all scattering photons propagate along some specific directions. As a result, total Purcell factors can reach more than $2 \times 10^4\gamma_0$ (γ_0 is the spontaneous emission rate in vacuum), among which the propagating part along the edge state channel is more than $10^4\gamma_0$. By reducing the photonic loss and guiding scattering photons into the edge state, this kind of Purcell enhancement will provide new sight for on-chip quantum light sources such as a single-photon source and nanolaser.

The mechanism of the edge state-led mode coupling under topological protection is first described, which is the origin of absorption reduction of Purcell enhancement. In the topological photonic structure, owing to the topological protection, surface plasmons of the antenna almost do not have any ability to influence the edge state, but the edge state greatly changes the shape of the local field of the resonant antenna [35]. Because the edge state is robust to any perturbation or imperfection, the resonant antenna is also one of the perturbations. Though a localized surface plasmon and guiding edge state simultaneously exist, owing to the topological protection, the mode coupling between them is a topological state-led coupling mechanism, leading to the influence being large from the edge state to the surface plasmon while small from the surface plasmon to the edge state, as shown in Fig. 1(b). Such a kind of topological state-led mode coupling mechanism has never been reported before, different from previously reported mode splitting in a whispering guided resonator containing nanoparticles [36], mode shift in gap plasmon structures [32–34], and Fano line shape in hybrid molecular-plasmon structures [37]. This mechanism can be extended to other composite photonic structures with topological protection, such as various 2D topological PCs containing a resonant nanoantenna.

Then, if putting a quantum emitter into the near-field region around the antenna, whether with or without a PC, large Purcell factors are obtained due to strong local field enhancement [Figs. 1(c) and 1(d)]. Following the above edge state-led mode coupling mechanism, under topological protection, electric fields around the nanoantenna are pulled away by the edge state, leading to a deformation or reduction of the near field. As a result, an obvious absorption reduction appears, shown as a dip in the spontaneous emission spectra [Fig. 1(d)]. Simultaneously, almost all scattering photons around the antenna can transfer as the photons of the edge state through the near field overlapping. In the following, as expected, the overlapping degree between their near fields determines the ratio of absorption reduction of Purcell enhancement.

We choose 1D topological photonic structure composed of two semi-infinite PCs with layers A and B [Fig. 1(a)]. This kind of topological PC proposed by Xiao, Zhang, and Chan [5] is characterized as Zak phases. Zak phases were also discussed in various 2D topological structures [38–41] and were applied to topological light trapping [42] and a nanolaser [43]. Edge states in a topological PC, originating from the difference between Zak phases, are robust to small plasmon nanoparticles and the perturbation of unit cells [35]. The edge state in a dielectric PC cannot effectively enhance the spontaneous emission, where only dozens of γ_0 are obtained [35], while a resonant metallic nanoparticle with a strong local field can take great Purcell enhancement [29–31]. However, due to the loss originating from absorption and scattering, the single photons dispersing around the nanoparticle are difficult to utilize. Therefore, by combining the advantages of the topological PC and plasmon nanoparticle, we design the topological photonic structure containing a 1D PC and metallic nanoantenna [Fig. 1(a)].

In this topological structure, if putting a quantum emitter into the near-field region of nanoparticle, the total Purcell enhancement can be divided into three parts, i.e., $\gamma_{\text{tot}} = \gamma_{\text{ab}} + \gamma_{\text{ed}} + \gamma_{\text{sc}}$, where γ_{ab} is the absorption part, γ_{ed} the decay rate into the edge state, and γ_{sc} the radiative part into free space. Different from the situation of a metallic nanoparticle embedded in the dielectric, $\gamma_{\text{tot}} = \gamma_{\text{ab}} + \gamma_{\text{sc}}$, among which γ_{sc} scatters into all directions of the free space [29–31]. Here, if the metallic nanoparticle is small enough, γ_{sc} can be neglected due to topological protection from impurities. For our designed topological photonic structure, γ_{sc} is totally suppressed, while γ_{ed} collects all the scattering photons [35]; i.e., $\gamma_{\text{tot}} = \gamma_{\text{ab}} + \gamma_{\text{ed}}$ is validated. Thus, single photons from the part γ_{ed} can be directly used in the on-chip photonic devices without any scattering.

To compute the Purcell factors of this topological structure, 3D finite-element simulations are performed using COMSOL Multiphysics software, through which we have simulated optical modes, Purcell enhancement, photon collection, and photon-emitter coupling strength for various photonic structures [32–34,44–46]. To simulate the infinite 1D PC, a periodic boundary condition is applied for the y and z directions. In the x direction of propagation, five periods for both semi-infinite PCs are enough to perform infinitelike behavior. The emitter is represented by a y-polarized dipole point source. Computation details of γ_{tot}, γ_{ab}, γ_{sc}, and γ_{ed} are shown in Supplemental Material [35], where the correctness and validity of the above module are also proved.

We first investigate the edge state-led mode coupling under the topological protection. As shown in Fig. 1(a), two layers A and B have a thickness of $d_a = 120$ nm and $d_b = 100$ nm and a refractive index of $n_a = 2$ and $n_b = 1$, respectively. With these parameters, the edge state appears at $\lambda = 722.4$ nm [inset in Fig. 1(a)]. The Ag nanoantenna with $r = 7$ nm, $a = 24.5$ nm, and $d = 10$ nm is placed parallel into the interface of two semi-infinite PCs, whose resonant wavelength is also designed as 722.4 nm. The dielectric constant of silver is taken from the experimental data [47]. The spectral linewidth of the edge state and nanoantenna (for $r = 7$ nm) are 2.7 and 18.8 nm, respectively. It is found that surface plasmons in the nanoantenna do not have any effect on the position of edge state, but the edge state dominates the behavior of the near field around the antenna; i.e., besides the local field deformation, almost all scattering photons are transferred as photons of the edge state [inset in Fig. 1(a) and Figs. 2(a) and 2(b)]. Different from previously reported mode splitting [36], mode shift [32–34], and Fano line shape [37] in composite nanostructures, here is a typical topological state-led mode coupling.

When a quantum emitter is placed at the nanoscale gap of the antenna, nonscattering large Purcell enhancement is obtained. As shown in Fig. 1(d), at the edge state, total Purcell factor $\gamma_{\text{tot}}/\gamma_0$ can reach more than 2×10^4, among which the part $\gamma_{\text{ed}}/\gamma_0$ guided into the edge state is 10^4. Owing to the multiple reflection in a 1D PC structure, there is almost no photon scattering for a trivial PC and for the edge state [Figs. 2(a)–2(d)]. But the mode coupling mechanism is different. In a defect PC, the mode splitting can be obtained, while for a topological PC, it is edge state dominated under topological protection [35]. If only a

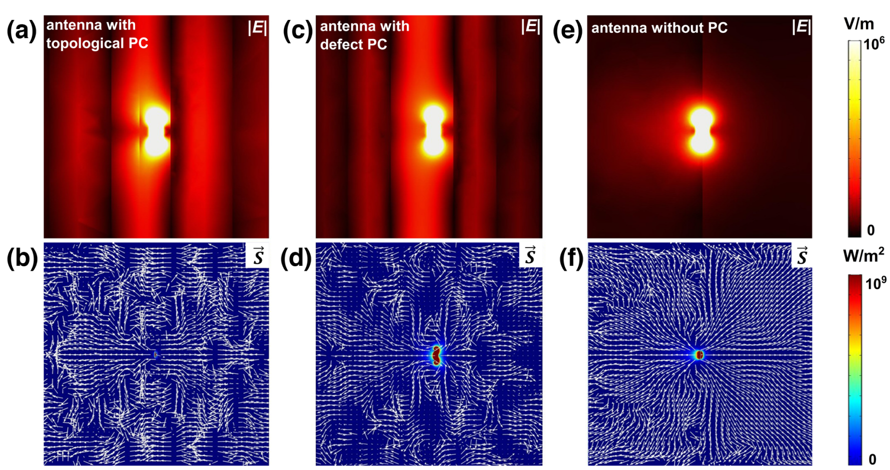

FIG. 2. The electric field $|E|$ and energy flux $\vec{S}$ distributions (a),(b) with a topological PC, (c),(d) with a defect PC, and (e),(f) without a PC when the quantum emitter is at the gap center of the nanoantenna. The selected areas are 800×800 nm^2 (a),(c),(e) and 2.2×2.2 μm^2 (b),(d),(f) in the xy plane. The parameters are the same as those in Fig. 1.

TABLE I. Absorption reduction of Purcell enhancement at the edge state. (a) Ratios of γ_{ab}/γ_{tot}, γ_{ed}/γ_{tot}, and near-field overlapping degree η with a topological PC and (b) ratios of γ_{ab}/γ_{tot} and γ_{sc}/γ_{tot} without a PC at different radius r of the nanoantenna. Here $\lambda = 722.4$ nm and $d = 10$ nm, and other parameters are $r = 5$ nm with $a = 18.9$ nm, $r = 7$ nm with $a = 24.5$ nm, and $r = 10$ nm with $a = 30.5$ nm, separately.

(a) Antenna with PC				
r (nm)	γ_{tot}/γ_0	γ_{ab}/γ_{tot}	γ_{ed}/γ_{tot}	η
5	39 003	63.2% (24 659)	36.8% (14 344)	6.857
7	22 003	37.8% (8323)	62.2% (13 680)	8.932
10	9901	20.5% (2029)	79.5% (7872)	9.725
(b) Antenna without PC				
r (nm)	γ_{tot}/γ_0	γ_{ab}/γ_{tot}	γ_{sc}/γ_{tot}	
5	41 590	67.9% (28 252)	32.1% (13 338)	
7	25 298	45.6% (11 533)	54.4% (13 765)	
10	12 156	24.5% (2974)	75.5% (9182)	

topological PC, i.e., without the nanoantenna, the Purcell enhancement is very low [35]. While only the antenna exists, Purcell enhancement is very large due to its strong local field [Figs. 2(e) and 2(f)]. Here, owing to the near field overlapping between the nanoantenna and edge state, almost all the electric field around the resonant nanoantenna is guided into the edge state, leading to large nonscattering Purcell enhancement. This ultralarge nonscattering enhancement is superior to that of gap surface plasmon structures, where the Purcell factor is also very large, but the guided part is relatively small and stray light exists [32–34].

Surprisingly, there is a dip in the spectra of Purcell factors γ_{tot}/γ_0 and γ_{ab}/γ_0 [Fig. 1(d)] due to the existence of the edge state. As shown in Table I, for $r = 7$ nm, the ratio γ_{ab}/γ_{tot} ($= 37.8\%$) of the absorption part to total Purcell factor in the topological structure is less than γ_{ab}/γ_{tot} ($= 45.6\%$) in dielectric [Figs. 1(c) and 1(d)]. Besides the ratio decrease of γ_{ab}/γ_{tot} in both cases, the absolute value $8323\gamma_0$ of γ_{ab} in the topological structure is also less than $11533\gamma_0$ in the dielectric case. Owing to the near field overlapping between the resonant nanoantenna and the edge state, electric fields around the nanoantenna are pulled away by the edge state [Figs. 1(b), 2(a), and 2(b)], leading to an obvious absorption reduction of Purcell enhancement. Moreover, the near field in topological structures is not so localized as that in dielectric; thus, there is a little decrease of γ_{tot}.

Next, we use the overlapping degree η to quantitatively study the absorption reduction, which is defined as $\eta = \int(|\vec{E}_1 \cdot \vec{E}_2|/E_0^2 V_m)dV$, where $\vec{E}_1$ ($\vec{E}_2$) is the electric field of the edge state (the resonant nanoantenna without a PC), E_0 the background field, and V_m the computation volume around the nanoantenna (see more details in Ref. [35]). As shown in Table I, whether there is a

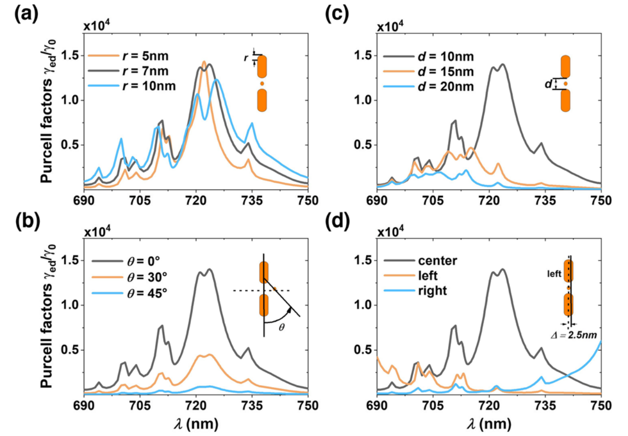

FIG. 3. Nonscattering Purcell factors γ_{ed}/γ_0 for various parameters of a resonant nanoantenna embedded in a topological PC. Purcell factors γ_{ed}/γ_0 (a) with different radius r of nanoantenna, (b) with varying the position of the quantum emitter, (c) with different distance d, and (d) with moving the position of the nanoantenna as a function of λ. Other parameters are the same as those in Table I.

topological structure or not, the ratio of γ_{ab}/γ_{tot} is smaller when r becomes larger due to less localized field. Meanwhile, for the same r, the ratio γ_{ab}/γ_{tot} in a topological structure is smaller than that in a dielectric medium; namely, it is an obvious absorption reduction in Purcell enhancement. As expected, the overlapping degree η between their near fields determines the ratio of absorption reduction of Purcell enhancement (Table I). Therefore, putting the resonant metallic structure into a topological structure can effectively reduce its absorption. The absorption is always a drawback in applications of the surface plasmon. Using the topological state of a photonic structure, the idea of absorption reduction can be extended to other topological applications, such as nanolaser and quantum light sources.

While keeping the condition of topological protection, we explore the effect of varying the antenna's radius r and emitter's position on γ_{ed}/γ_0. When the radius r is smaller, both γ_{tot} and γ_{ed} become larger due to a more localized electric field [Fig. 3(a) and Table I(a)]. We also change the relative angle θ between the emitter and nanoantenna [Fig. 3(b)]. It is found that away from near-field region, such as $\theta = 45°$, γ_{ed} decreases abruptly. This is similar to the case of a resonant metallic nanorod embedded in the dielectric medium, where the scattering part γ_{sc}/γ_0 is very sensitive to the position of the emitter [29–31]. In the near-field region, the ratios of γ_{ed}/γ_{tot} in a topological structure and γ_{sc}/γ_{tot} in a dielectric medium are relatively high (Table I). But away from the near-field region, these ratios as well as γ_{tot} descend rapidly [Fig. 3(b)]. Therefore, by changing the structure parameters of the nanoantenna or the position of the emitter, the magnitude of γ_{ed}/γ_0 and γ_{tot}/γ_0 can be well modulated.

Owing to the narrow linewidth of the edge state, Purcell enhancement is very sensitive to resonance matching between the nanoantenna and edge state. For $r = 7$ nm, when the gap distance d of antenna is changed from 10 to 20 nm, γ_{ed}/γ_0 decreases rapidly due to the off-resonance condition [Fig. 3(c)]. If we slightly move the position of the antenna away from the center of two PC layers, there is a large decrease in γ_{ed} due to the mismatching of their resonance wavelengths [Fig. 3(d)]. Thus, the resonance matching to a large extent determines the Purcell enhancement of this kind of topological structure.

Also, Purcell enhancement is sensitive to the polarization of the quantum emitter. Only if the nanoantenna is sufficiently excited can large Purcell enhancement be obtained due to large near-field overlapping. For linear polarization, large Purcell enhancement is obtained only at the polarization with the same direction as the resonant nanoantenna's axis, while for circular polarization, the propagation direction of photons is the same as the case of linear polarization, but the Purcell factor is reduced by half [35].

With the resonance matching condition, we also study the Purcell enhancement in the topological PC containing other kinds of nanoparticles [35]. It turns out that, as long as the topological protection is conserved, the equation $\gamma_{tot} = \gamma_{ed} + \gamma_{ab}$ is satisfied and large nonscattering Purcell enhancement is maintained. Overall, nanoantennas have larger Purcell enhancement than those of single nanorods; nanoantennas and nanorods parallel to the interface have a larger ratio of γ_{ed}/γ_{tot} and a larger absorption reduction of Purcell enhancement proven by overlapping degree η [35]. These results are helpful to experimental realization of this protocol.

Finally, we address the fabrication possibility of our scheme. Nowadays, nanoantennas [48] and topological PCs [49] can be fabricated by state-of-the-art nanotechnology. The single emitter can be realized in many forms, such as classical atoms [50], Rydberg atoms [51], and quantum dots [52]. Single emitters embedded in a PC waveguide have been realized through scanning tunneling microcopy [53]. However, the main challenge of fabricating our designed topological photonic structure is to integrate all these elements together with nanoscale precision. In recent experimental research, metal nanoparticles such as Au nanoparticles have been fabricated to study the fundamental nature of strong coupling regime of cavity quantum electrodynamics (CQED) systems [54–56]. The similar nanotechnology can also be applied in Purcell enhancement of present topological structures. Thus, it is possible to realize our proposal experimentally in the near future.

We have proposed the mechanism of edge state-led mode coupling under topological protection. Based on this mechanism, we have explained the absorption reduction in the spontaneous emission spectra. We have also obtained nonscattering extra-large Purcell factors at the edge state, which will provide practical use for on-chip quantum light sources, such as single-photon sources and nanolasers. This topological state-led mode coupling mechanism has never been reported before, which is a universal law under topological protection and will have a profound effect on other composite topological photonic structures, such as 2D or higher-dimension topological structures. Introducing topological protection into the Purcell enhancement will take some new insights in the topological structure-based CQED. In the principle of CQED, the essence of both weak coupling (Purcell effect) and strong coupling is the coupling between the emitter and optical modes. So in this system, if weak coupling is achieved, through well-designed topological composite structure, strong coupling [45,54–58] should also be possible due to a strong local field enhancement around the plasmon nanoantenna.

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[35] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.126.023901 for 1D topological photonic structure, module simulation with COMSOL, robustness of the edge state, Purcell factors in topological photonic structures, Purcell factors with various nanostructures in topological PCs, nonscattering of topological photonic structures, and the overlapping of the near field.

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