Non-Hermitian Waveguide Cavity QED with Tunable Atomic Mirrors

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Optical mirrors determine cavity properties by means of light reflection. Imperfect reflection gives rise to open cavities with photon loss. We study an open cavity made of atom-dimer mirrors with a tunable reflection spectrum. We find that the atomic cavity shows anti-$\mathcal{PT}$ symmetry. The anti-$\mathcal{PT}$ phase transition controlled by atomic couplings in mirrors indicates the emergence of two degenerate cavity supermodes. Interestingly, a threshold of mirror reflection is identified for realizing strong coherent cavity-atom coupling. This reflection threshold reveals the criterion of atomic mirrors to produce a good cavity. Moreover, cavity quantum electrodynamics with a probe atom shows mirror-tuned properties, including reflection-dependent polaritons formed by the cavity and probe atom. Our Letter presents a non-Hermitian theory of an anti-$\mathcal{PT}$ atomic cavity, which may have applications in quantum optics and quantum computation.

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*Introduction.—*Quantum cavities are the cornerstone of quantum optics for interfacing light-matter interaction [1–4]. The Fabry-Perot interferometer is a cavity that consists of two parallel optical mirrors. A Fabry-Perot cavity can be realized in many quantum systems with varieties of light reflectors [5]. Meanwhile, Fabry-Perot cavities can be synthesized with quantum mirrors, e.g., atoms or artificial atoms [6–12], based on the remarkable photon scattering effects of single atoms in one-dimensional (1D) waveguides [13–21]. Recently, experiments have realized strong coupling in cavity quantum electrodynamics (QED) with single-atom mirrors [22]. Large reflection of atomic mirrors at the central frequency gives rise to a dark mode, i.e., the effective cavity mode [6,9]. Atomic cavities receive much attention for studying quantum optics with tailored light-matter interaction [23–29]. However, due to the limitation in tuning mirror reflection, atomic cavities are far from being thoroughly understood.

Generally speaking, photon loss is unavoidable in quantum cavities [30], because of imperfect mirror reflections that lead to the coupling between cavity modes and continuum in free space [31–34]. Indeed, open cavities have substantial applications in quantum computation [35,36] and quantum networks [37–39]. Knowing how mirrors alter photon reflections is central to design novel quantum devices [40–42]. For example, tailored reflection (transmission) of cavities is useful for practical quantum technologies, such as single-photon resources [43,44] and Fano lasers [45,46]. A puzzle naturally arises: what is the fate of an open cavity if the mirror reflection is strongly modified? Different from previous theories of open cavities based on conventional light reflectors [31–34,43–46], waveguide-interfaced quantum light-matter interactions [47,48] make atomic cavities an excellent platform to study cavity QED [6–12,22–29] and might shed new light on open cavities.

In this Letter, we study a cavity consisting of atomic mirrors with two-coupled atoms, i.e., atom dimer, coupled to a 1D coplanar waveguide in superconducting quantum circuits [49]. We find that the atom-dimer cavity has anti-parity-time (anti-$\mathcal{PT}$) symmetry. Different from previous works that tune anti-$\mathcal{PT}$ symmetric systems via frequency detunings [50–58], here atomic couplings in mirrors alter light reflection and induce non-Hermitian phase transitions of the cavity. Therefore, two degenerate cavity supermodes are created. We propose a non-Hermitian theory for atomic cavity QED.

*Tunable reflection by anti-Bragg atom-dimer mirror.—*Figure 1(a) shows the schematics of a Fabry-Perot cavity with a probe atom. The mirror can be realized, e.g., with a single two-level atom coupled to a waveguide [14–16]. The single-atom reflection spectrum has a Lorentzian line shape [14] $R(\Delta) = |\Gamma/(\Delta + i\Gamma)|^2$, with atomic decay rate Γ and detuning $\Delta = \omega - \omega_0$. Here, ω and ω_0 are the frequencies of the driving field and atom, respectively. Because of this single-peak reflection, a dark cavity mode can be generated in an atomic cavity [22].

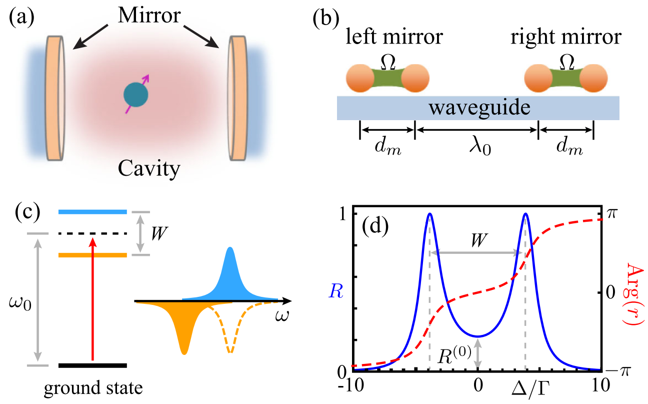

FIG. 1. (a) Schematic of a Fabry-Perot cavity with two parallel mirrors. (b) Atomic cavity consisting of two atom-dimer mirrors, separated by a distance λ_0, coupled to a waveguide. For each mirror, we consider a direct atomic coupling Ω and anti-Bragg condition $d_m = \lambda_0/4$. (c) Energy levels of scattering states in the anti-Bragg atom-dimer mirror with $W = 2(\Omega + \Gamma)$ (left) and corresponding reflected photon amplitudes (right). (d) Reflection $R = |r|^2$ (blue solid) and photon phase shift $\mathrm{Arg}(r)$ (red dashed) produced by the atom-dimer mirror.

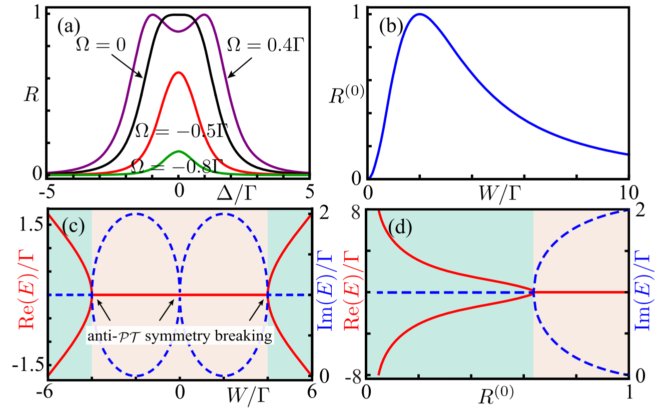

FIG. 2. (a) Reflection of the atom-dimer mirror for various values of atomic coupling. (b) Reflection $R^{(0)}$ at $\Delta = 0$ versus the frequency difference W between two scattering states in the mirror. (c) Anti-$\mathcal{PT}$ phase transitions in the anti-Bragg atom-dimer cavity. Red solid and blue dashed curves correspond to real and imaginary parts of two supermodes. (d) Reflection-dependent atom-dimer cavity. A low-loss cavity supermode is produced by large mirror reflection.

Two atoms produce a scattering state with radiation rate 2Γ [20,59] for an atomic spacing $n\lambda_0/4$, with an even number n and single-photon wavelength $\lambda_0 = 2\pi c/\omega_0$, i.e., the Bragg condition [60,61]. Such collectively enhanced scattering state (superradiant state) leads to broadband reflection with a Lorentzian profile, useful for high-finesse cavities [9]. However, the scenario is different for spacing $m\lambda_0/4$ (with m an odd number), i.e., the anti-Bragg condition [62,63]. We study an atom dimer with $d_m = \lambda_0/4$ [49], as shown in Fig. 1(b). The master equation is ($\hbar = 1$) $\dot{\rho}(t) = -i[H_m, \rho(t)] + \mathcal{D}[\rho]$, where the Hamiltonian is $H_m = \sum_{j=1,2} \omega_0 \sigma_j^+ \sigma_j^- + (\Omega + \Gamma)(\sigma_1^+ \sigma_2^- + \mathrm{H.c.})$, with a direct atomic coupling Ω and waveguide-mediated dispersive coupling Γ. Here, $\sigma_j^+ = |e_j\rangle\langle g_j|$ with the ground (excited) state $|g\rangle$ ($|e\rangle$). The Lindblad operator is $\mathcal{D}[\rho] = \sum_j \Gamma(2\sigma_j^- \rho \sigma_j^+ - \sigma_j^+ \sigma_j^- \rho - \rho \sigma_j^+ \sigma_j^-)$. In this mirror, there are two scattering states $\Phi_\pm = (1/\sqrt{2})(1, \pm 1)^\top$ with equal decay rate Γ, as shown in Fig. 1(c). The photon amplitude reflected by the anti-Bragg atom-dimer mirror is [64]

$$r(\Delta) = \sum_{n=\pm} (-1)^n \frac{\Gamma}{(\Delta - \delta_n + i\Gamma)}, \tag{1}$$

where $\delta_\pm$ are frequencies of the scattering states with respect to ω_0. Quantum interference between reflected photons is determined by the frequency difference $W = 2(\Omega + \Gamma)$ between two scattering states. Figure 1(d) shows the intensity and phase shift of the reflected photon. At the central frequency $\Delta = 0$, phase shifts 0 and π are produced, respectively, for anti-Bragg atom-dimer mirrors with $W > 0$ and $W < 0$, due to swapping of scattering states. Without loss of generality, we focus on the regime $W \geq 0$.

In Fig. 2(a), we show details of the reflection spectra altered by the atomic coupling Ω. At $\Omega = -\Gamma$ ($W = 0$), atoms in the mirror have no coupling [49]. Interestingly, degenerate scattering states produce out-of-phase photon components. Because of destructive quantum interference, the anti-Bragg atom-dimer mirror becomes transparent for incident photons with various frequencies, i.e., trivial mirror. Single- and two-peak reflection spectra are obtained for $-\Gamma < \Omega \leq 0$ and $\Omega > 0$, respectively, enabling the study of reflection-tuned atomic cavities. From Eq. (1), we obtain the reflection at $\Delta = 0$,

$$R^{(0)} = \frac{\Gamma^2 W^2}{(\Gamma^2 + \frac{W^2}{4})^2}. \tag{2}$$

The reflection $R^{(0)}$ responsible for cavity losses [9,45] is nontrivially changed by W. As shown in Fig. 2(b), $R^{(0)}$ increases with W for single-peak reflection. After reaching unity at $W = 2\Gamma$, $R^{(0)}$ is reduced, producing a two-peak reflection spectrum. Therefore, W plays an important role in controlling the reflection spectrum of the atom-dimer mirror.

Atomic cavity protected by anti-$\mathcal{PT}$ symmetry.—To explore the relation between atomic mirrors and cavity, we consider two atom-dimer mirrors with Hamiltonian $H_0 = \sum_i \Omega(\sigma^+_{\mathcal{M}_i,\mathcal{A}_1} \sigma^-_{\mathcal{M}_i,\mathcal{A}_2} + \mathrm{H.c.})$, where $i = l, r$ denotes the left and right atomic mirror, and $\mathcal{A}_1$, $\mathcal{A}_2$ represent mirror atoms. Considering the cavity architecture in Fig. 1(b), we trace out the degrees of freedom of photons in the waveguide [66–72] and obtain an effective non-Hermitian Hamiltonian in the single-excitation subspace $\{|\psi_j\rangle = \sigma_j^+|g_1g_2g_3g_4\rangle\}$ of four mirror atoms [64],

$$H_c = (\Omega+\Gamma)s_0 \otimes \tau_x + \Gamma s_x \otimes \tau_0 - i\Gamma s_y \otimes \tau_y - i\Gamma s_0 \otimes \tau_0, \tag{3}$$

where s_n and τ_n $(n = x, y, z)$ are Pauli matrices in the space $\{\mathcal{M}_l, \mathcal{M}_r\}$ of two mirrors and the subspace $\{\mathcal{A}_1, \mathcal{A}_2\}$ of mirror atoms, respectively. We have assumed that two atomic mirrors are separated by λ_0. Equation (3) describes the quantum light-mirror interaction in the atomic cavity. To clarify the mechanism of the cavity, we make a unitary transformation to Eq. (3) (see Supplemental Material [64]) and simplify the system as two decoupled subsystems $\mathcal{H}_1 \oplus \mathcal{H}_2$ with

$$\mathcal{H}_1 = \begin{pmatrix} -\Omega - i\Gamma & -i\Gamma \\ -i\Gamma & \Omega - i\Gamma \end{pmatrix}, \tag{4}$$

$$\mathcal{H}_2 = \begin{pmatrix} -\Omega - 2\Gamma - i\Gamma & i\Gamma \\ i\Gamma & \Omega + 2\Gamma - i\Gamma \end{pmatrix}. \tag{5}$$

$\mathcal{H}_1$ and $\mathcal{H}_2$ are protected by anti-$\mathcal{PT}$ symmetry $(\mathcal{PT})\mathcal{H}_i(\mathcal{PT})^{-1} = -\mathcal{H}_i$ [73–76]. Importantly, without using frequency detunings [50–58], here anti-$\mathcal{PT}$ phase transitions are produced by atomic couplings, which can uncover novel properties of anti-$\mathcal{PT}$ symmetric systems. Moreover, we avoid the influence of frequency-dependent couplings [77,78] on the atom-dimer cavity.

The anti-$\mathcal{PT}$ symmetry inspires us to study the atom-dimer cavity using non-Hermitian theory [79–82]. We diagonalize the system as $H_c = \sum_n E_n|\Psi_n^R\rangle\langle\Psi_n^L|$, with the biorthogonal basis $\langle\Psi_n^L|\Psi_m^R\rangle = \delta_{nm}$. The index j labels supermodes of the atomic cavity. In Fig. 2(c), we show real and imaginary parts of the eigenvalues for two supermodes in the anti-$\mathcal{PT}$-symmetry-protected regimes $W \in (-4\Gamma, 0) \cup (0, 4\Gamma)$. Anti-$\mathcal{PT}$ phase transitions take place at second-order exceptional points $W = 0, \pm 4\Gamma$. For $0 \leq W \leq 4\Gamma$, the eigenvalues of $\mathcal{H}_1$ correspond to two degenerate supermodes $\Psi_\pm$ with decay rates

$$\Gamma_\pm = \Gamma \pm \sqrt{\Gamma^2 - \Omega^2}. \tag{6}$$

At $\Omega = 0$, a long-living supermode exists in the atom-dimer cavity with mirrors having complete reflection $R^{(0)}$ at the central frequency. This supermode plays the role of a cavity mode [22] and becomes dissipative for reduced $R^{(0)}$. By solving Eq. (2) for Ω and substituting the solutions to Eq. (6), we obtain reflection-tuned energy levels and decay rates of the supermodes $\Psi_\pm$ for $W \geq 2\Gamma$, as shown in Fig. 2(d). For weak reflection, these two supermodes have equal decay rate Γ, the same as individual mirror atoms. However, large reflection leads to an anti-$\mathcal{PT}$ phase transition, producing cavity supermodes with controlled loss.

Reflection threshold for strong cavity-atom coupling.— In addition to photon loss, the mode profile is a fundamental property of cavities [83,84]. In optical cavities, the cavity-atom coupling is proportional to the cavity mode electric field, which is related to boundary conditions imposed by mirrors [43,44]. To study cavity fields affected by atomic mirrors, we consider a probe atom [see Fig. 1(a)]. The atom-cavity interaction is described by $H_{\rm int} = (\delta\omega - i\gamma)\sigma_p^+\sigma_p^- - i\sqrt{\gamma\Gamma}\sum_{j=1}^4 e^{i\phi_j}(\sigma_j^+\sigma_p^- + \sigma_p^+\sigma_j^-)$. Here, $\delta\omega = \omega_p - \omega_0$ is the detuning between the probe atom and mirror atoms, γ is decay rate of the probe atom, $\sigma_j^\pm$ are operators of the jth mirror atoms, and $\phi_j = 2\pi|x_j - x_p|/\lambda_0$ [85–87]. The probe atom is placed at $x_p = \lambda_0/4$ in the cavity, such that the couplings vanish between the probe atom and supermodes unprotected by anti-$\mathcal{PT}$ symmetry [64]. By writing the whole Hamiltonian $\tilde{H} = H_c + H_{\rm int}$ in terms of two supermodes $\Psi_\pm$, we obtain

$$\tilde{H} = \begin{pmatrix} -i\Gamma_- & 0 & G_L \\ 0 & -i\Gamma_+ & V_L \\ G_R & V_R & \delta\omega - i\gamma \end{pmatrix}, \tag{7}$$

where the couplings are $G_L = -i\sqrt{\gamma\Gamma}\sum_j e^{i\phi_j}\langle\Psi_-^L|\psi_j\rangle$, $G_R = -i\sqrt{\gamma\Gamma}\sum_j e^{i\phi_j}\langle\psi_j|\Psi_-^R\rangle$, and similar for $V_{L,R}$ by considering the supermode Ψ_+. With the protection of anti-$\mathcal{PT}$ symmetry, the probe atom is coherently and dissipatively coupled to the slow- and fast-decay supermodes with the same coupling strength, i.e., ${\rm Im}[G_R] = 0$ and $V_R = iG_R$. As shown in Fig. 3(a), the probe atom is

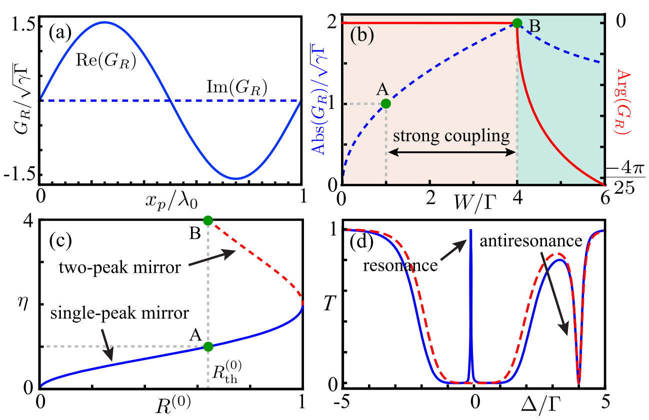

FIG. 3. (a) Coupling between probe atom and the slow-decay supermode. The solid curve and dashed line denote the real and imaginary parts of the coupling G_R. The horizontal axis represents the position of the probe atom in the cavity. (b) Absolute value and argument of cavity-atom coupling G_R for the slow-decay supermode. The probe atom is located at $x_p = 0.25\lambda_0$. (c) Atomic cavity field changed by the mirror reflection. (d) Transmission spectrum of the far-detuned probe atom. Red dashed and blue solid curves correspond to $\Omega = 0$ and 0.2Γ, respectively.

maximally coupled to the supermode Ψ_- at $x_p = \lambda_0/4$. We find $G_L = G_R/\sqrt{1-\Omega^2/\Gamma^2}$ and $V_L = V_R/\sqrt{1-\Omega^2/\Gamma^2}$, which diverge at exceptional points. Hence, G_R and V_R characterize the effective fields of the atomic cavity.

Figure 3(b) presents the absolute value and argument of the coupling G_R between the atom and the slow-decay supermode. Indeed, the coupling is coherent for $0 \le W \le 4\Gamma$, and its concise form is

$$G_R = \sqrt{\gamma W}. \tag{8}$$

This equation uncovers an intrinsic relation between mirror reflection and atom-dimer cavity: the frequency difference W between mirror's scattering states determines the atom-cavity coupling. At point A, $W = \Gamma$ indicates the emergence of enhanced cavity-atom coupling with respect to the couplings between probe atom and mirror atoms. At point B with $W = 4\Gamma$, the cavity undergoes a phase transition and the coherent cavity-atom coupling reaches its maximum. Therefore, the parameter space between A and B is the strong-coupling regime.

To gain further insight into the relation between mirror reflection and the atom-dimer cavity, we define a coupling factor $\eta = G_R^2/\gamma\Gamma$ in terms of $R^{(0)}$ via Eq. (2). The coupling factor corresponding to atomic mirrors with single-peak reflection spectra is $\eta = 2(1-\sqrt{1-R^{(0)}})/\sqrt{R^{(0)}}$. As shown in Fig. 3(c), η monotonically increases with $R^{(0)}$, showing a reflection-controlled cavity field [33]. For two-peak mirrors, the coupling factor becomes $\eta = 2\sqrt{R^{(0)}}/(1-\sqrt{1-R^{(0)}})$. It increases with growing W even though $R^{(0)}$ declines. However, when $R^{(0)}$ reduces to a critical value at point B, the coupling G_R becomes dissipative. Interestingly, we find that points A and B correspond to a reflection threshold $R_{\mathrm{th}}^{(0)} = 0.64$. The strong coherent coupling requires $R^{(0)} > R_{\mathrm{th}}^{(0)}$.

In Fig. 3(d), we show the transmission spectrum of the detuned cavity-atom system. The antiresonance in the transmission is due to the probe atom [14–16]. Owing to the anti-Bragg scattering, dissipative supermodes in the atomic cavity produce a transmissionless spectrum for $\Omega = 0$. Weak atomic coupling leads to a photon transmission amplitude $t \approx \Gamma_-/[i(\Delta + \Delta_p) + \Gamma_-]$, where Δ_p is the frequency shift induced by the probe atom. In contrast to conventional subradiant states that inhibit photon transmission [88], the slow-decay supermode Ψ_- enhances photon transmission. This cavitylike behavior [89] makes it useful to detect atomic cavity QED via photon transport in a waveguide.

Mirror-controlled cavity-atom polaritons.—In cavity QED, polaritons can be produced with interacting photons and atoms or excitons [90,91]. In our system, non-Hermitian cavity-atom interactions in Eq. (7) control the formation of cavity-atom polaritons. Solutions of the equation $\det(\tilde{H} - E) = 0$ can be derived using Cardano's formula [64,92]. In Fig. 4(a), we show the eigenspectrum of the cavity-atom system. In the strong-coupling regime, the probe atom hybridizes intensely with the slow-decay supermode, giving rise to two equally decaying polaritons. We find that, at the condition $\Omega = \gamma$, the eigenvalues are $E_{1,2} = \pm\sqrt{\Omega^2 + 2\Gamma\gamma}$ and $E_3 = -i(2\Gamma + \gamma)$. Here, $E_{1,2}$ correspond to two polaritons without dissipation, i.e., dark polaritons; while E_3 contains the whole dissipation. Therefore, the fast-decay supermode is crucial for tuning decay rates of polaritons. Moreover, the dark polaritons are only generated in cavities with two-peak atom-dimer mirrors, because $\gamma > 0$. As shown in Fig. 4(b), the cavity-atom polaritons can be detected by cavity transmission. The vanishing signals at resonance represent dark polaritons. The dark polaritons studied here emerge from the novel non-Hermitian interaction between the probe atom and the two-mode atomic cavity and cannot be produced by single-mode optical cavities [93].

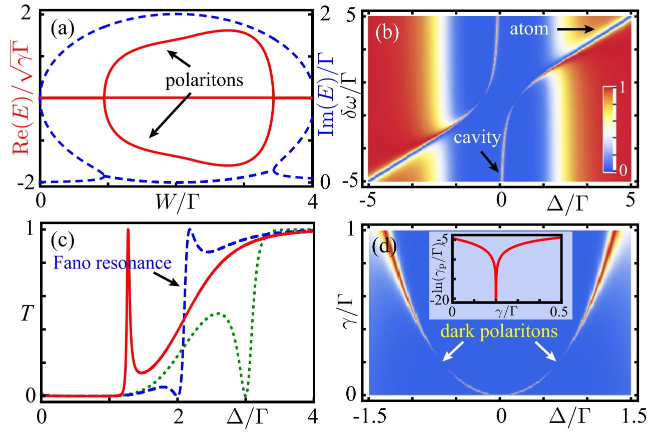

FIG. 4. (a) Cavity-atom polaritons are formed with $\gamma = 0.005\Gamma$. (b) Transmission detection of polaritons for $\gamma = 0.2\Gamma$. (c) Polariton-induced Fano resonance. Red solid, blue dashed, and green dotted curves correspond to $\delta\omega/\Gamma = 1$, 2, and 3, respectively. (d) γ-dependent polaritons. The inset shows $\ln(\gamma_p/\Gamma)$ versus γ, where γ_p denotes decay rate of polaritons. We consider $\Omega = 0.2\Gamma$ in (b)–(d), $\gamma = 0.2\Gamma$ in (b),(c), and $\delta\omega = 0$ in (a),(d).

In Fig. 4(c), we show the transmission of one polariton for various atom-cavity frequency detunings. A Fano resonance is found around $\delta\omega = 2\Gamma$. Considering distinct spectroscopic signatures of the probe atom and the cavity supermode Ψ_- shown in Fig. 3(d), the Fano resonance reveals the half-matter half-light nature of polaritons, useful for optical switching and sensing [94]. Figure 4(d) displays the transmission spectrum of γ-dependent polaritons. The frequencies of polaritons agree with Eq. (8). This confirms the effective cavity-atom coupling represented by G_R. The inset shows the linewidth of polaritons versus γ with a minimum at $\gamma = \Omega$.

Applications of the atom-dimer cavity.—Slow-decay states, or subradiant states, are useful for quantum

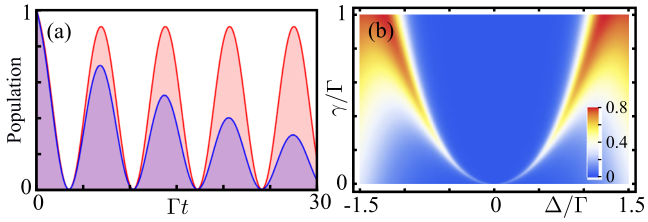

FIG. 5. (a) Rabi oscillations of a probe atom due to the dark polaritons. We consider an atomic coupling $\Omega = 0.1\Gamma$ and decay rate $\gamma = 0.1\Gamma$ of probe atom. Red and blue curves respond to free-space loss $\gamma' = 0$ and $\gamma' = 0.02\Gamma$, respectively. (b) Transmission spectrum of cavity-atom polaritons for $\Omega = -0.2\Gamma$ and free-space loss $\gamma' = 0.02\Gamma$.

information storage [95,96]. However, it is challenging to access and manipulate these subtle many-body states [97–99]. The atom-dimer cavity provides an interface between a single atom and a subradiant state. We show the persistent Rabi oscillations of the probe atom in Fig. 5(a), produced by dark polaritons. After considering the free-space loss [22], the population transfer is still efficient. Because of this cavity-atom interface, quantum information can be flexibly stored in and retrieved from the atom-dimer cavity. Figure 5(b) shows the transmission spectrum of polaritons for a cavity with single-peak mirrors. Different from the two-peak atomic cavity, only bright polaritons are formed.

Conclusions.—In this Letter, we study an open cavity with tunable atom-dimer mirrors. Atomic couplings in mirrors nontrivially control the anti-$\mathcal{PT}$-symmetry-protected cavity and produce two reflection-dependent degenerate supermodes. The coherent coupling between the slow-decay supermode and the probe atom is related to frequency difference between mirror's scattering states. We propose a non-Hermitian cavity QED theory and identify a reflection threshold for strong cavity-atom coupling. The roles played by the slow- and fast-decay supermodes are clarified for realizing dark polaritons. Our Letter presents a novel cavity in a coupling-controlled anti-$\mathcal{PT}$ symmetric system, which allows one to study non-Hermitian light-matter interaction.

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