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Invited Paper

Threshold for formation of atom-photon bound states in a coherent photonic band-gap reservoir

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ABSTRACT

We study the threshold for the formation of atom-photon bound (APB) states from a two-level atom embedded in a coherent photonic band-gap (PBG) reservoir. It is shown that the embedded position of the atom plays an important role in the threshold. By varying the atomic embedded position, a part of formation range of APB states can be moved from inside to outside the band gap. The direct link between the steady-state entanglement and APB states is also investigated. We show that the values of entanglement between reservoir modes reflect the amount of bounded energy caused by APB states. The feasible experimental systems for verifying the above phenomena are discussed. Our results provide a clear clue on how to form and control APB states in PBG materials.

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1. Introduction

Photonic band-gap materials are structures where the photonic mode density is zero [1]. For an atom with transitions inside a PBG, a photon emitted by the atom will only penetrate a finite length scale, forming the APB state [2–4]. This Non-Markovian atom-field interaction leads to many remarkable phenomena, including suppression of spontaneous emission [5–8], fractionalized single-atom inversion [9,10], photon hopping conduction [11], and population trapping [12]. Additionally, the formation of APB states has broad applications in quantum information processing. Theoretical studies [13–15] have shown that the existence of APB states can lead to quantum entanglement preservation between atoms as well as permanent effective coupling between reservoir modes. Most notably, the photonic component of the APB state can be thought of as an atom-induced cavity mode, which can be used to realize tunable long-range interaction between atoms [16]. Experimentally, the Non-Markovian atom-field interaction in PBG reservoirs has been directly observed [17–20].

In view of these applications, it is necessary to further study the dynamical control of APB states in PBG reservoirs. Studies have shown that APB states can be controlled by a classical driving field [21,22]. An and her co-workers [23–25] have studied the condition for formation of APB states and its direct consequence on the population trapping of atoms embedded in a single-band PBG reservoir. The criteria for population trapping in thermalization processes have been analyzed in Ref. [26]. It leads us to pose the next questions: (1) How to determine the threshold of APB states formation reflected by the population trapping? (2) What is the effect of the relative position of the atom embedded in photonic crystals on the formation of APB states?

In this paper we focus on these questions and elucidate the physical nature of population trapping in PBG materials. We consider a two-level atom coupled to a coherent two-band PBG reservoir, where the atom-coupling fields from the two-band reservoir are two coherent waves and depend on the atomic position. While the spontaneous emission of a three-level atom embedded in a coherent PBG reservoir has been mentioned by Cheng [27], the discussions are limited to long-time spontaneous emission spectra. In contrast, we focus in this work on the threshold for formation of APB states.

It is shown that the condition for formation of the APB state is just the criteria for population trapping. By means of this criteria, we find that the embedded position of the atom plays a key role in manipulating the formation of APB states. With the variation of the atomic embedded position, a part of the formation range of APB states can be moved from inside to far outside the band gap, and the threshold coupling strength β_c, above which the APB state occurs, can be changed. The direct link between APB states and the population trapping as well as the steady-state entanglement is also investigated. These results would be useful for experimental exploration of Non-Markovian features in quantum systems composed of quantum dots or Rydberg atoms in PBG materials.

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This paper is organized as follows. The theoretical model is given in Section 2. Section 3 is devoted to presenting population trapping caused by the formation of APB states. In Section 4, we derive the threshold for formation of APB states and discuss the effect of the atomic position on the threshold. In Section 5, the steady-state entanglement between the atom and its reservoir modes and also between different reservoir modes caused by APB states are discussed. We summarize our results in Section 6

2. Physical model

We consider a two-level atom situated at location $\mathbf{r}_0$ in a double-band isotropic photonic crystal. The Hamiltonian, in the rotating-wave approximation, for this system is ($\hbar = 1$)

$$H = H_0 + H_I \tag{1}$$

with

$$H_0 = \omega_0\sigma_+\sigma_- + \sum_u \omega_u a_u^\dagger a_u + \sum_\iota \omega_\iota b_\iota^\dagger b_\iota \tag{2}$$

and

$$H_I = i\sum_u (g_u(\mathbf{r}_0)a_u^+\sigma_- - H.c.) + i\sum_\iota (g_\iota(\mathbf{r}_0)b_\iota^+\sigma_- - H.c.). \tag{3}$$

where ω_0 is the atomic transition frequency, $\omega_{u(\iota)}$ is the photonic eigenmode frequency, $\sigma_- = |0\rangle\langle 1|$ and $\sigma_+ = |1\rangle\langle 0|$ are the atomic transition operators, $a_u^\dagger$ (a_u) and $b_\iota^\dagger$ (b_ι) are the creation (annihilation) operators for the upper and lower band reservoirs, respectively. The spatial dependence atom-mode coupling strength can be given by [28]

$$g_{u(\iota)}(\mathbf{r}_0) = \omega_0 d_0\left(\frac{1}{2\varepsilon_0\omega_{u(\iota)}V}\right)^{1/2}\mathbf{u}_d\cdot\mathbf{E}^*_{u(\iota)}(\mathbf{r}_0). \tag{4}$$

Here V is the quantization volume, d_0 and $\mathbf{u}_d$ are the magnitude and the unit vector of the atomic dipole moment, respectively, and $\mathbf{E}^*_{u(\iota)}(\mathbf{r}_0)$ is the atom-coupling electric field from the upper-band (lower-band) reservoir. We note that the eigenmodes in photonic crystals can be characterized by Bloch modes, which are different from that in free space. As a result, the electric field varies from point to point within a unit cell of the crystal. Here, we assume that the distributions of electric fields from the double-band reservoir can be written as [27]

$$\mathbf{E}^*_u(\mathbf{r}_0) = E_\mathbf{k}\cos\theta(\mathbf{r}_0)\mathbf{e}, \tag{5}$$

$$\mathbf{E}^*_\iota(\mathbf{r}_0) = E_\mathbf{k}\sin\theta(\mathbf{r}_0)\mathbf{e}, \tag{6}$$

where $E_\mathbf{k}$ and $\mathbf{e}$ are the amplitude and the unit vector of the electric field with wave vector $\mathbf{k}$, respectively, $\theta(\mathbf{r}_0)$ is the angle parameter seen by the atom located at $\mathbf{r}_0$. Thus, the fields of the two-band reservoir are two coherent modes with phase difference $\pi/2$. The coupling constants can be assumed to be $g_u(\mathbf{r}_0) \cong g_\mathbf{k}\cos\theta(\mathbf{r}_0)$ and $g_\iota(\mathbf{r}_0) \cong g_\mathbf{k}\sin\theta(\mathbf{r}_0)$ with real constant $g_\mathbf{k} = \omega_0 d_0(\frac{1}{2\varepsilon_0\omega_\mathbf{k}V})^{1/2}E_\mathbf{k}(\mathbf{u}_d\cdot\mathbf{e})$.

Near the two band edges, the dispersion relation has the form of

$$\omega_1 = \omega_{c_1} + A_1(k-k_0)^2 \quad \omega_1 \geq \omega_{c_1}, \tag{7}$$

$$\omega_2 = \omega_{c_2} - A_2(k-k_0)^2 \quad \omega_2 \leq \omega_{c_2}, \tag{8}$$

here $A_m = \omega_{cm}/k_0^2$ ($m = 1, 2$), $\omega_{c_1(c_2)}$ is the upper (lower) band edge frequency and k_0 is a constant characteristic of the dielectric material.

We assume that at time $t=0$, the atom is in the excited state $|1\rangle$ and the two reservoir modes are in the vacuum states $|\tilde{0}_u\rangle$ and $|\tilde{0}_\iota\rangle$, respectively. The state vector is therefore

$$|\varphi(t)\rangle = a(t)e^{-i\omega_0 t}|1, \tilde{0}_u, \tilde{0}_\iota\rangle + \sum_u c_u(\mathbf{r}_0, t)e^{-i\omega_u t}|0, \tilde{1}_u, \tilde{0}_\iota\rangle + \sum_\iota c_\iota(\mathbf{r}_0, t)e^{-i\omega_\iota t}|0, \tilde{0}_u, \tilde{1}_\iota\rangle, \tag{9}$$

where the radiation state $|0, \tilde{1}_u, \tilde{0}_\iota\rangle$ ($|0, \tilde{0}_u, \tilde{1}_\iota\rangle$) describes the mode of upper (lower) band reservoir with frequency $\omega_{u(\iota)}$ having one excitation.

Using the Schrödinger equation, the expansion coefficients can be expressed as a set of coupled equations:

$$i\dot{a}(t) = \sum_u g_u(\mathbf{r}_0)c_u(\mathbf{r}_0, t)e^{-i(\omega_u-\omega_0)t} + \sum_\iota g_\iota(\mathbf{r}_0)c_\iota(\mathbf{r}_0, t)e^{-i(\omega_\iota-\omega_0)t}, \tag{10}$$

$$i\dot{c}_u(\mathbf{r}_0, t) = g_u(\mathbf{r}_0)a(t)e^{i(\omega_u-\omega_0)t}, \tag{11}$$

$$i\dot{c}_\iota(\mathbf{r}_0, t) = g_\iota(\mathbf{r}_0)a(t)e^{i(\omega_\iota-\omega_0)t}. \tag{12}$$

Formally integrating Eqs. (11) and (12) and substituting the solution into Eq. (10), we can obtain

$$\dot{a}(t) = -\int_0^t d\tau a(\tau)\{\Gamma_u(t-\tau)\cos^2\theta(\mathbf{r}_0)[\cos^2\theta(\mathbf{r}_0) + e^{i\Delta_c t}\sin^2\theta(\mathbf{r}_0)] + \Gamma_\iota(t-\tau)\sin^2\theta(\mathbf{r}_0)[\sin^2\theta(\mathbf{r}_0) + e^{-i\Delta_c t}\cos^2\theta(\mathbf{r}_0)]\}, \tag{13}$$

where we have approximated $c_u(\mathbf{r}_0, t) = c_\mathbf{k}(t)\cos\theta(\mathbf{r}_0)$ and $c_\iota(\mathbf{r}_0, t) = c_\mathbf{k}(t)\sin\theta(\mathbf{r}_0)$, and $\Delta_c = \omega_u - \omega_\iota \cong \omega_{c_1} - \omega_{c_2}$. The memory kernels from the two-band reservoir read

$$\Gamma_u(t-\tau) = \sum_\mathbf{k} g_\mathbf{k}^2 e^{-i(\omega_u-\omega_0)(t-\tau)}, \tag{14}$$

$$\Gamma_\iota(t-\tau) = \sum_\mathbf{k} g_\mathbf{k}^2 e^{-i(\omega_\iota-\omega_0)(t-\tau)}. \tag{15}$$

The Laplace transform of $a(t)$ can be given by

$$\tilde{a}(s) = \frac{1 - \sin^2\theta(\mathbf{r}_0)\cos^2\theta(\mathbf{r}_0)}{s + \Gamma_u(s)\cos^4\theta(\mathbf{r}_0) + \Gamma_\iota(s)\sin^4\theta(\mathbf{r}_0)} \simeq \tilde{a}^{(0)}(s) \{1 - \sin^2\theta(\mathbf{r}_0)\cos^2\theta(\mathbf{r}_0) [a^{(0)}(s+i\Delta_c)\Gamma_\iota(s+i\Delta_c) + a^{(0)}(s-i\Delta_c)\Gamma_u(s-i\Delta_c))\} \tag{16}$$

with $\tilde{a}^{(0)}(s) = [s + \Gamma_u(s)\cos^4\theta(\mathbf{r}_0) + \Gamma_\iota(s)\sin^4\theta(\mathbf{r}_0)]^{-1}$. The Laplace transforms of $\Gamma_u(t-\tau)$ and $\Gamma_{(\iota)}(t-\tau)$ are

$$\Gamma_u(s) = \beta_1^{3/2}\int_{-\infty}^{\infty}\frac{\rho_1(\omega)}{s + i(\omega-\omega_0)}d\omega = \frac{-i\beta_1^{3/2}}{\sqrt{\varepsilon} + \sqrt{-is-\delta_1}}, \tag{17}$$

$$\Gamma_\iota(s) = \beta_2^{3/2}\int_{-\infty}^{\infty}\frac{\rho_2(\omega)}{s + i(\omega-\omega_0)}d\omega = \frac{i\beta_2^{3/2}}{\sqrt{\varepsilon} + \sqrt{is+\delta_2}}, \tag{18}$$

where $\rho(\omega)$ is the density of modes, which has the form of

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