Spontaneous emission from a microwave-driven four-level atom in an anisotropic photonic crystal*

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(Received 4 March 2016; revised manuscript received 28 April 2016; published online 25 August 2016)

The spontaneous emission from a microwave-driven four-level atom embedded in an anisotropic photonic crystal is studied. Due to the modified density of state (DOS) in the anisotropic photonic band gap (PBG) and the coherent control induced by the coupling fields, spontaneous emission can be significantly enhanced when the position of the spontaneous emission peak gets close to the band gap edge. As a result of the closed-loop interaction between the fields and the atom, the spontaneous emission depends on the dynamically induced Autler–Townes splitting and its position relative to the PBG. Interesting phenomena, such as spectral-line suppression, enhancement and narrowing, and fluorescence quenching, appear in the spontaneous emission spectra, which are modulated by amplitudes and phases of the coherently driven fields and the effect of PBG. This theoretical study can provide us with more efficient methods to manipulate the atomic spontaneous emission.

Keywords: anisotropic photonic crystal, spontaneous emission, microwave field, quantum coherence

PACS: 42.70.Qs, 32.80.Qk, 42.50.Gy **DOI:** 10.1088/1674-1056/25/10/104204

1. Introduction

Spontaneous emission is a fundamental process resulting from the interaction between radiation and matter in quantum optics.[1] It is applied to many important physical phenomena, such as lasing without population inversion,[2] coherent population trapping (CPT),[3] modified quantum beats,[4] dark-state polaritons,[5] etc. Studies have shown that spontaneous emission depends not only on the properties of the atomic system but also on the nature of the environment. When the atom is placed in different reservoirs, such as in a vacuum, frequency-dependent reservoirs[6] and microwave cavities,[7] spontaneous emission can be coherently controlled.

Photonic crystal (PC), as a new type material, was discovered first by John[8] in 1984 and investigated by Yablonovitch[9] in 1996. This artificial periodic material has special density of states (DOS), which can greatly affect the atomic action and the electromagnetic wave propagation with frequencies being in its forbidden gap.[10] Then, based on the background of PCs, many interesting optical effects have been found, such as giant Lamb shift,[11] localization of light,[12] photon-bound states,[13,14] suppression and even complete cancellation, and enhancement of spontaneous emission,[15] electromagnetically induced transparency (EIT),[16] etc. Another way to control spontaneous emission is to drive the atom with an external coupling field. Zhu *et al.* considered an excited two-level atom when either the atomic upper or lower level is coupled by a coherent field to a third level, and they found that by spectral narrowing, a dark line can be realized due to the quantum interference effect.[17] Paspalakis and Knight proposed a phase controlled scheme in a four-level atom driven by two lasers with the same frequencies, where the relative phase of the two lasers was used to obtain partial cancellation in the spontaneous emission spectrum.[18] Li *et al.* studied a four-level atomic model with two laser fields in a ladder configuration for controlling the spontaneous emission spectra and simulation of multiple SGC.[19] Generally, in the atomic system with three levels driven by two optical fields, a closed-loop configuration can be formed when a microwave field is used to couple the electric-forbidden transition. Then the optical properties of the atoms are dependent on the relative phase among the three fields. Ghafoor *et al.* investigated the amplitude and phase control of spontaneous emission and obtained a wide variety of spectral behaviors, ranging from a very narrow single spectral line to six spectral lines of varying widths.[20] Li studied the features of the spontaneous emission spectra in a coherently driven cold four-level atomic system with a cyclic configuration, in which the spontaneous emission can be controlled via varying the phase, the frequency, and the intensity of an external coherent magnetic field.[21] A similar atomic system was proposed to investigate the quantum interference effect and Autler–Townes triplet spectroscopy.[22]

When researchers utilize PCs to control the spontaneous emission process in a coherently driven atomic system, there must be more interesting phenomena and important applica-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11447232, 11204367, 11447157, and 11305020).
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tions. Ding *et al*. investigated spontaneous emission of an RF-driven five-level atom[23] and a double Λ-type four-level atom[24] embedded in a three-dimensional anisotropic double-band PC; they found that the photonic band gap (PBG) and the quantum interference effect induced by the RF-driven field have great influence on the spontaneous emission spectra. Jiang *et al*. studied the spontaneous emission spectrum of a three-level Λ-type atom coupled by a microwave field, and discussed the influences of PBG and Rabi frequency of the microwave field on the emission spectrum.[25] In the present paper, motivated by previous studies, we propose a four-level atomic system embedded in an anisotropic double-band PBG, which consists of three upper levels driven by three coupling fields forming a closed-loop. So far, no further theoretical or experimental work has been carried out to explore the spontaneous emission properties of such a closed-loop driven atomic system. With the help of a Laplace transform and final-value theorem, the expression of spontaneous emission spectrum is derived and numerically investigated. Most interestingly, it is shown that many phenomena, such as spectral-line suppression, enhancement and narrowing, and fluorescence quenching, can occur in the spectra. Furthermore, we realize that these properties depend on the quantum interference and the DOS of the PBG reservoir in the dressed-state picture. The effects of system parameters, such as the relative phase and amplitude of the coupling fields, and the width and position of the PBG on the spectra are discussed in detail. As a result, this phase-sensitive atomic system may be relevant to the optical memory device.

The rest of this paper is organized as follows. In Section 2, the models and their equations for the upper three-level coupling atomic system in an anisotropic PBG are discussed. The analytical results of the spontaneous emission spectra are briefly discussed in Section 3. The possible experimental realization of the proposed atomic system is also considered in cold ^{87}Rb atoms. Finally, some conclusions are drawn from the present studies in Section 4.

2. Basic theory

In this paper, we consider a four-level atomic system which consists of three upper levels $|1\rangle$, $|2\rangle$, $|3\rangle$, and one ground level $|4\rangle$. The three upper transitions $|1\rangle \leftrightarrow |2\rangle$, $|2\rangle \leftrightarrow |3\rangle$, and $|1\rangle \leftrightarrow |3\rangle$ are coherently driven by three coherent fields (two laser fields and one microwave field) with the Rabi frequencies Ω_1, Ω_2, and Ω_3, respectively. All of the following discussion is based on the case that the spontaneous decays between these transitions are neglected according to Ref. [26]. In the atomic system, the three transitions form a closed-loop configuration, and then the resulting spontaneous emission is dependent on the relative phase of the coupling fields. In the following, we suppose that Ω_1 is complex while Ω_2 and Ω_3 are real, i.e., $\Omega_1 = |\Omega_1| e^{i\theta}$ with θ being the relative phase among the three coupling fields. The transition between levels $|1\rangle$ and $|4\rangle$ is in the double-band anisotropic PBG reservoir, as shown in Fig. 1(a).

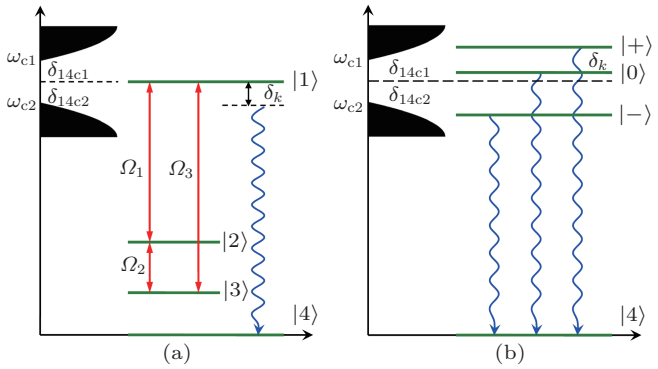


Fig. 1. (color online) (a) Schematic diagram of a coherently driven four-level atom in a double-band anisotropic PBG reservoir. (b) Corresponding atomic system in dressed-state picture of the coupling fields.

For a double-band anisotropic PBG reservoir, the dispersion relations near the photonic band edges are approximated by

$$\omega_k = \begin{cases} \omega_{c_1} + A_1 |k - k_0|^2, & |k| > |k_0|, \\ \omega_{c_2} - A_2 |k - k_0|^2, & |k| < |k_0|, \end{cases} \tag{1}$$

where $A_n \approx \omega_{cn}/k_0^2$ $(n = 1, 2)$ with ω_{c_1} and ω_{c_2} being the upper and lower frequencies of the photonic band edge, respectively. The Hamiltonian describing the dynamics of this system in the interaction picture with the rotating-wave approximation and the electric-dipole approximation can be written as

$$\begin{aligned} H_I &= \hbar(\Omega_1 |1\rangle\langle 2| + \Omega_2 |2\rangle\langle 3| + \Omega_3 |1\rangle\langle 3|) \\ &\quad + \hbar \sum_k g_k e^{i\delta_k t} b_k |1\rangle\langle 4| + \text{H.c.}, \end{aligned} \tag{2}$$

where $b_k^\dagger$ and b_k represent the creation and annihilation operators for the k-th vacuum mode with frequency ω_k, and the frequency-dependent coupling constant between the transition $|1\rangle \leftrightarrow |4\rangle$ and the mode $\{k\}$ of radiation field is $g_k = \omega_{14} d_{14}/\hbar\sqrt{\hbar/(2\varepsilon_0\omega_k V_0)}\hat{e}_k \cdot \hat{u}_d$, with d_{14} and $\hat{u}_d$ denoting the magnitude and unit vector of the atomic dipole moment, V_0 the quantized volume, and $\hat{e}_k$ the polarization unit vectors. The detuning of the spontaneously emitted photon is defined as $\delta_k = \omega_k - \omega_{41}$.

The state vector of the system at time t can be expressed as

$$\begin{aligned} |\Psi(t)\rangle &= A_1(t)|1,\{0\}\rangle + A_2(t)|2,\{0\}\rangle + A_3(t)|3,\{0\}\rangle \\ &\quad + \sum_k A_{4k}(t)|4,\{k\}\rangle. \end{aligned} \tag{3}$$

Substituting the Hamiltonian (Eq. (2)) and state vector (Eq. (3)) into the Schrödinger equation, we can derive the first-order differential equations for the amplitudes as follows:

$$\dot{A}_1(t) = -i\Omega_1 A_2(t) - i\Omega_3 A_3(t) - i\sum_k g_k e^{-i\delta_k t} A_{4k}(t), \tag{4a}$$

$$\dot{A}_2(t) = -\mathrm{i}\Omega_1^* A_1(t) - \mathrm{i}\Omega_2 A_3(t), \tag{4b}$$

$$\dot{A}_3(t) = -\mathrm{i}\Omega_3^* A_1(t) - \mathrm{i}\Omega_2 A_2(t), \tag{4c}$$

$$\dot{A}_{4k}(t) = -\mathrm{i}A_1(t) g_k^* \mathrm{e}^{\mathrm{i}\delta_k t}. \tag{4d}$$

With the Laplace transform, the steady state expression for the probability amplitudes $A_k(t\to\infty)$ is then given by the following equation

$$A_{4k}(t\to\infty) = g_k^* \frac{(\Omega_2^2-\delta_k^2)A_1(0) - (\Omega_2\Omega_3 + |\Omega_1|\,\mathrm{e}^{\mathrm{i}\theta}\delta_k)A_2(0) - (|\Omega_1|\,\mathrm{e}^{\mathrm{i}\theta}\Omega_2 + \Omega_3\delta_k)A_3(0)}{-\delta_k^3 + \Omega_2\delta_k + 2|\Omega_1|\,\Omega_2\Omega_3\cos\theta + \mathrm{i}(\Omega_2^2-\delta_k^2)\cdot\tilde{G}(s\to-\mathrm{i}\delta_k)}, \tag{5}$$

in which, $\Omega^2 = |\Omega_1|^2 + \Omega_2^2 + \Omega_3^2$ represents the total Rabi frequency; $A_1(0)$, $A_2(0)$, and $A_3(0)$ are the initial probability amplitudes of the three upper levels; function $\tilde{G}(s)$ is the Laplace transform of the delay Green's function

$$G(t-t') = \sum_k g_k^{j1} g_k^{j1} \mathrm{e}^{\mathrm{i}(\omega_{j1}-\omega_k)(t-t')},$$

which is obviously determined by the dispersion relations of photonic crystal in Eq. (1). Following the way in Ref. [26], for an anisotropic PBG reservoir, Green's function can be expressed as

$$G(t-t') = \frac{1}{2}\alpha_{14}\left(\frac{\exp\{\mathrm{i}[\delta_{14c1}(t-t')+\pi/4]\}}{\sqrt{4\pi(t-t')^3}} + \frac{\exp\{\mathrm{i}[\delta_{14c2}(t-t')-\pi/4]\}}{\sqrt{4\pi(t-t')^3}}\right). \tag{6}$$

Here, the definitions of the parameters are

$$\alpha_{14} = \frac{1}{2\pi\varepsilon_0}\frac{\omega_{14}^2 d_{14}^2 \omega_{c1}^{1/2}}{3\hbar c^3},$$

$$\delta_{14c1} = \omega_{14} - \omega_{c1} \quad \delta_{14c2} = \omega_{14} - \omega_{c2}, \tag{7}$$

δ_{14c1} and δ_{14c2} represent detuning frequencies between the resonant transition frequency and the upper band frequency and the lower band edge frequency, respectively.

From Eq. (6), we can obtain the Laplace transform of the Green function given by

$$\tilde{G}(s) = \frac{1}{2}\alpha_{14}(-\mathrm{i}\sqrt{\mathrm{i}s+\delta_{14c2}} + \sqrt{\mathrm{i}s+\delta_{14c1}}). \tag{8}$$

We aim to investigate the effects of external fields and reservoirs on spontaneous emission. The spontaneous emission spectrum of the atom is the Fourier transform of

$$\begin{aligned}&\langle E^+(t+\tau)E^-(t)\rangle_{t\to\infty}\\ &= \langle\Psi(t)|\sum_{kk'} a_k^\dagger a_{k'}\,\mathrm{e}^{\mathrm{i}\omega_k(t+\tau)}\,\mathrm{e}^{-\mathrm{i}\omega_{k'}t}\,|\rangle_{t\to\infty}.\end{aligned} \tag{9}$$

From Eqs. (3) and (9), we have

$$\begin{aligned}&\langle E^+(t+\tau)E^-(t)\rangle_{t\to\infty}\\ &= \sum_k A_{4k}^*(\infty)A_{4k}(\infty)\,\mathrm{e}^{\mathrm{i}\omega_k\tau}\\ &= \int_{-\infty}^{+\infty}\mathrm{e}^{\mathrm{i}\omega_k\tau}d\omega_k D(\omega_k)\int A_{4k}^*(\infty)A_{4k}(\infty).\end{aligned} \tag{10}$$

Substituting Eq. (5) into Eq. (10), the spontaneous emission spectrum can be derived as

$$S(\omega_k) \propto D(\omega_k)\left|g_k^*\frac{(\Omega_2^2-\delta_k^2)A_1(0) - (\Omega_2\Omega_3 + |\Omega_1|\,\mathrm{e}^{\mathrm{i}\theta}\delta_k)A_2(0) - (|\Omega_1|\,\mathrm{e}^{\mathrm{i}\theta}\Omega_2 + \Omega_3\delta_k)A_3(0)}{-\delta_k^3 + \Omega^2\delta_k + 2|\Omega_1|\,\Omega_2\Omega_3\cos\theta + \mathrm{i}(\Omega_2^2-\delta_k^2)\cdot\tilde{G}(s\to-i\delta_k)}\right|^2. \tag{11}$$

Here, $D(\omega_k)$ is the DOS of anisotropic PBG reservoir, which is given by

$$D(\omega_k) \approx \sqrt{\omega_k-\omega_{c1}}\Theta(\omega_k-\omega_{c1}) + \sqrt{\omega_{c2}-\omega_k}\Theta(\omega_{c2}-\omega_k), \tag{12}$$

with Θ denoting the Heaviside step function.

According to Eq. (11), we can apparently see that the spontaneous emission is kept at zero all the time whatever the detuning frequency is, when the initial condition of the atomic system is

$$\begin{cases} A_1(0) = 0, \\ \dfrac{\Omega_1}{\Omega_3} = -\dfrac{A_3(0)}{A_2(0)}. \end{cases} \tag{13}$$

It refers to the condition of coherent population trapping (CPT). So in the case of Eq. (13), there is no photon spontaneously emitted from the atom, and all the population is coherently trapped in the superposition state $|\Psi\rangle = \Omega_3|2\rangle - \Omega_1|3\rangle$.

Generally, we can see from Eq. (13) that the spontaneous emission spectrum vanishes at two different positions, which are expressed as

$$\delta_k = \frac{-\Omega_3 A_3(0) - \Omega_1 A_2(0)}{2A_1(0)} \pm \frac{\sqrt{[\Omega_3 A_3(0) + \Omega_1 A_2(0)]^2 - 4A_1(0)[-\Omega_2^2 A_1(0) + \Omega_1\Omega_2 A_3(0) + \Omega_2\Omega_3 A_2(0)]}}{2A_1(0)}. \tag{14}$$

When the atom is initially prepared in level $|1\rangle$, i.e., $A_1(0) = 1$, the spontaneous emission can be suppressed at $\delta_k = \pm\Omega_2$, which correspond to two dark lines in the spectrum. This phenomenon is associated with the quantum interference effect of the three transitions in the dressed-state picture of the driven fields. As all the atomic initial population is in level $|2\rangle$, i.e., $A_2(0) = 1$, if the relative phase is an integral number of π, we can obtain one quenching point at $\delta_k = -\Omega_2\Omega_3/|\Omega_1|\,\mathrm{e}^{\mathrm{i}\theta}$. If not, there will be no dark line in the spontaneous emission spectrum.

3. Results and discussion

In this section, we will study the spontaneous emission of an atom in the double-band anisotropic PBG reservoir based on Eq. (11). In the following part, the influences of the band gap positions and widths, driven field intensity and phase, and initial states of the atom on the spontaneous emission spectrum are emphatically investigated. All these parameters in the numerical calculations are scaled by α_{14}^2 (to be convenient, we assume it to equal 1).

First of all, in order to investigate the effect of PBG on the spontaneous emission spectrum, we plot the curves of $S(\delta_k)$ versus δ_k for different detunings of atomic resonant frequency from the double band edges in Fig. 2. The parameters are set to be $\Omega_1 = 0.5$, $\Omega_2 = 0.5$, and $\phi = 0.2\pi$. The atomic initial population are all in level $|2\rangle$, i.e., $A_2(0) = 1$. When we chose a very narrow band gap width such as $\delta_{14c1} = 0.1$ and $\delta_{14c2} = 0.15$ in Fig. 2(a), which means the excited state $|1\rangle$ is inside of the upper photonic band and the band gap width $\delta_{c1c2} = 0.05$ is very narrow, we can observe four spontaneous emission peaks in the spectra, in which next to the lower band edge is the strongest one. Spontaneous emission in the band gap is completely forbidden. As the atomic resonant frequency moves inside the band gap ($\delta_{14c1} = -0.1$ and $\delta_{14c2} = 0.3$) and the band gap width becomes bigger ($\delta_{c1c2} = 0.4$) [see Fig. 2(b)], the two central peaks are almost covered by the band gap with dramatically reducing intensities. However, the two sideband peaks have no obvious changes as compared with those in Fig. 2(a). In the case where the band gap width is relatively large ($\delta_{c1c2} = 3.1$) and the atomic resonant frequency is at the center of the photonic band gap as shown in Fig. 2(c), there are only two sideband spontaneous emission peaks whose intensities are both enhanced compared with those in Figs. 2(a) and 2(b). These interesting phenomena can be quantitatively explained by using the dressed-state picture. As a result of the ac-Stark effect, the levels $|1\rangle$, $|2\rangle$, and $|3\rangle$ split into three dressed levels $|+\rangle$, $|0\rangle$, and $|-\rangle$ with eigenvalues, respectively, being λ_+, λ_0, and λ_- under the action of the coupling fields, which are the linear superposition of states $|1\rangle$, $|2\rangle$, and $|3\rangle$ as shown in Fig. 1(b).

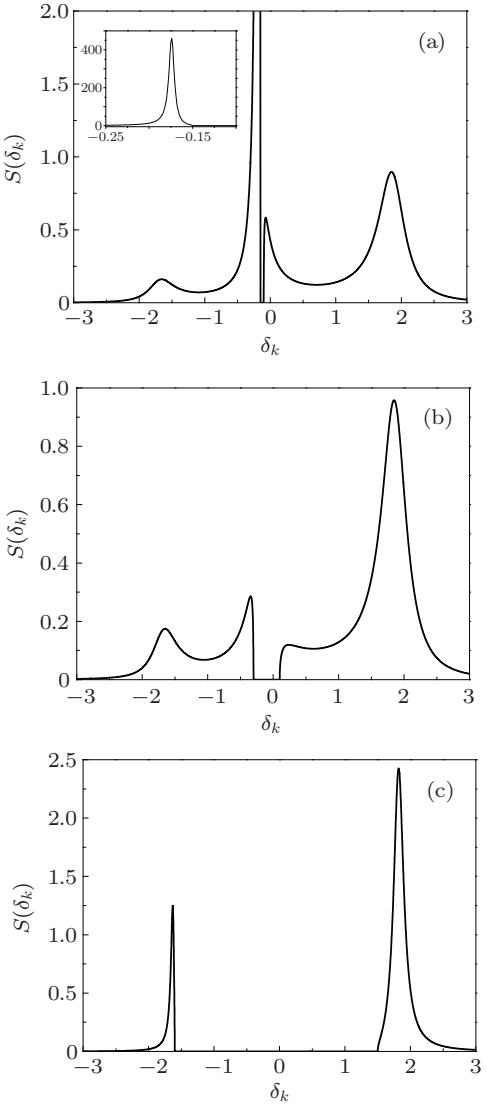


Fig. 2. Spontaneous emission spectra (in units of $\alpha_{14}^2 = 1$) as a function of detuning frequency δ_k for different photonic band gap widths and positions. (a) $\delta_{14c1} = 0.1$, $\delta_{14c2} = 0.15$; (b) $\delta_{14c1} = -0.1$, $\delta_{14c2} = 0.3$; (c) $\delta_{14c1} = -1.5$, $\delta_{14c2} = 1.6$. The other parameters are set to be $|\Omega_1| = 0.5$, $\Omega = 0.5$, $\Omega_3 = 2$, $\theta = 0.2\pi$, $A_1(0) = 0$, $A_2(0) = 1$, and $A_3(0) = 0$.

By calculations, the eigenvalues of the dressed states for this atomic system are $\lambda_+ = 2.2$, $\lambda_0 = -0.2$, and $\lambda_0 = -2.2$, respectively. In this case, the dressed state $|0\rangle$ is in the lower photonic band of Figs. 2(a) and 2(b), and its width is larger than the band gaps. Therefore the resulting spontaneous emission peak from the transition $|0\rangle \to |4\rangle$ is split by the band gap into two narrow peaks. In Fig. 2(a), the dressed state $|0\rangle$ has a little red-shift to the lower band edge, and then the spontaneous emission peak next to the lower band edge can be dramatically enhanced. Figure 2(c) refers to the case that dressed state $|0\rangle$ locates deep in the wide band gap, and the dressed states $|-\rangle$, $|+\rangle$ are respectively within the upper and lower photonic bands and very close to the band edges. Then the spontaneous emission from transition $|0\rangle \to |4\rangle$ can be completely suppressed due to the band gap effect. Meanwhile the spontaneous emission from transition $|-\rangle \to |4\rangle$ and $|+\rangle \to |4\rangle$ can be enhanced. These enhancement effects of the middle

peak in Fig. 2(a) and two sideband peaks in Fig. 2(c) can be attributed to the DOS when the positions of dressed states are within the photonic band and close to the band edge.

Besides the PBG, the driven fields induced phase-dependent coherence has a significant effect on the spontaneous emission. In this part, we emphasize our discussion on the spontaneous emission spectra by adjusting the relative phase among the three coupling fields as shown in Fig. 3.

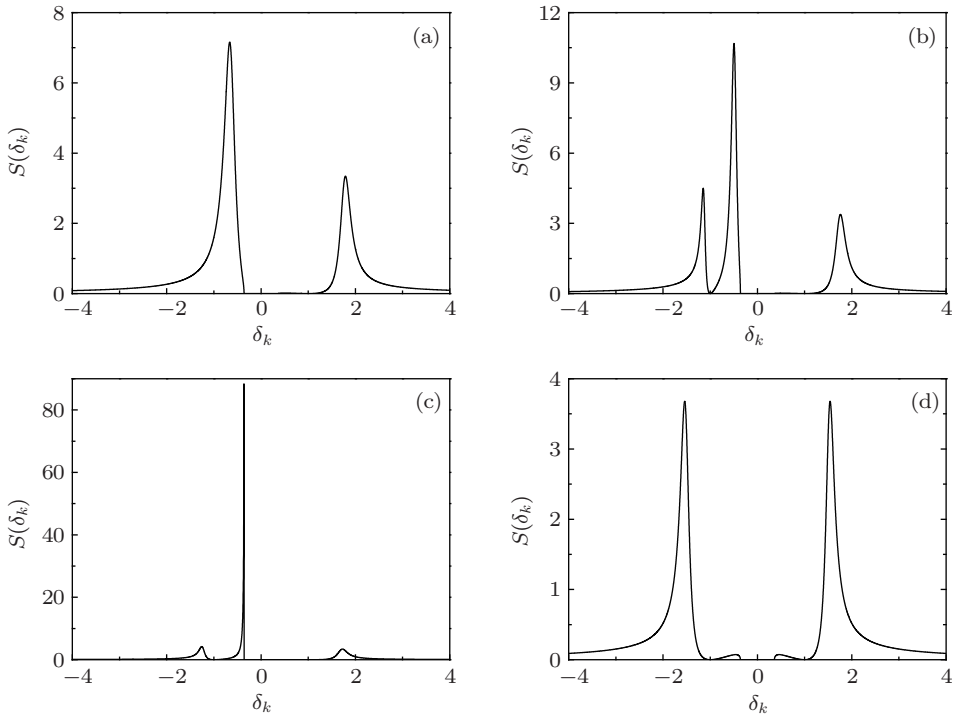


Fig. 3. Spontaneous emission spectra $S(\delta_k)$ (in units of $\alpha_{14}^2 = 1$) each as a function of detuning frequency δ_k for different relative phases of the coupling fields. (a) $\theta = 0$, (b) $\theta = \pi/6$; (c) $\theta = \pi/4$, (d) $\theta = \pi/2$. The other parameters are set to be $|\Omega_1| = 1$, $\Omega_2 = 1$, $\Omega_3 = 1$, $A_1(0) = 1$, $A_2(0) = 0$, $A_3(0) = 0$, $\delta_{14c1} = -0.36$, and $\delta_{14c2} = 0.36$.

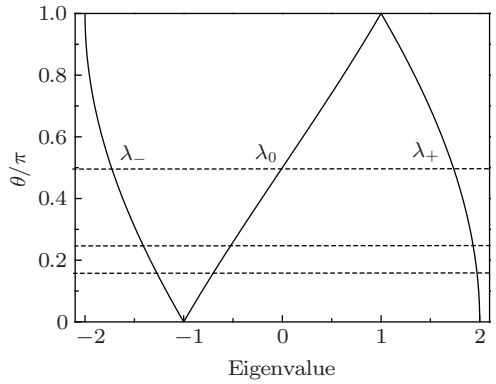


Fig. 4. Eigenvalues of the three dressed states $|-\rangle$, $|0\rangle$, $|+\rangle$ each as a function of the relative phase of the coupling fields. The parameters are the same as those in Fig. 3.

In the calculations, we set three equal intensities of coupling fields to be $|\Omega_1| = 1$, $\Omega_2 = 1$, and $\Omega_3 = 1$, the initial populations are all in the upper level $|1\rangle$, and the atom is embedded in the middle of the band gap with the detuning frequencies being $\delta_{14c1} = -0.36$ and $\delta_{14c2} = 0.36$.

Figures 3(b)–3(d) each show that there exist two dark lines in the spectra at the positions of $\delta_k = \pm\Omega_2$. We attribute these quenching points of spontaneous emission to the quantum interference effect between three transitions in the dressed-state picture of the coherently driven atom. In the considered system, Autler–Townes splitting, i.e., the dressed state of the atom, depends on the relative phases among the three fields due to the closed loop configuration of the coherently driven transitions

$$|1\rangle \xrightarrow{\Omega_1} |2\rangle \xrightarrow{\Omega_2} |3\rangle \xrightarrow{\Omega_3} |1\rangle.$$

Therefore, three eigenvalues changing with the phase in a vacuum are plotted in Fig. 4 under the same parameters with Fig. 3. From Fig. 4, we can see that when the relative phase is $\theta = 0$, the dressed states $|-\rangle$ and $|0\rangle$ are degenerate and there are only two dressed states with eigenvalues being $\lambda_0 = -1$ and $\lambda_+ = 2$. However, the positions of the two resulting spontaneous emission peaks in the anisotropic PBG are not exactly at $\delta_k = -1$ and $\delta_k = 2$ [see Fig. 3(a)]. This is ascribed to the anisotropic reservoir which differs from the vacuum. With increasing the relative phase, three peaks can be obtained in the spontaneous emission spectra as shown in Figs. 3(b)–3(d), in which three peaks are all shifted a little compared with the eigenvalues of the corresponding dressed states in Fig. 4. In the case of $\theta = \pi/6$, the dressed state $|0\rangle$ is close to the lower band gap edge and the middle spontaneous peak is enhanced a little. When the phase changes to $\theta = \pi/4$, dressed state $|0\rangle$ is slightly red shifted to the lower band edge and then the middle spontaneous peak is enhanced significantly. These phenomena are all attributed to the particular DOS of the anisotropic

photonic crystal. For the case that $\theta = \pi/2$, the dressed state $|0\rangle$ is in the band gap and then the middle spontaneous peak will disappear due to the forbidden effect of PBG. However, as is well known, any spontaneous emission line has its certain width, which is larger than the double band gap width in this situation, as a result, two small wings appear symmetrically in the photonic band nearby the upper and lower band edge as shown in Fig. 3(d). Moreover, we can conclude from Eq. (11) that the spontaneous emission is phase-sensitive with a period of π.

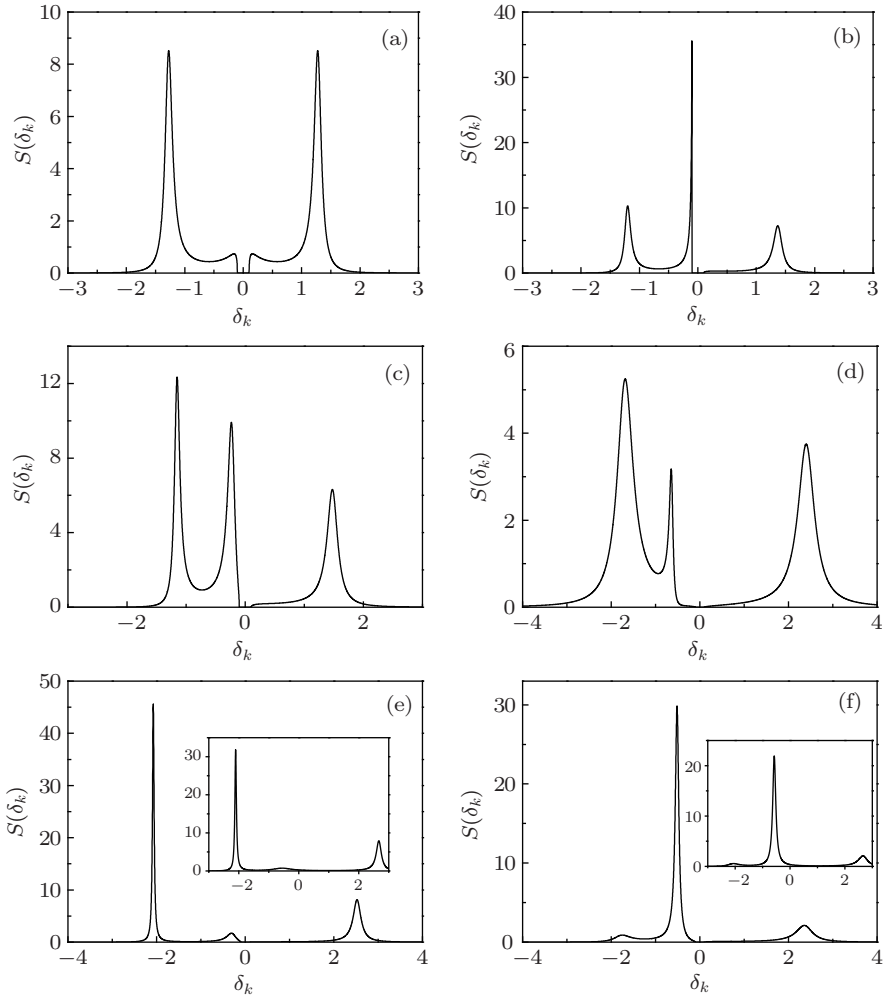


Fig. 5. (color online) Spontaneous emission spectra $S(\delta_k)$ (in units of $\alpha_{14}^2 = 1$) each as a function of detuning frequency δ_k for different amplitudes of three coupling fields. (a) $|\Omega_1| = 0$, $\Omega_2 = 1$, $\Omega_3 = 1$; (b) $|\Omega_1| = 0.25$, $\Omega_2 = 1$, $\Omega_3 = 1$; (c) $|\Omega_1| = 0.5$, $\Omega_2 = 1$, $\Omega_3 = 1$; (d) $|\Omega_1| = 2$, $\Omega_2 = 1$, $\Omega_3 = 1$; (e) $|\Omega_1| = 1$, $\Omega_2 = 2$, $\Omega_3 = 1$; (f) $|\Omega_1| = 1$, $\Omega_2 = 1$, $\Omega_3 = 2$. The other parameters are set to be $\theta = 0.2\pi$, $A_1(0)$, $A_2(0) = 1$, $A_3(0) = 0$, $\delta_{14c1} = -0.1$, and $\delta_{14c2} = 0.1$.

Details about the variation of the spontaneous emission spectra with the Rabi frequencies of the three driven fields are shown in Fig. 5. At first, we study the dependence of spontaneous emission on the amplitude of coupling field $|\Omega_1|$. Figures 5(a)–5(d) show the spontaneous emission spectra when $|\Omega_1|$ increases from 0 to 2. We find that three spontaneous emission peaks always exist and no fluorescence quenching point appears because the condition of Eq. (14) cannot be fulfilled in the condition that $\theta \neq n\pi$ (n is integer). In the case of $|\Omega_1|$, as can be seen from Fig. 5(a), there are two symmetrical peaks on both sides of the PBG and the central peak is suppressed with only two small wings left. When the amplitude $|\Omega_1|$ increases, the right and left peaks move towards the opposite directions of the sideband, while the middle peak in the spectra shifts to the left as shown in Figs. 5(b)–5(d). More specifically, the middle peak moves from the center of PBG into the lower band with the increase of $|\Omega_1|$. Meanwhile, its position gets gradually further away from the band edge. Then the effect of a peculiar DOS of anisotropic PBG on the transition $|0\rangle \rightarrow |4\rangle$ in the dressed-state picture becomes increasingly weak. As a result, the intensity of the middle spontaneous emission peak decreases gradually. Next, the control of spontaneous emission with the other two fields is considered. By comparison with Fig. 5(d) in which $|\Omega_1| = 2$, we plot the spectra with $\Omega_2 = 2$ in Fig. 5(e) and $\Omega_3 = 2$ in Fig. 5(f). From these three figures, we can observe that three spontaneous peaks take place at different positions with unequal widths and strengths. In general, the central peaks in these figures are not covered by the photonic band gap, and it is more or less enhanced compared with the cases in a vacuum

as shown in the insets of Figs. 5(e) and 5(f). This enhancement is attributed to the effect of the peculiar DOS. In addition, the amplitudes of coupling fields affect the component of state $|1\rangle$ in the three dressed states, and then the electric dipoles of the corresponding transitions in the dressed-state picture are dependent on the Rabi frequencies of the coupling fields. Consequently, the width of the spectral line can be manipulated, if need be.

In the above discussion, we have investigated the effects of reservoir and driven fields on the spontaneous emission. From Eq. (11) it is found that the spontaneous emission can also rely on the initial state of the atom [see Fig. 6]. For the case where the initial population are all in the upper level $|1\rangle$ ($A_1(0) = 1$), as can be seen in Fig. 6(a), three peaks and two dark lines at $\delta_k = \pm 0.5$ can be observed in the spectra. This interesting phenomenon is qualitatively attributed to the quantum interference between multiple decay channels among the transitions $|-\rangle \to |4\rangle$, $|0\rangle \to |4\rangle$, and $|+\rangle \to |4\rangle$ in the dressed-state picture. It can also be explained in the bare-state picture. Under the condition of $A_1(0) = 1$, the bare-state decays to the ground state through three main processes: $|1\rangle \to |2\rangle \to |3\rangle \to |1\rangle \to |4\rangle$, $|1\rangle \to |3\rangle \to |2\rangle \to |1\rangle \to |4\rangle$, and $|1\rangle \to |4\rangle$. Destructive quantum interference among these three competitive pathways will lead to fluorescence quenching at $\delta_k = \pm\Omega_2$. Meanwhile, the position of dressed state $|0\rangle$ is close to the lower band gap edge so that the middle spontaneous peak can be enhanced. When we set the initial population on level $|2\rangle$ ($A_2(0) = 1$) as seen in Fig. 6(b), there are also three peaks but no dark line in the spontaneous emission spectra. With this initial atomic state, the atom decays to the ground state through two competitive ways, $|2\rangle \to |1\rangle \to |4\rangle$ and $|2\rangle \to |3\rangle \to |1\rangle \to |4\rangle$. Under these parameters, the condition of Eq. (14) cannot be fulfilled, and therefore there is no quantum interference between the two competitive pathways. As the population is initially prepared in a superposition state of $|1\rangle$ and $|2\rangle$ as shown in Fig. 6(c), there are three spontaneous emission peaks. Compared with only two peaks in the spectrum in a vacuum [see the inset of Fig. 6(c)], the small peak on the left of the lower band edge can be attributed to the interaction between the atom and the reservoir of anisotropic photonic crystal. For the case where the initial population is in a superposition state of $|2\rangle$ and $|3\rangle$ as shown in Fig. 6(d), there are three peaks and one quenching point in the spontaneous emission spectrum. Compared with the spontaneous emission in a vacuum as shown in the inset, the central peak is enhanced because its position is nearby the edge of the lower band gap.

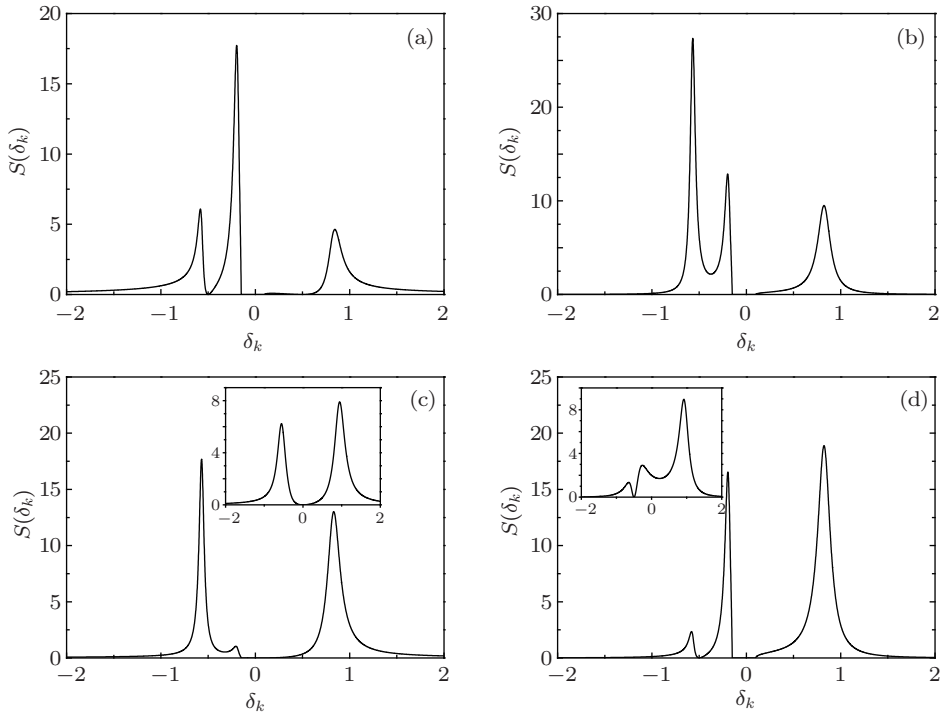


Fig. 6. Spontaneous emission spectra $S(\delta_k)$ (in units of $\alpha_{14}^2 = 1$) each as a function of detuning frequency δ_k for different atomic initial states. (a) $A_1(0) = 1$, $A_2(0) = 0$, $A_3(0) = 0$; (b) $A_1(0) = 0$, $A_2(0) = 1$, $A_3(0) = 0$; (c) $A_1(0) = \sqrt{2}/2$, $A_2(0) = \sqrt{2}/2$, $A_3(0) = 0$; (d) $A_1(0) = 0$, $A_2(0) = \sqrt{2}/2$, $A_3(0) = \sqrt{2}/2$. The other parameters are set to be $|\Omega_1| = 0.5$, $\Omega_2 = 0.5$, $\Omega_3 = 0.5$, $\theta = 0.2\pi$, $\delta_{14c1} = -0.1$, and $\delta_{14c2} = 0.15$.

Finally, we briefly consider the possible experimental realization of the atomic system. For instance, our proposed configuration can be realized with the D1 line of ^{87}Rb atoms.[27] Its wavelength is about 795 nm and can be obtained from an external cavity diode laser. The atomic states in Fig. 1(a) can be chosen as follows: $|1\rangle = |5P_{1/2}, F = 1, m_F = -1\rangle$, $|2\rangle = |5S_{1/2}, F = 2, m_F = 0\rangle$, $|3\rangle = |5S_{1/2}, F = 1, m_F = 0\rangle$, and $|4\rangle = |5S_{1/2}, F = 1, m_F = -1\rangle$. The microwave cavity with the frequency of 6.835 GHz is utilized to couple the two states $|2\rangle = |5S_{1/2}, F = 2, m_F = 0\rangle$ and $|3\rangle = |5S_{1/2}, F = 1, m_F =$

$0\rangle$.[28] The transition from the excited state $|1\rangle = |5P_{1/2}, F = 1, m_F = -1\rangle$ to the ground state $|4\rangle = |5S_{1/2}, F = 1, m_F = -1\rangle$ is coupled to the double-band anisotropic reservoir. Moreover, in order to eliminate the Doppler broadening effect, ^{87}Rb atoms should be cooled in a magneto-optical trap (MOT).

4. Conclusions and perspectives

In this paper, we study the spontaneous emission of a microwave-driven four-level atom embedded in the double-band anisotropic photonic crystal. The results show that many interesting phenomena, such as spectral-line suppression, enhancement and narrowing, and fluorescence quenching exist in the spontaneous spectra. The explicit dependence of the spectra on the system parameters is also discussed. In the dressed-state picture, qualitative analyses indicate that the anisotropic photonic DOS can dramatically enhance the spontaneous emission when the positions of dressed states are within the photonic band and close to the band edge. As a result of interaction with closed-loop, the spontaneous emission is phase-sensitive and the widths of the spontaneous spectral lines can be manipulated by the amplitudes of the coupling fields. The dark lines are attributed to the quantum interference effect. Finally, we give the possible experimental realization of the atomic system. These investigations provide us with more efficient means for controlling the spontaneous emission of an atom in photonic crystal, which has potential applications, such as photonic crystal lasers.

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