Control of spontaneous emission from a microwave-field-coupled three-level Λ-type atom in photonic crystals

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The spontaneous emission spectrum of a three-level Λ-type atom driven by a microwave field was studied. For the two transitions coupled to the same modified reservoir, we discussed the influence of photonic band gap and Rabi frequency of the microwave field on the emission spectrum. The emission spectrum is given for different locations of the upper band-edge frequency. With the transition frequencies moving from outside the band gap to inside, the number of peaks decreases in the emission spectrum and the multipeak structure of spectral line is finally replaced by a strong non-Lorentzian shape. With increase of the Rabi frequency of the microwave field, we find the spectral line changes from a multipeak structure to a two-peak structure, originating from the inhibition of spontaneous emission for the corresponding decay channel.

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I. INTRODUCTION

Coherent control of spontaneous emission has been an active area of quantum optics because of its potential applications in short-wavelength lasers, photonics devices, and quantum information processing, etc. There are two basic ways of controlling atomic spontaneous emission. One is placing the atom in different circumstances such as in free space, an optical cavity, and in photonic crystals [1,2]. The early works on spontaneous emission are mainly focused on an atom embedded in the free space and a cavity. Agarwal [3] gave a good review of several methods to study spontaneous emission. The spontaneous emission properties for atomic systems, including a two-level atom, a three-level atom, and an atom driven by an external field, were investigated using quantum statistical theory. The cavity is a typical non-Markov reservoir in which the atom shows different decay properties compared with that in free space. Since the pioneering work of Purcell [4], the inhibition [5] and enhancement [6] of spontaneous emission and quantum beats in atomic populations [7] have been studied. The spontaneous emission properties of lanthanon ions in asymmetric microcavities [8] has also been researched. For atomic transition near the photonic band edge, the emission dynamics are modified relative to free space, and the investigation of decay properties of atoms embedded in photonic crystals has been a subject of interest. Some novel phenomena and effects were found, such as oscillatory behavior of the population [9] and enhanced quantum interference effects [10], etc. Wang *et al.* [11] studied the decay kinetic properties of a two-level atom in photonic crystals based on Green's function for evolution operators, and the Rabi oscillation and fractional trapping behavior in the population of the excited state were found. John and Quang studied [9] the spontaneous emission from a three-level Λ-type atom considering one transition coupled to a photonic band-gap reservoir and the other to the free space, in which they found the oscillation of the upper state population and spectral splitting. In our previous work [12] we extended John and Quang's work and considered the two transitions coupled to the same modified reservoir. The population evolution and the spontaneous emission spectra were obtained for cases where the transition frequencies are outside and deeply inside of the band gap.

The other way to control atomic spontaneous emission is to drive the atom with an external field. Through changing the Rabi frequency, phase, and detuning of the external field, effective control of atomic decay properties can be achieved. Javanainen [13] discussed the influence of spontaneous generation of coherence on the laser-driven transitions in a three-level Λ system. Zhu and Scully [14] investigated the quenching of spontaneous emission of an open V-type atom. Later Berman [15] gave an analysis of dynamic suppression of spontaneous emission for a similar atomic system; he found that the origin of the suppression of spontaneous emission proposed by Zhu and Scully can be traced to a metastable state that is hidden in their calculations. The phase dependence of the resonance fluorescence spectrum of a Λ-type atom [16] is studied and a two-color coherent phase control scheme is proposed by Paspalakis and Knight [17]. Certain studies have been done on the spontaneous emission of driven multilevel atoms in photonic crystals [18–21]. In this paper we study the influence of photonic band gap and Rabi frequency of the external field on the spontaneous emission spectrum, considering that the two lower levels of three-level Λ-type atoms are coupled by a microwave field.

II. THEORETICAL MODEL AND EQUATIONS

The atomic model considered here is shown in Fig. 1(a), where two lower levels $|1\rangle$ and $|2\rangle$ are coupled by corresponding electric dipoles to a common excited level $|3\rangle$. The frequency spacing between the two lower states ($|1\rangle$and $|2\rangle$) is ω_{21}, and the atom is coupled by a microwave field with a carry frequency ω_0 and a Rabi frequency Ω_0. Both $|3\rangle \rightarrow |1\rangle$ and $|3\rangle \rightarrow |2\rangle$ transitions are coupled to the photonic band-gap reservoir. The Hamiltonian in the interaction representation

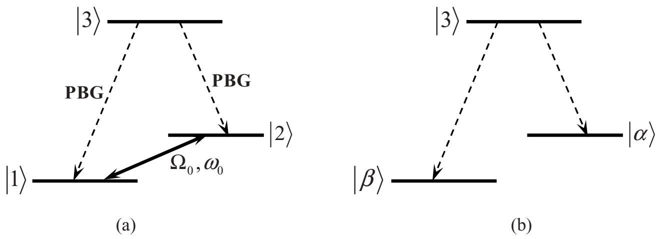

FIG. 1. Level scheme of the model atom, where ω_0 and Ω_0 denote the carrier and the complex Rabi frequency of the microwave field, respectively. (a) Bare-state representation. The two lower states $|1\rangle$ and $|2\rangle$ are coupled by a microwave field with frequency ω_0 and phase ϕ_0. (b) Dressed-state representation.

takes the form

$$H = H_A + H_B(t) \tag{1}$$

where

$$H_A = -\hbar\delta_0|2\rangle\langle 2| + i\hbar(\Omega_0|2\rangle\langle 1| - \Omega_0^*|1\rangle\langle 2|) \tag{2}$$

$$\begin{aligned} H_B(t) = {} & i\hbar\sum_k g_k^{31}(a_k|3\rangle\langle 1|e^{-i\delta_k t} - a_k^+|1\rangle\langle 3|e^{i\delta_k t}) \\ & + i\hbar\sum_k g_k^{32}(a_k|3\rangle\langle 2|e^{-i(\delta_k+\omega_0)t} - a_k^+|2\rangle\langle 3|e^{-i(\delta_k+\omega_0)t}), \end{aligned} \tag{3}$$

where the detuning δ_0 and δ_k are defined by $\delta_0 = \omega_0 - \omega_{21}$ and $\delta_k = \omega_k - \omega_{31}$, respectively, and a_k^+ and a_k are the creation and annihilation operators for the kth mode of the electromagnetic field. g_k and g_k' are coupling constants between the kth mode of the field and the atom, associated with $|3\rangle \rightarrow |1\rangle$ transition and $|3\rangle \rightarrow |2\rangle$ transition, respectively. From dressed-state theory, due to the interaction of the atom with the microwave field, the levels $|1\rangle$ and $|2\rangle$ can be replaced by dressed levels $|\alpha\rangle$ and $|\beta\rangle$, respectively. The level scheme in the dressed-state picture is given in Fig. 1(b). The dressed states are defined by the eigenvalue equations $H_A|\alpha\rangle = \lambda_\alpha|\alpha\rangle$ and $H_A|\beta\rangle = \lambda_\beta|\beta\rangle$, where $\lambda_\alpha = -\delta_0/2 + \sqrt{(\delta_0/2)^2 + |\Omega|^2}$ and $\lambda_\beta = -\delta_0/2 - \sqrt{(\delta_0/2)^2 + |\Omega|^2}$ are the corresponding eigenvalue. The explicit expressions of the dressed state are

$$|\alpha\rangle = \sin\theta|1\rangle + ie^{i\phi_0}\cos\theta|2\rangle \tag{4}$$

$$|\beta\rangle = \cos\theta|1\rangle - ie^{i\phi_0}\sin\theta|2\rangle \tag{5}$$

where $\sin\theta = |\Omega_0|/\sqrt{\lambda_\alpha^2 + |\Omega_0|^2}$, $\cos\theta = \lambda_\alpha/\sqrt{\lambda_\beta^2 + |\Omega_0|^2}$. We can set the Rabi frequency as $\Omega_0 = |\Omega_0|e^{i\phi_0}$, where ϕ_0 is the phase of the microwave field. Under the dressed state the wave function of the system is in the form

$$|\Psi(t)\rangle = c_3(t)|3,0\rangle + \sum_k[\alpha_k(t)b_k^+|\alpha,0\rangle + \beta_k(t)b_k^+|\beta,0\rangle], \tag{6}$$

where $\langle 0|$ denotes the vacuum state of the electromagnetic field. From Eqs. (1)–(3) and (6) we can derive the equation of motion for the expansion amplitudes:

$$\begin{aligned} \frac{d}{dt}C_3(t) = {} & \sum_k\{g_k[\alpha_k(t)\sin\theta + \beta_k(t)\cos\theta]e^{-i\delta_k t} \\ & + ig_k'[\alpha_k(t)\cos\theta - \beta_k(t)\sin\theta]e^{i\phi_0}e^{-i(\delta_k+\omega_0)t}\}, \end{aligned} \tag{7}$$

$$\begin{aligned} \frac{d}{dt}(e^{i\lambda_\alpha t}\alpha_k(t)) = {} & C_3(t)[-g_k\sin\theta e^{i(\lambda_\alpha+\delta_k)t} \\ & + ig_k'\cos\theta e^{-i\phi_0}e^{i(\lambda_\alpha+\delta_k+\omega_0)t}], \end{aligned} \tag{8}$$

$$\begin{aligned} \frac{d}{dt}(e^{i\lambda_\beta t}\beta_k(t)) = {} & C_3(t)[-g_k\cos\theta e^{i(\lambda_\beta+\delta_k)t} \\ & - ig_k'\sin\theta e^{-i\phi_0}e^{i(\lambda_\beta+\delta_k+\omega_0)t}]. \end{aligned} \tag{9}$$

By substituting Eqs. (8) and (9) into Eq. (7) we can get

$$\begin{aligned} \frac{d}{dt}C_3(t) = {} & -\int_0^t dt'C_3(t')\sin^2\theta\sum_k g_k^2 e^{-i(\lambda_\alpha+\delta_k)(t-t')} + i\int_0^t dt'C_3(t')\sin\theta\cos\theta e^{-i\phi_0}e^{i\omega_0 t'}\sum_k g_k g_k' e^{-i(\lambda_\alpha+\delta_k)(t-t')} \\ & - \int_0^t dt'C_3(t')\cos^2\theta\sum_k g_k^2 e^{-i(\lambda_\beta+\delta_k)(t-t')} - i\int_0^t dt'C_3(t')\sin\theta\cos\theta e^{-i\phi_0}e^{i\omega_0 t'}\sum_k g_k g_k' e^{-i(\lambda_\beta+\delta_k)(t-t')} \\ & - i\int_0^t dt'C_3(t')\sin\theta\cos\theta e^{i\phi_0}e^{-i\omega_0 t'}\sum_k g_k g_k' e^{-i(\lambda_\alpha+\delta_k+\omega_0)(t-t')} - \int_0^t dt'C_3(t')\cos^2\theta\sum_k g_k'^2 e^{-i(\lambda_\alpha+\delta_k+\omega_0)(t-t')} \\ & + i\int_0^t dt'C_3(t')\sin\theta\cos\theta e^{i\phi_0}e^{-i\omega_0 t'}\sum_k g_k g_k' e^{-i(\lambda_\beta+\delta_k+\omega_0)(t-t')} - \int_0^t dt'C_3(t')\sin^2\theta\sum_k g_k'^2 e^{-i(\lambda_\beta+\delta_k+\omega_0)(t-t')}, \end{aligned} \tag{10}$$

with the initial conditions $C_3(0) = 1$, $\alpha_k(0) = \beta_k(0) = 1$. In our system, the two transitions from the upper level to the lower levels were coupled to the same modified reservoir, and therefore the Weisskopf-Wigner approximation is not applicable as the density of modes of the photonic band-gap reservoir vary much more quickly than those in free space. To solve this problem the memory kernel is introduced:

$$\begin{aligned} k_\alpha(t-t') = {} & \sum_k g_k^2 e^{-i(\lambda_\alpha+\delta_k)(t-t')} \approx g^{3/2} \\ & \times \int d\omega\rho(\omega)e^{-i(\omega_k-\omega_{31}+\lambda_\alpha)(t-t')}, \end{aligned} \tag{11a}$$

$$\begin{aligned} k_{\alpha 0}(t-t') = {} & \sum_k g_k'^2 e^{-i(\lambda_\alpha+\delta_k+\omega_0)(t-t')} \approx g^{3/2} \\ & \times \int d\omega\rho(\omega)e^{-i(\omega_k-\omega_{32}+\lambda_\alpha)(t-t')}, \end{aligned} \tag{11b}$$

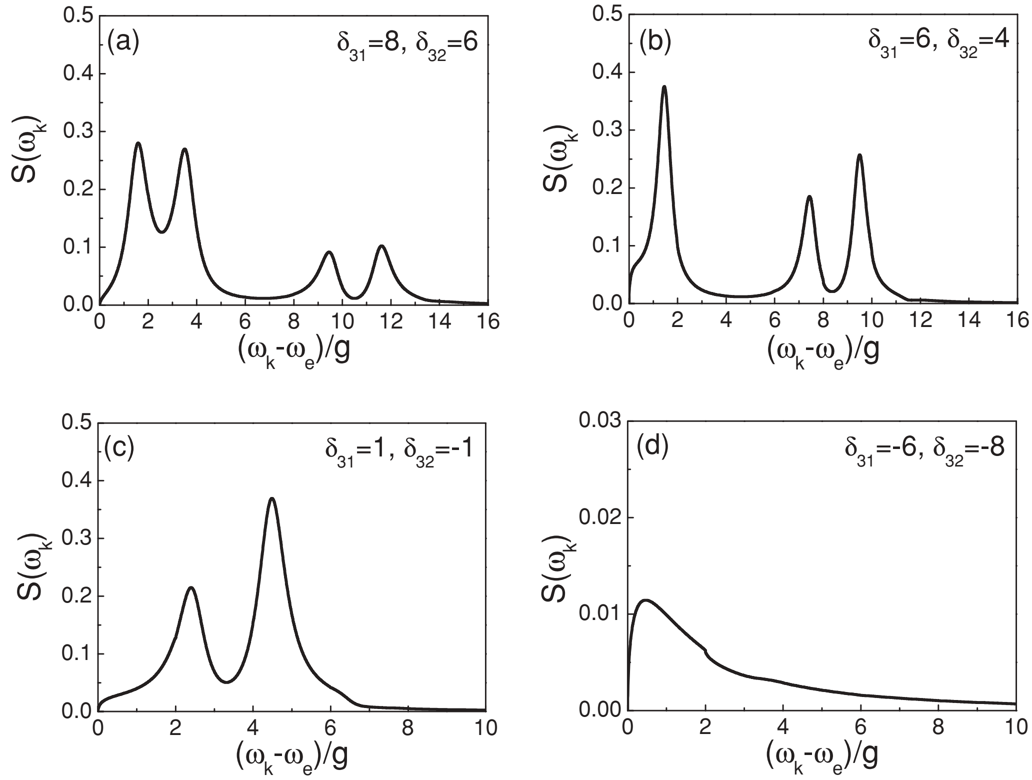

FIG. 2. The spontaneous emission spectrum $S(\omega_k)$ as a function of $(\omega_k - \omega_e)/g$ for various positions of the upper band edge with $|\Omega_0| = 4$, $\phi_0 = 0$: (a) $\delta_{31} = 8,\ \delta_{32} = 6$; (b) $\delta_{31} = 6,\ \delta_{32} = 4$; (c) $\delta_{31} = 1,\ \delta_{32} = -1$; and (d) $\delta_{31} = -6,\ \delta_{32} = -8$.

$$k_\beta(t-t') = \sum_k g_k^2 e^{-i(\lambda_\beta+\delta_k)(t-t')} \approx g^{3/2} \times \int d\omega\rho(\omega)e^{-i(\omega_k-\omega_{31}+\lambda_\beta)(t-t')}, \quad (11c)$$

$$k_{\beta 0}(t-t') = \sum_k g_k^2 e^{-i(\lambda_\beta+\delta_k+\omega_0)(t-t')} \approx g^{3/2} \times \int d\omega\rho(\omega)e^{-i(\omega_k-\omega_{32}+\lambda_\beta)(t-t')}, \quad (11d)$$

where g denotes the coupling constants of the atom to the non-Markovian reservoir and $\rho(\omega) = \Theta(\omega-\omega_e)/\sqrt{\omega-\omega_e}/\pi$ is the density of modes of the photonic band-gap reservoir. To avoid the singularity of density of modes at the band edge, we use the modified isotropic model [22,23]

$$\rho(\omega) = \frac{1}{\pi}\frac{\sqrt{\omega-\omega_e}}{\varepsilon+\omega-\omega_e}\Theta(\omega-\omega_e), \quad (12)$$

where ω_e is the upper band-edge frequency and ε the smooth factor. Therefore Eq. (10) can be written as

$$\begin{aligned}\frac{d}{dt}C_3(t) = &-\int_0^t dt' C_3(t')\sin^2\theta k_\alpha(t-t') + i\int_0^t dt' C_3(t')\sin\theta\cos\theta e^{-i\phi_0}e^{i\omega_0 t'}k_\alpha(t-t') - \int_0^t dt' C_3(t')\cos^2\theta k_\beta(t-t')\\ &- i\int_0^t dt' C_3(t')\sin\theta\cos\theta e^{-i\phi_0}e^{i\omega_0 t'}k_\beta(t-t') - i\int_0^t dt' C_3(t')\sin\theta\cos\theta e^{i\phi_0}e^{-i\omega_0 t'}k_{\alpha 0}(t-t') \\ &- \int_0^t dt' C_3(t')\cos^2\theta k_{\alpha 0}(t-t') + i\int_0^t dt' C_3(t')\sin\theta\cos\theta e^{i\phi_0}e^{-i\omega_0 t'}k_{\beta 0}(t-t') - \int_0^t dt' C_3(t')\sin^2\theta k_{\beta 0}(t-t').\end{aligned} \quad (13)$$

Taking the Laplace transform of Eq. (13) yields

$$\begin{aligned} &sC_3(s) - C_3(0)\\ &= -k_\alpha(s)C_3(s) + i\sin\theta\cos\theta e^{-i\phi_0}k_\alpha(s)C_3(s-i\omega_0) - \cos^2\theta k_\beta(s)C_3(s) - i\sin\theta\cos\theta e^{-i\phi_0}k_\beta(s)C_3(s-i\omega_0)\\ &\quad - i\sin\theta\cos\theta e^{i\phi_0}k_{\alpha 0}(s)C_3(s+i\omega_0) - \cos^2\theta k_{\alpha 0}(s)C_3(s) + i\sin\theta\cos\theta e^{i\phi_0}k_{\beta 0}(s)C_3(s+i\omega_0) - \sin^2\theta k_{\beta 0}(s)C_3(s), \end{aligned} \quad (14)$$

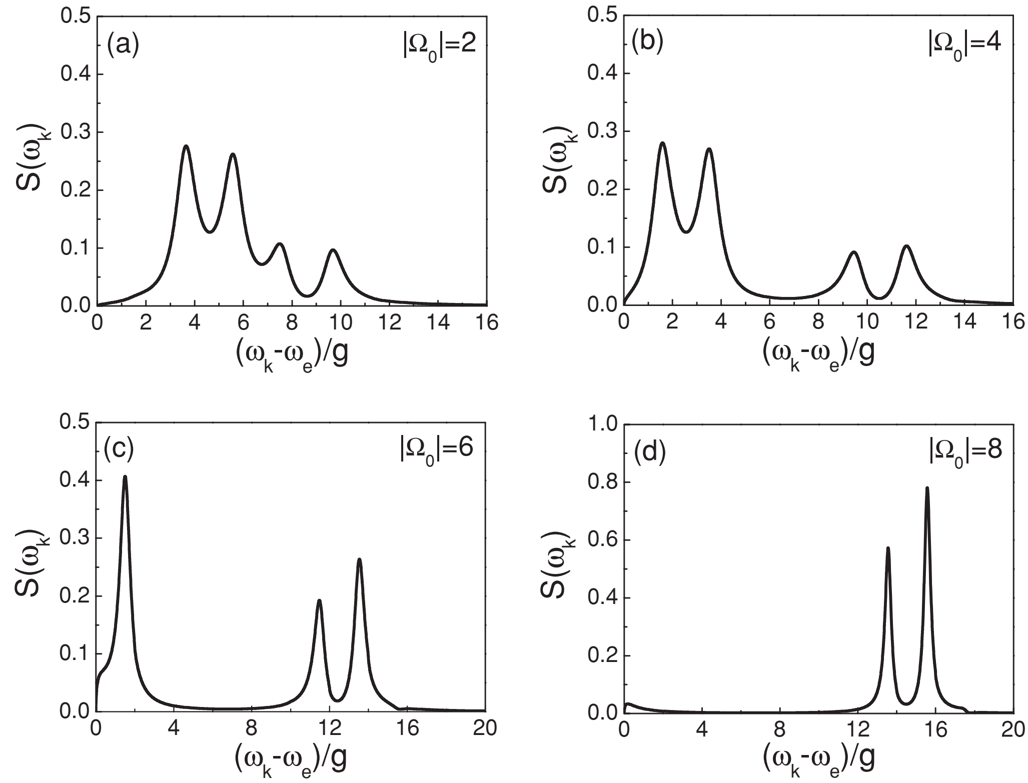

FIG. 3. The spontaneous emission spectrum $S(\omega_k)$ as a function of $(\omega_k - \omega_e)/g$ for the various Rabi frequencies of the microwave field with $\delta_{31} = 8,\ \delta_{32} = 6, \phi_0 = 0$: (a) $|\Omega_0| = 2$, (b) $|\Omega_0| = 4$, (c) $|\Omega_0| = 6$, and (d) $|\Omega_0| = 8$.

where $k_{i(i0)}(s)$ is the Laplace transform of $k_{i(i0)}(t - t')$. Performing the Laplace transform of Eq. (11a) we have

$$k_\alpha(s) = \frac{g^{3/2}}{i\sqrt{\varepsilon} + \sqrt{is + \delta_{31} - \lambda_\alpha}}, \tag{15a}$$

$$k_{\alpha 0}(s) = \frac{g^{3/2}}{i\sqrt{\varepsilon} + \sqrt{is + \delta_{32} - \lambda_\alpha}}, \tag{15b}$$

$$k_\beta(s) = \frac{g^{3/2}}{i\sqrt{\varepsilon} + \sqrt{is + \delta_{31} - \lambda_\beta}}, \tag{15c}$$

$$k_{\beta 0}(s) = \frac{g^{3/2}}{i\sqrt{\varepsilon} + \sqrt{is + \delta_{32} - \lambda_\beta}}, \tag{15d}$$

where $\delta_{31} = \omega_{31} - \omega_e$, $\delta_{32} = \omega_{32} - \omega_e$ are detunings of the two transition frequencies from the band edge. The positive (negative) δ_{ij}means the transition frequency ω_{ij} is outside (inside) the band gap. Here we used the iterative method once in Eq. (14) to obtain

$$C_3(s) = \frac{\begin{array}{c}\{1 + i \sin\theta \cos\theta e^{-i\phi_0}[k_\alpha(s) - k_\beta(s)]C_3^0(s - i\omega_0).\\ - i \sin\theta \cos\theta e^{i\phi_0}[k_{\alpha 0}(s) - k_{\beta 0}(s)]C_3^0(s + i\omega_0)\}\end{array}}{s + \sin^2\theta[k_\alpha(s) - k_{\beta 0}(s)] + \cos^2\theta[k_{\alpha 0}(s) - k_\beta(s)]}, \tag{16}$$

with $C_3^0(s) = \frac{1}{s+\sin^2\theta[k_\alpha(s)-k_{\beta 0}(s)]+\cos^2\theta[k_{\alpha 0}(s)-k_\beta(s)]}$. By using the Laplace transform and final-value theorem in Eqs. (8) and (9) we can get the amplitudes for time t sufficiently long:

$$\begin{aligned}\alpha_k(t \to \infty) = &-g_k \sin\theta C_3(-i\lambda_\alpha - i\delta_k)\\ &+ i g_k' \cos\theta e^{-i\phi_0} C_3(-i\lambda_\alpha - i\delta_k - i\omega_0),\end{aligned} \tag{17}$$

$$\begin{aligned}\beta_k(t \to \infty) = &-g_k \cos\theta C_3(-i\lambda_\beta - i\delta_k)\\ &- i g_k' \sin\theta e^{-i\phi_0} C_3(-i\lambda_\beta - i\delta_k - i\omega_0).\end{aligned} \tag{18}$$

The spontaneous emission spectrum $S(\omega_k)$is given by

$$S(\omega_k) = \rho(\omega_k)(|\alpha_k(t \to \infty)|^2 + |\beta_k(t \to \infty)|^2). \tag{19}$$

If the transition frequencies$\omega_{31}$and ω_{32} are coupled to free space or far from the band edge ($\delta_{31} \gg 0, \delta_{32} \gg 0$), the spectral lines associated with $|\alpha_k|^2$ are replaced by the mirror image of the spectral lines associated with $|\beta_k|^2$ when the phase of the microwave field is increased from 0 to π [16]. However, when the transition frequencies are close to the band edge or inside the band gap, due to the existence of the photonic band gap the emission spectrum does not show obvious variation with the phase of microwave field changes. Meanwhile the properties of the mirror-originated phase disappear and the phase just influences the height of spectral lines associated with $|\alpha_k|^2$and$|\beta_k|^2$. Therefore we do not discuss the influence of phase of the microwave field on spontaneous emission spectra. Here, we consider only the impact of photonic band gap and Rabi frequency of the external field on the spontaneous emission spectrum. The results are illustrated in Figs. 2 and 3, respectively. For simplicity we set $g_k = g_k' = g$ in all the figures; the other parameters are in units of $g (g = 1)$.

III. RESULTS AND DISCUSSION

We know that if there is no external field, the spectral line will show a superposition of two Lorentzian shapes. Due to the existence of a microwave field, according to dressed state theory, the levels $|1\rangle$ and $|2\rangle$ are replaced by two dressed levels $|\alpha\rangle$ and $|\beta\rangle$, which are the linear superpositions of levels $|1\rangle$ and $|2\rangle$. Therefore, both transitions $|3\rangle \rightarrow |\alpha\rangle$ and $|3\rangle \rightarrow |\beta\rangle$ consist of two transitions, respectively. Consequently, the emission spectrum shows four-peak structure as shown in Fig. 2(a), in which the left (right) two peaks associate with $|\alpha_k|^2$ ($|\beta_k|^2$) when both transition frequencies are outside the band gap and far from the band edge ($\delta_{31} = 8, \delta_{32} = 6$) for a fixed Rabi frequency. It is seen from Eqs. (17) and (18) that the spectral structure of $|\alpha_k|^2$ consists of two lines centered near $\omega_{32} - \omega_e - |\Omega_0|$ and $\omega_{31} - \omega_e - |\Omega_0|$, while that of $|\beta_k|^2$ consists of two lines centered near $\omega_{32} - \omega_e + |\Omega_0|$ and $\omega_{31} - \omega_e + |\Omega_0|$, respectively. From $\delta_{31} = 8,\ \delta_{32} = 6$ and $|\Omega_0| = 4$, we get $\omega_{32} - \omega_e - |\Omega_0| = 2 > 0$, $\omega_{31} - \omega_e - |\Omega_0| = 4 > 0$, $\omega_{32} - \omega_e + |\Omega_0| = 10 > 0$, and $\omega_{31} - \omega_e + |\Omega_0| = 12 > 0$. These suggest that all the transition frequencies associated with $|3\rangle \rightarrow |\alpha\rangle$ and $|3\rangle \rightarrow |\beta\rangle$ fall outside the band gap. Therefore the emission spectrum shows the superposition of four Lorentzian shapes. As shown in Fig. 2(b), when both of the transition frequencies move closer to the band gap ($\delta_{31} = 6, \delta_{32} = 4$), one transition frequency of $|3\rangle \rightarrow |\alpha\rangle$ associated with the spectral line centered near $\omega_{32} - \omega_e - |\Omega_0|$ falls within the band gap and the corresponding transition is inhibited initially, and the other three transition frequencies remain outside the band gap; hence the emission spectrum shows a three-peak structure. When the transition frequency ω_{32} drops into the band gap ($\delta_{31} = 1,\ \delta_{32} = -1$), where $\omega_{32} - \omega_e - |\Omega_0| = -5$ and $\omega_{31} - \omega_e - |\Omega_0| = -3$, the two transition frequencies associated with transition $|3\rangle \rightarrow |\alpha\rangle$ fall into the band gap and the corresponding transitions are forbidden totally. In this case since $\omega_{31} - \omega_e + |\Omega_0| = 5$ and $\omega_{32} - \omega_e + |\Omega_0| = 3$, the transition frequencies associated with $|3\rangle \rightarrow |\beta\rangle$ are still outside the band gap; hence the emission spectrum shows a double-peak structure. From Fig. 2(d) we can see that when both transition frequencies are deeply inside the band gap ($\delta_{31} = -6,\ \delta_{32} = -8$), all the transitions are suppressed and the emission spectrum shows a strong non-Lorentzian with a very small amount of radiation.

In Fig. 3 we present the results for the spontaneous emission spectrum at different Rabi frequencies $|\Omega_0|$ of microwave field and for the case that $\delta_{31} = 8$, $\delta_{32} = 6$. If $\omega_{32} - \omega_e + |\Omega_0| - (\omega_{31} - \omega_e - |\Omega_0|) > 0$, that is, $\omega_{21} < 2|\Omega_0|$, the two spectral structures $|\alpha_k|^2$ and $|\beta_k|^2$ are without interlacement, located on the left of ω_{31} and the right of ω_{32}, respectively. From Fig. 3 we can see that with increase of Rabi frequency $|\Omega_0|$, the transition frequencies associated with transition $|3\rangle \rightarrow |\beta\rangle$ are always outside the band gap and hence the right part of the emission spectrum shows two peaks. For the transition $|3\rangle \rightarrow |\alpha\rangle$ we define two new transition frequencies $\omega'_{32} = \omega_{32} - |\Omega_0|$ and $\omega'_{31} = \omega_{31} - |\Omega_0|$. When the Rabi frequency increases from 2 to 4, although the distances between two pairs of resonances associated with $|\alpha_k|^2$ and $|\beta_k|^2$ become larger, all the transition frequencies are outside the band gap and the emission spectrum shows a four-peak structure. As depicted in Fig. 3(c), when Rabi frequency is increased to $|\Omega_0| = 6$, $\omega'_{32} = \omega_{32} - |\Omega_0| = 0$ and $\omega'_{31} = \omega_{31} - |\Omega_0| = 2$. This implies that the left peak for $|\alpha_k|^2$ is pushed into the band gap. As a result, the emission spectrum displays triple-peak structure. When the Rabi frequency is further increased to $|\Omega_0| = 8$, the transition frequencies $\omega'_{32} = \omega_{32} - |\Omega_0| = -2$ and $\omega'_{31} = \omega_{31} - |\Omega_0| = 0$. This means the two transitions associated with $|3\rangle \rightarrow |\alpha\rangle$ are both pushed into the band gap. In this case the emission spectrum shows only two peaks that belong to $|\beta_k|^2$, as given in Fig. 3(d).

IV. CONCLUSION

In summary, we have studied the control of spontaneous emission from a three-level Λ-type atom coupled by a microwave field in photonic crystals. We can carry out the control of spontaneous emission by changing the position of the upper band edge and Rabi frequency of the external field. When the two transition frequencies are far from the band gap, the spectral properties are similar to the case in free space. If one transition is outside the band gap and the other inside, the emission associated with transition $|3\rangle \rightarrow |\alpha\rangle$ will be inhibited and the emission spectrum shows two-peak structure. If both the transition frequencies are deep within the band gap, the spontaneous emission will be inhibited strongly and the spectral line shows strong non-Lorentzian. With increase of the Rabi frequency of the microwave field, the corresponding transition frequency is pushed into the photonic band gap, which results in a disappearance of the partial spectral line.

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