Non-Markovian decay of a three-level Λ-type atom in a photonic-band-gap reservoir

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Considering a three-level Λ-type atom with both transitions coupled to a single photonic-band-gap reservoir, we investigate the upper-state population and spontaneous emission spectra by using the resolvent operator for the isotropic dispersion model, and give their analytical solutions. For the case of two transitions coupled to the same reservoir, the upper-state population always displays an oscillatory behavior and finally reaches a steady-state value. For atomic transition frequencies in the vicinity of the band-gap edge or inside the gap, the spontaneous emission spectra become strongly non-Lorentzian.

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I. INTRODUCTION

Since the pioneering work of Yablonovitch [1] and John [2], the robust characteristics of a photonic crystal (PC) have stimulated investigations of a broad range of problems pertaining to the interaction of few-level atoms with unusual reservoirs. The unconventional photonic density of states (DOS) associated with such material leads to the prediction of many interesting effects [3], such as modified reservoir-induced transparency [4], population trapping in a two-atom system [5], enhanced quantum interference effect [6], anomalous Lamb shift [7], phase-dependent behavior of the population dynamics [8], and transient lasing without inversion [9], among others.

Three-level atomic systems are of particular interest in quantum optics, including V-, cascade-, or Λ-type arrangements. For the V-type system, its decay properties have been discussed [10–13] considering both transitions coupled to the same reservoir with one or two band gaps for isotropic and anisotropic dispersion models. The spontaneous emission spectrum for an atomic cascade system where one transition is coupled near resonantly to the edge of a photonic band gap (PBG) and the other transition is coupled to a flat background of radiation modes was investigated, and shown to be strongly non-Lorentzian [14]. For the same atomic system, the problem with both photons strongly coupled to the PBG continuum has been treated by Nikolopoulos *et al.* [15] through replacing the DOS by a sufficiently large set of discrete modes, which leads to the formation of a two-photon "photon-atom bound state." In addition, Dalton *et al.* [16] gave a general discussion about the dynamical behavior of a three-level atomic system in a cascade configuration in which both transitions are coupled to a single or two separate structured reservoirs of electromagnetic field modes using Laplace transform methods. For the Λ-type system, John *et al.* [17] have studied its spontaneous emission properties by Laplace transform methods, considering one transition coupled to the edge of a PBG and the other to a flat background of radiation modes in an isotropic model. In addition, the spontaneous emission, absorption, and dispersion properties of a Λ-type three-level atom where one transition interacts near resonantly with a double-band PC were investigated in an isotropic model by Angelakis *et al.* [18]. The oscillatory behavior of spontaneous emission and the occurrence of dark lines (zeros in the spectrum at certain values of the emitted photon frequency) in the emission spectrum were noted.

To our knowledge, previous studies for the Λ-type system were limited to the case of only one transition coupled to a PBG reservoir. In this paper we study the population evolution and spontaneous emission spectra of a three-level Λ-type system, concentrating on the case of both transitions coupled to the same PBG reservoir. The paper is organized as follows. In Sec. II, we apply the resolvent operator to describe the interaction of our system with the PBG reservoir and derive the matrix elements of the resolvent operator G. In Sec. III, by using the matrix elements of G we obtain the analytical expression for the upper-state population and the spontaneous emission spectrum for a three-level Λ atom in the case of two transitions coupled to the same reservoir for the isotropic model. Finally, we summarize our findings in Sec. IV.

II. THEORY

The three-level Λ-type atom we studied is shown in Fig. 1, where two lower levels $|b\rangle$ and $|c\rangle$ are coupled by corresponding electric dipoles to the common excited level $|a\rangle$. The atom is assumed to be initially in the state $|a\rangle$. The transitions $|a\rangle \leftrightarrow |c\rangle$ and $|a\rangle \leftrightarrow |b\rangle$ are coupled to the same modified reservoir. The Hamiltonian that describes the dy-

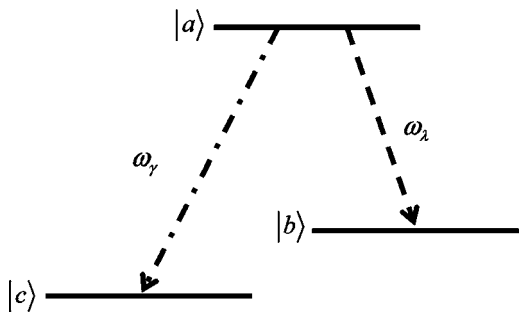

FIG. 1. Three-level atom in a Λ configuration.

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namics of this system, in the rotating wave approximation, is given by

$$H = H_0 + V,$$

$$H_0 = \hbar\omega_2\sigma_{aa} + \hbar(\omega_2 - \omega_1)\sigma_{bb} + \hbar\sum_{\lambda}\omega_\lambda a_\lambda^\dagger a_\lambda + \hbar\sum_{\gamma}\omega_\gamma a_\gamma^\dagger a_\gamma,$$

$$V = i\hbar\sum_{\lambda}[g_\lambda^{ab}\sigma_{ba}a_\lambda^\dagger - (g_\lambda^{ab})^*\sigma_{ab}a_\lambda] + i\hbar\sum_{\gamma}[g_\gamma^{ac}\sigma_{ca}a_\gamma^\dagger - (g_\gamma^{ac})^*\sigma_{ac}a_\gamma], \quad (1)$$

where the atomic transition frequencies are ω_2 for $|a\rangle \to |c\rangle$ and ω_1 for $|a\rangle \to |b\rangle$, $\sigma_{i,j}$ are atomic pseudospin operators, while $a_\lambda^\dagger(a_\gamma^\dagger)$ and $a_\lambda(a_\gamma)$ are the creation and annihilation operators of the structured continuum, which is coupled to the atomic transitions via the respective coupling constants g_γ^{ac} and g_λ^{ab}. $\hbar\omega_\lambda(\hbar\omega_\gamma)$ is the energy of the λth (γth) reservoir mode. Operators H_0 and V represent the noninteraction Hamiltonian and the interaction Hamiltonian, respectively. Setting $\hbar = 1$ and introducing the resolvent operator [19]

$$G(z) = \frac{1}{z - H}, \quad (2)$$

we have $(z - H_0)G(z) = 1 + VG(z)$. The wave function of the system is given by

$$|\Psi(t)\rangle = c_a(t)|a;0\rangle + \sum_{\lambda} c_{b,\lambda}(t)|b;1_\lambda\rangle + \sum_{\gamma} c_{c,\gamma}(t)|c;1_\gamma\rangle \equiv U(t)|\Psi(0)\rangle, \quad (3)$$

where $U(t)$ is the time evolution operator. With the system initially in the state $|a\rangle$, the resolvent operator equations read

$$(z - \omega_a)G_{aa} = 1 + \sum_{\lambda} V_{ab_\lambda}G_{b_\lambda a} + \sum_{\gamma} V_{ac_\gamma}G_{c_\gamma a},$$

$$(z - \omega_{b_\lambda})G_{b_\lambda a} = V_{b_\lambda a}G_{aa},$$

$$(z - \omega_{c_\gamma})G_{c_\gamma a} = V_{c_\gamma a}G_{aa}, \quad (4)$$

where $\omega_a = \omega_2$, $\omega_{b_\lambda} = \omega_2 - \omega_1 + \omega_\lambda$, $\omega_{c_\gamma} = \omega_\gamma$, $V_{ij} = \langle i|V|j\rangle$, and $G_{ij} = \langle i|G|j\rangle$. From Eq. (4) we obtain

$$G_{aa} = \frac{1}{z - \omega_a - R_{ac} - R_{ab}}, \quad (5)$$

$$G_{b_\lambda a} = \frac{V_{b_\lambda a}}{z - \omega_{b_\lambda}}\frac{1}{z - \omega_a - R_{ac} - R_{ab}}, \quad (6)$$

$$G_{c_\gamma a} = \frac{V_{c_\gamma a}}{z - \omega_{c_\gamma}}\frac{1}{z - \omega_a - R_{ac} - R_{ab}}, \quad (7)$$

where

$$R_{ac} = \sum_{\gamma}\frac{V_{ac_\gamma}^2}{(z - \omega_{c_\gamma})}, \quad R_{ab} = \sum_{\lambda}\frac{V_{ab_\lambda}^2}{(z - \omega_{b_\lambda})}.$$

III. RESULTS AND DISCUSSION

A. Upper-state population for the isotropic dispersion model

As we know from Eq. (3), $|\Psi(t)\rangle = U(t)|\Psi(0)\rangle$, where $|\Psi(0)\rangle = |a;0\rangle$ is the initial atomic wave function. To obtain the population evolution $U_{ij}(t)$, it is necessary to carry out the contour integral of $G_{ij}(z)$ by the residue method, i.e.,

$$U_{ij}(t) = \frac{1}{2\pi i}\int_{+\infty+i\varepsilon}^{-\infty+i\varepsilon} dz\, e^{-izt}G_{ij}(z), \quad (8)$$

where ε is an infinitesimal small positive quantity. To evaluate the integral, we close the contour with a semicircle in the lower half of the complex plane and use the residue theorem. Using the identity $1/(x \pm i\eta) = p(1/x) \mp i\pi\delta(x)$ with p denoting the principal value part of the integral. The values of R_{ac} and R_{ab} near the real axis are given by

$$R_{ac} = \Delta_{ac} - i\frac{\Gamma_{ac}}{2}, \quad (9)$$

$$R_{ab} = \Delta_{ab} - i\frac{\Gamma_{ab}}{2}, \quad (10)$$

where Δ_{ij} and Γ_{ij} represent the level shift and the spontaneous emission rate of a photon from the excited state to a state of lower energy, respectively. Here, neglecting Δ_{ij}, Γ_{ij} can be written as $\Gamma_{ij}(z) = 2\pi|g_{ij}|^2\rho(z)$; thus we have

$$R_{ab} = -i\pi c_1\rho(z), \quad R_{ac} = -i\pi c_2\rho(z), \quad (11)$$

where the constants c_1 and c_2 represent the effective coupling of two atomic transitions to the reservoir and equal the squares of the coupling constants, respectively. In general, the coupling constants g_γ^{ac} and g_λ^{ab} are unequal and thus for the rest of this paper we assume that c_1 and c_2 are different from each other.

From Eqs. (11) and (5), we obtain

$$G_{aa}(z) = \frac{1}{z - \omega_a + i\pi(c_1 + c_2)\rho(z)}. \quad (12)$$

For the isotropic dispersion model, $\rho(z) = (1/2\pi)\theta(z - \omega_e)/\sqrt{z - \omega_e}$, where ω_e is the upper-band-edge frequency. Through the change of variable $z \to z + \omega_2 - \omega_1 + \omega_a$, Eq. (12) can also be written as

$$G_{aa}(z) = \frac{1}{z + \omega_2 - \omega_1 + i(c_1 + c_2)/\sqrt{z + \omega_2 - \omega_1 + \omega_a - \omega_e}/2}. \quad (13)$$

For simplicity, we define $\delta_2 = \omega_2 - \omega_e$, $\delta_1 = \omega_1 - \omega_e$ as detuning of the two transition frequencies from the band edge, respectively. Through some algebraic manipulations, $\omega_2 - \omega_1 = \delta_2 - \delta_1$, $\omega_2 - \omega_1 + \omega_a - \omega_e = 2\delta_2 - \delta_1$, we obtain

$$G_{aa}(z) = \frac{1}{z + \delta_2 - \delta_1 + i(c_1 + c_2)/\sqrt{z + 2\delta_2 - \delta_1}/2}. \quad (14)$$

Substituting Eq. (14) into Eq. (8), we can get the upper-state population. Figure 2 gives the upper-state population evolution of a Λ-type system with two transitions coupled to the

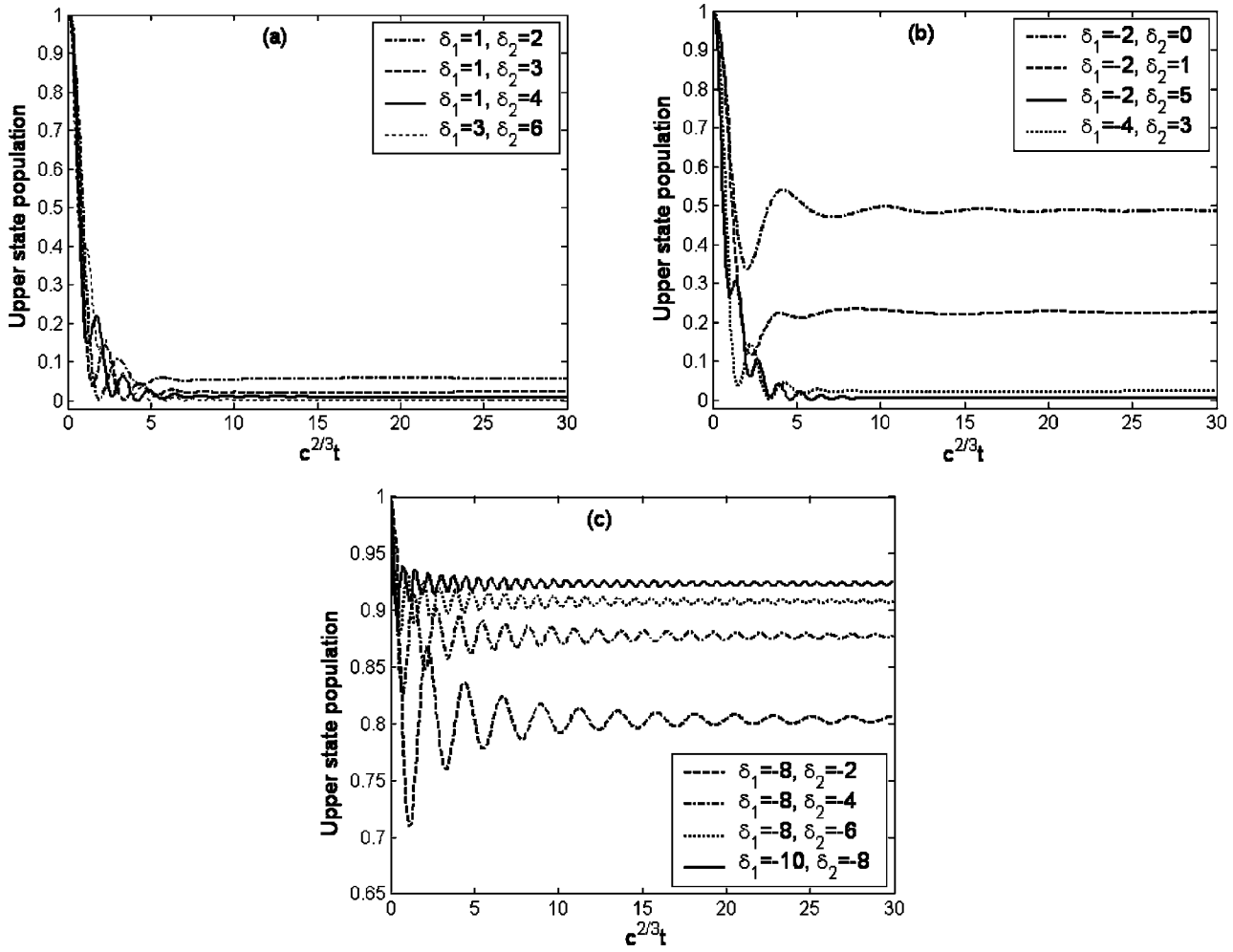

FIG. 2. The upper-state population evolution of a Λ system with two transitions coupled to the same reservoir versus dimensionless time $c^{2/3}t$. (a) Both transition frequencies are outside the gap; (b) transition frequency ω_1 is inside the gap, with the other transition frequency ω_2 outside the gap; (c) both transition frequencies are inside the gap for the isotropic dispersion model.

same reservoir for various transition frequencies.

In Ref. [17], for various spontaneous decay rates, the excited-state population was given with one transition coupled to the PBG reservoir and the other to free space. For a nonzero value of the decay rate into the open space, the oscillations characterizing the photon-atom bound state are damped with the atom ending up in the lower state. For our system with both transitions coupled to the same structured reservoir, the excited-state population is stable and nonzero for transition frequencies inside the gap, but dissipates into the open space for transition frequencies far outside the gap. In Fig. 2(a) where both transition frequencies are outside the gap, we find that the spontaneous emission is partially inhibited, but the steady-state value is very small and decreases with increasing δ_2. In Fig. 2(b) where the transition frequency ω_1 (ω_2) is inside (outside) the gap, the spontaneous emission is still inhibited partially but the upper-state population can reach a much larger steady-state value and increases with decreasing δ_2. In Fig. 2(c), for both transition frequencies sufficiently inside the gap, the spontaneous emission is almost completely inhibited with the steady-state value increasing to relatively high values.

For the upper-state population in all figures, we can identify a transient regime, within a very short time period, where part of the atomic population is lost. On a longer time scale, populations in atomic levels undergo oscillations and are strongly dependent on the relative detuning from the band edge, which reflects the emission and reabsorption of photons. The period of oscillations is determined by the real pole and the real part of the complex roots of the denominator of $G_{aa}(z)$. That implies that the effective frequency of oscillations is determined by δ_1, δ_2, c_1, and c_2. For fixed c_1 and c_2, the effective frequencies of the oscillation increase with increasing values of δ_1 and δ_2. In addition, it is clear that, once an atom is trapped in the dark state, it will not oscillate between the excited level and the ground levels. That is, only the bright state contributes to the population oscillation, while the dark state does not.

In general, the poles in the expressions of the resolvent operator amplitudes are strongly connected with the behavior of the atomic system as indicated by Eq. (8). The pole with a positive imaginary part falls outside the contour of integration, while the complex poles with negative imaginary part lead to a transient dissipative behavior but do not contribute

to the stable behavior. The purely real poles, on the other hand, represent a stable nondecaying state of the system and thus determine the behavior in the long-time limit. In Fig. 2, for both transition frequencies near the band edge or far outside the gap, $G_{aa}(z)$ has a pure real pole and two conjugated complex poles. Only the pure real pole and the complex poles with negative imaginary part will contribute to the oscillatory behavior of spontaneous emission. If both transition frequencies far inside the gap, $G_{aa}(z)$ has two real poles, corresponding to two nondecaying states, which leads to strongly inhibited spontaneous emission.

In the language of dressed states, the oscillations in the populations of the atomic levels reflect the interference between the dressed states of the atom. The dressed state outside the gap will lose all its population through a long time evolution, while the one inside the gap is protected from dissipation and thus is stable. In Fig. 2(a), both transition frequencies are outside the gap, the corresponding dressed states represent two propagating modes decreasing with time in the emitted field. These two decaying states lead to the loss of upper-state population. But in the vicinity of the band edge we find the partial trapping of population. In Fig. 2(b), the dressed state corresponding to transition frequency inside the gap is a nondecaying photon-atom bound state, but a propagating state corresponding to transition frequency outside the gap. It is the interference between the photon-atom bound state and the propagating state that leads to the quasiperiodic oscillatory behaviors of the population. In Fig. 2(c), both frequencies are inside the gap and the corresponding dressed states are nondecaying localized states, while the interference between the bound dressed states results in strong oscillation and inhibition of the spontaneous emission.

B. Spectral distribution of photons spontaneous emitted by an excited atom

To obtain the spectral distribution of emitted photons, we must calculate the emission amplitude $U_{b_\lambda a}(t)$ and $U_{c_\gamma a}(t)$ for a time t sufficiently long. From Eqs. (11) and (6), we obtain

$$G_{b_\lambda a}(z) = \frac{1}{z-\omega_2+\omega_1-\omega_\lambda}\frac{\sqrt{c_1}}{z-\omega_a+i\pi(c_1+c_2)\rho(z)}. \tag{15}$$

Substituting Eq. (15) into Eq. (8), using the residue method, and considering a time t long enough so that only one pole $z=\omega_2-\omega_1+\omega_\lambda$ contributes to the integral, we have

$$U_{b_\lambda a}(t\to\infty) = \frac{\sqrt{c_1}}{\omega_2-\omega_1+\omega_\lambda-\omega_a+i\pi(c_1+c_2)\rho(\omega_2-\omega_1+\omega_\lambda-\omega_e)}. \tag{16}$$

For the isotropic dispersion model we get

$$U_{b_\lambda a}(t\to\infty) = \frac{\sqrt{c_1}\sqrt{\omega_\lambda-\omega_e-\delta_1+\delta_2}}{(\omega_\lambda-\omega_e-\delta_1)\sqrt{\omega_\lambda-\omega_e-\delta_1+\delta_2}+i(c_1+c_2)/2}, \tag{17}$$

where the definitions of δ_1 and δ_2 are the same as before. Through a similar derivation process we obtain

$$G_{c_\gamma a}(z) = \frac{1}{z-\omega_\gamma}\frac{\sqrt{c_2}}{z-\omega_a+i\pi(c_1+c_2)\rho(z)}. \tag{18}$$

Substituting Eq. (18) into Eq. (8), using the residue method, and considering a time t sufficiently long so that only one pole $z=\omega_\gamma$ contributes to the integral, we get

$$U_{c_\gamma a}(t\to\infty) = \frac{\sqrt{c_2}}{\omega_\gamma-\omega_a+i\pi(c_1+c_2)\rho(\omega_\gamma-\omega_e)}. \tag{19}$$

Substituting the DOS into the above equation, we have

$$U_{c_\gamma a}(t\to\infty) = \frac{\sqrt{c_2}\sqrt{\omega_\gamma-\omega_e}}{(\omega_\gamma-\omega_e-\delta_2)\sqrt{\omega_\gamma-\omega_e}+i(c_1+c_2)/2}. \tag{20}$$

The long-time spontaneous emission spectrum in our system is given by

$$S(\omega_\lambda-\omega_e) = \rho(\omega_\lambda-\omega_e)[|U_{b_\lambda a}(t\to\infty)|^2+|U_{c_\lambda a}(t\to\infty)|^2]. \tag{21}$$

The spontaneous emission spectrum is calculated and the results are given in Figs. 3–5, which show the spontaneous emission spectra of a three-level Λ-type system with two transitions coupled to the same reservoir for various δ_1 and δ_2.

If a three-level Λ-type system with two transitions is coupled to free space, the corresponding spectrum is the noncoherent superposition of two Lorentzian line shapes [20]. The spontaneous emission spectrum shows different line shapes for a three-level atom interacting with differently structured reservoirs. Compared with the case of only one transition coupled to the PBG reservoir as discussed in Ref. [17], the spectra shown in Figs. 3–5 are greatly different and the spectrum profile is fairly sensitive to the detuning of the atomic transition frequency from the band edge. In Fig. 3(a), with both transition frequencies outside the gap, each spectrum shows two Lorentzian-like peaks. In Fig. 4(a), when one transition frequency ω_1 is inside the gap while the other ω_2 is outside the gap, the spectrum approaches a Lorentzian profile with ω_2 far outside the gap, or the spectrum distribution has a "shoulder" with both transition frequencies near the band-gap edge. Figure 5(a) shows a divergent tail and becomes strongly non-Lorentzian when both transition frequencies are far inside the gap.

For our system, both transitions are coupled to the same modified reservoir. The dressed states were formed due to the upper-atomic-level splitting. When two transition frequencies are outside the gap, the corresponding dressed states are two propagating states. The corresponding spectrum is a

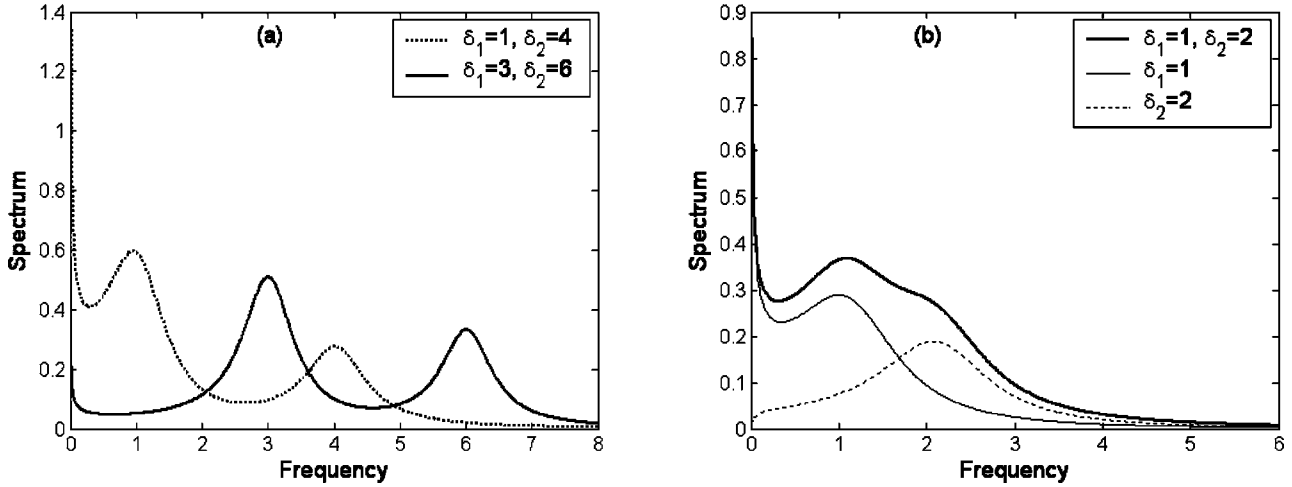

FIG. 3. A Λ system with two transitions coupled to the same reservoir for both transition frequencies outside the gap: (a) spontaneous emission spectra $S(\delta_\lambda)$ for various δ_1 and δ_2 (in arbitrary units); (b) individual spectral lines and their sum.

noncoherent superposition of two Lorentzian profiles as shown in Fig. 3(b). In Fig. 4(b), with one transition frequency inside the gap and the other outside, one localized state and one propagating state are formed. Thus, the corresponding spectrum is a noncoherent superposition of a Lorentzian profile and a non-Lorentzian profile. In Fig. 5, two localized states occur when both transition frequencies lie in the gap. The corresponding spectrum is a strongly non-Lorentzian profile.

In Ref. [17] the result that the spontaneous emission spectrum splits into a double peak with a dark line is given. This doublet is coupled to free space, which corresponds to a V-type three-level system with spontaneously generated coherence [21]. Then the atom from the excited state decays to the ground state with two relaxation channels and the quantum interference between them leads to the formation of a dark line [22]. For our system, from Eqs. (17), (20), and (21), it is concluded that the dark line exists in the spectra when $\omega_\lambda - \omega_e - \delta_1 + \delta_2 = \omega_\lambda - \omega_e = 0$, i.e., $\delta_1 = \delta_2$. In Figs. 3–5, however, no dark line appears that is due to $\delta_1 - \delta_2 = \omega_1 - \omega_2 \neq 0$ for a three-level Λ-type system. The lack of the dark line in the spectra can also be rationalized in a language more familiar to quantum optics. Due to the strong spike in the DOS at the edge, the coupling in the vicinity of $\delta = 0$ causes a strong Autler-Townes splitting. For the double PBG Λ case, for each transition, one of the two levels in the doublet is pushed into the gap, and hence does not radiate, thus suppressing quantum interference. By contrast, in the single PBG Λ case, the doublet line inside the gap can also radiate via the open channel, providing an effective V-type system for interference.

IV. CONCLUSION

Concerning a three-level Λ-type atom with both transitions coupled to a single PBG reservoir, the upper-state population evolution and the spontaneous emission spectrum have been studied. The upper-state population shows an os-

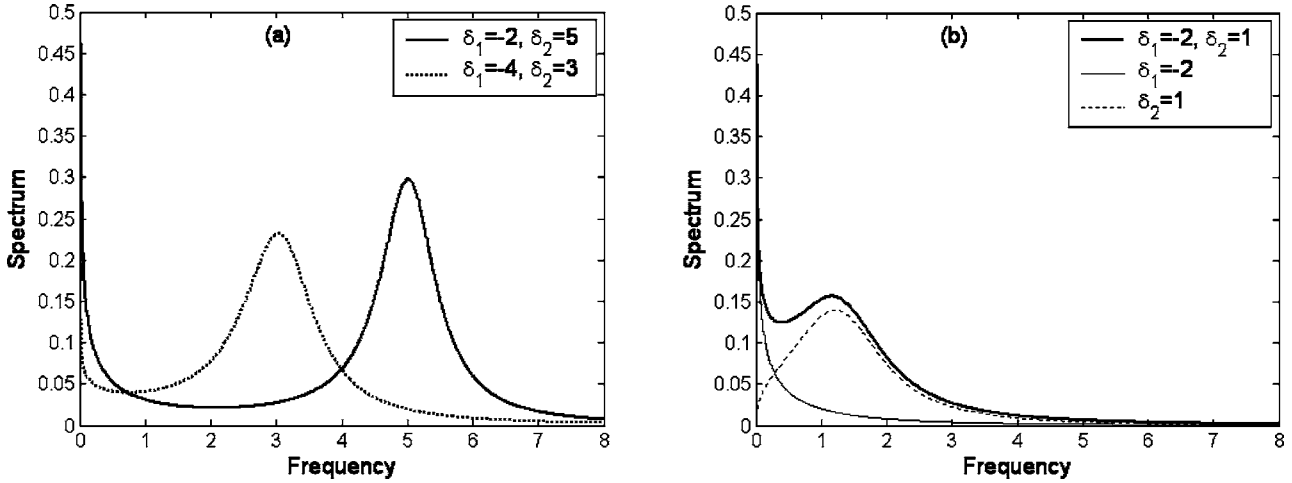

FIG. 4. A Λ system with two transitions coupled to the same reservoir for transition frequency ω_1 inside the gap and the other transition frequency ω_2 outside the gap: (a) spontaneous emission spectra $S(\delta_\lambda)$ for various δ_1 and δ_2 (in arbitrary units); (b) individual spectral lines and their sum.

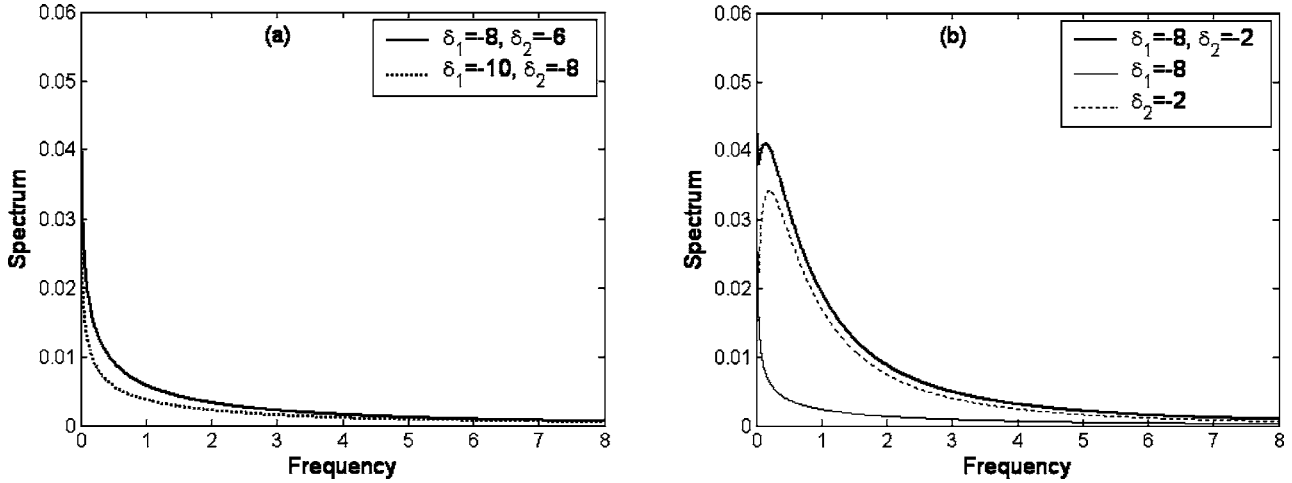

FIG. 5. A Λ system with two transitions coupled to the same reservoir for both transition frequencies inside the gap: (a) spontaneous emission spectra $S(\delta_\lambda)$ for various δ_1 and δ_2 (in arbitrary units); (b) individual spectral lines and their sum. In all the figures $c_1=1.2c, c_2=1.1c$, and the other parameters are in units of $c^{2/3}$, while the parameter c is an arbitrary constant. For the spectra the thin solid line represents the spectral line of transition $|a\rangle \rightarrow |b\rangle$; the thin dashed line that of transition $|a\rangle \rightarrow |c\rangle$; and the thick solid line represents the noncoherent superposition of the two spectral lines.

cillatory behavior but always reaches a constant for any detuning value. The steady population gradually decreases when one transition frequency is outside the gap with increasing detuning. When both transition frequencies are inside the gap, strong inhibition of the spontaneous emission can be realized, which then results in a larger steady-state population with increase of the detuning. In addition, for the spontaneous emission spectra we obtain the usual Lorentzian spectrum when the atomic transition frequencies are tuned far outside the gap. For atomic frequencies in the vicinity of the band-gap edge or far inside the gap, the spectra become strongly non-Lorentzian. The fact that no dark lines appear in the spontaneous emission spectra is due to the fact that the quantum interference of two adjacent transitions is suppressed. When the frequency difference between the two low levels is large enough, the corresponding spectrum connected with two transitions can be completely distinguished.

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