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Control of spontaneous emission from a driven five-level atom in a photonic-band-gap reservoir

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ABSTRACT

We investigate the spontaneous emission properties of a five-level atom driven by a microwave field, where the two transitions are coupled to a double-band photonic-band-gap reservoir. The effects of the band-edge positions and the Rabi frequency of the microwave field on the emission spectrum are discussed. It is found that several interesting phenomena in spontaneous emission spectra such as spectral-line enhancement, spectral-line elimination, and fluorescence quenching can be controlled simply by adjusting the Rabi frequency of the driving field and the transition frequency detunings from band edges. These phenomena originate from quantum interference induced by band-edge modes and the driving field.

1. Introduction

Spontaneous emission is a basic problem in quantum optics, which has attracted extensive attention because of its potential applications in high-precision spectroscopy and magnetometery [1,2], lasing without inversion [3,4], transparent high-index materials [5], etc. In 1946, Purcell was the first to point out that spontaneous emission [6] rates of atoms can be enhanced when they are matched in a resonant cavity. Since then, many schemes, such as vacuum induce coherence [7], phase control spontaneous emission [8], and external driving fields [9–12], have been proposed to modify spontaneous emission. As a fundamental process in the interaction between radiation and matter, vacuum induce coherence has been applied in coherent population trapping (CPT), ultrafast all-optical switching [13], quantum information processing [14], etc. Recently, quantum interference induced by the driving field has become one of the important methods of controlling spontaneous emission. Wu et al. have studied the spontaneous emission spectra of a coherently driven four-level atom, and shown a very rich behavior of the spectrum originated from the quantum interference between competitive decay channels [12]. Li et al. reveal the quantum interference resulting from energy shifts and the effect of the dynamic energy shift on the decay rate [15].

Another relevant and very interesting topic is the photonic band gap materials [16–19], which have been investigated both experimentally and theoretically. One can design and construct photonic crystals with defects, preventing light from propagating in certain directions with specified frequencies. A defect can be used as a highly efficient resonant cavity. Hence one can achieve Purcell's scheme to control spontaneous emission in photonic crystal defect cavity efficiently. Particularly, spontaneous emission near the edge of a photonic-band-gap has aroused intensive interest during the past two decades [20–27]. John and Quang studied the spontaneous emission from a three-level atom coupled to the non-Markovian reservoir, in which they found the spectral splitting and subnatural linewidth of spontaneous emission [28]. Although the spontaneous emission spectrum in a Λ-type system has been studied using the two-band model, it is considered one transition coupled to a modified reservoir and other to occur in free space [29]. They have demonstrated that the emission spectrum is quite dependent on the embedded position of the atom and the width of the photonic-band-gap. Since the driving field can be used as an effective way to control the spontaneous emission, a three-level atom [11] and a four-level atom [21] driven by a microwave field have been studied theoretically. In this paper we investigate the spontaneous emission spectrum of a five-level atom in a non-Markovian reservoir using a two-band mode, in which the effect of Rabi frequency of the external field and the transition frequency detunings from band edges are discussed in detail.

2. Theoretical model and equations

We consider a five-level atom as shown in Fig. 1(a). The upper level $|1\rangle$ is coupled by a two-band reservoir to the two lower levels $|3\rangle$ and $|4\rangle$, and by a microwave field with frequency ω_c and a Rabi frequency Ω to anther lower level $|2\rangle$, while the transition from the excited level $|1\rangle$ to the metastable level $|m\rangle$ is assumed to be

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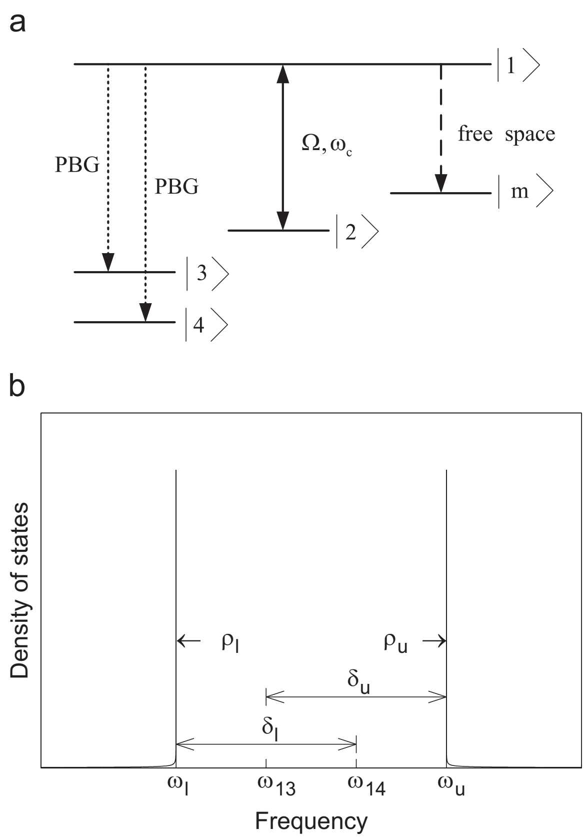

Fig. 1. (a) Schematic representation of a five-level atom, where ω_c and Ω denote carrier and Rabi frequency of a microwave field respectively, and the excited level $|1\rangle$ is coupled by a modified reservoir to the two lower levels $|3\rangle$ and $|4\rangle$. (b) Density of states of the two-band model.

coupled by vacuum modes in free space. The density of states of the two-band model is shown in Fig. 1(b). The transition between $|1\rangle\to|3\rangle$ ($|1\rangle\to|4\rangle$) is considered to be near resonant with the lower band-edge (upper band-edge) of the photonic band gap reservoir, while the transition between $|1\rangle\to|4\rangle$ ($|1\rangle\to|3\rangle$) is assumed to be far away from the lower band-edge (upper band-edge). The Hamiltonian in the interaction representation is given by

$$H=H_A+H_B, \tag{1}$$

with

$$H_A=-\hbar\Delta|2\rangle\langle 2|+i\hbar\Omega|1\rangle\langle 2|-i\hbar\Omega^*|2\rangle\langle 1|, \tag{2}$$

$$\begin{aligned}H_B(t)=\ & i\hbar\sum_\lambda g_\lambda e^{-i(\omega_\lambda-\omega_{10})t}|1\rangle\langle m|a_\lambda\\ &+i\hbar\sum_k g_{3k}e^{-i(\omega_k-\omega_{13})t}|1\rangle\langle 3|a_k\\ &+i\hbar\sum_k g_{4k}e^{-i(\omega_k-\omega_{14})t}|1\rangle\langle 4|a_k+\text{H.c}\quad.,\end{aligned} \tag{3}$$

where the detuning Δ is defined by $\Delta=\omega_{12}-\omega_c$, g_λ denotes the coupling constant of the atom with the free space vacuum modes (λ) associated with the transition $|1\rangle\to|m\rangle$, while g_{3k} and g_{4k} denote the coupling constant of the atom with the kth mode of the field, associated with the two transitions $|1\rangle\to|3\rangle$ and $|1\rangle\to 4\rangle$, respectively. Based on the dressed-state theory, with regard to our atom system with an external field, the two old levels $|1\rangle$ and $|2\rangle$ can be substituted with the dressed levels $|\alpha\rangle$ and $|\beta\rangle$. The dressed-state is defined by the eigenvalue equations $H_A|\alpha\rangle=\hbar\lambda_\alpha|\alpha\rangle$ and $H_A|\beta\rangle=\hbar\lambda_\beta|\beta\rangle$, where $\lambda_\alpha=-\Delta/2+\sqrt{(\Delta/2)^2+|\Omega|^2}$ and $\lambda_\beta=-\Delta/2-\sqrt{(\Delta/2)^2+|\Omega|^2}$. The explicit form of the dressed-state is given by

$$\begin{aligned}|\alpha\rangle&=\sin\,\theta|2\rangle+ie^{i\phi_c}\cos\,\theta|1\rangle,\\ |\beta\rangle&=\cos\,\theta|2\rangle-ie^{i\phi_c}\sin\,\theta|1\rangle,\end{aligned} \tag{4}$$

where $\sin\,\theta=|\Omega|/\sqrt{\lambda_\alpha^2+|\Omega|^2}$, $\cos\,\theta=\lambda_\alpha/\sqrt{\lambda_\alpha^2+|\Omega|^2}$, and $\Omega=|\Omega|e^{i\phi_c}$, where ϕ_c is defined as the phase of the microwave field. The state vector of the atomic system at an arbitrary time t can be written as

$$\begin{aligned}|\Psi(t)\rangle=&\sum_\lambda b_{m\lambda}(t)a_\lambda^\dagger|m,\{0\}\rangle+\alpha(t)|\alpha\rangle+\beta(t)|\beta\rangle\\ &+\sum_k[b_{3k}(t)a_k^\dagger|3,\{0\}\rangle+b_{4k}(t)a_k^\dagger|4,\{0\}\rangle].\end{aligned} \tag{5}$$

where $|\{0\}\rangle$ represents the vacuum of electromagnetic field, and $a_k^\dagger$ is the creation operator for the kth vacuum mode with frequency ω_k. From Eqs. (1)–(3) and (5), after some simple calculations, we can derive the coupled amplitude equations

$$\dot b_{m\lambda}=ig_\lambda e^{i\phi_c}e^{i(\omega_\lambda-\omega_{10})t}[\beta(t)\sin\,\theta-\alpha(t)\cos\,\theta], \tag{6}$$

$$\begin{aligned}&\dot\alpha(t)\cos\,\theta-\dot\beta(t)\sin\,\theta\\ &\quad=-ie^{i\phi_c}\Omega\{[\alpha(t)\sin\,\theta+\beta(t)\cos\,\theta]\\ &\qquad+\sum_\lambda g_\lambda b_{m\lambda}(t)e^{-i(\omega_\lambda-\omega_{10})t}+\sum_k\Big[g_{3k}b_{3k}(t)e^{-i(\omega_k-\omega_{13})t}\\ &\qquad+g_{4k}b_{4k}(t)e^{-i(\omega_k-\omega_{14})t}\Big]\Big\},\end{aligned} \tag{7}$$

$$\begin{aligned}\dot\alpha(t)\sin\,\theta+\dot\beta(t)\cos\,\theta=\ &i\Delta[\alpha(t)\sin\,\theta+\beta(t)\cos\,\theta]\\ &+i\Omega^*e^{i\phi_c}[\beta(t)\sin\,\theta-\alpha(t)\cos\,\theta],\end{aligned} \tag{8}$$

$$\dot b_{3k}(t)=ig_{3k}e^{i\phi_c}e^{i(\omega_k-\omega_{13})t}[\beta(t)\sin\,\theta-\alpha(t)\cos\,\theta], \tag{9}$$

$$\dot b_{4k}(t)=ig_{4k}e^{i\phi_c}e^{i(\omega_k-\omega_{14})t}[\beta(t)\sin\,\theta-\alpha(t)\cos\,\theta]. \tag{10}$$

By substituting Eqs. (6), (9) and (10) into Eq. (7) we obtain integrodifferential equation

$$\begin{aligned}&\dot\alpha(t)\cos\,\theta-\dot\beta(t)\sin\,\theta\\ &\quad=\int_0^t dt'[\beta(t')\sin\,\theta-\alpha(t')\cos\,\theta]\Big[\sum_\lambda g_\lambda^2e^{-i(\omega_\lambda-\omega_{10})(t-t')}\\ &\qquad+\sum_k g_{3k}^2e^{-i(\omega_k-\omega_{13})(t-t')}+\sum_k g_{4k}^2e^{-i(\omega_k-\omega_{14})(t-t')}\Big]\\ &\qquad-i\Omega e^{-i\phi_c}[\alpha(t)\sin\,\theta+\beta(t)\cos\,\theta]\end{aligned} \tag{11}$$

The first summation in Eq. (11) can be dealt with the Weisskopf–Wigner approximation and we obtain

$$\sum_\lambda g_\lambda^2e^{-i(\omega_\lambda-\omega_{10})(t-t')}=\frac{\gamma}{2}\delta(t-t'). \tag{12}$$

For the second and third summations in Eq. (11), however, the Weisskopf–Wigner approximation is not applicable as the density of states of the double-band photonic-band-gap reservoir varies much more quickly than that in free space. Hence the above result cannot be applied to the modified reservoir modes, to solve this problem, we introduce the following memory kernel:

$$\begin{aligned}K_{13}(t-t')&=\sum_k g_{3k}^2e^{-i(\omega_k-\omega_{13})(t-t')}\\ &=g_{13}^{3/2}\int d\omega\rho_l(\omega)e^{-i(\omega-\omega_{13})(t-t')},\\ K_{14}(t-t')&=\sum_k g_{4k}^2e^{-i(\omega_k-\omega_{14})(t-t')}\\ &=g_{14}^{3/2}\int d\omega\rho_u(\omega)e^{-i(\omega-\omega_{14})(t-t')},\end{aligned} \tag{13}$$

where g_{13} and g_{14} are coupled constants of the two transitions $|1\rangle\to|3\rangle$ and $|1\rangle\to|4\rangle$, respectively, while ρ_u and ρ_l are the density of