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Spontaneous emission with a cascaded driving field in the same transition channel

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ABSTRACT

We study the spontaneous emission spectrum of a driven four-level atom in both Markovian reservoir and non-Markovian reservoir, in which the two driving fields are applied to the same transition channel. It is very interesting that the increase of the Rabi frequency of the first driving field leads to the emission spectrum enhancement in Markovian reservoir, but the increase of the second one can suppress the emission spectrum significantly. The phenomenon originates from the dressed states variation induced by the first driving field. For non-Markovian reservoir case, the rich spectrum behavior is due to a strong coupling between driving fields and modified reservoir.

1. Introduction

Modification of spontaneous emission has attracted considerable attention in recent years, because of its potential applications in various quantum optical effects like lasing without inversion (LWI) [1,2], transparent high-index materials [3], and quantum information and computing [4,5]. It is well known that spontaneous emission depends not only on the properties of the excited atom but also on the nature of surrounding environment. The spontaneous emission can be significantly suppressed or enhanced for excited atoms in cavities. Since an effective high-Q cavity [6] can be obtained by using photonic band gap material [7–12], the spontaneous emission near the edge of a photonic-band-gap has attracted substantial attention in the literature [13–16].

Another relevant and very interesting topic is the control of spontaneous emission in the laser-driven system. The spontaneous emission spectra of a four-level atom driven by two coherent laser fields have been investigated [17]. They find a few interesting phenomena in the spontaneous emission spectra, such as spectral-line enhancement, spectral-line elimination and spectral-line narrowing. The spontaneous generated coherence (SGC) can be regarded as a fundamental process in the interaction between matter and radiation. The effect of SGC on spontaneous emission and dynamical evolution of a driven atomic system has been studied in [18]. Apart from spectral-line enhancement and spectral-line narrowing, it is also possible to realize spectral-line suppression and fluorescence quenching by changing amplitude and phase of the microwave field. Recently, the external driving field scheme [19–21] is still an active area studied to modify spontaneous emission. Furthermore, for an atom in free space, quantum interference [22–24] is also a significant mechanism for modifying spontaneous emission in the non-Markovian reservoir case. We have studied the effect of a driving field on the spontaneous emission spectrum of a five-level atom embedded in non-Markovian reservoir [25]. The rich spectrum behavior originates from quantum interference induced by band-edge modes and the driving field.

The spontaneous emission properties of a driven multi-level atom have been investigated extensively [17–21]. The case in which two driving fields are added to the same transition channel, however, seems unsolved and may present other new effects. The current work aims to address this issue, and benefits much from the dressed-state theory. We consider that one driving field is added to the system firstly, and the dressed states occur, then the other driving field is added to the atomic system, hence the new dressed states occur. In this paper we study the influence of two driving fields on the spontaneous emission spectrum, where both Markovian reservoir and non-Markovian reservoir cases will be discussed in detail.

2. Theoretical model and equations

We consider a four-level atom as shown in Fig. 1(a). The

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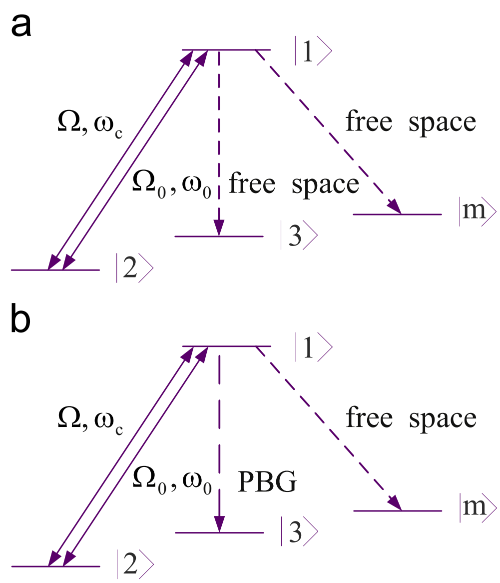

Fig. 1. (a) Schematic representation of a four-level atom, where ω_0 (ω_c) and Ω_0 (Ω) denote carrier and Rabi frequency of the first (second) driving field respectively, and the excited level $|1\rangle$ is coupled by Markovian reservoir to the two lower levels $|3\rangle$ and $|m\rangle$. (b) The only difference with (a) is that the excited level $|1\rangle$ is coupled by modified reservoir to the lower level $|3\rangle$.

transitions $|1\rangle \to |m\rangle$ and $|1\rangle \to |3\rangle$ are assumed to be coupled by vacuum modes in free space, and the level $|1\rangle$ is coupled to $|2\rangle$ by two driving fields in proper sequence. We first use a single driving field with frequency ω_0 and Rabi frequency Ω_0 to the atomic system, hence the driven levels $|1\rangle$ and $|2\rangle$ can be replaced by the corresponding dressed states $|\alpha\rangle$ and $|\beta\rangle$. After the other driving field is added, the initial dressed states $|\alpha\rangle$ and $|\beta\rangle$ can be replaced by new dressed states $|\xi\rangle$ and $|\eta\rangle$ based on the dressed state theory. For Fig. 1(b) case, the only difference from above is that the transition $|1\rangle \to |3\rangle$ is coupled to the photonic band gap reservoir. Therefore, the Hamiltonian for the system can be written as

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

with

$$\begin{aligned} H_A &= -\hbar\Delta|\alpha\rangle\langle\alpha| + i\hbar\Omega|\alpha\rangle\langle\beta| - i\hbar\Omega^*|\beta\rangle\langle\alpha| \\ &= \hbar\left(\frac{i}{2}\Omega\sin 2\theta - \frac{i}{2}\Omega^*\sin 2\theta - \Delta\sin^2\theta\right)|2\rangle\langle 2| \\ &\quad - \hbar\left(\frac{i}{2}\Omega\sin 2\theta - \frac{i}{2}\Omega^*\sin 2\theta + \Delta\cos^2\theta\right)|1\rangle\langle 1| \\ &\quad + \hbar\left(i\Omega\cos^2\theta + i\Omega^*\sin^2\theta - \frac{1}{2}\Delta e^{-i\phi_c}\sin 2\theta\right)|1\rangle\langle 2| \\ &\quad - \hbar\left(i\Omega\sin^2\theta + i\Omega^*\cos^2\theta + \frac{1}{2}\Delta e^{i\phi_c}\sin 2\theta\right)|2\rangle\langle 1|, \end{aligned} \tag{2}$$

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

where the detuning Δ is defined by $\Delta = \omega_{\alpha\beta} - \omega_c$, $\omega_{\alpha\beta}$ is the energy separation between the dressed states $|\alpha\rangle$ and $|\beta\rangle$, and ϕ_c is defined as the phase of the driving fields. The other energy separations of the states are denoted by $\omega_{ab} = \omega_a - \omega_b$ and ω_k (ω_λ) is the energy of the k (λ)-th reservoir mode. a_k (a_λ) is the annihilation operator of the k (λ)-th reservoir mode. g_λ denotes the coupling constant of the atom with the free space vacuum modes associated with the transition $|1\rangle \to |m\rangle$, while g_k denote the coupling constant of the atom with the k-th mode of the field associated with the transition $|1\rangle \to |3\rangle$. Based on dressed-state theory, for the system with a single driving field, the two dressed states $|\alpha\rangle$ and $|\beta\rangle$ can be replaced by the new dressed levels $|\xi\rangle$ and $|\eta\rangle$. The dressed-state is defined by the eigenvalue equations $H_A|\xi\rangle = \hbar\lambda_\xi|\xi\rangle$ and $H_A|\eta\rangle = \hbar\lambda_\eta|\eta\rangle$, where $\lambda_\xi = -\Delta/2 + \sqrt{(\Delta/2)^2 + |\Omega|^2}$ and $\lambda_\eta = -\Delta/2 - \sqrt{(\Delta/2)^2 + |\Omega|^2}$. Hence the explicit form of the dressed-state is given by

$$\begin{aligned} |\eta\rangle &= \cos(\varphi - \theta)|2\rangle + \sin(\varphi - \theta)e^{-i\phi_c}|1\rangle, \\ |\xi\rangle &= -e^{i\phi_c}\sin(\varphi - \theta)|2\rangle + \cos(\varphi - \theta)|1\rangle, \end{aligned} \tag{4}$$

where $\sin\theta = |\Omega_0|/\sqrt{\lambda_\alpha^2 + |\Omega_0|^2}$, $\cos\theta = \lambda_\alpha/\sqrt{\lambda_\alpha^2 + |\Omega_0|^2}$, $\sin\varphi = |\Omega|/\sqrt{\lambda_\xi^2 + |\Omega|^2}$, $\cos\varphi = \lambda_\xi/\sqrt{\lambda_\xi^2 + |\Omega|^2}$, and $\Omega = |\Omega|e^{i\phi_c}$, where $\Omega_0 = |\Omega_0|e^{i\phi_c}$. The wave function of the system could be written as

$$\begin{aligned} |\Psi(t)\rangle &= \sum_\lambda b_\lambda(t)a_\lambda^\dagger|m, \{0\}\rangle + \eta(t)|\eta, \{0\}\rangle + \xi(t)|\xi, \{0\}\rangle \\ &\quad + \sum_k b_k(t)a_k^\dagger|3, \{0\}\rangle, \end{aligned} \tag{5}$$

where $|\{0\}\rangle$ denotes the vacuum state of the electromagnetic field. From Eqs. (1)–(3) and (5) we can derive the coupled amplitude equations:

$$\begin{aligned} &\dot\eta(t)\sin(\varphi - \theta)e^{-i\phi_c} + \dot\xi(t)\cos(\varphi - \theta) \\ &= \sum_\lambda g_\lambda b_\lambda(t)e^{-i(\omega_\lambda - \omega_{1m})t} + \sum_k g_k b_k(t)e^{-i(\omega_k - \omega_{13})t} \\ &\quad + \left[i\Delta\cos^2\theta + \frac{1}{2}\sin 2\theta(\Omega^* - \Omega)\right] \\ &\quad [e^{-i\phi_c}\sin(\varphi - \theta)\eta(t) + \cos(\varphi - \theta)\xi(t)] \\ &\quad + \left[\frac{i}{2}\Delta e^{-i\phi_c}\sin 2\theta + (\Omega\cos^2\theta + \Omega^*\sin^2\theta)\right] \\ &\quad [\cos(\varphi - \theta)\eta(t) - e^{i\phi_c}\sin(\varphi - \theta)\xi(t)], \end{aligned} \tag{6}$$

$$\begin{aligned} &\dot\eta(t)\cos(\varphi - \theta) - \dot\xi(t)\sin(\varphi - \theta)e^{i\phi_c} \\ &= \left[\frac{1}{2}\sin 2\theta(\Omega - \Omega^*) + i\Delta\sin^2\theta\right] \\ &\quad [\cos(\varphi - \theta)\eta(t) - e^{i\phi_c}\sin(\varphi - \theta)\xi(t)] \\ &\quad - \left(\frac{i}{2}\Delta e^{i\phi_c}\sin 2\theta + \Omega\sin^2\theta + \Omega^*\cos^2\theta\right) \\ &\quad [e^{-i\phi_c}\sin(\varphi - \theta)\eta(t) + \cos(\varphi - \theta)\xi(t)], \end{aligned} \tag{7}$$

$$\dot b_\lambda(t) = -g_\lambda e^{i(\omega_\lambda - \omega_{1m})t}[e^{-i\phi_c}\sin(\varphi - \theta)\eta(t) + \cos(\varphi - \theta)\xi(t)], \tag{8}$$

$$\dot b_k(t) = -g_k e^{i(\omega_k - \omega_{13})t}[e^{-i\phi_c}\sin(\varphi - \theta)\eta(t) + \cos(\varphi - \theta)\xi(t)]. \tag{9}$$

By substituting Eqs. (8) and (9) into Eq. (6) one can obtain the integrodifferential equation as follows: