Spontaneous emission from an atom in a photonic crystal with two coherent bands*

Huang Xian-Shan(黄仙山)†, Liu Hai-Lian(刘海莲), and Wang Dong(王 东)

School of Mathematics and Physics, Anhui University of Technology, Maanshan 243002, *China*

(Received 14 August 2011; revised manuscript received 14 November 2011)

The dynamic and the radiative properties of an excited three-level atom embedded in an anisotropic photonic crystal with two coherent bands are investigated. The relative position of the atom in a Wigner–Seitz cell is described with a position-dependent parameter $\theta(\boldsymbol{r}_0)$, which is used as the coherent parameter for the two bands. The result shows that the dynamic properties of the atomic system are not only determined by atomic transition frequencies, but also affected by the gap width and the coherence of the two bands. In addition, the spontaneous emission spectrum of the atomic transition in free space is discussed. The center and the intensity of the spectrum can be obviously manipulated via the coherent parameter.

Keywords: spontaneous emission, photonic crystals, coherent photonic reservoir

PACS: 42.70.Qs, 42.50.Gy **DOI:** 10.1088/1674-1056/21/5/054218

1. Introduction

As is well known, Yablonovitch[1] and John[2] first discovered photonic crystals (PCs) in 1987. The PC is a new kind of artificial optical material with a period dielectric structure. By redistributing the density of states (DOS), a photonic band gap (PBG) is created, and those optical and electromagnetic waves with frequencies located in the PBG are forbidden to propagate in the PC. In recent years, the PC, as a key material in the technology for manipulating the spontaneous emission (SE) of light from atoms and molecules, has been found to have potential applications in many fields, such as light emitting devices,[3−5] solar cells,[6−8] and quantum information and optical devices.[9−13] As the photonic DOS near the PBG is obviously different from that in free space, the radiative properties of an excited atom in a PC can be modified, and many novel phenomena have been studied in quantum optics, such as photon–atom bound states,[14−17] spectral splitting,[18−21] reservoir-induced transparency,[22] giant Lamb shift,[23] and non-Markovian effects.[14,19−26]

However, in most of the previous studies about the SE in PC, the one-band approximation was used.[14,15,17,18,26] Actually, the infinite PBG does not exist in a real PC. When the PBG is relatively wide and the atomic transition frequencies are near the band edge, the one-band approximation is valid. If the PBG is narrow, for the coupling between a photon and an atom, the two-band case must be considered. Most of the earlier papers used the two-band approximation, in which the double bands were usually regarded as two independent and incoherent parts.[16,19,20,27,28] It was often assumed that the coupling between the atom and each individual part was equal and independent of the atomic position. In fact, the photon–atom interaction in the PC depends on the atomic position.[21,29,30] Li *et al.*[29] investigated the photonic DOS and the local density of states (LDOS) near the PBG. They found that the SE decay rate was proportional to the LDOS, which depended on the positions of atoms lying at different sites inside a unit cell of the crystal. For the sake of simplicity, in the narrow gap case, the two bands should be considered as a whole reservoir with a coherent property coming from the atomic position. The coherence of the two-band photonic reservoir can be described by the phase difference between the two bands. Cheng *et al.*[17] studied the SE spectrum, the absorption property, and the dispersion relation of a three-level atom in a coherent two-band reservoir. In their model, the dispersion relation was isotropic, and the square-root singularities occurred at the two band edges, which perhaps resulted in many non-physical phenomena.

In the present paper, we consider an anisotropic

*Project supported by the Natural Science College Key Projects of Anhui Province, China (Grant No. KJ2010A335) and the National Natural Science Foundation of China (Grant No. 41075027).

†Corresponding author. E-mail: mailhuangxiansh@yahoo.com.cn

© 2012 Chinese Physical Society and IOP Publishing Ltd

case, and mainly focus on the dynamic and the radiative properties of a Λ-typed atom in a coherent PBG reservoir. In the model, two atomic transitions are related to the excited level $|2\rangle$. One atomic transition $|2\rangle \leftrightarrow |1\rangle$ is coupled to the coherent PBG reservoir, and the other transition $|2\rangle \leftrightarrow |0\rangle$ is in the free space vacuum. As the two atomic transitions interact with each other, the SE light of the transition $|2\rangle \leftrightarrow |0\rangle$ can be affected by the transition $|2\rangle \leftrightarrow |1\rangle$ in the coherent photonic reservoir. The result shows that the dynamic properties of the atom are not only determined by the atomic transition frequencies, but also affected by the gap width and the coherence of the two bands. In addition, the SE spectrum of the atomic transition in free space is discussed. The center and the intensity of the spectrum can be obviously manipulated via the coherent photonic reservoir.

The rest of this paper is organized as follow. In Section 2, we derive the basic theory about the model to be used. In Section 3, we analyze the dynamic and the radiative properties of the atom in the coherent PBG reservoir. Finally, we summarize the results in Section 4.

2. Basic theory

We consider an excited Λ-type atom embedded in an anisotropic PC with two coherent bands. The upper energy level is $|2\rangle$, while $|1\rangle$ and $|0\rangle$ are two lower energy levels. The atomic transition frequency (ATF) ω_{21} between $|2\rangle$ and $|1\rangle$ is assumed to be near the PBG, but the ATF ω_{20} between $|2\rangle$ and $|0\rangle$ is far from the gap. Under the rotating-wave approximation and the electronic dipole approximation, the interaction Hamiltonian for the system can be written as

$$H = \mathrm{i}\hbar\Big\{\sum_{\lambda} g_\lambda b_\lambda |2\rangle\langle 0| + \sum_{u} g_u(\boldsymbol{r}_0) b_u |2\rangle\langle 1| + \sum_{l} g_l(\boldsymbol{r}_0) b_l |2\rangle\langle 1|\Big\} + \mathrm{H.c.}, \quad (1)$$

where g_λ, $g_u(\boldsymbol{r}_0)$, and $g_l(\boldsymbol{r}_0)$ characterize the coupling strengths of the atom with the free space vacuum, the upper band, and the lower band, respectively. The coupling coefficient of the atom–field interaction in the dipole approximation can be written as $g_{\boldsymbol{k}}(\boldsymbol{r}_0) = -\boldsymbol{D}_{21}\cdot\boldsymbol{E}_{\boldsymbol{k}}(\boldsymbol{r}_0)$, and the LDOS for the PC can be defined as $\rho(\omega,\boldsymbol{r}_0) = \sum_{\boldsymbol{k}} |g_{\boldsymbol{k}}(\boldsymbol{r}_0)|^2\delta(\omega-\omega_{\boldsymbol{k}})$,[29] where $\boldsymbol{D}_{21}$ is the atomic dipole moment vector, $\boldsymbol{E}_{\boldsymbol{k}}(\boldsymbol{r}_0)$ is the quantized electromagnetic field, and $\omega_{\boldsymbol{k}}$ is the frequency of eigenmode $\boldsymbol{k}$. As the atom–field interaction in the two-band photonic reservoir essentially depends on the atomic position $\boldsymbol{r}_0$ in a unit cell of the crystal, for simplicity, coupling coefficients $g_u(\boldsymbol{r}_0)$ and $g_l(\boldsymbol{r}_0)$ in Eq. (1) can be expressed as $g_u(\boldsymbol{r}_0) = g_{\boldsymbol{k}}\sin\theta(\boldsymbol{r}_0)$ and $g_l(\boldsymbol{r}_0) = g_{\boldsymbol{k}}\cos\theta(\boldsymbol{r}_0)$ via using a phase difference. The parameter $\theta(\boldsymbol{r}_0)$, originating from the relative position of atom $\boldsymbol{r}_0$, describes the coherence of the two bands. The b_λ, b_u, and b_l are the emitted field annihilation operations for the λ-th, the u-th, and the l-th reservoir modes with frequencies ω_λ, ω_u, and ω_l, respectively. For the two-band anisotropic PC, the dispersion relation near the gap can be expressed as $\omega_{\boldsymbol{k}} = \omega_{\mathrm{c}1} + C_1|\boldsymbol{k}-\boldsymbol{k}_{10}^i|^2$ for $\omega_{\boldsymbol{k}} > \omega_{\mathrm{c}1}$ and $\omega_{\boldsymbol{k}} = \omega_{\mathrm{c}2} - C_2|\boldsymbol{k}-\boldsymbol{k}_{20}^j|^2$ for $\omega_{\boldsymbol{k}} < \omega_{\mathrm{c}2}$, where C_1 and C_2 are model-related constants, and $\omega_{\mathrm{c}1}$ ($\omega_{\mathrm{c}2}$) is the upper (lower) band edge.

We assume that the atom is initially at the excited state $|2\rangle$. The state vector of the system at arbitrary time t can be written as

$$\begin{aligned}|\Psi(t)\rangle = {} & A(t)\,\mathrm{e}^{-\mathrm{i}\omega_2 t}|2,\{0\}\rangle \\ & + \sum_u B_{1u}(t)\,\mathrm{e}^{-\mathrm{i}(\omega_1+\omega_u)t}|1,\{1_u\}\rangle \\ & + \sum_l B_{1l}(t)\,\mathrm{e}^{-\mathrm{i}(\omega_1+\omega_l)t}|1,\{1_l\}\rangle \\ & + \sum_\lambda B_{0\lambda}(t)\,\mathrm{e}^{-\mathrm{i}(\omega_0+\omega_\lambda)t}|0,\{1_\lambda\}\rangle, \quad (2)\end{aligned}$$

where $A(t)$ and $B_{0\lambda}(t)$ are the probability amplitudes of the atom in states $|2,\{0\}\rangle$ and $|0,\{1_\lambda\}\rangle$, respectively, which describe the probabilities for the atom to be in state $|2\rangle$ with no photon and in state $|0\rangle$ with a single λ-th mode photon, respectively, and $B_{1u}(t)$ ($B_{1l}(t)$) is the probability amplitude of the atom in state $|1,\{1_u\}\rangle$ ($|1,\{1_l\}\rangle$) with a single u-th (l-th) mode photon in the upper (lower) band.

Substituting Eqs. (1) and (2) into the time-dependent Schrödinger equation, we can obtain the following differential equations for amplitudes $A(t)$, $B_{0\lambda}(t)$, $B_{1u}(t)$, and $B_{1l}(t)$:

$$\begin{aligned}\mathrm{i}\frac{\mathrm{d}A(t)}{\mathrm{d}t} = {} & \sum_\lambda g_\lambda B_{0\lambda}(t)\,\mathrm{e}^{-\mathrm{i}(\omega_\lambda-\omega_{20})t} \\ & + \sum_u g_u(\boldsymbol{r}_0)B_{1u}(t)\,\mathrm{e}^{-\mathrm{i}(\omega_u-\omega_{21})t} \\ & + \sum_l g_l(\boldsymbol{r}_0)B_{1l}(t)\,\mathrm{e}^{-\mathrm{i}(\omega_l-\omega_{21})t}, \quad (3a)\end{aligned}$$

$$\mathrm{i}\frac{\mathrm{d}B_{0\lambda}(t)}{\mathrm{d}t} = g_\lambda A(t)\,\mathrm{e}^{\mathrm{i}(\omega_\lambda-\omega_{20})t}, \quad (3b)$$

$$\mathrm{i}\frac{\mathrm{d}B_{1u}(t)}{\mathrm{d}t} = g_u(\boldsymbol{r}_0)A(t)\,\mathrm{e}^{\mathrm{i}(\omega_u-\omega_{21})t}, \quad (3c)$$

$$\mathrm{i}\frac{\mathrm{d}B_{1l}(t)}{\mathrm{d}t} = g_l(\boldsymbol{r}_0)A(t)\,\mathrm{e}^{\mathrm{i}(\omega_l-\omega_{21})t}. \quad (3d)$$

As the transition $|2\rangle \leftrightarrow |0\rangle$ couples to the free space vacuum, the Weisskopf–Wigner approximation

can be applied to the atomic transition with free space λ-th mode, and the decay rate of the transition is assumed to be γ. With the help of the complex function integration and the residue theorem, from Eq. (3), we can obtain

$$\begin{aligned} A(t) = & \sum_j \mathrm{e}^{x_j^{(1)}\beta t}/F'(x_j^{(1)}) + \sum_j \mathrm{e}^{x_j^{(2)}\beta t}/G'(x_j^{(2)}) \\ & + \sum \mathrm{e}^{x_j^{(3)}\beta t}/K'(x_j^{(3)}) \\ & + \frac{1}{\pi}\int_0^\infty \{\mathrm{e}^{\mathrm{i}\delta_1 t}\,\mathrm{e}^{-x\beta t}J_1(x) \\ & + \mathrm{e}^{\mathrm{i}\delta_2 t}\,\mathrm{e}^{-x\beta t}J_2(x)\}\,\mathrm{d}x. \end{aligned} \tag{4}$$

In Eq. (4), for simplicity, we have assumed that $C_1 = C_2 = C$. We obtain

$$\beta^{3/2} = (\omega_{21}\boldsymbol{D}_{21})^2 \sum_j \sin^2\varphi_j/(8\pi\varepsilon_0\hbar C^{3/2}),$$

where φ_j is the angle between the dipole vector $\boldsymbol{d}_{21}$ and the finite collection of symmetry related point $\boldsymbol{k}_{10}^i$ ($\boldsymbol{k}_{20}^j$). The $F'(x)$, $G'(x)$, and $K'(x)$ are the derivative functions of $F(x)$, $G(x)$, and $K(x)$, respectively, and $F(x) = x + \gamma/2 - \mathrm{i}\sin^2\theta/\sqrt{\omega_{\mathrm{c}1}} + \sqrt{-\mathrm{i}x - \delta_1} + \mathrm{i}\cos^2\theta/\sqrt{\omega_{\mathrm{c}2}} + \sqrt{\mathrm{i}x + \delta_2}$, with $\mathrm{Re}(x) > 0$ or $\delta_1 < \mathrm{Im}(x) < \delta_2$; $G(x) = x + \gamma/2 - \mathrm{i}\sin^2\theta/\sqrt{\omega_{\mathrm{c}1}} + \sqrt{-\mathrm{i}x - \delta_1} + \mathrm{i}\cos^2\theta/\sqrt{\omega_{\mathrm{c}2}} + \mathrm{i}\sqrt{-\mathrm{i}x - \delta_2}$, with $\mathrm{Re}(x) < 0$ and $\mathrm{Im}(x) > \delta_2$; $K(x) = x + \gamma/2 - \mathrm{i}\sin^2\theta/\sqrt{\omega_{\mathrm{c}1}} - \mathrm{i}\sqrt{\mathrm{i}x + \delta_1} + \mathrm{i}\cos^2\theta/\sqrt{\omega_{\mathrm{c}2}} + \sqrt{\mathrm{i}x + \delta_2}$, with $\mathrm{Re}(x) < 0$ and $\mathrm{Im}(x) < \delta_1$. In Eq. (4),

$$\begin{aligned} & J_1(x) \\ = & \ \mathrm{i}\sin^2\theta\sqrt{-\mathrm{i}x}/[(M(x)\sqrt{\omega_{\mathrm{c}1}} - \mathrm{i}\sin^2\theta)^2 - \mathrm{i}xM^2(x)], \\ & J_2(x) \\ = & \ \cos^2\theta\sqrt{-\mathrm{i}x}/[(N(x)\sqrt{\omega_{\mathrm{c}2}} + \mathrm{i}\cos^2\theta)^2 + \mathrm{i}xN^2(x)], \end{aligned}$$

with

$$\begin{aligned} & M(x) \\ = & -x + \mathrm{i}\delta_1 + \gamma/2 + \mathrm{i}\cos^2\theta/(\sqrt{\omega_{\mathrm{c}2}} + \sqrt{-\mathrm{i}x + \Delta}), \\ & N(x) \\ = & -x + \mathrm{i}\delta_2 + \gamma/2 - \mathrm{i}\sin^2\theta/(\sqrt{\omega_{\mathrm{c}1}} + \sqrt{\mathrm{i}x + \Delta}), \end{aligned}$$

where $\delta_1 = \omega_{21} - \omega_{\mathrm{c}1}$, $\delta_2 = \omega_{21} - \omega_{\mathrm{c}2}$, and $\Delta = \omega_{\mathrm{c}1} - \omega_{\mathrm{c}2}$. The $x_j^{(1)}$ in Eq. (4) is the root of $F(x) = 0$ with $\mathrm{Re}(x_j^{(1)}) > 0$ or $\delta_1 < \mathrm{Im}(x_j^{(1)}) < \delta_2$; $x_j^{(2)}$ is the root of $G(x) = 0$ with $\mathrm{Re}(x_j^{(2)}) < 0$ and $\mathrm{Im}(x_j^{(2)}) > \delta_2$; $x_j^{(3)}$ is the root of $K(x) = 0$ with $\mathrm{Re}(x_j^{(3)}) < 0$ and $\mathrm{Im}(x_j^{(3)}) < \delta_1$.

3. Atomic SE properties in the coherent PBG reservoir

From Eq. (4), we can see that the roots, i.e., $x_j^{(1)}$, $x_j^{(2)}$, and $x_j^{(3)}$, are important for the study of the dynamic properties of the atom. By numerical calculation, we find that there is only one complex root. According to the value of the root, it can be divided into three regions. In region I, there is one complex root $x^{(2)}$ with $\mathrm{Re}(x^{(2)}) < 0$ and $\mathrm{Im}(x^{(2)}) > \delta_2$. In region II, there is one complex root $x^{(1)}$ with $\mathrm{Re}(x^{(1)}) < 0$ and $\delta_1 < \mathrm{Im}(x^{(1)}) < \delta_2$. In region III, there is one complex root $x^{(3)}$ with $\mathrm{Re}(x^{(3)}) < 0$ and $\mathrm{Im}(x^{(3)}) < \delta_1$. As shown in Fig. 1, the characteristics of the roots depend on the width of the PBG Δ and the ATF ω_{21}, and they are affected by coherent parameter θ between the two bands. In other words, the dynamic and the radiative properties can be adjusted by the three factors above.

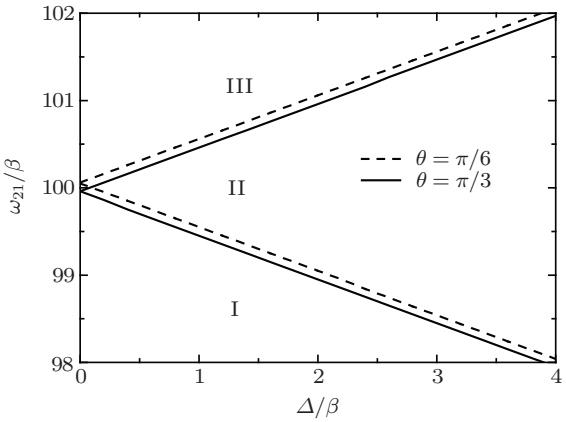


Fig. 1. Atomic transition frequency versus width of the PBG for decay rate $\gamma = 0.01\beta$ and different coherent parameters.

In addition, the roots are directly related to the properties of the emitted fields around the atom. For the radiation modes near the band edges, the emitted field $\boldsymbol{E}(\boldsymbol{r}, t)$ at a particular space point $\boldsymbol{r}$ can be written as[26]

$$\boldsymbol{E}(\boldsymbol{r}, t) = \sum_{\boldsymbol{k}} \sqrt{\frac{\hbar\omega_{\boldsymbol{k}}}{2\varepsilon_0 V}}\,\mathrm{e}^{-\mathrm{i}(\omega_{\boldsymbol{k}}t - \boldsymbol{k}\cdot\boldsymbol{r})} B_{1\boldsymbol{k}}(t)\boldsymbol{e}_{\boldsymbol{k}}. \tag{5}$$

From Eqs. (3c), (3d), and (4), we can obtain that $\omega_{21} - \mathrm{Im}(x^{(n)})$ ($n = 1, 2, 3$) is the frequency of the emitted field $\boldsymbol{E}(\boldsymbol{r}, t)$.[31] When the ATF is in region II, the corresponding dressed state[26,31] caused by the interaction between the atom and its own radiation occurs at frequency $\omega_{21} - \mathrm{Im}(x^{(1)})$, and $\omega_{\mathrm{c}2} < \omega_{21} - \mathrm{Im}(x^{(1)}) < \omega_{\mathrm{c}1}$ in the gap. Due to the existence of the transition $|2\rangle \leftrightarrow |0\rangle$ in the free space

vacuum, root $x^{(1)}$ is not a purely imaginary one, but a complex one with a negative real part, which will cause the corresponding dressed state to decay with time. In physics, the emitted field has non-localized features.[32] When the ATF is in region I (III), there exists root $x^{(2)}$ ($x^{(3)}$), because $\omega_{21} - \mathrm{Im}(x_j^{(2)}) < \omega_{c2}$ ($\omega_{21} - \mathrm{Im}(x_j^{(3)}) > \omega_{c1}$) in the lower (upper) band, then the corresponding emitted field $\boldsymbol{E}(\boldsymbol{r}, t)$ can propagate more easily than that in the gap.

The influence of the two coherent bands on the dynamic properties can be investigated by examining the time evolution of the population in the upper level, $P_2(t) = |A(t)|^2$. In Fig. 2, the time evolutions of the population in the upper level $|2\rangle$ are plotted for different coherent parameters. When the ATF ω_{21} is located at the upper and the lower band edges, respectively, the population evolutions have two opposite trends. When the coherent parameter θ varies from $\pi/6$ to $\pi/3$, from Fig. 1, we can see that the boundary of the different regions shifts downward. The physical reason is that the coupling between the atom and the photons is modified by the coherent photonic reservoir. When $\theta = \pi/3$ ($\theta = \pi/6$), the DOS of the upper (lower) band will be enlarged, and the coupling will be strengthened for the ATF in the upper (lower) band. Thus, the decay processes have different trends when the atomic transition $|2\rangle \leftrightarrow |1\rangle$ lies in different bands, as shown in Fig. 2.

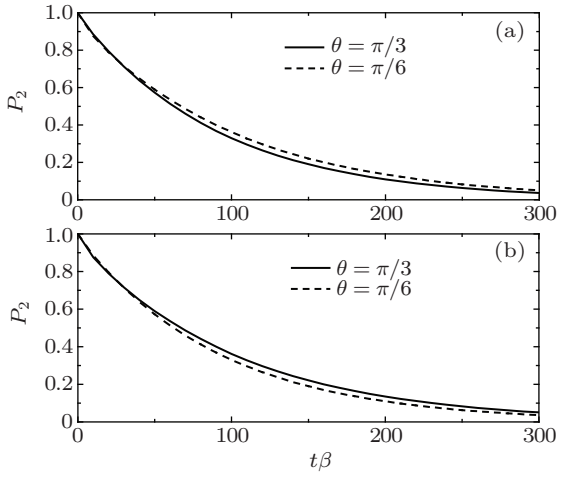


Fig. 2. Time evolutions of the upper level population for different values of coherent parameter θ. The parameters used are $\omega_{c2} = 99.5\beta$, $\omega_{c1} = 100\beta$, $\gamma = 0.01\beta$, and (a) $\omega_{21} = 100\beta$, or (b) $\omega_{21} = 99.5\beta$.

In order to further study the coherence effect of the two bands, we also consider the SE spectrum of the atomic transition $|2\rangle \leftrightarrow |0\rangle$, which in the free space vacuum is regarded as a Markovian reservoir. The spectrum of the atomic transition is given by $S(\delta_\lambda) \propto |B_{0\lambda}(t \to \infty)|^2$ with detuning frequency $\delta_\lambda = \omega_\lambda - \omega_{20}$. From Eq. (3), by using the final-value theorem and the Laplace transform, we can obtain the spectral intensity $S(\delta_\lambda) \propto \gamma|\tilde{A}(-\mathrm{i}\delta_\lambda)|^2$, where $\tilde{A}(s)$ ($\tilde{B}_{0\lambda}(s)$) is the Laplace transform of $A(t)$ ($B_{0\lambda}(t)$). As shown in Fig. 3, the spectrum of the atomic transition $|2\rangle \leftrightarrow |0\rangle$ has a Lorentzian shape with a single peak. As the DOS of the anisotropic PC near the band edge is very small, the spectrum in free space cannot be split by the electromagnetic modes around the atom. In contrast, in the isotropic case, the spectrum no longer has a Lorentzian shape, and it is intensively changed by the huge DOS near the band edge, as shown in some previous papers.[21,25,29] Furthermore, as singularity points do not exist at the band edges, dark lines do not occur in the spectrum either.

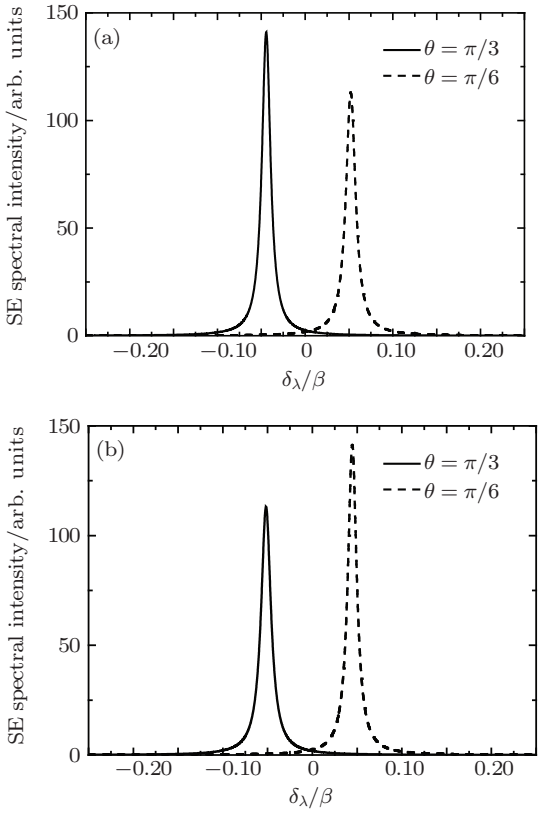


Fig. 3. SE spectral intensities versus δ_λ/β for different values of coherent parameter θ. The parameters are $\gamma = 0.01\beta$, $\omega_{c2} = 99.5\beta$, $\omega_{c1} = 100\beta$, and (a) $\omega_{21} = 99.4\beta$, or (b) $\omega_{21} = 100.1\beta$.

As shown in Fig. 3, as θ increases from $\pi/6$ to $\pi/3$, the spectral center shifts, and the spectral intensity changes. When $\theta = \pi/6$ ($\theta = \pi/3$), the DOS of the lower (upper) band is enhanced, and thus the coupling strength becomes larger in the lower (upper) band. It naturally pushes the atomic transition towards the upper (lower) band, in other words, the center of the spectrum can be manipulated by changing

the coherent parameter θ. In addition, as the transition $|2\rangle \leftrightarrow |1\rangle$ lies in the lower (upper) band, the interaction between the atom and the coherent PBG reservoir also becomes stronger, and accordingly the spectral intensity of the transition $|2\rangle \leftrightarrow |0\rangle$ becomes smaller.

4. Conclusion

The dynamic and the radiative properties of an excited three-level atom embedded in an anisotropic photonic crystal with two coherent bands have been studied. The atom–photon interaction depends on the position of the atom. The relative position of the atom in a Wigner–Seitz cell can be described by the position-dependent parameter $\theta(\boldsymbol{r}_0)$, which reflects the coherence between the two bands. By numerical calculation and theoretical analysis, we find that the dynamic properties of the system are not only determined by the atomic transition frequency, but also affected by the gap width and the coherence between the two bands. The distribution of the dressed states caused by the interaction between the atom and its own radiation field in the photonic reservoir is shown in Fig. 1. The time evolution of the population of the upper level $|2\rangle$ is plotted with the coherent parameter in Fig. 2. As the transition $|2\rangle \leftrightarrow |1\rangle$ is respectively located at the upper and the lower band edges, the population evolutions have two opposite trends. Furthermore, the spectrum of the atomic transition coupling to the free space vacuum can be manipulated by using the coherence between the two bands. The spectral center and the intensity can be obviously controlled by the coherent photonic reservoir.

References

[1] Yablonovitch E 1987 *Phys. Rev. Lett.* **58** 2059

[2] John S 1987 *Phys. Rev. Lett.* **58** 2486

[3] Chen L and Nurmikko A V 2004 *Appl. Phys. Lett.* **85** 3663

[4] Brinkley S, Lin Y D, Chakraborty A, Pfaff N, Cohen D, Speck J S, Nakamura S and DenBaars S P 2011 *Appl. Phys. Lett.* **98** 011110

[5] Agrawal M, Sun Y, Forrest S R and Peumans P 2007 *Appl. Phys. Lett.* **90** 241112

[6] Nishimura S, Abrams N, Lewis B A, Halaoui L I, Mallouk T E, Benkstein K D, van de Lagemaat J and Frank A J 2003 *J. Am. Chem. Soc.* **125** 6306

[7] Bermel P, Luo C Y, Zeng L R, Kimerling L C and Joannopoulos J D 2007 *Opt. Express* **15** 16986

[8] Zeng L, Yi Y, Hong C Y, Liu J, Feng N N, Duan X, Kimerling L C and Alamariu B 2006 *Appl. Phys. Lett.* **89** 111

[9] Khodjasteh K and Lidar D A 2003 *Phys. Rev.* A **68** 022322

[10] Noda S, Fujita M and Asano T 2007 *Nature Photon.* **1** 449

[11] Liu J T, Xiao W B, Huang J H, Yu T B and Deng X H 2010 *Acta Phys. Sin.* **59** 1665 (in Chinese)

[12] Solomon G S, Pelton M and Yamamoto Y 2001 *Phys. Rev. Lett.* **86** 3903

[13] Han K, Wang Z Y, Shen X P, Wu Q H, Tong X, Tang G and Wu Y X 2011 *Acta Phys. Sin.* **60** 044212 (in Chinese)

[14] John S and Wang J 1990 *Phys. Rev. Lett.* **64** 2418

[15] Bay S, Lambropoulos P and Molmer K 1997 *Phys. Rev. Lett.* **79** 2654

[16] Yang Y P, Fleischhauer M and Zhu S Y 2003 *Phys. Rev.* A **68** 043805

[17] Cheng S C, Wu J N, Yang T J and Hsieh W F 2009 *Phys. Rev.* A **79** 013801

[18] John S and Quang T 1994 *Phys. Rev.* A **50** 1764

[19] Angelakis D G, Paspalakis E and Knight P L 2001 *Phys. Rev.* A **64** 013801

[20] Zhou B, Du C G and Li S Q 2004 *Chin. Phys. Lett.* **21** 856

[21] Li Z Y and Xia Y 2001 *Phys. Rev.* A **63** 043817

[22] Angelakis D G, Paspalakis E and Knight P L 2000 *Phys. Rev.* A **61** 055802

[23] Wang X H, Yuri S, Kivshar and Gu B Y 2004 *Phys. Rev. Lett.* **93** 073901

[24] Liu N H, Xu J P and Zhu S Y 2006 *Phys. Rev.* B **74** 075314

[25] Inés de Vega and Alonso D 2008 *Phys. Rev.* A **77** 043836

[26] Scully M O and Zubairy M S 1997 *Quantum Optics* (Cambridge: Cambridge University Press) Chap. 4

[27] Paspalakis E, Angelakis D G and Knight P L 1999 *Opt. Commun.* **72** 229

[28] Wang J, Yang D and Zhang H Z 2005 *Chin. Phys.* **14** 0323

[29] Li Z Y, Lin L L and Zhang Z Q 2000 *Phys. Rev. Lett.* **84** 4341

[30] Vats N, John S and Busch K 2002 *Phys. Rev.* A **65** 043808

[31] Yang Y P and Zhu S Y 2000 *Phys. Rev.* A **62** 013805

[32] Huang X S and Yang Y P 2007 *J. Opt. Soc. Am.* B **24** 699