Spontaneous emission of a three-level atom in a coherent photonic band gap reservoir

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Abstract: The optical spectra of a three-level atom embedded in a photonic crystal is studied by considering the coherent two-band photonic reservoir. We find that the spectrum is shifting with respect to the atomic position.

Keywords: optical spectra, coherent photonic reservoir

1. INTRODUCTION

It is well-known that spontaneous emission (SE) rate and optical properties can be modified effectively by placing the atoms in photonic band gap (PBG) materials [1-3], where the density of modes of the reservoirs has significant deviation from that of free space vacuum. This modification changes the atomic coherence and quantum interference effects and provides potential application to quantum optical communication. Here we propose a new point of view on controlling the SE and optical resonant spectra through changing the relative position of embedded atom in photonic crystals (PCs). It originates from the fact that the strength of photon-atom interaction depends on the atomic position [2] and two-band reservoir becomes coherent and can interfere with each other. These results of varying atomic position leading to the change of the spectra provide a new degree of freedom to control the SE and optical properties in PCs, especially for nonlinear optical phenomena.

2. MODEL

In this paper, a Λ-type three-level atom embedded in a PBG structure with two-band isotropic effective-mass model is studied (Fig.1). One transition level of the atom (|2⟩ → |1⟩) lies near the PBG edge; the other transition (|2⟩ → |0⟩) is far from the PBG edge and couples with the Markovian reservoir. The distributions of the electric fields from this two-band reservoir are expressed as

\[ \hat{E}_{\text{air}}(\vec{r}) = \hat{E}_0 \cos \theta(\vec{r}) \quad \text{and} \quad \hat{E}_{\text{di}}(\vec{r}) = \hat{E}_0 \sin \theta(\vec{r}) \]

with single amplitude \( \hat{E}_0 \) and angle parameter \( \theta(\vec{r}) \) being a function of atomic position \( \vec{r} \). This expression results from the definite phase difference between the air-band and dielectric-band fields of PBG whose energies concentrate in the low dielectric and high dielectric layers, respectively.

3. OPTICAL SPECTRUM

The SE spectra were plotted as a function of detuning frequency \( \delta = \omega - \omega_0 \) in Fig. 2 (a) and (b). As expected for the large gap width \( \Delta = \omega_2 - \omega_1 = 6 \) in Fig. 2 (a), the
spectrum shows single Lorentzian peak because of the radiated photon coupling to the free-space vacuum, which is referred as the free-space light. As the gap width decreases, other than the main peak, we observed two symmetric side lobes separated by zeros. These two side lobes, which are referred as the PBG light, originate from strong coupling of the excited atoms through the $|2\rangle \rightarrow |1\rangle$ transition with the PBG reservoir at these two band edges, where have the largest DOS. This coherent coupling effect grows stronger for the smaller gap width as a result of considering the fields of the non-Markovian reservoirs as coherent mode fields. The intensity changes of the free-space light and PBG light reveal the coherent property of the PBG reservoir because of the free-space light being significantly quenched by the atom’s emitting the PBG light or loss population by the $|2\rangle \rightarrow |1\rangle$ transition. For the small PBG, the spectra of the PBG light show quantum interference effect by means of kinks of side lobes because the field modes from the air band interfere strongly with those from the dielectric band via the atom. The effect of the relative position of the atom in a Wigner-Seitz cell on SE spectra is shown in Fig. 2 (b). We observed that the free-space light makes a blue shift with increasing $\theta(\vec{r})$ but does not have much change in intensities. The increase of $\theta(\vec{r})$ means the stronger coherent coupling of the excited atoms through the $|2\rangle \rightarrow |1\rangle$ transition with dielectric-band field pushes the free-space light toward the air band. The absorption and dispersion spectra for two-coherent-band system were plotted in Fig. 2 (c) and (d) by applying a weak probe laser with field angular frequency $\omega \cong \omega_{20}$ to the atomic initial ground state $|0\rangle$. With the variation of $\theta(\vec{r})$, the coherent property of the reservoir could also be observed through the shifts of the free-space absorption line in Fig. 2 (c) and frequency shifts of the slow photons in Fig. 2 (d). The quantum interference effect is also illustrated through the intensity changes of the absorption side lobes of the system with small PBG. These noticeable results can be verified experimentally in photonic crystals with quantum dots in the air and dielectric region, respectively.

REFERENCES

[1] S.-C. Cheng, J.-N. Wu, M.-R. Tsai, and W.-F. Hsieh, “Spontaneous emission near the band edge of a three-dimensional photonic crystal: a fractional calculus approach,” J. Phys.: Condens. Matter 21, 015503-015507 (2009).

[2] S.-C. Cheng, J.-N. Wu, T.-J. Yang, and W.-F. Hsieh, “Effect of atomic position on the spontaneous emission of a three-level atom in a coherent photonic-band-gap reservoir,” Phys. Rev. A 79, 013801 (2009).

[3] J.-N. Wu, T.-J. Yang, S.-C. Cheng, “Coherent coupling between a three-level atom and structured reservoir,” Journal of the Korean Physical Society (JKPS) 53, 3802 (2008).

![Fig. 2](attachment:fig2.png)