Optics Communications 369 (2016) 209–214

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Spontaneous emission control of quantum dots embedded in photonic crystals: Effects of external fields and dimension

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ARTICLE INFO

Article history:
Received 8 January 2016
Accepted 16 February 2016
Available online 2 March 2016

Keywords:
Photonic crystal
Quantum dot
Spontaneous emission
Spectrum

ABSTRACT

In this paper simultaneous effects of external electric and magnetic fields and quantum confinement on the radiation properties of spherical quantum dot embedded in a photonic crystal are investigated. Under the influence of photonic band-gap, effects of external static fields and dot dimension on the amplitude and spectrum of different radiation fields emitted by the quantum dot are studied. Our results show the considerable effects of external fields and quantum confinement on the spontaneous emission of the system.

1. Introduction

Photonic crystals have been developed recently not only as a source of light-matter interaction, but also as an important tool for optical devices [1–9]. Electromagnetic(EM) waves traveling in photonic crystals are described in terms of photonic bands with the exitances of photonic band gap (PBG) where the propagation of EM waves is forbidden [10–15]. It has been demonstrated theoretically and experimentally that PBG has considerable influence on the spontaneous emission and radiation of an atom embedded in a photonic crystal [16–24]. Since control the spontaneous emission has different applications ranging from lasers and light emitting diodes to solar cells, biosensors, displays and optical communications [25–31], thus photonic crystals produce suitable environment for these applications.

Impressive developments in nanofabrication technology have made it now possible to design quantum dots(QDs) [32,33]. In such systems, few electrons are confined into a point-like structure and they can behave as an artificial atom. Consequently, they can be used to design electronic and optical devices [34–37]. Confinement of carriers in these structures lead to formation of atomic-like discrete energy levels (subbands), as oppose to Bloch energy bands in crystals [38,39]. The most interesting properties of the QDs is the possible occurrence of these inter subbands optical transitions. The dipole matrix element of the optical transition between the subbands of the QDs has dramatically large value and lead to interesting optical properties that may be absent in atomic systems.

Thus, the advent of QDs make them excellent candidates for light emitters instead of atomic systems due to novel optical properties and the possibility of controlling their physical properties with precise engineering and via external agents [40,41]. In this regard, QDs embedded in photonic crystals have been a subject of several researches recently [42–44]. In the current work we have studied the effects of external electric and magnetic fields and quantum confinement on the radiation fields and spectrum of spherical QDs embedded in a photonic crystal. Our results show that these external factors have considerable effects on the radiative properties of QDs in the photonic crystals and it is possible to control these properties via external agents.

2. Theory

The Hamiltonian of a quantum mechanical system interacting with the quantized EM field in the rotating wave and electric dipole approximation is given by [45]

$$H = \hbar\omega_a|a\rangle\langle a| + \hbar\omega_b|b\rangle\langle b| + \sum_k \hbar\omega_k a_k^\dagger a_k + i\hbar\sum_k g_k(\sigma_{ab}a_k - \sigma_{ba}a_k^\dagger). \quad (1)$$

Here we have considered two active levels $|a\rangle$ and $|b\rangle$ are the lower and upper energy states of the system with frequencies ω_a and ω_b, respectively. Also, $a_k(a_k^\dagger)$ is the annihilation (creation) operator for the k-th electromagnetic mode with frequency ω_k, g_k is the coupling constant between the k-th EM mode and the quantum

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http://dx.doi.org/10.1016/j.optcom.2016.02.037
0030-4018/

transition $|a\rangle \leftrightarrow |b\rangle$. To study the system dynamics one have to find the state vector at any arbitrary time, t, as follows:

$$|\psi(t)\rangle_I = A(t)|a\rangle|0\rangle_f + \sum_k B_k(t)|b\rangle|1_k\rangle_f, \tag{2}$$

where $|0\rangle_f(|1\rangle_f)$ represents no photon (one photons) in any mode, k. Inserting Eqs. (1) and (2) in the Schrödinger equation gives the following coupled equations for $A(t)$ and $B(t)$ [23,45]

$$\frac{\partial A(t)}{\partial t} = \sum_k g_k B_k(t) e^{i\Delta t}, \tag{3}$$

$$\frac{\partial B_k(t)}{\partial t} = -g_k A(t) e^{-i\Delta t}, \tag{4}$$

where $\Delta = \omega_{ab} - \omega_k = \omega_a - \omega_b - \omega_k$ is the detuning parameter. Near the band edge of the photonic crystal, the dispersion relation is approximated by $\omega_k \simeq \omega_e + A(k-k_0)^2$, A is a model-dependent constant, ω_e and k_0 are the cut-off frequency and the wave vector corresponding to the band edge, respectively. Using the Laplace transformation method to solve coupled Eqs. (3) and (4) gives the following expressions for $A(t)$ and $B(t)$:

$$A(t) = \sum_j \frac{e^{x_1^j t}}{F'(x_1^j)} + \sum_j \frac{e^{x_2^j t}}{E'(x_2^j)} - \frac{e^{i\omega_{ae}t}}{2\pi i}\int_0^\infty \left(\frac{I_1(x)}{I_1(x)L_1(x) + 2i\beta^{\frac{3}{2}}} - \frac{I_2(x)}{I_2(x)L_1(x) + 2i\beta^{\frac{3}{2}}}\right) e^{-xt}\,dx, \tag{5}$$

$$B_{k(t)} = -g_k \sum_j \left(\frac{1}{F'(x_j^1)} \frac{e^{-i(\omega_a-\omega_k)t + x_j^1 t} - 1}{-i(\omega_a-\omega_k) + x_j^1}\right) - g_k \sum_j \left(\frac{1}{E'(x_j^2)} \frac{e^{-i(\omega_a-\omega_k)t + x_j^2 t} - 1}{-i(\omega_a-\omega_k) + x_j^2}\right) + \frac{g_k}{2\pi i}\int_0^\infty \left(\frac{I_1(x)}{I_1(x)L_1(x) + 2i\beta^{\frac{3}{2}}} - \frac{I_2(x)}{I_2(x)L_1(x) + 2i\beta^{\frac{3}{2}}}\right) \frac{e^{-i(\omega_a-\omega_k)t - xt} - 1}{-i(\omega_a-\omega_k) - x}\,dx. \tag{6}$$

In the above equations $F(x) = \frac{i\beta^{\frac{3}{2}}}{\sqrt{\omega_e} + \sqrt{-\omega_{ae} - ix}} - x$, $E(x) = \frac{i\beta^{\frac{3}{2}}}{\sqrt{\omega_e} - \sqrt{-\omega_{ae} - ix}} - x$, $I_1(x) = \sqrt{\omega_e} + \sqrt{ix}$, $I_2(x) = \sqrt{\omega_e} + \sqrt{ix}$, $L_1(x) = x - i\omega_{ae}$ and $\beta^{\frac{3}{2}} = \frac{(\omega_{ab} d)^2}{3\varepsilon_0 \pi \hbar A^{\frac{3}{2}}}$. Moreover x_j^1 are the roots of the equation $F(x) = 0$ in the regions $Im(x_j^1) > \omega_{ae}$ or $Re(x_j^1) > 0$ and x_j^2 are the roots of the equation $E(x) = 0$ in the regions $Im(x_j^2) < \omega_{ae}$ and $Re(x_j^2) < 0$. Now it is possible to calculate the emitted field from $B_k(t)$ by the following relation [45]:

$$\vec{E}(\vec{r}, t) = \sum_k \sqrt{\frac{\hbar\omega_k}{2\varepsilon_0 V}}\, e^{-i(\omega_k t - \vec{k}\cdot\vec{r})} B_k(t)\hat{\varepsilon}_k. \tag{7}$$

Using Eqs. (6) and (7), $\vec{E}(\vec{r}, t)$ at any point r from the dot center is expressed as the sum of three parts

$$\vec{E}(\vec{r}, t) = \vec{E}_l(\vec{r}, t) + \vec{E}_p(\vec{r}, t) + \vec{E}_d(\vec{r}, t). \tag{8}$$

The first part is the localized field and is given by

$$\vec{E}_l(\vec{r}, t) = \sum_j E_l^j(0) \frac{1}{r} e^{-i(\omega_a - b_j^1)t - rl_j}\,\Theta\left(t - \frac{l_j r}{2A}\right), \tag{9}$$

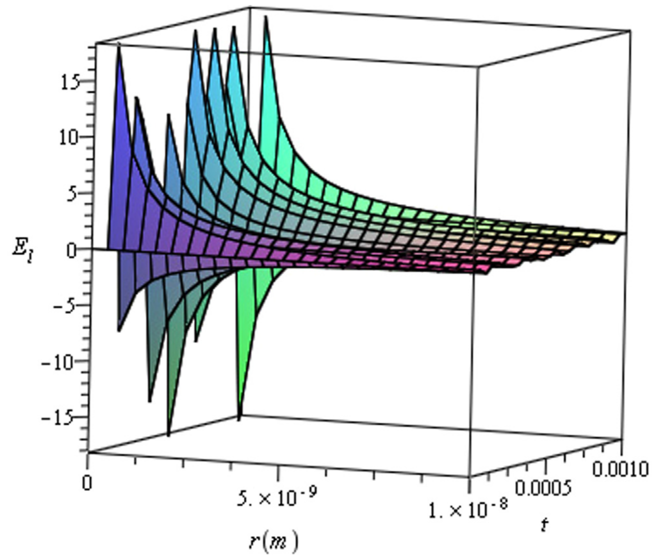

Fig. 1. Variation of the localized field as a function of time and distance, $B = 1$ T.

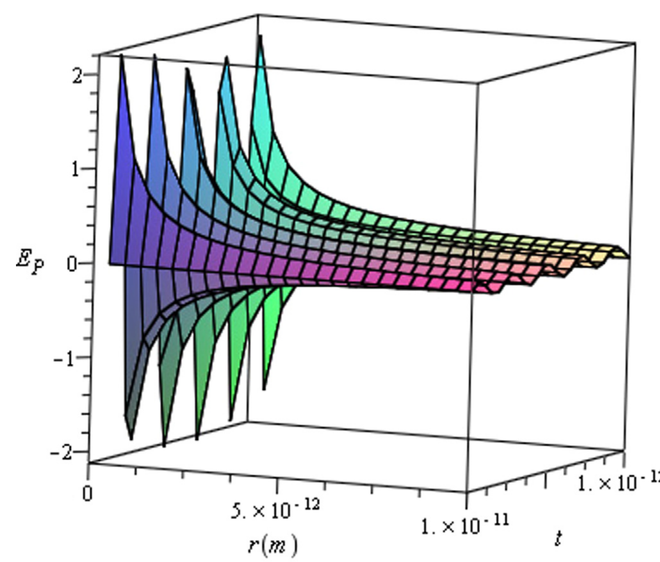

Fig. 2. Variation of the propagation field as a function of time and distance, $B = 1$ T.

with

$$E_l^j(0) = \frac{\omega_a d}{4A\pi\varepsilon_0 i} \frac{1}{F'(x_j^1)} e^{i\vec{k}_0\cdot\vec{r}} \left(\hat{u} - \frac{\vec{k}_0(\vec{k}_0\cdot\hat{u})}{(\vec{k}_0)^2}\right), \tag{10}$$

$$\Theta(x) = \begin{cases} 0 & x < 0 \\ 1 & x \geq 0 \end{cases}, \tag{11}$$

$$l_j = \left[\frac{(-ix_j^1 - \omega_{ae})}{A}\right]^{\frac{-1}{2}}. \tag{12}$$

The second part is the propagating field

$$\vec{E}_p(\vec{r}, t) = \sum_j E_p^j(0) \frac{1}{r} e^{-i(x_j^2 - i\omega_a)t + iq_j}\,\Theta\left(t - \frac{r}{2A[Re(q_j) + Im(q_j)]}\right), \tag{13}$$