Available online at www.sciencedirect.com
ScienceDirect
Optik 120 (2009) 689–695
Optik Optics
www.elsevier.de/ijleo

Probe absorption spectra of a V-type atom embedded in PBG reservoir

Han Zhang[a], Xin Bo Li[b], Yang Liu[a], Han Zhuang Zhang[a,*]

[a]*College of Physics, Jilin University, Changchun 130023, PR China*
[b]*College of Communication Engineering, Jilin University, Changchun 130025, PR China*

Received 13 September 2007; accepted 15 February 2008

Abstract

In this paper, the probe absorption spectra of a V-type atom embedded in photonic band gap (PBG) reservoir have been investigated under conditions that quantum interference among decay channels is important. The effect of the probe polarization on the absorption amplitude and spectral structure is investigated in detail. Comparing with similar models located in vacuum reservoir studied earlier, the study here shows that the probe polarization has some different effects on the absorption spectra in PBG reservoir.

PACS: 42.50.Gy; 42.50.Ct; 42.70.Qs

Keywords: Photonic band gap; Quantum interference; Probe absorption spectrum

1. Introduction

Quantum interference [1–9], which plays an essential role in quantum mechanics, has been manifested in various branches of physics. In atomic, molecular and optical physics, absorption [1–3], stimulated emission [4–6] and spontaneous emission processes [7–9] subject to quantum interference resulting from different transition processes have been of considerable interest for many years. The weak probe absorption spectra of various atomic models in vacuum reservoir have been investigated by several authors [1,2,4,5,10]. The very different effects have attracted much attention.

In recent years, photonic band gap (PBG) structures have been shown to have different DOS compared with the free-space field [11,12]. The study of quantum and nonlinear optical phenomena for atoms embedded in such PBG reservoirs leads to the prediction of many interesting effects, for example, localization of light [13–15], photon-atom bound states [11–13,15,16] and other phenomena [17–25]. Even though many studies have been carried out on the PBG structures, there are few papers referring to the absorption spectra of an atom located in PBG reservoir as far as we know [19,26–31].

It is well known that in vacuum reservoir, the spontaneous emission process is incorporated in the reduced master equation by introducing the decay rates [32]. The susceptibility due to absorption has been calculated by using the master equation method in the linear response theory. In this paper, we present a detailed deduction of the "decay rate" terms of an atom located in PBG reservoir. The numerical emulation of the probe absorption spectrum of a V-type atom embedded in PBG reservoir is also performed. The probe polarization direction has been taken into account for a V-type atom with a closely spaced doublet under

*Corresponding author. Tel.: +86 431 88498034.
E-mail address: zhanghanjlu@yahoo.com.cn (H.Z. Zhang).

0030-4026/$ - see front matter © 2008 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2008.02.018

conditions that quantum interference among decay channels is important. Comparing with similar models located in vacuum studied earlier, the study here shows that the probe polarization has some different effects on the absorption spectra in PBG reservoir. Most interestingly, the frequency shifts of atomic levels resulting from interaction with the PBG reservoir lead to quite different quantum interference effects.

The paper is organized as follows. In Section 2, the equations of the "decay rate" terms of an atom located in PBG reservoir are deduced in detail. In Section 3, the theoretical deduction of the probe absorption spectra of a V-type atom with the transitions coupled to PBG modes are investigated. The main results and discussions are given in Section 4. The major conclusions are summarized in Section 5.

2. The deduction of "decay rate" terms in PBG reservoir

We consider a two-level atom damped by a reservoir of simple harmonic oscillators described by annihilation (and creation) operators b_k (and b_k^+), and the index k labels the momentum and polarization indices of the kth field mode whose frequency is ω_k. The levels of the atom are denoted by $|0\rangle$ (the ground state) and $|1\rangle$ (the excited state). In the interaction picture and the rotating-wave approximation, the Hamiltonian is simply

$$H_i = \hbar \sum_k g_k (b_k^+ \sigma_- e^{i(\mu_k - \Delta_p)t} + \sigma_+ b_k e^{-i(\mu_k - \Delta_p)t}), \tag{1}$$

where $\sigma_- = |0\rangle\langle 1|$ and $\sigma_+ = |1\rangle\langle 0|$. In the interaction picture, within the Born approximation, the evolution of the atomic system is described by the following reduced master equation:

$$\begin{aligned}
\dot{\rho}_{\text{atom}} = & -i/\hbar Tr_R[H(t), \rho_{\text{atom}}(t_i) \otimes \rho_R(t_i)] \\
& - 1/\hbar^2 Tr_R \int_{t_i}^{t} [H(t), [H(t'), \rho_{\text{atom}}(t') \otimes \rho_R(t_i)]]\, dt' \\
= & -i \sum_k g_k \langle b_k^+ \rangle [\sigma_-, \rho_{\text{atom}}(t_i)] e^{i(\mu_k - \Delta_p)t} \\
& - \int_0^t dt' \sum_{k,k'} g_k g_{k'} \{[\sigma_- \sigma_- \rho_{\text{atom}}(t') - 2\sigma_- \rho_{\text{atom}}(t') \sigma_- \\
& + \rho_{\text{atom}}(t') \sigma_- \sigma_-] e^{i(\mu_k - \Delta_p)t + i(\mu_k - \Delta_p)t'} \langle b_k^+ b_{k'}^+ \rangle \\
& + [\sigma_- \sigma_+ \rho_{\text{atom}}(t') - \sigma_+ \rho_{\text{atom}}(t') \sigma_-] e^{i(\mu_k - \Delta_p)t - i(\mu_k - \Delta_p)t'} \\
& \langle b_k^+ b_{k'} \rangle + [\sigma_+ \sigma_- \rho_{\text{atom}}(t') - \sigma_- \rho_{\text{atom}}(t') \sigma_+] \\
& \times e^{-i(\mu_k - \Delta_p)t + i(\mu_k - \Delta_p)t'} \langle b_k b_{k'}^+ \rangle + \text{H.c.},
\end{aligned} \tag{2}$$

where the expectation values refer to the initial state of the reservoir.

$$\begin{aligned}
& \langle b_k \rangle = \langle b_k^+ \rangle = 0, \langle b_k^+ b_{k'} \rangle = \bar{n}_k \delta_{kk'}, \\
& \langle b_k b_{k'}^+ \rangle = (\bar{n}_k + 1) \delta_{kk'}, \langle b_k b_{k'} \rangle = \langle b_k^+ b_{k'}^+ \rangle = 0.
\end{aligned} \tag{3}$$

Here $\bar{n}_k$ is the mean quantum numbers of the reservoir modes under thermal equilibrium, we consider the photonic reservoir to be initially in its vacuum state $\bar{n}_k = 0$. The Born approximation assumes a weak coupling between the atomic system and the radiation reservoir of the photonic crystal, and also that changes in the photonic reservoir as a result of atom-reservoir interaction are negligible. In anisotropic PBG reservoir, it has been shown that the non-Markovian effects associated with the fast variation of the density of states at the band-edge frequency can be analyzed within the framework of the Born approximation [30,31]. Using the statistical characteristics of the reservoir field operators, it can be easily shown that the reduced master equation is given below:

$$\begin{aligned}
\dot{\rho}_{\text{atom}} = & -\int_0^t dt' \sum_k g_k^2 [\sigma_+ \sigma_- \rho_{\text{atom}}(t') \\
& - \sigma_- \rho_{\text{atom}}(t') \sigma_+] e^{-i(\mu_k - \Delta_p)(t-t')} \\
& - \int_0^t dt' \sum_k g_k^2 [\rho_{\text{atom}}(t') \sigma_+ \sigma_- \\
& - \sigma_- \rho_{\text{atom}}(t') \sigma_+] e^{i(\mu_k - \Delta_p)(t-t')} \\
= & -\int_0^t dt' G_{10}(t-t') [|1\rangle\langle 1| \rho_{\text{atom}}(t') \\
& - |0\rangle\langle 1| \rho_{\text{atom}}(t') |1\rangle\langle 0|] \\
& - \int_0^t dt' G_{01}(t-t') [\rho_{\text{atom}}(t') |1\rangle\langle 1| \\
& - |0\rangle\langle 1| \rho_{\text{atom}}(t') |1\rangle\langle 0|],
\end{aligned} \tag{4}$$

where $G_{10}(t-t')$ and $G_{01}(t-t')$ are the delay Green function which can be expressed as follows, for the anisotropic PBG reservoir [33],

$$\begin{aligned}
G_{10}(t-t') = & \sum_k g_k^2 e^{-i(\mu_k - \Delta_p)(t-t')} \\
= & \frac{1}{2} \alpha_{10} \times \left\{ \frac{e^{i[\delta_{10c2}(t-t') + \pi/4] + i\Delta_p(t-t')}}{\sqrt{4\pi(t-t')^3}} \right. \\
& \left. + \frac{e^{i[\delta_{10c1}(t-t') - \pi/4] + i\Delta_p(t-t')}}{\sqrt{4\pi(t-t')^3}} \right\}. \\
G_{01}(t-t') = & \sum_k g_k^2 e^{i(\mu_k - \Delta_p)(t-t')} \\
= & \frac{1}{2} \alpha_{10} \times \left\{ \frac{e^{-i[\delta_{10c2}(t-t') + \pi/4] - i\Delta_p(t-t')}}{\sqrt{4\pi(t-t')^3}} \right. \\
& \left. + \frac{e^{-i[\delta_{10c1}(t-t') - \pi/4] - i\Delta_p(t-t')}}{\sqrt{4\pi(t-t')^3}} \right\}.
\end{aligned} \tag{5}$$