Physica A 425 (2015) 34–40

Contents lists available at ScienceDirect

Physica A

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

Susceptibility of a two-level atom near an isotropic photonic band edge: Transparency and band edge profile reconstruction

G.A. Prataviera *, M.C. de Oliveira

Departamento de Administração, FEARP, Universidade de São Paulo, 14040-905, Ribeirão Preto, SP, Brazil
Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, 13083-859, Campinas, São Paulo, Brazil

HIGHLIGHTS

- We consider the linear response of a driven two-level atom coupled to an isotropic band edge.
- We consider atomic decay in a vacuum with a flat and a non-flat density of modes.
- Transparency at certain frequencies occurs for an isotropic band gap density of modes.
- The band edge density of modes can be obtained from the measured susceptibility.

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form 19 December 2014
Available online 22 January 2015

Keywords:
Two-level
Band-gap
Susceptibility
Transparency

ABSTRACT

We discuss the necessary conditions for a two-level system in the presence of an isotropic band edge to be transparent to a probe laser field. The two-level atom is transparent whenever it is coupled to a reservoir constituted of two parts—a flat and a non-flat density of modes representing a PBG structure. A proposal on the reconstruction of the band edge profile from the experimentally measured susceptibility is also presented.

1. Introduction

The investigation of optical properties of atoms coupled to dissipative environments with a structured density of modes has been a topic of active research over the years [1–8]. Of particular interest is the discussion of atoms (impurities) embedded in two or three-dimensional periodic dielectric structures, known as photonic crystals [9–32], since they allow control over the electromagnetic density of modes and the spatial modulation of narrow-linewidth (high-Q) modes, in both microwave and optical regimes [23]. When these structures are used to create one or several forbidden frequency bands they allow control or complete suppression of spontaneous emission, as well as absorption from those embedded impurities [11,13,16–18,20,21,23–32]. It was particularly relevant to the early observation that a two-level atom embedded in a PBG [11,12,17,18] could retain some population in the upper level, even when the transition frequency was in the transmitting band, being the final state a dressed state of the atom with a localized field mode, which lies in the forbidden band. More recently the attention has been shifted to quantum dots embedded in photonic crystals where each individual quantum dot can be seen as an "artificial atom" [33–35]. The important feature in any of those situations above is that the

* Corresponding author at: Departamento de Administração, FEARP, Universidade de São Paulo, 14040-905, Ribeirão Preto, SP, Brazil.
E-mail addresses: prataviera@usp.br (G.A. Prataviera), marcos@ifi.unicamp.br (M.C. de Oliveira).

http://dx.doi.org/10.1016/j.physa.2015.01.044

"atom" placed in such a structure interacts with the field modes in the propagating frequency band and in the forbidden photonic band gap (PBG) as well, giving rise to many interesting coherent phenomena such as the possibility of controlling non-Markovian decay [5,27], localization of superradiance [17], quantum interference effects in spontaneous emission [20,28], transparency to a probe field [21], and squeezing in the in-phase quadrature spectra [25].

The majority of contributions regarding radiative properties consider only spontaneous emission of two, three, four and five level atoms embedded in a PBG structure [20,22,31,32,36,37], with only a few exceptions treating absorptive and dispersive properties [21,38]. As an important example of this last case, the absorption and dispersion properties of a Λ-type atom decaying spontaneously near the edge of a PBG was studied [21]. It was pointed out, within an isotropic PBG model, that the atom can become transparent to a probe laser field, even when other dissipative channels are present, suggesting that many surprising effects in the absorption and dispersion of atoms embedded in such structures can appear. Most of those effects were considered inside model systems composed by three or more levels [5,7,20,21,23,24,31,32,36,37], while they were not proved to be strictly necessary.

Pursuing this line we revisit the problem of transparency of an atom placed near an isotropic band edge [21], but consider the minimal situation of transitions between two-levels only. We show that for it to be transparent to a weak driven field, the two-level atom must be coupled to a reservoir constituted of two parts—a flat and a non-flat density of modes representing a PBG structure. Transparency is therefore an inner property of the reservoir engineering. As a side result of this approach we consider the related inverse problem considered in Refs. [14,39,40] on the possibility to obtain information about the band edge profile from two-level temporal decay in such structure. Here we show that it is also possible to reconstruct the band edge characteristics directly from the experimentally measured susceptibility.

This paper is organized as follows. In Section 2, we present the model considered and its stationary solution. In Section 3, the linear susceptibility is evaluated, and two models of isotropic band gap structures are analyzed. In Section 4, is discussed how to reconstruct the band edge characteristics from the experimentally measured susceptibility. Finally, in Section 5 we conclude the paper.

2. Model

The system considered here is a two-level atom with excited and ground state $|1\rangle$ and $|0\rangle$, respectively and with transition frequency ω_0. The atom is probed by a weak electric field with frequency ω detuned from ω_0 by $\delta = \omega - \omega_0$. The decay of the excited state is due to a coupling with vacuum modes described by a collection of harmonic oscillators with frequencies ω_m. In the rotating wave approximation and in the interaction picture the Hamiltonian of the system is given by

$$H = \left(\Omega \mathrm{e}^{\mathrm{i}\delta t} |0\rangle \langle 1| + H.c.\right) + \sum_m \left(g_m \mathrm{e}^{\mathrm{i}(\omega_m-\omega_0)t} b_m^\dagger |0\rangle \langle 1| + H.c.\right), \tag{1}$$

where $\Omega = -\mu_{10}E_o$ is the Rabi frequency, μ_{10} is the atomic electric dipole moment, and E_o is electric field amplitude. The g_m represents the coupling between the atom and the vacuum modes and $b_m^\dagger$ and b_m are the creation and annihilation operators for excitations in the reservoir, with $m = \lambda, \mathbf{k}$ indicating a photon state with polarization λ and momentum $\mathbf{k}$. For sake of simplicity we assume Ω and g_m as real. In the period of time t the state of total system, *atom + reservoir modes*, can be written as a superposition given by

$$|\psi(t)\rangle = a_0(t)\,|0, \{0\}\rangle + a_1(t)\mathrm{e}^{-\mathrm{i}\delta t}\,|1, \{0\}\rangle + \sum_m \alpha_m(t)\,|0, \{m\}\rangle\,. \tag{2}$$

The coefficients $a_0(t)$ and $a_1(t)$ are the probability amplitudes to find the atom in the ground and excited states and the photon reservoir in the vacuum state, respectively, while the coefficient $\alpha_m(t)$ gives the probability amplitude to find the atom in the ground state and a single photon in the state m of the vacuum modes. Substituting Eq. (2) into the Schrödinger equation containing the Hamiltonian (1) and projecting into each state at the right-hand-side of Eq. (2) gives the following equations of motion for the time dependent coefficients a_l and α_m,

$$\mathrm{i}\dot{a}_0(t) = \Omega a_1(t), \tag{3}$$

$$\mathrm{i}\dot{a}_1(t) = \Omega a_0(t) - \delta a_1(t) + \sum_m g_m \mathrm{e}^{-\mathrm{i}(\omega_m-\omega_0-\delta)t}\alpha_m(t), \tag{4}$$

$$\mathrm{i}\dot{\alpha}_m(t) = g_m \mathrm{e}^{\mathrm{i}(\omega_m-\omega_0-\delta)t}\,a_1(t). \tag{5}$$

Integrating Eq. (5) and eliminating the vacuum amplitude in the equations for $a_0(t)$ and $a_1(t)$ it follows that

$$\mathrm{i}\dot{a}_0(t) = \Omega a_1(t), \tag{6}$$

$$\mathrm{i}\dot{a}_1(t) = \Omega a_0(t) - \delta a_1(t) - \mathrm{i}\int_0^t K(t-t')a_1(t')\mathrm{d}t', \tag{7}$$

where the kernel, $K(t-t')$, is given by

$$K(t-t') = \sum_m g_m^2 e^{-\mathrm{i}(\omega_m-\omega_0-\delta)(t-t')}. \tag{8}$$