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Absorption–dispersion in a three-level electromagnetically induced transparency medium including near dipole–dipole interaction effects

Amitabh Joshi [a,*], Juan D. Serna [b]

[a] Department of Physics and Optical Engineering, Rose-Hulman Institute of Technology, Terre Haute, IN 47803, USA
[b] Department of Physics and Electrical Engineering, University of Scranton, Scranton, PA 18510, USA

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ABSTRACT

Dynamical evolution and electromagnetically induced transparency (EIT) is investigated here in a three-level λ-type atomic system including near-dipole–dipole interaction among atoms. The system is driven by the probe and coupling fields. Exact numerical solutions under steady-state condition are given for the density operator equation to get information about population in various levels and the linear susceptibility of probe-transition. Also, obtained are the closed form expressions for linear and third order non-linear susceptibilities for the probe transition under perturbation approximation.

1. Introduction

It has been shown in the late eighties that the propagation of an electromagnetic field with a medium composed of two-level atoms can generate near dipole–dipole (NDD) interaction. Such NDD effects can result in the inversion-dependent-chirping of the single atom resonance frequency of such a two-level atomic dipole system. The NDD interactions give rise to a local effect that modifies the microscopic field coupling the atom and which is obtained from the macroscopic field and the induced polarization [1]. The significant contribution of the NDD interaction comes from the entities enclosed in a tiny volume of the order of a cubic wavelength, and that is prominent in a dense medium. The use of the modified Maxwell–Bloch equation allowed to predict many interesting results caused by NDD effects. For example, invariant pulse propagation that departs from the hyperbolic secant pulse shape (with pulse area different from 2π) related to self-induced transparency (SIT) [2] and self-phase modulation in SIT [3]. Other relevant results include the observation of intrinsic optical bistability (IOB) when the atomic number density and the oscillator strengths are very high [4]; enhancement of gain in systems showing inversionless lasing; optical switching; among others. When a sample of atoms interacts with the external driving field, then the generated reaction field due to the induced dipoles in this samples works against the applied field leading to a decrease in the net field. If the external driving field is stronger than the generated reaction field due to the dipole–dipole interaction, then the manifestation of the suppression of reaction field can be observed as a first-order phase transition far away from the equilibrium condition [5,6].

The importance and application of dipole–dipole interaction including NDD interaction in some physical processes is summarized in the following. The physical process in which two microscopic entities, e.g., atoms or artificial atoms (quantum dots), molecules, chromophores interacts through dipole–dipole interaction to transfer energy is potentially considered as a significant process during the photosynthesis [7,8]. The transfer of energy with dipole–dipole interaction process is also crucial in investigating protein conformational dynamics [9,10]. Transfer of energy through dipole–dipole interaction is beneficial in quantum information processing systems to achieve the entanglement of qubits [11]. The dipole–dipole interaction may be helpful to realize Bose–Einstein condensates at high temperatures [12]. The dipole–dipole interaction could be of near field type or far field type. This interaction depends on the relative distance of two atoms. The process of near-field dipole–dipole interaction is governed through virtual photon exchange in atoms.

Modified nonlinear Maxwell–Bloch equations are required to describe the interaction of the propagating electromagnetic field in a dense two-level medium [1]. In an optically dense medium, the near dipole–dipole interaction among atoms (occurring at microscopic scale) plays a significant role and leads to the renormalization of the resonance frequency of transition. This renormalization is governed by the population inversion in the two-level system. However, to get a relationship between the macroscopic electric field $\mathbf{E}_M$ and the polarization $\mathbf{P}$ to

* Corresponding author.
E-mail addresses: mcbamji@gmail.com (A. Joshi), juan.serna@scranton.edu (J.D. Serna).

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the microscopic field $\mathbf{E}_m$ (causing the excitation in the atomic system through the dipole interaction), the Lorentz–Lorentz relation

$$\mathbf{E}_m = \mathbf{E}_M + \frac{4\pi}{3}\mathbf{P} \tag{1}$$

is required. This equation is valid for homogeneous and isotropic media of the static fields. According to the extinction theorem [13], such an equation is also valid for the monochromatic time-dependent propagating field in a linear, homogeneous, and isotropic medium. However, in an optically dense medium where many interesting nonlinear effects can be studied, one needs to get a proper relationship between the microscopic and the macroscopic fields.

Maxwell's equations along with Eq. (1) (related to the local field correction) provide a Clausius–Mossotti relation between the microscopic polarizability β, and the macroscopic dielectric parameter ϵ_M, of any solid, liquid or gaseous medium. This relation takes the form [1]

$$\beta = \frac{3}{4\pi N}\left(\frac{\epsilon_M - 1}{\epsilon_M + 2}\right), \tag{2}$$

where N is the number of entities (atoms or molecules) per unit volume. Causality and retardation phenomena are essential to explain the propagation of time-dependent fields. In the literature, it has been shown using the extinction theorem that for a linear, homogeneous, and isotropic medium, Eq. (1) works well and hence Eq. (2) is also appropriate for such medium [1]. The propagation of a field in a dense and nonlinear medium consisting of multi-level atoms requires modified atomic and field equations to include the effect of induced dipole–dipole interaction in these equations.

The Maxwell's wave equation provides the relationship between the macroscopic electric field $\mathbf{E}_M$, and the macroscopic polarization $\mathbf{P}$

$$\nabla^2\mathbf{E}_M - \frac{1}{c^2}\frac{\partial^2\mathbf{E}_M}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2\mathbf{P}}{\partial t^2}, \tag{3}$$

with c the speed of light in vacuum. The vector quantities $\mathbf{E}_M$ and $\mathbf{P}$ are waves traveling in the z-direction and expressed as

$$\begin{aligned}\mathbf{E}_M &= \varepsilon\, e^{-i(\omega t - k_z z)} + c.c. \\ \mathbf{P} &= \wp\, e^{-i(\omega t - k_z z)} + c.c.\end{aligned} \tag{4}$$

with wave vector k_z, frequency ω, and slowly varying quantities ε and $\wp = i\mu N D_{ab}$. N is the density of two-level atoms in the medium and μD_{ab} is the transition dipole matrix element.

In general, the microscopic field interacting with the atomic dipole is not identical with the macroscopic field appearing in Maxwell's equations. This difference is because the field driving the atom does not contain the local field of the atom. On the other hand, the macroscopic field of Maxwell's equations does include the local field. Hence, it is essential to get a relationship between the microscopic and macroscopic field when the atomic system is optically dense (which means a large number of atoms within a cubic resonance wavelength) [1].

In previous works [1,6] for the two-level system, the Maxwell–Bloch equations for the dense medium under the slowly-varying-envelope approximation for the field were obtained for a homogeneous medium that contained a large number of atoms within a small volume determined by the cube of the resonance wavelength. In earlier work [14], the effects of near dipole–dipole interaction on a three-level system undergoing lasing without inversion were studied, and enhancements in inversionless gain and refractive index without absorption were predicted. However, in that work, the authors treated the problem differently from the way we intend to show in this present work on a three-level system. In another work, the effect of dipole–dipole interaction has been discussed in the cavity quantum electrodynamics of two-level atoms [15,16].

This paper is organized as follows: Section 2 describes the model under consideration followed by some analytical results for linear and third-order susceptibilities of the probe transition in Section 3. Numerical results for absorption and dispersion are discussed in Section 4 by solving the exact density matrix equation. In Section 5 some concluding remarks are provided.

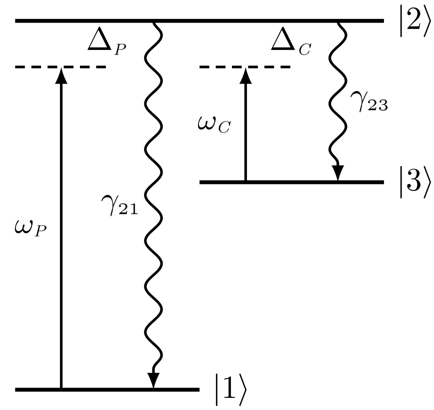

Fig. 1. Diagram of the three-level system in a Λ-configuration and driven by a probe and coupling lasers of frequencies ω_P and ω_C, respectively.

2. The model

In this work, we extend the development of atomic density operator equations for a three-level atomic system when the fields are propagating in an optically dense medium. Such a dense medium is characterized by a high number of atoms within the volume determined by the cube of the resonance wavelength. The medium consists of a three-level system in a λ-type configuration of its levels [17,18]. The model under consideration uses a semiclassical approximation where the system interacts with the classical electromagnetic fields of two lasers. The probe and coupling laser beams with frequencies ω_P and ω_C, respectively, interact with the atomic transitions ω_{21} and ω_{23}, as shown in Fig. 1. The Liouville equations of density-matrix elements in the dipole and rotating wave approximations are given by [17,18]

$$\begin{aligned}\dot{\rho}_{22} - \dot{\rho}_{11} =& -(\gamma_{23} + 2\gamma_{21})\rho_{22} + 2i\mu_{12}(\varepsilon_L^P)^*\rho_{21} - 2i\mu_{12}(\varepsilon_L^P)\rho_{12} \\ &+ i\mu_{23}(\varepsilon_L^C)^*\rho_{23} - i\mu_{23}(\varepsilon_L^C)\rho_{32} - \gamma_{31}(\rho_{33} - \rho_{11}), \\ \dot{\rho}_{22} - \dot{\rho}_{33} =& -(2\gamma_{23} + \gamma_{21})\rho_{22} + i\mu_{12}(\varepsilon_L^P)^*\rho_{21} - i\mu_{12}(\varepsilon_L^P)\rho_{12} \\ &+ 2i\mu_{23}(\varepsilon_L^C)^*\rho_{23} - 2i\mu_{23}(\varepsilon_L^C)\rho_{32} - \gamma_{31}(\rho_{11} - \rho_{33}), \\ \dot{\rho}_{23} =& -(\gamma + i\Delta_C)\rho_{23} + i\mu_{23}(\varepsilon_L^C)(\rho_{22} - \rho_{33}) - i\mu_{12}(\varepsilon_L^P)\rho_{13}, \\ \dot{\rho}_{21} =& -(\gamma + i\Delta_P)\rho_{21} + i\mu_{12}(\varepsilon_L^P)(\rho_{22} - \rho_{11}) - i\mu_{23}(\varepsilon_L^C)\rho_{31}, \\ \dot{\rho}_{31} =& -\left[\gamma_{31} + i(\Delta_P - \Delta_C)\right]\rho_{31} - i\mu_{23}(\varepsilon_L^C)^*\rho_{21} + i\mu_{12}(\varepsilon_L^P)\rho_{32}.\end{aligned} \tag{5}$$

In Eq. (5), ε_L^P and ε_L^C are complex, microscopic, slowly-varying electric field envelopes of the probe and coupling fields, respectively. The radiative decay rates from levels $|2\rangle$ to $|1\rangle$ and $|2\rangle$ to $|3\rangle$ are γ_{21} and γ_{23}, respectively. The non-radiative decay rate between levels $|3\rangle$ and $|1\rangle$ is γ_{31}. We also introduce $\gamma = \frac{1}{2}(\gamma_{21} + \gamma_{32} + \gamma_{31})$. The Rabi frequencies of the probe and coupling fields are defined as $\Omega^P = 2\mu_{12}\varepsilon_L^P$ and $\Omega^C = 2\mu_{32}\varepsilon_L^C$, respectively. The transition dipole matrix elements for transitions between levels $|1\rangle$ and $|2\rangle$ ($|3\rangle$) is μ_{12} (μ_{23}), which will be commonly represented by the symbol μ_i (with i = 12,23) in the subsequent discussion.

Since we have two electromagnetic fields interacting with the three-level system, we denote these microscopic fields by $\mathbf{E}_L^i$, with $i = P, C$, and P and C denoting the probe and coupling field, respectively. We consider fields to be linearly polarized and moving as plane waves. The three-level atom is stationary and located at position $\mathbf{r}_l$. The microscopic field is the sum of the external driving field and the reaction field of the induced dipoles in the medium [1]

$$\begin{aligned}\mathbf{E}_L^i(\mathbf{r}_l, t) = \mathbf{E}_{ext}^i(\mathbf{r}_l, t) + \sum_{m=1}^{N} \aleph_{lm}^i \exp\left[-i\mathbf{k}^i \cdot (\mathbf{r}_l - \mathbf{r}_m)\right] \\ \times \rho^i(t - r_l/c), \quad (i = P, C).\end{aligned} \tag{6}$$