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Optical Linearity Leading to Electromagnetically Induced Transparency in a Two Level System

J. Jayarubi, A. John Peter*

PG and Research Department of Physics, Government Arts College, Melur, Madurai – 625 106, Tamilnadu, India.

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ABSTRACT

In the present work, the possibility of observation of electromagnetically induced transparency in a two level system with the slow light propagation is investigated. The expression for the Rabi frequency is brought out within the rotating wave approximation and thereby it can be employed for the two level system in order to bring out the concepts of electromagnetically induced transparency in a two level system. The linear optical response of an atom with the resonant light in the medium is observed. The linear optical susceptibilities with the controlled field is found. The real part of the optical linearity leads to the refractive index of the medium.

1. Introduction

Two level quantum system can be directly applied for many physical processes in the frontier areas of quantum computation, storage of data, quantum information processing and atomic and molecular physics [1]. The possibility of observing electromagnetically induced transparency (EIT) in any low dimensional system is of great interests nowadays due to acquiring superluminal group velocities. EIT is a phenomenon in which the light controls the matter. EIT is a powerful tool which can be applied for any system transparent in accordance with the resonant oscillating field and it could be observed experimentally earlier [2-4]. In general, the EIT enhances the efficiency of any optical response in a system resulting the large optical nonlinearities [5]. The large optical susceptibilities and the large electric dipole moments are the effect of slow light propagation. EIT can be applied by manipulating signals in fibre optical communication systems [6]. The simplest example of light-atom interaction is the interaction of light in the two level system.

2. Theoretical Formulism

Here, the Hamiltonian consists of two parts namely free and interaction Hamiltonian of the system. In the presence of resonant oscillating electric field, for any two level system, the time dependent Schrödinger equation for a two level system is given by, [7]

$$\hat{H}(t) = \hat{H}_0 + \hat{H}_{int}(t) \tag{1}$$

where \hat{H}_0 which represents the unperturbed Hamiltonian having the two available eigen states denoted as $|g\rangle$ and $|e\rangle$, it is, in the absence of electric field, given by

$$\hat{H}_0 = E_1|g\rangle\langle g| + E_2|e\rangle\langle e| \tag{2}$$

with $E_2 = \hbar\omega_{eg}$ defines the energy of the excited state $|e\rangle$ which is considered with respect to the ground state $|g\rangle$. Here, the ground state

is measured as the origin of the energy axis and $\hbar\omega_{eg}$ is the atomic transition frequency. It results that the ground state energy is zero energy and the energy of the excited state is $\hbar\omega_{eg}$. Hence, the Eq.(2) becomes

$$\hat{H}_0 = \hbar\omega_{eg}|e\rangle\langle e| \tag{3}$$

The interaction Hamiltonian has the following form

$$\hat{H}_{int}(t) = \delta[|g\rangle\langle e| + |e\rangle\langle g|] \tag{4}$$

Here, δ represents the strength of the interaction. In fact, the interaction term includes the hermiticity of the Hamiltonian operator.

The second term in Eq.(1) which is defined as the interaction Hamiltonian and it is defined as

$$\hat{H}_0(t) = -\hat{p}E(z,t) \tag{5}$$

where \hat{p} is the oriented in the direction of the applied electric field and $E(z,t)$ is the oscillating electric field and it is estimated at the position of the atom expressed as

$$E(z,t) = E_0(z,t)\exp(i\omega t) + E_0^*(z,t)\exp(-i\omega t) \tag{6}$$

where E_0 is the peak amplitude of the applied electric field and E_0^* is its corresponding complex conjugate.

The dipole moment operator for a two level system is given by

$$\hat{p} = D[|g\rangle\langle e| + |e\rangle\langle g|] \tag{7}$$

where D is the modulus of the dipole moment interacting the states defined as $\langle g|x|e\rangle$. It refers the coupling strength of the laser with respect to the transition of the atom.

Hence, combining Eq.(6) and Eq.(7), the interaction term becomes,

*Corresponding Author: a.john.peter@gmail.com(A. John Peter)

$$\hat{H}_0(t) = -e\vec{E}_0(z,t)\exp(i\omega t) + \vec{E}_0^*(z,t)\exp(-i\omega t) \cdot \vec{D} [|g\rangle\langle e| + |e\rangle\langle g|] \quad (8)$$

Therefore,

$$\hat{H}_0(t) = \left[\begin{aligned} &e\vec{E}_0 \cdot \vec{D} \exp(i\omega t) |g\rangle\langle e| + e\vec{E}_0 \cdot \vec{D} \exp(i\omega t) |e\rangle\langle g| + e\vec{E}_0^* \cdot \vec{D} \exp(-i\omega t) |g\rangle\langle e| \\ &+ e\vec{E}_0^* \cdot \vec{D} \exp(-i\omega t) |e\rangle\langle g| \end{aligned} \right] \quad (9)$$

Using the time evolution operator and the interaction picture, the interaction Hamiltonian becomes,

$$\hat{H}_0(t) = \left[\begin{aligned} &e\vec{E}_0 \cdot \vec{D} \exp(2i\omega t) |g\rangle\langle e| + e\vec{E}_0 \cdot \vec{D}^* |e\rangle\langle g| + e\vec{E}_0^* \cdot \vec{D} |g\rangle\langle e| \\ &+ e\vec{E}_0^* \cdot \vec{D}^* \exp(-2i\omega t) |e\rangle\langle g| \end{aligned} \right] \quad (10)$$

Neglecting the fast oscillating term in a Hamiltonian to the time evolution of the system, known as rotating wave approximation, the Eq.(9) becomes,

$$\hat{H}_0(t) = \frac{1}{2} \hbar [\Omega |e\rangle\langle g| + \Omega^* |g\rangle\langle e|] \quad (11)$$

where the Rabi frequency (Ω) is defined as the measure of strength of the applied oscillating electric field defined as

$$\Omega = \frac{2e\vec{E}_0 \cdot \vec{D}^*}{\hbar} \quad (12)$$

The EIT arises due to the interaction of strong controlled frequency (ω_c) and the amplitude of the field (E_0) with the atomic system. Thus, the Rabi frequency becomes, $\Omega_c = (\Omega^2 + \Delta_c^2)^{1/2}$ with $\Delta_c = \omega_c - \omega_{21}$. Here, ω_{21} is the atomic transition frequency as explained earlier. Using density matrix equations of motion [8], the linear susceptibility is given by [9]

$$\chi^1(\omega_s) = \frac{2N |eD|^2 (A^* - \delta) [(\delta + i)\omega_0 - \Omega_c p_0] + \frac{1}{2} |\Omega_c|^2 \omega_0}{\hbar\Gamma (A + \delta)(A^* - \delta)(\delta + i) + (\delta + i\vec{\gamma}) |\Omega_c|^2} \quad (13)$$

with $A = (\Delta_c + i\gamma) / \Gamma$, $\delta = (\omega_s - \omega_c) / \Gamma$,

$$p_0 = -\Omega_c A^* / 2(|A|^2 + \gamma |\Omega_c|^2) \text{ and } \vec{\gamma} = \gamma / \Gamma.$$

3. Results and Discussion

Fig. 1 shows the real part of linear optical susceptibilities as a function of δ and curve brings out the optical property of the two level system. The linear optical susceptibility is based on the quantum interference. The tuned controlled field is applied to the system. This is an important condition for the occurrence of electromagnetically induced transparency. Figure clearly brings out that light passes through the medium slowly and

retains more time in the medium. Both real and imaginary parts of the linear optical susceptibilities disappear in the presence of two photon resonance. The result of coherent evolution is characterized by the Rabi flopping [10]. The optical linearities are found to be enhanced.

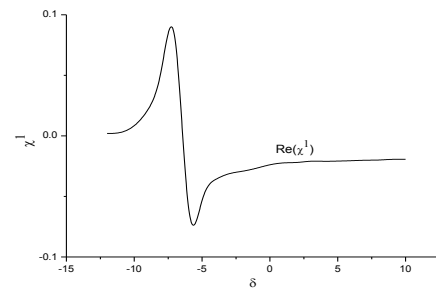


Fig. 1 Variation of linear optical susceptibilities in the presence of detuned controlled fields ($\Omega_c = 10, A = 5, \vec{\gamma} = 1$)

4. Conclusion

In conclusion, the possibility of observation of electromagnetically induced transparency in a two level system with the slow light propagation has been brought out. The expression for the Rabi frequency has been obtained and thereby applied for the two level system in order to bring out the concepts of electromagnetically induced transparency in a two level system. The linear optical response in the medium has been observed. The linear optical susceptibilities with the controlled field has been found. The enhanced optical linear susceptibilities have been observed. We hope that this two level system can be applied for various linear optical processes including optical amplification and soliton propagation in future.

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