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Effect of thermal motion on the phenomenon of electromagnetically induced transparency

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ABSTRACT

Atoms and molecules are always in random thermal motion, especially in gas system. This paper investigated the effect of thermal motion on Electromagnetically induced transparency (EIT). During this course, we adopt the theory of density matrix equation for the description of a ladder-type three-level system. The results showed that thermal motion will influence the appearance of EIT greatly and makes EIT is relate to temperature further. An obvious transparent window can be observed only when the temperature is less than 50 K. With the increase of temperature, the depth of EIT window decreases quickly until to disappear. At room temperature, we can only see the double peaks of Aulter-Townes with strong coupling field. In addition, we have also observed an interesting phenomenon that with the increase of frequency detuning of the coupling field, the peak that is away from the resonant frequency will develop into an ultra narrow one. Thermal motion will make this narrow peak disappear. Just then, the height of the whole absorption profile increases and the line width of it decreases with the increase of frequency detuning.

1. Introduction

Electromagnetically induced transparency (EIT) enables propagation of light through an opaque medium without significant damping. It is a quantum interference effect induced by a strong-coupling field interacts with two energy levels of the medium. The reduction of absorption at the resonance frequency is accompanying with a dramatically variation of dispersive [1,2]. This bring up many strange effects, such as ultraslow light propagation [3,4], no absorption enhancement of the refractive index [1,2], and nonlinear effect of single photon [5]. These unique nonlinear effects will lead to useful new devices [6–8], storage of light pulse [9,10], ultra-fine spectroscopy [11] etc. So the investigation of EIT has been an interesting topic since it was reported. Literatures show that there are three typical configurations for the formation of EIT. These include lambda, V and ladder-type. The appearance of EIT is related to the circumstance condition. For example, the height of EIT line shape increases in a nonlinear way with gradually increasing the pump power, while its width is linear [12]. The line width of EIT decreases with the increase of temperature [13]. There is competition between EIT and Raman process. At low atomic number density, EIT-induced probe spectrum is pronounced in comparison to the high-order Raman sidebands. While the generated Raman fields become dominant as the atomic number density is ten times higher [14]. Harris's demonstrated the EIT effect in a three-level ladder type lead atoms and with the probe and coupling laser propagate collinearly through the lead vapor cell. The observation of EIT requires Rabi frequency of the coupling field exceeds the inhomogeneously broadened

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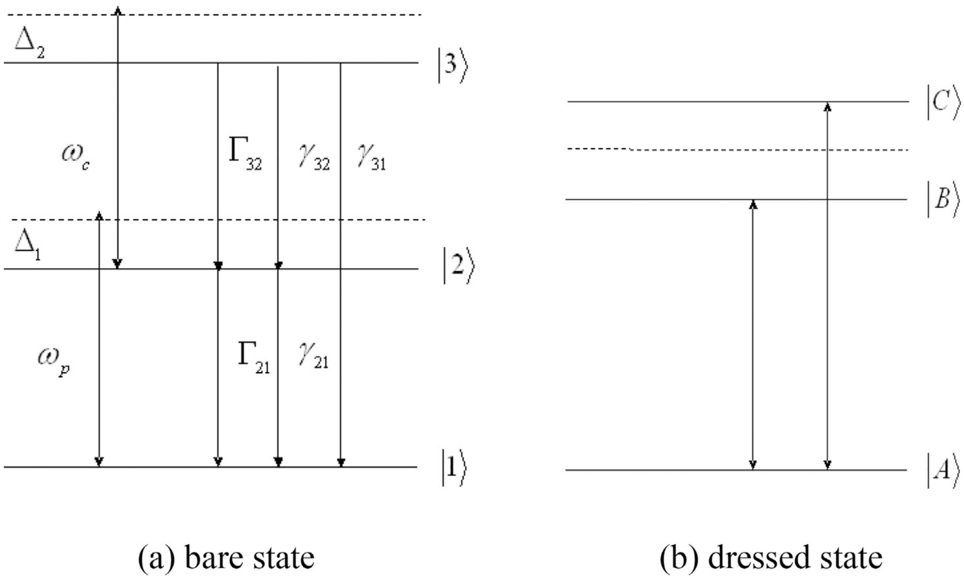

Fig. 1. Schematic diagram of ladder-type three-levels. (a) bare state. (b) dressed state.

width of the transition line. It needs a strong pulse laser as coupling field. For diminish the influence of inhomogeneously broadening on EIT, they further reduce the temperature to 2.5 K and reduce the speed of light to 17 m/s [15]. Li reported the investigation of EIT in an Rb vapor cell at room temperature and with cw diode lasers for both coupling and probe beams in a Doppler-free system [16]. These experimental results show that inhomogeneously broadening, which is caused by the thermal motion of atoms will influence the modification of EIT. This paper has done some discussion on the influence of thermal motion on EIT theoretically with the essential theory of density matrix equations.

2. Model and corresponding density matrix equations

We adopt a physical model of ladder-type three-level system. As is shown in Fig. 1(a), the three levels are coupled by two fields, one is a strong coupling laser with carrier frequency ω_c and the other is a weak probe laser with carrier frequency ω_p. The Rabi frequency of the coupling and probe fields are defined as $\Omega_c = \mu_{23}E_c/\hbar$ and $\Omega_p = \mu_{12}E_p/\hbar$ respectively. Here E_c and E_p are the amplitude of the coupling and probe field. μ_{12} and μ_{23} represent the dipole matrix element of transition $|1> \leftrightarrow |2>$ and $|2> \leftrightarrow |3>$. The transition frequency of $|2> \leftrightarrow |3>$ is ω_{32}. It is pumped by the strong coupling laser. The weak probe field drives the transition of $|1> \leftrightarrow |2>$, whose frequency is ω_{12}. The longitudinal relaxation rate Γ_{32} and Γ_{21} describe the population decay rate from level |3> and |2>. The transverse relaxation rate is $\gamma_{ij}(i>j)$. It correlates with the linewidth of spectral transition. Under rotating-wave approximation, the variation of the density matrix element about this three-level system can be written as,

$$\frac{\partial\rho_{11}}{\partial t} = i\frac{\Omega_p}{2}(\rho_{21} - \rho_{12}) + \Gamma_{21}\rho_{22} \tag{1}$$

$$\frac{\partial\rho_{22}}{\partial t} = i\frac{\Omega_c}{2}(\rho_{32} - \rho_{23}) + i\frac{\Omega_p}{2}(\rho_{12} - \rho_{21}) + \Gamma_{32}\rho_{33} - \Gamma_{21}\rho_{22} \tag{2}$$

$$\frac{\partial\rho_{33}}{\partial t} = i\frac{\Omega_c}{2}(\rho_{23} - \rho_{32}) - \Gamma_{32}\rho_{33} \tag{3}$$

$$\frac{\partial\rho_{32}}{\partial t} = d_{32}\rho_{32} - i\frac{\Omega_c}{2}(\rho_{33} - \rho_{22}) - i\frac{\Omega_p}{2}\rho_{31} \tag{4}$$

$$\frac{\partial\rho_{31}}{\partial t} = d_{31}\rho_{31} + i\frac{\Omega_c}{2}\rho_{21} - i\frac{\Omega_p}{2}\rho_{32} \tag{5}$$

$$\frac{\partial\rho_{21}}{\partial t} = d_{21}\rho_{21} - i\frac{\Omega_p}{2}(\rho_{22} - \rho_{11}) + i\frac{\Omega_c}{2}\rho_{31} \tag{6}$$

Where $d_{32} = i\Delta_2 - \gamma_{32}$, $d_{31} = i(\Delta_1 + \Delta_2) - \gamma_{31}$ and $d_{21} = i\Delta_1 - \gamma_{21}$ represent the complex detuning, $\Delta_1 = \omega_{21} - \omega_p$ and $\Delta_2 = \omega_{32} - \omega_c$ are the frequency detuning of the probe and the coupling field. The transition between levels |1> and |3>