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Wavelength mismatch effect in electromagnetically induced absorption

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ABSTRACT

We present a theoretical investigation of the phenomenon of electromagnetically induced absorption (EIA) in a 4-level system consisting of vee and ladder subsystems. The four levels are coupled using one weak probe field, and two strong control fields. We consider an experimental realization using energy levels of Rb. This necessitates dealing with different conditions of wavelength mismatch—near-perfect match where all three wavelengths are approximately equal; partial mismatch where the wavelength of one control field is less than the other fields; and complete mismatch where all three wavelengths are unequal. We present probe absorption profiles with Doppler averaging at room temperature to account for experiments in a room temperature Rb vapor cell. Our analysis shows that EIA resonances can be studied using Rydberg states excited with diode lasers.

1. Introduction

The phenomenon of electromagnetically induced transparency (EIT) is one where an initially absorbing medium is rendered transparent by having a strong control field on an auxiliary transition. EIT therefore requires the presence of at least three levels, and consequently has been studied in the three canonical types of 3-level systems, namely lambda (Λ), vee (V), and ladder (Ξ) [1,2]. The presence of additional levels allows the use of additional control fields, which leads to a modification of the EIT window. Such extended systems allow the possibility of electromagnetically induced absorption (EIA), a phenomenon where an initially absorbing medium shows enhanced absorption at line center. EIA has been studied—both theoretically and experimentally—primary in N-type ($\Lambda + \mathrm{V}$) 4-level systems [3–6]. We have recently shown that EIA resonances are also possible in a new kind of 4-level system made by adding vee and ladder configurations [7]. This configuration opens up the possibility of observation of EIA in Rydberg atoms, and has potential applications in switching a medium between sub-luminal and super-luminal light propagation.

When EIT and EIA phenomena are studied in an atomic vapor at a finite temperature, the thermal motion affects the probe absorption profile due to the Doppler effect. The Doppler shift is determined by the velocity of the atom and the wavelengths of the fields, which then determines the detunings Δ_p and Δ_c in the atom's frame of reference. Since the two-photon absorption for a V-type system contains the term $\Delta_p - \Delta_c$, the medium can be made Doppler free by choosing the beams to be co-propagating and of the same wavelengths. Similarly, the two-photon absorption for a ladder-type system contains the term $\Delta_p + \Delta_c$, and hence the medium can be made Doppler free by using counter-propagating beams that are of the same wavelength. This corresponds to a perfect wavelength matching condition, and results in a narrowing of the transparency window [8–10].

However, experimental realization in a real atomic system cannot always satisfy this perfect wavelength matching condition. The difference in wavelengths then leads to a modification of the absorption profile. EIT, under conditions of wavelength mismatch, has therefore been investigated in the three types of 3-level systems [8, 11–15]. It has also been studied in a Y-type 4-level system which only shows EIT (and not EIA) [16,17].

In this work, we extend the study of wavelength mismatch to the phenomenon of EIA in a 4-level system made using vee and ladder subsystems. This analysis is particularly important when the uppermost state is a Rydberg state. In fact, one proposed method of populating Rydberg states using diode lasers [18] results in the EIA window disappearing due to Doppler averaging of the mismatched wavelengths. We therefore propose an alternate scheme for excitation of Rydberg state.

2. Theoretical considerations

The combination of vee and ladder configuration used to form the 4-level system is shown in Fig. 1. The weak probe field is com-

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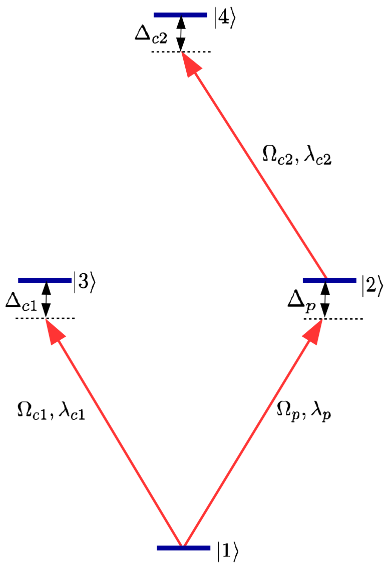

Fig. 1. (Color online) 4-level vee + ladder system under consideration.

mon to both configurations, and couples levels $|1\rangle$ and $|2\rangle$. The vee configuration is formed using level $|3\rangle$, with a strong control field coupling levels $|1\rangle$ and $|3\rangle$. The ladder configuration is formed using level $|4\rangle$, with a strong control field coupling levels $|2\rangle$ and $|4\rangle$. The respective fields are denoted by: wavelength λ, strength Ω, and detuning Δ.

The Hamiltonian of the system (in the rotating wave approximation) for an atom moving with velocity v is given by

$$\begin{aligned} H = {} & \frac{\hbar}{2}\left[\Omega_p\,|1\rangle\langle 2| + \Omega_{c1}\,|1\rangle\langle 3| + \Omega_{c2}\,|2\rangle\langle 4|\right] + \text{h.c.} \\ & + \hbar\left[\left(\Delta_p \pm k_p v\right)|2\rangle\langle 2| + \left(\Delta_{c1} \pm k_{c1} v\right)|3\rangle\langle 3| \right. \\ & \left. + \left(\Delta_p \pm k_p v + \Delta_{c2} \mp k_{c2} v\right)|4\rangle\langle 4|\right] \end{aligned} \tag{1}$$

where $k = 2\pi/\lambda$, is the wavevector of the respective field, and kv is the corresponding Doppler shift seen by the atom. As discussed earlier, the Doppler shift is minimized by having the probe and control 1 fields co-propagating (for the vee subsystem), and control 2 field counter-propagating (for the ladder subsystem). The equations of motion for the various density-matrix elements for this system are given in Appendix A.

The observable in this work is the absorption of the probe field in the presence of the two control fields. It is proportional to the imaginary part of the coherence between levels $|1\rangle$ and $|2\rangle$, and is given by $\text{Im}\{\rho_{12}\Gamma_2/\Omega_p\}$. As shown in Appendix B, the system reaches steady state after a few lifetimes of $|2\rangle$, which means it is reached in 2 μs or less. For comparison to earlier expressions for EIT in the three-level subsystems [19,20]—which can be obtained by setting the appropriate control Rabi frequency to 0—we give below an analytic expression for ρ_{12} in steady state and to first order in Ω_p.

$$\begin{aligned} \rho_{12} = {} & -\frac{i\Omega_p\rho_{11}}{2\gamma_{12}\beta} + \frac{i\Omega_p|\Omega_{c1}|^2(\rho_{11}-\rho_{33})}{8\gamma_{12}\gamma_{31}\gamma_{32}\beta} \\ & \times\left(1 - \frac{|\Omega_{c2}|^2}{4\gamma_{32}\gamma_{34}\alpha} - \frac{|\Omega_{c2}|^2}{4\gamma_{14}\gamma_{34}\alpha}\right) \end{aligned} \tag{2}$$

where

$$\rho_{11} - \rho_{33} = \left[1 + \frac{|\Omega_{c1}|^2}{2\left(\frac{\Gamma_3^2}{4} + (\Delta_{c1} \pm k_{c1}v)^2\right)}\right]^{-1}$$

$$\beta = 1 + \frac{|\Omega_{c1}|^2}{4\gamma_{12}\gamma_{32}} + \frac{|\Omega_{c2}|^2}{4\gamma_{12}\gamma_{14}} - \frac{|\Omega_{c1}|^2|\Omega_{c2}|^2}{16\gamma_{12}\gamma_{34}\alpha}\left[\frac{1}{\gamma_{32}} + \frac{1}{\gamma_{14}}\right]^2$$

$$\alpha = 1 + \frac{|\Omega_{c1}|^2}{4\gamma_{14}\gamma_{34}} + \frac{|\Omega_{c2}|^2}{4\gamma_{32}\gamma_{34}}$$

$$\gamma_{12} = \left(-\frac{\Gamma_2}{2} + i(\Delta_p \pm k_p v)\right)$$

$$\gamma_{31} = \left(-\frac{\Gamma_3}{2} - i(\Delta_{c1} \pm k_{c1} v)\right)$$

$$\gamma_{14} = \left(-\frac{\Gamma_4}{2} + i(\Delta_p \pm k_p v + \Delta_{c2} \mp k_{c2} v)\right)$$

$$\gamma_{32} = \left(-\frac{\Gamma_2 + \Gamma_3}{2} - i(\Delta_{c1} \pm k_{c1} v - \Delta_p \mp k_p v)\right)$$

$$\gamma_{34} = \left(-\frac{\Gamma_3 + \Gamma_4}{2} + i(\Delta_p \pm k_p v + \Delta_{c2} \mp k_{c2} v - \Delta_{c1} \mp k_{c1} v)\right)$$

In Eq. (2), Γ's are the relaxation rates of corresponding energy levels.

3. Results and discussion

We will analyze different mismatching conditions by looking at experimental realization of the 4 levels using appropriate energy levels of Rb. Probe absorption given by Eq. (2) is shown for the various cases, along with Doppler averaging to account for the situation in room temperature vapor. In all cases, level $|1\rangle$ is taken to be the $5S_{1/2}$ ground state with $\Gamma = 0$. The results are shown for resonant control fields, i.e. $\Delta_{c1} = \Delta_{c2} = 0$. The strengths of both fields are taken to be equal to $3\Gamma_2$, i.e. $\Omega_{c1} = \Omega_{c2} = 3\Gamma_2$. The strength of the probe field is taken to be small enough to satisfy the weak probe condition, i.e. $\Omega_p/2\pi = 0.001$ MHz.

3.1. Near-perfect match

This situation corresponds to $\lambda_p \approx \lambda_{c1} \approx \lambda_{c2}$. It is realized using the following states:

Level	Rb state	$\Gamma/2\pi$ (MHz)	Wavelength (nm)
$\|2\rangle$	$5P_{3/2}$	6.1	$\lambda_p = 780$
$\|3\rangle$	$5P_{1/2}$	5.9	$\lambda_{c1} = 795$
$\|4\rangle$	$5D_{5/2}$	0.68	$\lambda_{c2} = 776$

The results for this case are shown in Fig. 2. The 3D contour plot in part (a) shows the variation with both atomic velocity and probe detuning. There is an EIA peak on resonance and increased absorption at $\Delta_p = \pm 3\Gamma_2$, because the poles in Eq. (2) are at $(\pm\Omega_{c1} \pm \Omega_{c2})/2$. The near-equal wavelengths makes the geometry of the beams Doppler free. Therefore, the EIA peak at line center survives Doppler averaging. These results are shown in part (b), and correspond to a Maxwell–Boltzmann distribution covering a velocity range of −500 to +500 m/s, which is adequate for room temperature vapor.

3.2. Partial mismatch

This situation corresponds to the wavelength of the probe field being approximately equal to that of one control field, but differing from the other one. This is further distinguished into two, depending on the relative value of the mismatched wavelength.

Case 1. $\lambda_p \approx \lambda_{c1} > \lambda_{c2}$

This case is realized using the following states:

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