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Absorptive reduction and width narrowing in Λ-type atoms confined between two dielectric walls

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This paper investigates the absorptive reduction and the width narrowing of electromagnetically induced transparency (EIT) in a thin vapour film of Λ-type atoms confined between two dielectric walls whose thickness is comparable with the wavelength of the probe field. The absorptive lines of the weak probe field exhibit strong reductions and very narrow EIT dips, which mainly results from the velocity slow-down effects and transient behaviour of atoms in a confined system. It is also shown that the lines are modified by the strength of the coupling field and the ratio of L/λ, with L the film thickness and λ the wavelength of the probe field. A simple robust recipe for EIT in a thin medium is achievable in experiment.

Keywords: absorptive reduction, width narrowing, electromagnetically induced transparency
PACC: 0765, 6800

1. Introduction

Electromagnetically induced transparency (EIT) termed by Harris and co-workers is a quantum interference effect introduced by driving the upper two levels of a three level atomic system with a strong coherent field. Under appropriate conditions, the medium becomes effectively transparent (zero absorption) for a probe field.[1−3] The importance of EIT stems from the fact that it gives rise to greatly enhanced nonlinear susceptibility in the spectral region of induced transparency of the medium and is associated with steep dispersion, this gives ultraslow group velocities and the storage of light which may be used in quantum information processing.[3,4] Various mediums have been used in previous investigation of EIT, the first observation of EIT was in an optically thick medium of a strontium vapour,[1] then in solids,[5] vapour cells,[6,7] atomic beams,[8] laser cooled atoms,[9] and even Bose Einstein condensates.[10]

In this paper, we examine the EIT effect discussed in Ref.[7], and extend to a system with atomic vapour confined between two $\lambda/2$ or λ separated dielectric walls. The difference from Ref.[7] is that we give an analytical solution of the density matrix element, by which we investigate the EIT features in a thin atomic vapour film modified by L/λ and the strength of the coupling field. By using such a system, a simple recipe is achievable for strong absorptive reductions and width narrowing in EIT. This indicates a perfect EIT and ultraslow group velocities, which could be used in light storage and the quantum information processing.

2. Formulation

A vapour of Λ-type three-level atoms confined in an ultrathin cell of thickness L with two antireflection coated windows (i.e., the Fabry–Perot effects are neglected) is considered here. The atomic level scheme is presented in Fig.1, three unperturbed levels $|1\rangle$, $|2\rangle$ and $|3\rangle$ have energies E_1, E_2 and E_3, respectively. The transition frequency of $|1\rangle-|3\rangle$ is ω_{31}, and ω_{32} for the transition $|2\rangle-|3\rangle$. Two laser fields are applied to the system, $\omega_{\rm p}$ is the frequency of the probe field $E_{\rm p}$ (with a detuning $\varDelta_{\rm p}=\omega_{\rm p}-\omega_{31}$) and $\omega_{\rm c}$ is the frequency of the coupling field $E_{\rm c}$ (with a detuning $\varDelta_{\rm c}=\omega_{\rm c}-\omega_{32}$).

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For simplicity, the initial phases of E_p and E_c are assumed to be the same.

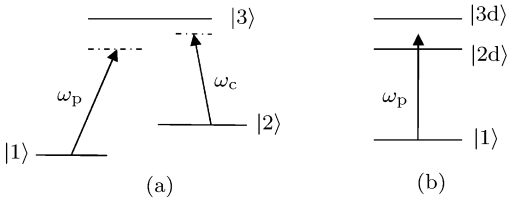

Fig.1. Configuration in a Λ-type three level system for (a) level diagram, and (b) dressed-state picture.

The state of the atoms in the vapour is determined by the density matrix $\rho(v,z,t)$, which yields the master equation

$$\left[\frac{\partial}{\partial t}+v\frac{\partial}{\partial z}\right]\rho=-\frac{\mathrm{i}}{\hbar}[H,\rho]-\varGamma\rho. \quad (1)$$

The diagonal elements of the Hamiltonian H are the energies E_1, E_2 and E_3 of levels $|1\rangle$, $|2\rangle$ and $|3\rangle$ respectively, whereas the off-diagonal ones represent the interaction energies with the radiation field. In the rotating-wave approximation, these off-diagonal elements are given by the expressions

$$\begin{aligned}H_{31}=&-\hbar\varOmega_\mathrm{p}\exp[-\mathrm{i}(\omega_\mathrm{p}t-k_\mathrm{p}z)],\quad H_{13}=H_{31}^*,\\H_{32}=&-\hbar\varOmega_\mathrm{c}\exp[-\mathrm{i}(\omega_\mathrm{c}t-k_\mathrm{c}z)],\quad H_{23}=H_{32}^*,\\H_{12}=&H_{21}^*=0.\end{aligned} \quad (2)$$

Where $\varOmega_\mathrm{p}$ and $\varOmega_\mathrm{c}$ are Rabi frequencies defined as $\varOmega_\mathrm{p}=\mu_{31}E_\mathrm{p}/\hbar$ and $\varOmega_\mathrm{c}=\mu_{31}E_\mathrm{c}/\hbar$ respectively with μ_{31} and μ_{32} the transition dipole moments, k_p and k_c are wave vectors of the probe and the coupling fields respectively.

The term $-\varGamma\rho$ in Eq.(1) describes spontaneous decay in atomic system, in our situation, only following transverse relaxations are considered

$$\begin{aligned}-(\varGamma\rho)_{21}&=-\gamma_{21}\rho_{21},\\-(\varGamma\rho)_{32}&=-\gamma\rho_{32},\\-(\varGamma\rho)_{31}&=-\gamma\rho_{31}.\end{aligned} \quad (3)$$

Where the average decay rate is given by $\gamma=(\gamma_{32}+\gamma_{31}+\gamma_{21})/2$, γ_{31} and γ_{32} are the decay rates from level $|3\rangle$ to levels $|1\rangle$ and $|2\rangle$ respectively. It is assumed that the transition between level $|1\rangle$ and level $|2\rangle$ is dipole forbidden, as is the case for hyperfine sublevels of an atomic ground sate. The nonradiative decay rate (including transient effects and collisional dephasing) between these two lower levels is denoted by γ_{21}.

We introduce time-reduced form density matrix σ by introducing transformations

$$\begin{aligned}\rho_{31}&=\sigma_{31}\exp[-\mathrm{i}(\omega_\mathrm{c}t-k_\mathrm{c}z)],\\\rho_{32}&=\sigma_{32}\exp[-\mathrm{i}(\omega_\mathrm{p}t-k_\mathrm{p}z)],\\\rho_{21}&=\sigma_{21}\exp\{-\mathrm{i}[(\omega_\mathrm{p}-\omega_\mathrm{c})t-(k_\mathrm{p}-k_\mathrm{c})z]\},\end{aligned} \quad (4)$$

together with conjugate expressions of Eq.(4). Here in our model for a co-propagation regime k_p and k_c are in the same sign, for simplicity we assume $k_\mathrm{p,c}>0$. For such a three-level system, we consider only following equations obtained by combining Eqs.(1)–(4):

$$\partial\sigma_{31}/\partial t=-\varLambda_{31}\sigma_{31}+\mathrm{i}\varOmega_\mathrm{p}(\sigma_{11}-\sigma_{33})+\mathrm{i}\varOmega_\mathrm{c}\sigma_{21}, \quad (5a)$$

$$\partial\sigma_{21}/\partial t=-\varLambda_{21}\sigma_{21}-\mathrm{i}\varOmega_\mathrm{p}\sigma_{23}+\mathrm{i}\varOmega_\mathrm{c}\sigma_{31}, \quad (5b)$$

$$\partial\sigma_{23}/\partial t=-\varLambda_{32}^*\sigma_{23}-\mathrm{i}\varOmega_\mathrm{p}\sigma_{21}-\mathrm{i}\varOmega_\mathrm{c}(\sigma_{22}-\sigma_{33}). \quad (5c)$$

Where we have used Doppler-shifted detuning defined as

$$\begin{aligned}\varLambda_{31}=&\gamma-\mathrm{i}(\varDelta_\mathrm{p}-k_\mathrm{p}v),\\\varLambda_{32}=&\gamma-\mathrm{i}(\varDelta_\mathrm{c}-k_\mathrm{c}v),\\\varLambda_{21}=&\gamma_{21}-\mathrm{i}[(\varDelta_\mathrm{p}-k_\mathrm{p}v)-(\varDelta_\mathrm{c}-k_\mathrm{c}v)].\end{aligned}$$

Assume that the very weak absorption in the thin vapour is satisfied, then the relative absorption A is given in Ref.[7] by

$$A=\frac{I_\mathrm{p}(0)-I_\mathrm{p}(L)}{I_\mathrm{p}(0)}=\int_0^L\alpha(z)\mathrm{d}z. \quad (6)$$

Where the intensity of the probe field $I_\mathrm{p}(z)$ is proportional to $|E_\mathrm{p}|^2$, the local absorption α of the medium is defined as

$$\alpha=4\pi k_\mathrm{p}\mathrm{Im}\left(\frac{P_\mathrm{o}(z)}{E_\mathrm{p}}\right). \quad (7)$$

If the atomic thermal motion is taken into account, which is assumed to obey the Maxwell distribution $W(v)=(u\sqrt{\pi})^{-1}\exp(-v^2/u^2)$ with u being the probable velocity, the medium polarization in Eq.(7) is given by

$$\begin{aligned}P_\mathrm{o}(z)=&N\mu_{31}\int_{-\infty}^{\infty}W(v)[\varTheta(v)\sigma_{31}^+\\&+\varTheta(-v)\sigma_{31}^-]\mathrm{d}v.\end{aligned} \quad (8)$$

Where $\varTheta(v)$ and $\varTheta(-v)$ are Heaviside functions, N is the density of atoms in the vapour, σ_{31}^+ and σ_{31}^- are the density matrix elements for $v>0$ and $v<0$ respectively.

One then gets the absorption averaged over the velocity distribution from Eqs.(6)–(8) as

$$\begin{aligned}\langle A\rangle=&4\pi k_\mathrm{p}N\mu_{31}\int_{-\infty}^{\infty}W(v)\mathrm{d}v\\&\times\int_0^L\mathrm{Im}\left[\frac{\varTheta(v)\sigma_{31}^++\varTheta(-v)\sigma_{31}^-}{E_\mathrm{p}}\right]\mathrm{d}z.\end{aligned} \quad (9)$$

We consider here that only the first order solution of σ_{31} for the probe field is much weak than the coupling field, and the population in the high level is assumed much less than that in the ground level. Thus $\Omega_{\rm p}$ in Eq.(5b) can be neglected, and an approximation can be done

$$\sigma_{11}^{(0)} \approx 1, \sigma_{22}^{(0)} = \sigma_{33}^{(0)} = 0. \tag{10}$$

By using Laplace transform, Eqs.(5a) and (5b) can be expressed as

$$(s + \Lambda_{31})L[\sigma_{31}^1] = {\rm i}\Omega_{\rm p}/s + {\rm i}\Omega_{\rm c}L[\sigma_{21}^1], \tag{11a}$$

$$(s + \Lambda_{21})L[\sigma_{21}^1] = {\rm i}\Omega_{\rm c}L[\sigma_{31}^1]. \tag{11b}$$

To get Eqs.(11a) and (11b), we have assumed $\sigma_{31}^1(t = 0) = \sigma_{21}^1(t = 0) = 0$ for the initial conditions. Solving Eqs.(11a) and (11b), one has

$$L[\sigma_{31}^1] = \frac{{\rm i}\Omega_{\rm p}(s + \Lambda_{21})}{s[(s + \Lambda_{21})(s + \Lambda_{31}) + \Omega_{\rm c}^2]}. \tag{12}$$

The first order solution σ_{31}^1 can be obtained by using inverse-Laplace transform to Eq.(12), and expressed as

$$\sigma_{31}^1(t) = {\rm i}\Omega_{\rm p}[D_0 + D_1\exp(-\lambda_1 t) + D_2\exp(-\lambda_2 t)]. \tag{13}$$

Where

$$D_0 = \frac{\Lambda_{21}}{\lambda_1\lambda_2}, \qquad D_1 = \frac{-\lambda_1 + \Lambda_{21}}{\lambda_1(\lambda_1 - \lambda_2)},$$
$$D_2 = \frac{-\lambda_2 + \Lambda_{21}}{\lambda_2(-\lambda_1 + \lambda_2)}$$

with

$$\lambda_{1,2} = \frac{p_{1,2} - (\Lambda_{21} + \Lambda_{31})}{2},$$

$$p_{1,2} = \pm\sqrt{|q|}\,\{\cos[{\rm Arg}(q)/2] + {\rm i}\sin[{\rm Arg}(q)/2]\}\,,$$

and

$$q = (\Lambda_{31} - \Lambda_{21})^2 - \Omega_{\rm c}^2.$$

Atoms experience inelastic collisions with the walls, during these collisions they lose optical excitation and all memory about the previous state, then it is justified to assume that atoms get de-excited at a collision with the wall, and are in the ground states at the instant that they leave the wall after a collision. Thus we use $t = z/v$ for $v > 0$ and $t = (z - L)/v$ for $v < 0$, substituting Eq.(13) into Eq.(9) and changing the integrate orders of z and v, one then get

$$\langle A\rangle = 4\pi N\mu_{31}^2/\hbar\int_{-\infty}^{\infty} k_{\rm p}|v|W(v){\rm d}v{\rm Im}\Big\{{\rm i}D_0L + {\rm i}\sum\frac{D_j|v|}{\lambda_j}[1 - \exp(-\lambda_jL/|v|)]\Big\}, \quad (j = 1, 2). \tag{14}$$

Equation (14) is the main result of our calculation. The form is similar to the formulation we obtained and discussed in previous papers.[11,12] It is apparent that the absorption and the phase shift are modified by the thickness of the vapour film, i.e., Dicke-narrowing induced by atom–wall collision and the transient effect of atoms confined between dielectric walls are important factors which contribute to EIT effect just as it is in a usual thin vapour spectroscopy.

3. Numerical results and conclusion

Equation (14) is used for numerical calculation of the absorption lines of the probe field, where parameters are chosen to correspond to D_1 line of ^{87}Rb, the coupling beam couples level $|2\rangle$ ($F = 2, 5^2S_{1/2}$) to level $|3\rangle$ ($F = 2, 5^2P_{1/2}$), and level $|1\rangle$ ($F = 1, 5^2S_{1/2}$) to level $|3\rangle$ ($F = 2, 5^2P_{1/2}$) for the weak probe beam. Other selected values are $\gamma_{31} = 2\pi\times 4.79\,$MHz, $\gamma_{32} = 2\pi\times 2.87\,$MHz, $\gamma_{21} = 2\pi\times 10\,$kHz, and $\omega_{32} \approx \omega_{31} = 2\pi\times 377.11\,$THz (a Doppler free configuration). For a typical vapour cell we assume that $N = 6\times 10^{12}/{\rm cm}^3$, $u = 274\,$m/s (assuming the vapour is heated to 120°C). In all cases the coupling field accurately detuned to the transition $|2\rangle - |3\rangle$ is assumed, i.e. $\Delta_{\rm c} = 0$.

As is shown in Fig.2, the absorption lines versus $\Delta_{\rm p}/\gamma$ are obtained for different coupling strength. Where only two typical thickness half λ and λ are considered. We find that EIT effect is manifest for both $L = \lambda/2$ and $L = \lambda$ cases when the resonant strong coupling field is applied to the system. This is similar to a usual macroscopic vapour cell for EIT resulting from a combination of the ac-Stark splitting and the interference between two dressed states (Fig.1) created by the coupling laser.[1] The different points for EIT in a thin cell are the strong absorptive reduction, the much narrow width of EIT dips. This mainly results from two factors, one is the slowest atoms trapped in a dark state in the thin vapour which do not contribute to absorption, and another is the strength of the coupling field. With a stronger coupling field applying to the system, more atoms with a relatively small velocity are trapped, which enhance the absorptive reduction and the very narrow EIT width. However when the coupling field is much strong, the power broadening is also induced, which increases the width of EIT dips. As the strength of the coupling field increases, a perfect EIT can be found in Fig.2, e.g., 2(c) and 2(d). Atom-wall collision also contributes to the width narrowing of EIT, for only the slowest atoms are responsible for the EIT effect, and the ground levels' coherence relaxation time for these atoms is very large, thus very narrow EIT dips are obtained.[7] Another point should be noted is that, the magnitude but not the width of lines are strongly modified by L/λ. The Dicke type narrowing phenomena appear both for $L = \lambda/2$ and $L = \lambda$, this is because both Doppler free and Dicke-narrowing regime contribute to line shape narrowing as has been discussed in Ref.[12].

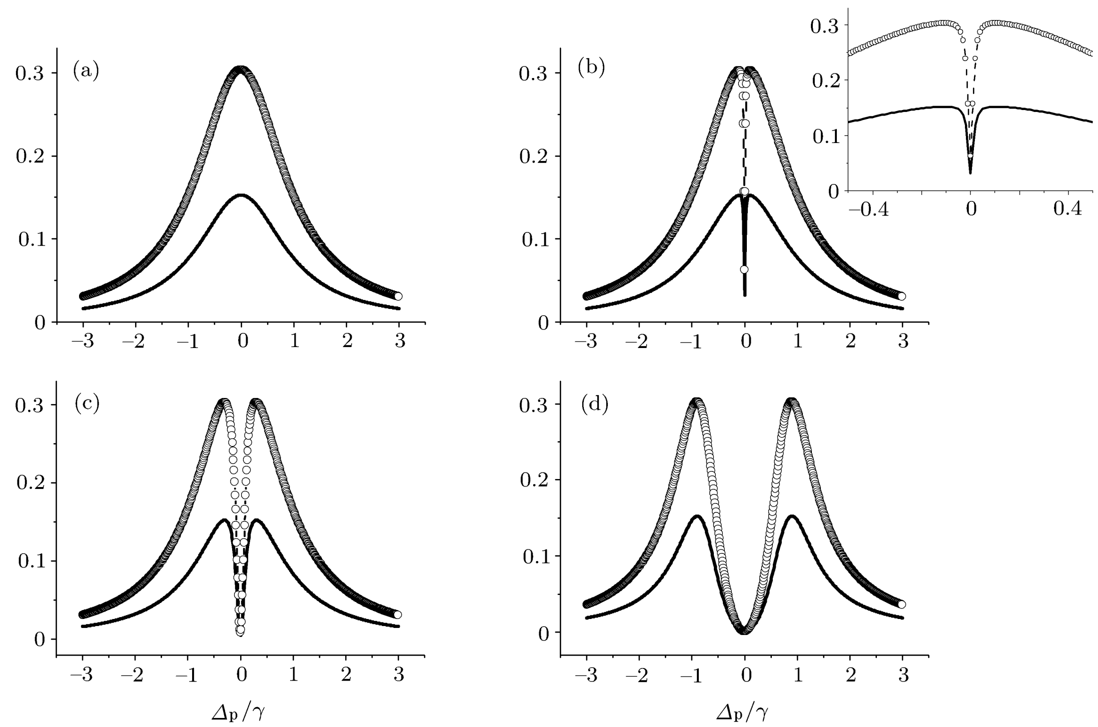

Fig.2. Absorption lines as a function of Δ_p/γ, solids for $L = \lambda/2$ and circles plus dashed lines for $L = \lambda$, (a), (b), (c), and (d) for $\Omega_\mathrm{c} = 0$, 0.1γ, 0.3γ, and 0.9γ respectively.

A surface plotting given in Fig.3 shows the absorption of confined atoms as a function of Δ_p/γ and Ω_c/γ for (a) $L = \lambda/2$, and (b) $L = \lambda$ respectively. The similar shape clearly shows that the ratio L/λ modifies mainly the absorptive deepness rather than lines width in such a two photon case. As increasing the strength of the coupling field, the absorptive reduction enhances, and the width of the dips of EIT gets weaker. Keeping the probe field much weak than the coupling field, in this case when $\Omega_\mathrm{c} > 0.3\gamma$, the complete transparency can be easily achieved.

In conclusion, we investigate EIT in a thin vapour film of Λ-type atoms confined between two dielectric walls whose thickness is $\lambda/2$ or λ, with λ the wavelength of the probe field. Strong absorptive reductions, very narrow EIT dips resulting from the slowest atoms and the transient effects in such a confined system indicate a simple robust recipe for EIT experiment in a thin vapour medium. Comparing with expensive cold atom technology, we easily implement ultraslow group velocities and the storage of light.

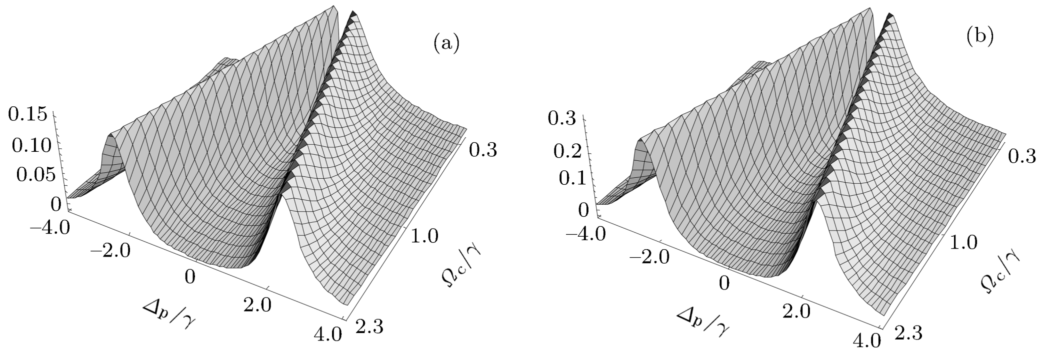

Fig.3. Absorption as a function of $\Delta_{\rm p}/\gamma$ and $\Omega_{\rm c}/\gamma$ for (a) $L = \lambda/2$, and (b) $L = \lambda$.

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