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Absorption properties of a driven Doppler-broadened ladder system with hyperfine structure*

Wu Jin-Hui(吴金辉)[a] and Gao Jin-Yue(高锦岳)[a,b]

[a] *College of Physics, Jilin University, Changchun* 130023, *China*

[b] *China Center of Advanced Science and Technology (World Laboratory), Beijing* 100080, *China*

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We have studied the absorption spectrum of a Doppler-broadened ladder system, where the highest level is coupled into two middle hyperfine sublevels by a strong coherent field. We find that, when the system is considered as homogeneous, either two or three spectral components are observed, depending on the detuning of the coherent field. But when the velocity distribution of atoms is considered, we can always observe one electromagnetically induced transparency (EIT) window with high dispersion. So the atomic hyperfine structure cannot be an impediment for obtaining EIT.

Keywords: absorption spectrum, electromagnetically induced transparency, dressed atomic states
PACC: 4250, 3150

1. Introduction

The study of spectral properties in multi-level atomic systems has been a focus of quantum optics research since the 1970s.[1,2] In the last ten years, with the advance in electromagnetically induced transparency (EIT),[3−6] lasing without population inversion (LWI)[7−11] and electromagnetically induced two-photon transparency (EITT),[12−14] it is again an interesting research field.[15−17] Most often, no hyperfine structure is considered either in a three-level system or in a four-level system. While in a real atomic system, atomic states always have hyperfine structure, which it is essential to consider if the system is optically thick (which means that the Doppler broadening has to be included) or the coherent field is very strong (comparable to the energy difference between hyperfine sublevels). The question then arises: how do the hyperfine sublevels affect mutually to contribute a spectrum that is different from that of a system without hyperfine structures? For simplicity in calculation, here we just consider a system with only two hyperfine sublevels, but conclusions in this paper can be easily generalized to systems with more hyperfine sublevels.

In this paper, we focus on the absorption spectrum of a four-level ladder system (see Fig.1) both with and without Doppler broadening. If we ignore the velocity distribution of atoms, i.e. the system is considered as homogeneous, we find that the absorption spectrum here is different from that of a driven three-level ladder system, because a third spectral component may appear or disappear depending on the detuning of the coherent field. However, if the atomic velocity distribution is taken into consideration, then only one EIT window can be observed at the point of $\Delta_{\rm p} = \Delta_{\rm c}$, even if there are three spectral components in fact. The Doppler-broadened dispersion spectrum is also explored, which is similar to that of a corresponding driven three-level system.

This paper is organized as follows. Firstly, we obtain the complex susceptibility of the probe transition by a semiclassical analysis in section 2. Then, a few graphic results under different situations are illustrated and analysed in the dressed-state representation in section 3. Finally, a few important conclusions are presented in section 4.

2. Calculation of the complex susceptibility

As shown in Fig.1, a coherent field couples level $|4\rangle$ into two hyperfine sublevels $|2\rangle$ and $|3\rangle$ simultaneously. $G_{\rm c} = \dfrac{\boldsymbol{E}_{\rm c}\cdot\boldsymbol{\mu}_{\rm c}}{2\hbar}$, $\omega_{\rm c}$ and $\Delta_{\rm c}$ are the Rabi frequency, carrier frequency and detuning of the strong coherent field, respectively. $G_{\rm p} = \dfrac{\boldsymbol{E}_{\rm p}\cdot\boldsymbol{\mu}_{\rm p}}{2\hbar}$, $\omega_{\rm p}$ and $\Delta_{\rm p}$ are the Rabi frequency, carrier frequency and de-

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tuning of the weak probe field, respectively. γ_{21}, γ_{31}, γ_{42}, and γ_{43} are the spontaneous decay rates of the corresponding atomic levels, respectively. 2Δ is the frequency difference between the two middle sublevels. To simplify the following calculation, Rabi frequencies $G_{\rm c}$ and $G_{\rm p}$ are set to be real numbers and the constant $\hbar$ is set to equal one.

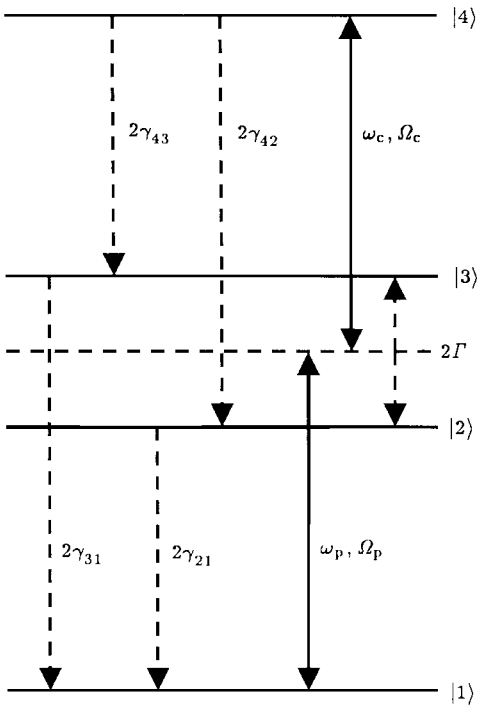


Fig.1. A schematic representation of a four-level ladder atomic system with a hyperfine structure.

Under the dipole approximation and the rotating-wave approximation, the absorption and dispersion spectra of this system can be obtained as follows. In the interaction picture, the interaction Hamiltonian of this ladder system with a hyperfine structure can be expressed as

$$H_{\rm I} = \begin{pmatrix} 0.0 & -G_{\rm p} & -G_{\rm p} & 0.0 \\ -G_{\rm p} & \Delta_{\rm p}-\Delta & 0.0 & -G_{\rm c} \\ -G_{\rm p} & 0.0 & \Delta_{\rm p}+\Delta & -G_{\rm c} \\ 0.0 & -G_{\rm c} & -G_{\rm c} & \Delta_{\rm p}+\Delta_{\rm c} \end{pmatrix}, \tag{1}$$

where $\Delta_{\rm c} = (\omega_4 - \omega_0) - \omega_{\rm c}$, $\Delta_{\rm p} = \omega_0 - \omega_{\rm p}$, $\Delta = \frac{1}{2}(\omega_3 - \omega_2)$, $\omega_0 = \frac{1}{2}(\omega_3 + \omega_2)$.

The master equation of motion for the density operator in an arbitrary multi-level atomic system in the interaction picture can be written as

$$\frac{\partial \rho}{\partial t} = -\frac{\rm i}{\hbar}[H_{\rm I}, \rho] + \Lambda\rho. \tag{2}$$

On the right-hand side of Eq.(2), the first part includes all the coherent terms arising from the coherent and probe fields, while the second part includes all irreversible contributions due to the spontaneous emissions. For the system under study, according to Eqs.(1) and (2), we obtain the following equations of density matrix

$$\begin{aligned}
\dot\rho_{11} =& 2\gamma_{21}\rho_{22} + 2\gamma_{31}\rho_{33} + {\rm i}G_{\rm p}\rho_{31} \\
&+ {\rm i}G_{\rm p}\rho_{21} - {\rm i}G_{\rm p}\rho_{12} - {\rm i}G_{\rm p}\rho_{13}, \\
\dot\rho_{12} =& ({\rm i}\Delta_{\rm p} - {\rm i}\Delta - \gamma_{21})\rho_{12} + {\rm i}G_{\rm p}\rho_{32} \\
&+ {\rm i}G_{\rm p}(\rho_{22} - \rho_{11}) - {\rm i}G_{\rm c}\rho_{14}, \\
\dot\rho_{13} =& ({\rm i}\Delta_{\rm p} + {\rm i}\Delta - \gamma_{31})\rho_{13} + {\rm i}G_{\rm p}\rho_{23} \\
&+ {\rm i}G_{\rm p}(\rho_{33} - \rho_{11}) - {\rm i}G_{\rm c}\rho_{14}, \\
\dot\rho_{14} =& ({\rm i}\Delta_{\rm c} + {\rm i}\Delta_{\rm p} - \gamma_{42} - \gamma_{43})\rho_{14} \\
&+ {\rm i}G_{\rm p}(\rho_{24} + \rho_{34}) - {\rm i}G_{\rm c}(\rho_{12} + \rho_{13}), \\
\dot\rho_{22} =& 2\gamma_{42}\rho_{44} - 2\gamma_{21}\rho_{22} \\
&+ {\rm i}G_{\rm p}(\rho_{12} - \rho_{21}) + {\rm i}G_{\rm c}(\rho_{42} - \rho_{24}), \\
\dot\rho_{23} =& (2{\rm i}\Delta - \gamma_{21} - \gamma_{31})\rho_{23} \\
&+ {\rm i}G_{\rm p}(\rho_{13} - \rho_{21}) + {\rm i}G_{\rm c}(\rho_{43} - \rho_{24}), \\
\dot\rho_{24} =& ({\rm i}\Delta_{\rm c} + {\rm i}\Delta - \gamma_{21} - \gamma_{42} - \gamma_{43})\rho_{24} \\
&+ {\rm i}G_{\rm p}\rho_{14} - {\rm i}G_{\rm c}\rho_{23} + {\rm i}G_{\rm c}(\rho_{44} - \rho_{22}), \\
\dot\rho_{33} =& 2\gamma_{43}\rho_{44} - 2\gamma_{31}\rho_{33} \\
&+ {\rm i}G_{\rm p}(\rho_{13} - \rho_{31}) + {\rm i}G_{\rm c}(\rho_{43} - \rho_{34}), \\
\dot\rho_{34} =& ({\rm i}\Delta_{\rm c} - {\rm i}\Delta - \gamma_{31} - \gamma_{42} - \gamma_{43})\rho_{34} \\
&+ {\rm i}G_{\rm p}\rho_{14} - {\rm i}G_{\rm c}\rho_{32} + {\rm i}G_{\rm c}(\rho_{44} - \rho_{33}),
\end{aligned} \tag{3}$$

$$\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1,$$

$$\rho_{ij} = \rho_{ji}^{*}.$$

Since the probe (coherent) field is a weak (strong) field, i.e. $G_{\rm p} \ll \gamma_{ij} \ll G_{\rm c}$, the polarizations ρ_{12} and ρ_{13} just need to be calculated to the first order of $G_{\rm p}$, but all orders of $G_{\rm c}$. Solving Eqs.(3) in steady state order-by-order, we obtain

$$\rho_{12}^{(1)} = \frac{-\mathrm{i}G_\mathrm{p}(\gamma_{42}+\gamma_{43}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta_\mathrm{c})(\gamma_{31}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta)}{(\gamma_{42}+\gamma_{43}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta_\mathrm{c})(\gamma_{31}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta)(\gamma_{21}-\mathrm{i}\Delta_\mathrm{p}+\mathrm{i}\Delta)+G_\mathrm{c}^2(\gamma_{21}+\gamma_{31}-2\mathrm{i}\Delta_\mathrm{p})}, \tag{4}$$

$$\rho_{13}^{(1)} = \frac{-\mathrm{i}G_\mathrm{p}(\gamma_{42}+\gamma_{43}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta_\mathrm{c})(\gamma_{21}-\mathrm{i}\Delta_\mathrm{p}+\mathrm{i}\Delta)}{(\gamma_{42}+\gamma_{43}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta_\mathrm{c})(\gamma_{31}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\Delta)(\gamma_{21}-\mathrm{i}\Delta_\mathrm{p}+\mathrm{i}\Delta)+G_\mathrm{c}^2(\gamma_{21}+\gamma_{31}-2\mathrm{i}\Delta_\mathrm{p})}. \tag{5}$$

A straightforward semiclassical analysis shows that the total linear complex susceptibility of the probe transition is given by

$$\chi = \chi_1 + \chi_2 = \frac{N_0\mu_\mathrm{p}^2(\rho_{12}+\rho_{13})}{2\varepsilon_0 G_\mathrm{p}}, \tag{6}$$

where $\mu_\mathrm{p} = \mu_{21} = \mu_{31}$ is the dipole moment of the probe transition, N_0 is the density of all atoms, and $\chi_1(\chi_2)$ represents the linear complex susceptibility arising from the transition of $|1\rangle \leftrightarrow |2\rangle(|1\rangle \leftrightarrow |3\rangle$. In an optically thick inhomogeneous medium, the atomic velocity distribution cannot be neglected. The contribution of the atoms with velocity v to the complex susceptibility of the probe transition is

$$\chi(v) = \frac{-\mathrm{i}N_0\mu_\mathrm{p}^2/(2\sqrt{\pi}\,\varepsilon_0 v_\mathrm{p})}{\dfrac{\left(\gamma_{31}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\dfrac{v}{c}\omega_\mathrm{p}-\mathrm{i}\Delta\right)\left(\gamma_{21}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\dfrac{v}{c}\omega_\mathrm{p}+\mathrm{i}\Delta\right)}{\gamma_{21}+\gamma_{31}-2\mathrm{i}\Delta_\mathrm{p}-2\mathrm{i}\dfrac{v}{c}\omega_\mathrm{p}} + \dfrac{G_\mathrm{c}^2}{\left(\gamma_{42}+\gamma_{43}-\mathrm{i}\Delta_\mathrm{c}+\mathrm{i}\dfrac{v}{c}\omega_\mathrm{c}-\mathrm{i}\Delta_\mathrm{p}-\mathrm{i}\dfrac{v}{c}\omega_\mathrm{p}\right)}} \times \exp\left(-\frac{v^2}{v_\mathrm{p}^2}\right)\mathrm{d}v, \tag{7}$$

where v is the most probable velocity of all atoms. Then the absorption and dispersion coefficients of the probe field can be calculated from the imaginary and real parts of the complex susceptibility of all atoms χ, respectively. In the next section, for simplicity in calculation, we set $\frac{N_0\mu_\mathrm{p}^2}{2\varepsilon_0} = 1$ $\left(\frac{N_0\mu_\mathrm{p}^2}{2\sqrt{\pi}\varepsilon_0 v_\mathrm{p}} = 1\right)$ when the atomic velocity distribution is neglected (included).

3. Analysis of the results

In this section, the main task is to show a few graphic results under specific conditions according to the equations in section 2. Firstly, a few cases are considered, where the velocity distribution of atoms is neglected. When the coherent field does not exist, i.e. G_c=0, Δ_c=0, as depicted by the dashed curve in Fig.2(a), there are two components in the absorption spectrum due to the two hyperfine sublevels $|2\rangle$ and $|3\rangle$, as expected.

When the coherent field is employed and at resonance with the transition between level $|4\rangle$ and the centre of gravity of levels $|2\rangle$ and $|3\rangle$, as shown by the solid curve in Fig.2(a), we can observe two spectral components whose locations are different from those by the dashed curve. This means that the EIT of the two sublevels has been reached, but the coherent field does not contribute more spectral components in this resonant case. In the following, we show why only two, but not three, spectral components are observed in this case.

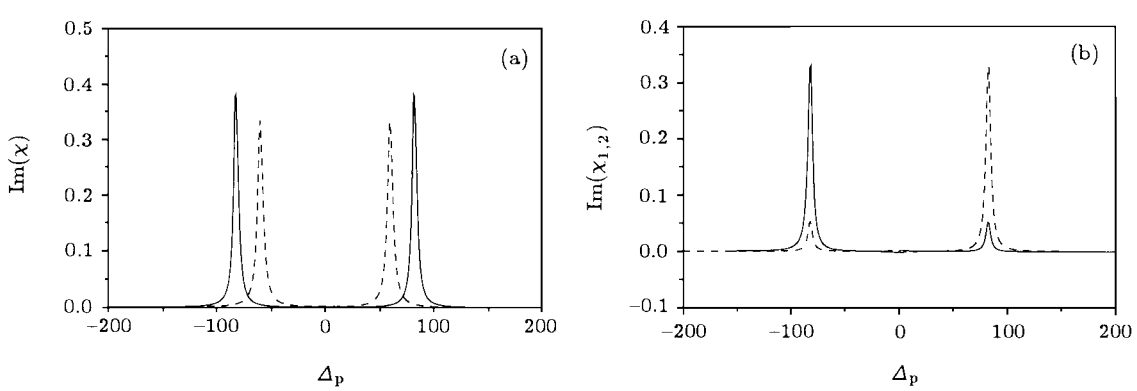


Fig.2. (a) The absorption spectrum Im(χ) without Doppler broadening against Δ_p for G_c=0 (dashed) and G_c=40 (solid). (b) The dashed (solid) curve Im(χ_1) (Im(χ_2)) corresponds to the contribution of ρ_{12} (ρ_{13}) to the solid curve in (a). Other parameters are: $\gamma_{21}=\gamma_{31}=3$, $\gamma_{42}=\gamma_{43}=0.5$, Δ=60, Δ_c=0.

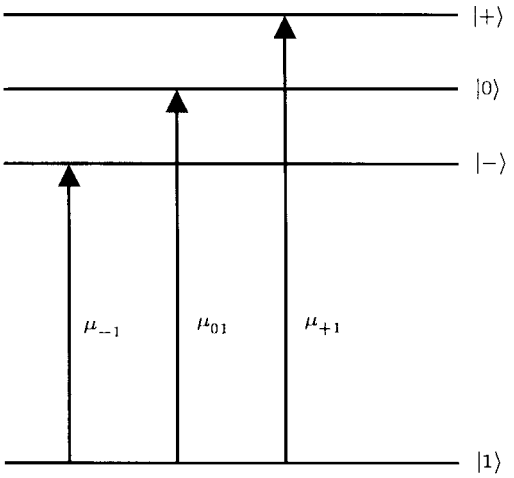


Fig.3. The corresponding dressed-state schematic representation when Δ_c=0.

As shown in Fig.3, it is obvious that, under the action of the coherent field, sublevels $|2\rangle$ and $|3\rangle$ should be split into three dressed-state levels. Under the eigenvalues of the dressed-state upper levels of the probe transition in the interaction picture can be obtained as $E_+ = \omega_0 + \sqrt{\Delta^2 + 2G_c^2}$, $E_0 = \omega_0$, $E_- = \omega_0 - \sqrt{\Delta^2 + 2G_c^2}$, and the corresponding eigenstates in the dressed representation are

$$
\begin{aligned}
|+\rangle =& \frac{1}{2}\left(1 - \frac{\Delta}{\sqrt{\Delta^2 + 2G_c^2}}\right)|2\rangle \\
&+ \frac{1}{2}\left(1 + \frac{\Delta}{\sqrt{\Delta^2 + 2G_c^2}}\right)|3\rangle \\
&+ \left(1 - \frac{G_c}{\sqrt{\Delta^2 + 2G_c^2}}\right)|4\rangle, \\
|0\rangle =& \frac{G_c}{\sqrt{\Delta^2 + 2G_c^2}}|2\rangle - \frac{G_c}{\sqrt{\Delta^2 + 2G_c^2}}|3\rangle \\
&+ \frac{\Delta}{\sqrt{\Delta^2 + 2G_c^2}}|4\rangle, \\
|-\rangle =& \frac{1}{2}\left(1 + \frac{\Delta}{\sqrt{\Delta^2 + 2G_c^2}}\right)|2\rangle \\
&+ \frac{1}{2}\left(1 - \frac{\Delta}{\sqrt{\Delta^2 + 2G_c^2}}\right)|3\rangle \\
&- \left(1 - \frac{G_c}{\sqrt{\Delta^2 + 2G_c^2}}\right)|4\rangle.
\end{aligned}
$$

With the above results, the dipole moments of the corresponding transitions in the dressed-state representation are derived as $\mu_{+1} = \langle +|P|1\rangle = \mu_p$, $\mu_{01} = \langle 0|P|1\rangle = 0$, $\mu_{-1} = \langle -|P|1\rangle = \mu_p$, where $P = \mu_p(|2\rangle\langle 1| + |3\rangle\langle 1|)$ is the atomic polarization operator of the probe transition. It is clear that the transition between levels $|0\rangle$ and $|1\rangle$ is not allowed because of the complete interference cancellation between the transitions of $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |3\rangle$. The heights of the two spectral components by the solid curve in Fig.2(a) are still symmetric because of $\mu_{+1} = \mu_{-1}$, while they are higher than those by the dashed curve in Fig.2(a) because of the interference enhancement contribution of $\mathrm{Im}(\chi_1)$ and $\mathrm{Im}(\chi_2)$, as shown in Fig.2(b). From Fig.2(b), it is also distinct that the contribution of $\mathrm{Im}(\chi_1)$ and $\mathrm{Im}(\chi_2)$ to the transition of $|1\rangle \leftrightarrow |0\rangle$ is interference cancellation, although the corresponding values are too small to be observed.

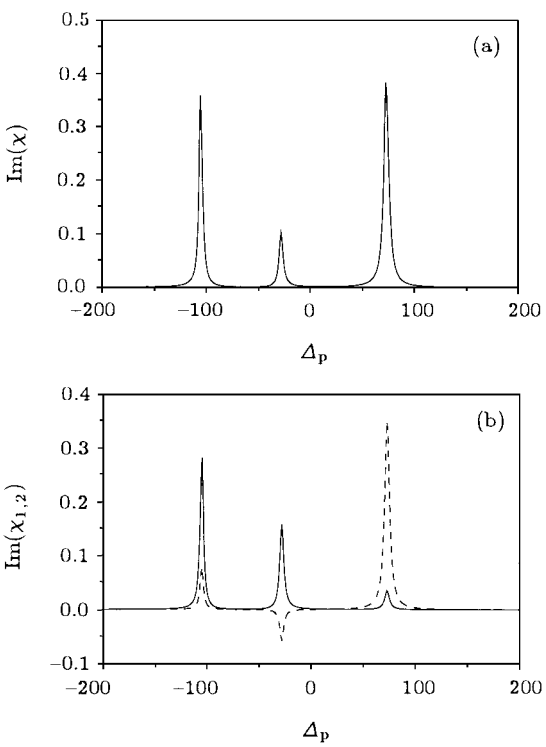


Fig.4. (a) The absorption spectrum $\mathrm{Im}(\chi)$ without Doppler broadening against Δ_p for G_c=40 and Δ_c=60. (b) The dashed (solid) curve $\mathrm{Im}(\chi_1)$ ($\mathrm{Im}(\chi_2)$) corresponds to the contribution of ρ_{12} (ρ_{13}) to the curve in (a). Other parameters are the same as those in Fig.2.

In Figs.4 and 5, two cases in which $\Delta_c \neq 0$ are taken into consideration, and we always observe three spectral components. Figure 4(a) corresponds to the case where the coherent field is at resonance with the transition $|3\rangle \leftrightarrow |4\rangle$. The locations of the left two spectral components are similar to those observed in a three-level ladder system, but those heights are not symmetric again because the coherent field is so strong that level $|2\rangle$ is coupled into them. Although the eigenvector of the dressed-state level $|0\rangle$ is difficult to obtain in this case, it can be inferred that the contributions of levels $|2\rangle$ and $|3\rangle$ to $|0\rangle$ should be opposite and unequal. Thus, due to the incomplete interference cancellation between the transitions of $|1\rangle \leftrightarrow |2\rangle$ and

$|1\rangle \leftrightarrow |3\rangle$, the middle spectral component is very small compared to the other components, which can also be explained by Fig.4(b). In Fig.4(b), the contributions of $\mathrm{Im}(\chi_1)$ and $\mathrm{Im}(\chi_2)$ to the transitions of $|1\rangle \leftrightarrow |-\rangle$ and $|1\rangle \leftrightarrow |+\rangle$ are interference enhanced, while their contribution to the transition of $|1\rangle \leftrightarrow |0\rangle$ is interference cancelled, which is the same as in Fig.2(b).

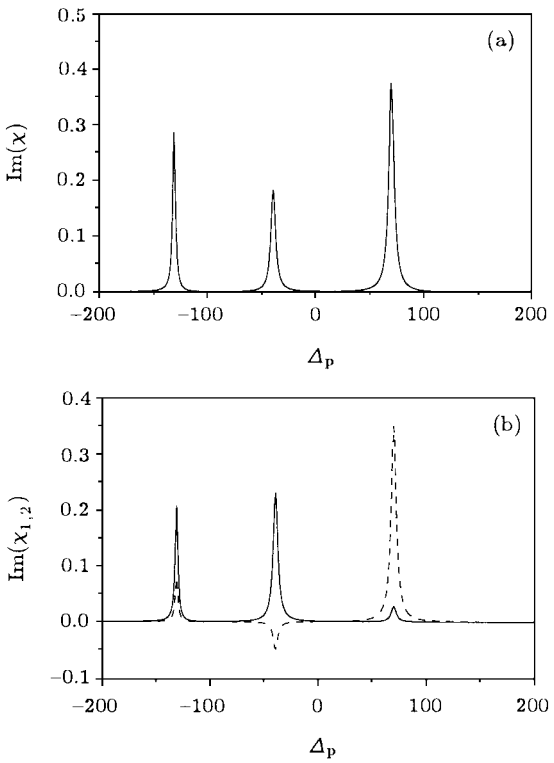


Fig.5. (a) The absorption spectrum $\mathrm{Im}(\chi)$ without Doppler broadening against Δ_p for G_c=40 and Δ_c=100. (b) The dashed (solid) curve $\mathrm{Im}(\chi_1)$ ($\mathrm{Im}(\chi_2)$) corresponds to the contribution of ρ_{12} (ρ_{13}) to the curve in (a). Other parameters are the same as those in Fig.2.

Figure 5 corresponds to the case when the coherent field is very far off resonance with the transition of $|2\rangle \leftrightarrow |4\rangle$. Then the height of the middle spectral component becomes closer to that of the left spectral component because level $|2\rangle$ cannot be effectively coupled into $|3\rangle$ and $|4\rangle$. Just as shown in Fig.5(b), the interference cancellation and enhancement of $\mathrm{Im}(\chi_1)$ and $\mathrm{Im}(\chi_2)$ become much weaker. It can be concluded directly that the left two spectral components will be the same as those observed in a corresponding three-level system if we choose $G_\mathrm{c} \ll \Delta$ and $\Delta_\mathrm{p} \geq \Delta$, since a weak and off-resonant coherent field cannot act on $|2\rangle$ effectively. So only when the coherent field is far off resonance with the transition $|2\rangle \leftrightarrow |4\rangle$ and its Rabi frequency is very small compared with the frequency difference between levels $|2\rangle$ and $|3\rangle$, can this homogeneously broadened system be simplified into a three-level system composed of levels $|1\rangle$, $|3\rangle$ and $|4\rangle$.

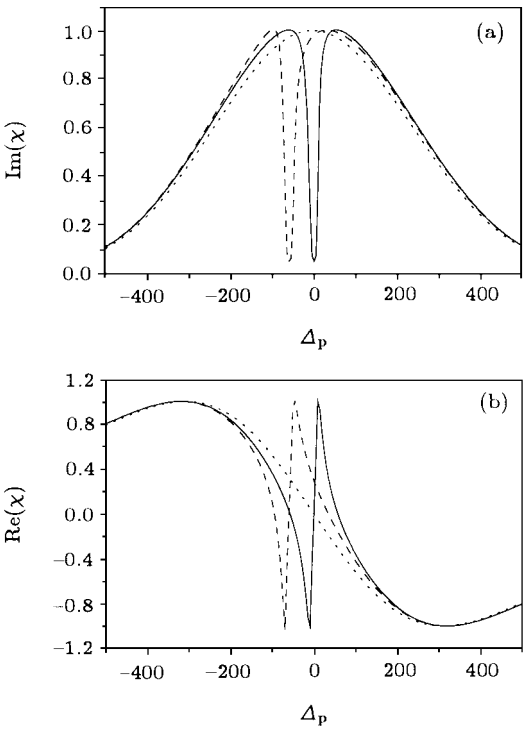


Fig.6. The Doppler-broadened (a) absorption spectrum $\mathrm{Im}(\chi)$; (b) dispersion spectrum $\mathrm{Re}(\chi)$ against Δ_p for $\delta\omega_\mathrm{D}$=530, v_p=250m·s^{-1}, ω_c=0.99ω_p. The dotted, solid, dashed curves correspond to $G_\mathrm{c}(\Delta_\mathrm{c})$=0, 40, 40 (0, 0, 60), respectively. Other parameters are the same as those in Fig.2.

Next, we show a few cases where the velocity distribution of atoms is included. In the following calculation, the most probable velocity v_p is set to equal 250m·s^{-1}, the Doppler width of the probe transition $\delta\omega_\mathrm{D} = 2\sqrt{\ln 2}\omega_\mathrm{p}v_\mathrm{p}/c$ is set to equal 530, and the frequency of the coherent field ω_c is set to equal 0.99ω_p. In Figs.6(a) and 6(b), the dotted curves correspond to the situation where the coherent field does not exist, the solid curves correspond to the situation where the detuning of the coherent field Δ_c equals zero, and the dashed curve corresponds to the situation where the detuning of the coherent field Δ_c equals Δ. All curves have been scaled by the value at the point of Δ_p=0 in the corresponding dotted curve. It is evident that only one EIT window with high dispersion at the point of $\Delta_\mathrm{p} = \Delta_\mathrm{c}$ is observed when the coherent field is employed and, with the same parameters, we can get the same results as those shown in Fig.6, if we consider this system as composed of levels $|1\rangle$, $|\alpha\rangle$ and $|4\rangle$, where $|\alpha\rangle$ is located at the centre of sublevels $|2\rangle$ and $|3\rangle$ (i.e. $\omega_\alpha = \omega_0$). Hence, even in an atomic system with two hyperfine sublevels, as long

as it is optically thick (the Doppler width is much larger than the frequency difference between hyperfine sublevels), we can still have a Doppler-broadened absorption spectrum similar to that of a three-level system. The above results can be easily generalized to systems with more hyperfine sublevels.

4. Conclusions

In summary, we have studied the steady-state absorption and dispersion spectra of a four-level ladder system with two hyperfine sublevels driven by a coherent field. After obtaining the complex susceptibility χ, which is relevant to the absorption and dispersion coefficients, by a straightforward semiclassical analysis, a few graphic results have been shown and analysed in the dressed-state representation.

The following have been found. (a) If the system under study is considered to be homogeneous, there may be two or three spectral components on the probe transition, whose locations depend on the detuning and intensity of the coherent field, indicating that the EIT of the two sublevels can be easily controlled by only one field. (b) The contributions of $\mathrm{Im}(\chi_1)$ and $\mathrm{Im}(\chi_2)$ to the spectral side components are always the same, while those contributions to the centre component are always opposite to each other, in particular the centre component disappears when Δ_c=0 because of the complete cancellation. (c) If the system is considered as inhomogeneous and optically thick, we will always observe one EIT window with high dispersion under the action of the coherent field, which is the same as that of a three-level system except for the location of the EIT window. Therefore the atomic hyperfine structure cannot be an impediment for obtaining EIT.

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