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Manipulation of multiple electromagnetically induced two-photon transparency in a six-level atomic system*

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In the five-level K-type atomic system, by using another control field to couple the excited level of the coupling transition to the sixth higher excited level, a six-level atomic system is constructed. In this system, the multiple electromagnetically induced two-photon transparency has been investigated. What is more, if choosing the parameters of the control fields properly the triple transparency window will reduce to a double one which means that the multiple electromagnetically induced two-photon transparency can be manipulated in this system. The physical interpretation of these phenomena is given in terms of the dressed states and the dark states.

Keywords: electromagnetically induced transparency, dressed states, dark states
PACC: 4250

1. Introduction

Studies of electromagnetically induced transparency (EIT) have made tremendous progress since the idea was proposed and demonstrated by Harris and co-workers,[1,2] because of a number of important applications in quantum optics and atomic physics. Much attention has been paid to the theoretical and experimental investigation of the slow light propagation,[3,4] quantum communication and quantum computation.[5] The enhancement or suppression of nonlinear atomic response is another important application of the EIT.[6−8] This phenomenon has been studied in many kinds of atomic configurations from three to five levels including V, Λ, ladder, Y, tripod, and K schemes.[8−12] It has been shown that the single-photon EIT in V, Λ, and ladder schemes can be generalized to the two-photon case in a Y-type, inversed Y type and K-type atoms. Meanwhile, multiple single-photon EIT can be realized in a four-level tripod-type atom and the simultaneous transition of the probe field at different wavelengths can be used for multi-channel optical communication or quantum information processing.

In the present paper, we use a control field to couple the excited level of the coupling transition in the five-level K-type atom with another higher excited level to construct a six-level atomic system. Numerical computation shows that in this configuration, the triple electromagnetically induced two-photon transparency can be obtained. In addition, we investigate the effects of the Rabi frequencies and the detunings of the control fields on the two-photon transparency spectra, and find that if the detunings and Rabi frequencies of the control fields satisfy some special relations, the triple two-photon transparency will change into a double one, which shows that in this six-level atomic system the parameters of the control fields play an important role on the multiplicity of electromagnetically induced two-photon transparency. The theoretical explanations for the numerical results are given in terms of the dressed states and the dark states.

2. Model and equation of motion

The energy level scheme of the six-level K-type atom is shown in figure 1. The experimental system for this atomic scheme can be realized by a Rb^{87} atom with $|5S_{1/2}, F = 1\rangle$, $|5P_{3/2}, F = 2\rangle$, $|7S_{1/2}, F = 1\rangle$, $|5S_{1/2}, F = 2\rangle$, $|5D_{5/2}, F = 3\rangle$, and $|4F_{7/2}, F = 2\rangle$ denoted by the labels $|1\rangle$, $|2\rangle$, $|3\rangle$, $|4\rangle$, $|5\rangle$, and $|6\rangle$ respectively. The two-photon transition of the atom under consideration is induced by two weak probe lasers with frequencies (amplitudes) w_1 ($\boldsymbol{\varepsilon}_1$) and w_2 ($\boldsymbol{\varepsilon}_2$), and the Rabi frequencies $G_1 = \boldsymbol{\mu}_{21} \cdot \boldsymbol{\varepsilon}_1/\hbar$ driving $|2\rangle \rightarrow |1\rangle$, $G_2 = \boldsymbol{\mu}_{32} \cdot \boldsymbol{\varepsilon}_2/\hbar$ driving $|3\rangle \rightarrow |2\rangle$ respectively. The first control laser with frequency (amplitude) w_3 ($\boldsymbol{\varepsilon}_3$) and Rabi frequency $G_3 = \boldsymbol{\mu}_{24} \cdot \boldsymbol{\varepsilon}_3/\hbar$ is applied to cou-

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ple the intermediate level $|2\rangle$ with the ground level $|4\rangle$. The second control laser with frequency (amplitude) $w_4\,(\boldsymbol{\varepsilon}_4)$ and Rabi frequency $G_4 = \boldsymbol{\mu}_{52}\cdot\boldsymbol{\varepsilon}_4/\hbar$ is used to couple the level $|2\rangle$ with the excited level $|5\rangle$. And the third control laser with frequency (amplitude) $w_5\,(\boldsymbol{\varepsilon}_5)$ and Rabi frequency $G_5 = \boldsymbol{\mu}_{65}\cdot\boldsymbol{\varepsilon}_5/\hbar$ is used to couple the level $|5\rangle$ with the higher excited level $|6\rangle$. $2\gamma_1$ and $2\gamma_3$ are the spontaneous decay rates from level $|2\rangle$ to levels $|1\rangle$ and $|4\rangle$, $2\gamma_2$ and $2\gamma_4$ correspond to the decay rates from levels $|3\rangle$ and $|5\rangle$ to $|2\rangle$ and $2\gamma_5$ is the decay rates from level $|6\rangle$ to $|5\rangle$. The detunings of the probe and coupling lasers are defined as $\Delta_1 = w_{21} - w_1$, $\Delta_2 = w_{32} - w_2$, $\Delta_3 = w_{24} - w_3$, $\Delta_4 = w_{52} - w_4$, and $\Delta_5 = w_{65} - w_5$ respectively.

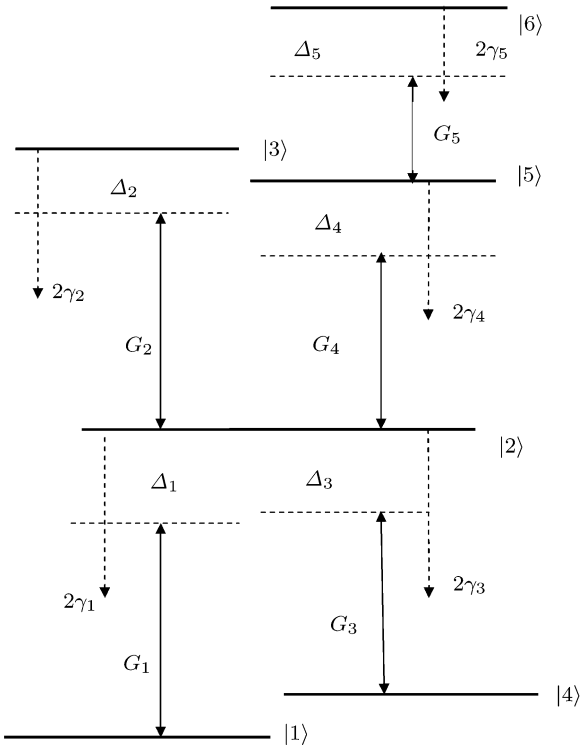


Fig.1. The energy level scheme of the six-level K-type atom. G_i are the Rabi frequencies, Δ_i are the detunings, and γ_i are the spontaneous decay rates respectively.

With dipole couplings under rotation-wave approximation, and fixing the level $|2\rangle$, the interacting Hamiltonian of the atom with the coherent laser fields reads

$$\begin{aligned}\hat{H}_{\rm I} = \hbar[&-\Delta_1|1\rangle\langle 1| + \Delta_2|3\rangle\langle 3| - \Delta_3|4\rangle\langle 4| \\ &+ \Delta_4|5\rangle\langle 5| + (\Delta_4+\Delta_5)|6\rangle\langle 6| - (G_1|2\rangle\langle 1| \\ &+ G_2|3\rangle\langle 2| + G_3|2\rangle\langle 4| + G_4|5\rangle\langle 2| \\ &+ G_5|6\rangle\langle 5| + \text{h.c.})].\end{aligned} \tag{1}$$

In this paper, we use the density matrix approach to analyze the system. The dynamical evolution of the system including spontaneous emission terms is governed by the density-matrix equations in a Liouvillian form

$$\begin{aligned}\frac{\partial}{\partial t}\hat{\rho} = &-\frac{\mathrm{i}}{\hbar}[\hat{H}_I,\hat{\rho}] + 2\rho_{22}(\gamma_1|1\rangle\langle 1| + \gamma_3|4\rangle\langle 4|) \\ &- (\gamma_1+\gamma_3)\{\hat{\rho},|2\rangle\langle 2|\} + 2|2\rangle\langle 2|(\gamma_2\rho_{33}+\gamma_4\rho_{55}) \\ &- \gamma_2\{\hat{\rho},|3\rangle\langle 3|\} - \gamma_4\{\hat{\rho},|5\rangle\langle 5|\} \\ &+ 2\rho_{66}\gamma_5|5\rangle\langle 5| - \gamma_5\{\hat{\rho},|6\rangle\langle 6|\},\end{aligned} \tag{2}$$

where the brackets $[\hat{A},\hat{B}]$ and $\{\hat{A},\hat{B}\}$ denote the commutation and anti-commutation relations of the operators $\hat{A}$ and $\hat{B}$ respectively. The density matrix elements obey the conditions $\sum_{i=1}^{6}\rho_{ii} = 1$ and $\rho_{ij} = \rho_{ji}^*$. The steady-state behavior in the six-level system can be described by setting $\dot{\rho}_{ij} = 0$. We shall investigate the two-photon absorption strength measured by ρ_{33} by numerical calculation. Throughout this paper, we restrict our discussion on the two-photon resonant condition $\Delta_1 + \Delta_2 = 0$.

3. Numerical results and theoretical explanations

We first describe the two-photon EIT in the five-level K-type atomic system in figure 2 by setting the parameters to the values $G_5 = 0$, $\Delta_5 = 0$, $\gamma_5 = 0$, $\Delta_3 = \Delta_4 = 0$ and $G_3 = G_4 = 50$.

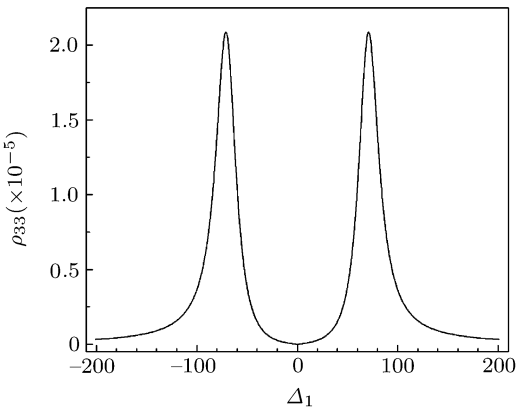


Fig.2. The two-photon absorption ρ_{33} as a function of the probe detuning Δ_1 in the five-level K-type atom with $G_5 = 0$, $\Delta_5 = 0$, and $\gamma_5 = 0$. Other parameters are $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 10$, $G_1 = G_2 = 1$, $G_3 = G_4 = 50$, $\Delta_3 = \Delta_4 = 0$, and $\Delta_1 + \Delta_2 = 0$.

The probe absorption spectrum displays the two-photon EIT with the transparent point at $\Delta_1 = 0$. When an additional control field G_5 coupling the levels $|5\rangle$ and $|6\rangle$ is included, the two-photon absorption

behavior in this six-level atomic system is remarkably changed. We plot the two-photon absorption ρ_{33} as a function of the probe detuning Δ_1 with $G_3 = G_4 = 50$ and different G_5 in figure 3. It can be seen from the curves in figure 3 that the two-photon transparency profile is still symmetric, but the original single transparency window in figure 2 is split into three by two in-between absorption peaks, and the phenomenon of triple two-photon transparency appears. It can be seen from the solid and dashed curves that the height of the two in-between peaks increases with the control Rabi frequency G_5, while the two outer ones decrease with the control field. The complete transparency point stands still at $\Delta_1 = 0$ for different G_5, and the absorption minima in the other two transparency windows appear at $\Delta_1 = \pm G_5$, namely, $\Delta_1 = \pm 50$ in the solid curve and $\Delta_1 = \pm 80$ in the dashed curve respectively. It is very interesting that when G_5 is large enough, the outer absorption peaks almost disappear, and the triple two-photon transparency changes into the ordinary single one with the transparency point located at $\Delta_1 = 0$, as shown by the dotted curve corresponding to $G_5 = 250$ in figure 3.

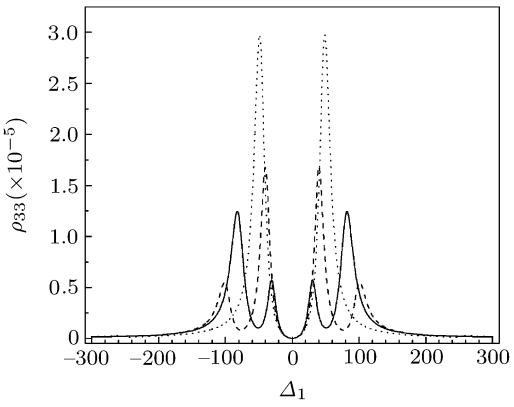


Fig.3. The two-photon absorption ρ_{33} as a function of the probe detuning Δ_1 with $G_3 = G_4 = 50$ and different control field $G_5 = 50$ (solid curve), $G_5 = 80$ (dashed curve), and $G_5 = 250$ (dotted curve). Other parameters are the same as those in Fig.2.

The above numerical results can be explained by virtue of the dressed states. The coherent interaction between the three coupling fields (G_3, G_4 and G_5) and the atom can be described by the Hamiltonian

$$\hat{H}_{\rm I} = \hbar[-\Delta_3|4\rangle\langle 4| + \Delta_4|5\rangle\langle 5| + (\Delta_4 + \Delta_5)|6\rangle\langle 6| - (G_3|2\rangle\langle 4| + G_4|5\rangle\langle 2| + G_5|6\rangle\langle 5| + \text{h.c.})]. \tag{3}$$

To investigate the influence of G_5, we set $G_3 = G_4 = G$, $G_5 = g$, and $\Delta_3 = \Delta_4 = \Delta_5 = 0$. In this case, the eigenstates and the eigenvalues of the Hanmiltonian Eq.(3) are given by

$$\begin{aligned}
|\phi_1\rangle &= \frac{1}{\chi_1}[G^2M|4\rangle - GM^2|2\rangle + M(M^2 - G^2)|5\rangle - g(M^2 - G^2)|6\rangle], \quad e_1 = M,\\
|\phi_2\rangle &= \frac{1}{\chi_2}[G^2N|4\rangle - GN^2|2\rangle + N(N^2 - G^2)|5\rangle - g(N^2 - G^2)|6\rangle], \quad e_2 = N,\\
|\phi_3\rangle &= \frac{1}{\chi_2}[-G^2N|4\rangle - GN^2|2\rangle - N(N^2 - G^2)|5\rangle - g(N^2 - G^2)|6\rangle], \quad e_3 = -N,\\
|\phi_4\rangle &= \frac{1}{\chi_1}[-G^2M|4\rangle - GM^2|2\rangle - M(M^2 - G^2)|5\rangle - g(M^2 - G^2)|6\rangle], \quad e_4 = -M,
\end{aligned} \tag{4}$$

where

$$M = \left(\frac{1}{2}(2G^2 + g^2) + \frac{1}{2}\sqrt{4G^4 + 4g^4}\right)^{1/2}, \quad N = \left(\frac{1}{2}(2G^2 + g^2) - \frac{1}{2}\sqrt{4G^4 + 4g^4}\right)^{1/2},$$

and

$$\begin{aligned}
\chi_1 &= \sqrt{M^6 - (G^2 - g^2)M^4 + 2G^2(G^2 - g^2)M^2 + G^4g^2},\\
\chi_2 &= \sqrt{N^6 - (G^2 - g^2)N^4 + 2G^2(G^2 - g^2)N^2 + G^4g^2}.
\end{aligned}$$

It can be seen from the above results that there will appear four absorption peaks symmetrically located at the two sides of the origin at $\Delta_1 = \pm M$ and $\Delta_1 = \pm N$ corresponding to the eigen-energy e_i, as shown in figure 3. Thus the width of the in-between window is $2N$, and those of the two outer windows are $M - N$. The probability of the two-photon absorption is given by

$$P_2 = \frac{2\pi}{\hbar}\left|\frac{\langle 1|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_1|\phi_1\rangle\langle\phi_1|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_2|3\rangle}{e_1+\hbar\Delta_1} + \frac{\langle 1|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_1|\phi_2\rangle\langle\phi_2|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_2|3\rangle}{e_2+\hbar\Delta_1} + \frac{\langle 1|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_1|\phi_3\rangle\langle\phi_3|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_2|3\rangle}{e_3+\hbar\Delta_1} + \frac{\langle 1|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_1|\phi_4\rangle\langle\phi_4|\boldsymbol{d}\cdot\boldsymbol{\varepsilon}_2|3\rangle}{e_4+\hbar\Delta_1}\right|^2 \times \delta(E_{31}-\hbar\omega_1-\hbar\omega_2), \quad (5)$$

where E_{31} represents the relative eigenvalue of the state $|3\rangle$ to the ground state $|1\rangle$. The occurrence of the minimum in the two-photon absorption needs the condition $P_2 = 0$, that is, the four excitation paths $|1\rangle \to |\phi_1\rangle \to |3\rangle$, $|1\rangle \to |\phi_2\rangle \to |3\rangle$, $|1\rangle \to |\phi_3\rangle \to |3\rangle$, and $|1\rangle \to |\phi_4\rangle \to |3\rangle$ interference destructively, which leads to the condition: $\Delta_1 = 0, \pm g$. This result shows that the positions of the two partial transparency points can be determined by the Rabi frequency G_5 and the complete one stands at rest for different G_5, as shown by the solid and dashed curves in figure 3. When $g \gg G$, clearly, $M \to g$, $N \to G$, thus the two outer peaks should appear at $\Delta_1 = \pm g$. Meanwhile, the above calculation has shown that in this case the two partial transparency points should also occur at $\Delta_1 = \pm g$, the peaks will be suppressed by the transparency points, only the two in-between peaks located at $\Delta_1 = \pm G$ remain, indicating that the triple window will change into a single one. This can also be understood by using dressed states: when $g \gg G$, the four dressed states in Eq.(4) are reduced to $|\phi_1\rangle = \frac{1}{\sqrt{2}}(|5\rangle - |6\rangle)$, $e_1 = g$; $|\phi_2\rangle = \frac{1}{\sqrt{2}}(|4\rangle - |2\rangle)$, $e_2 = G$; $|\phi_3\rangle = -\frac{1}{\sqrt{2}}(|4\rangle + |2\rangle)$, $e_3 = -G$; $|\phi_4\rangle = -\frac{1}{\sqrt{2}}(|5\rangle + |6\rangle)$, $e_4 = -g$. Obviously, the dressed states $|\phi_2\rangle$ and $|\phi_3\rangle$ with eigenvalues $\pm G$ both contain an admixture of the intermediate state $|2\rangle$, thus have nonzero dipole matrix elements with ground state $|1\rangle$, which correspond to the absorption peaks in the dotted curve in figure 3. While the dressed states $|\phi_1\rangle$ and $|\phi_4\rangle$ without the admixture of state $|2\rangle$ are dark states and decoupled from the system for the existence of the strong field $G_5 \gg G_3(G_4)$. Hence the remaining levels forming an inversed-Y type configuration with absorption spectrum have two absorption peaks located at $\Delta_1 = \pm G$ and the transparency point occurs at $\Delta_1 = 0$.[8,12]

By altering the detunings and Rabi frequencies of the control fields, the triple transparency window shown in figure 3 can change into a double one. The following theoretical analysis will show that the appearance of the double two-photon transparency is only related to the following parameters: the detunings of the control fields Δ_3, Δ_4, Δ_5, and the Rabi frequency G_5, but not depend on the Rabi frequencies of the other two control fields G_3 and G_4. Firstly, it can be proved that if we detune the probe field G_1 at $\Delta_1 = \Delta_3$ under the two-photon resonant condition $\Delta_1 + \Delta_2 = 0$, a dark state with eigenenergy $-\Delta_3$ will appear, i.e. there always exists a transparency point at $\Delta_1 = \Delta_3$ as shown in figures 3 and 4. Additionally in the following proof, the general condition for the appearance of double two-photon transparency can be given naturally. To this end, we start from the general Hanmiltonian Eq.(1) of the system under the condition $\Delta_1 + \Delta_2 = 0$. The eigenenergies of the system can be obtained by solving the equation $\det|H - E| = 0$. When $\Delta_1 = \Delta_3$ and $G_5 \neq \sqrt{(\Delta_3+\Delta_4)(\Delta_3+\Delta_4+\Delta_5)}$, the equation can be written as $\det|H - E| = (E+\Delta_3)^2 R = 0$, where R is a four-order polynomial of E. Thus $E = -\Delta_3$ is an eigenvalue of the system, its corresponding eigenstate reads

$$|\Psi\rangle = \frac{1}{\sqrt{G_1^2+G_3^2}}(G_1|4\rangle - G_3|1\rangle), \quad (6)$$

which does not contain the components of the intermediate state $|2\rangle$ and excited state $|3\rangle$, and is thus a dark state decoupled from the system. In this state, the population of the level $|3\rangle$ $\rho_{33} = 0$, hence when the detuning of the probe field G_1 is set as $\Delta_1 = \Delta_3$, the complete transparency point appears. Under the approximation of strong coupling and weak probe fields, the other four eigenstates are the dressed states of the system, which are in accordance with the four absorption peaks as shown in figure 3. When $\Delta_1 = \Delta_3$ and $G_5 = \sqrt{(\Delta_3+\Delta_4)(\Delta_3+\Delta_4+\Delta_5)}$, the eigenenergy of the system in this case can be obtained by solving the equation $\det|H - E| = (E+\Delta_3)^3 R' = 0$, where R' is a three-order polynomial of E. Thus the system must have an eigenstate

$$|\Psi'\rangle = \frac{1}{\sqrt{G_5^2(G_3^2+G_4^2)+G_3^2(\Delta_3+\Delta_4)^2}} \times (G_4G_5|4\rangle - G_3G_5|5\rangle - (\Delta_3+\Delta_4)|6\rangle) \quad (7)$$

with eigenvalue $E = -\Delta_3$. Clearly this state is a dark state corresponding to a complete two-photon transparency point at $\Delta_1 = \Delta_3$. In addition, it can be checked that the state $|\Psi'\rangle$ is also a dressed state with eigenenergy $-\Delta_3$ generated by the coherent interaction between the conrol fields and the atom. Since the intermediate state $|2\rangle$ is decoupled from the state $|\Psi'\rangle$, the resonant two-photon excitation in the channel $|1\rangle \rightarrow |\Psi'\rangle \rightarrow |3\rangle$ can be suppressed and induces a two-photon absorption minimum occurring at $\Delta_1 = \Delta_3$. Only three absorption peaks corresponding to the other three dressed states will appear and a form double transparency window in the spectrum, that is, the phenomenon of the double two-photon transparency. Thus

$$G_5 = \sqrt{(\Delta_3 + \Delta_4)(\Delta_3 + \Delta_4 + \Delta_5)} \qquad (8)$$

is the condition of the appearance of double two-photon transparency in this system. This means that if choosing the parameters G_5 and Δ_i $(i = 3, 4, 5)$ properly, a double two-photon transparency spectrum can be attained, as shown in Fig.4. It can be seen from Eq.(8) that the appearance of the double two-photon transparency is independent of the Rabi frequencies G_3 and G_4, as shown in Fig.4(a). In addition, figures 4(b) and 4(c) depict two other special cases: when $\Delta_3 = \Delta_5 = 0$, the condition Eq.(8) change into $G_5 = |\Delta_4|$, and when $\Delta_4 = \Delta_5 = 0$, $G_5 = |\Delta_3|$. Note that when $\Delta_3 + \Delta_4 = 0$, or $\Delta_3 + \Delta_4 + \Delta_5 = 0$, there is not nonzero G_5 satisfying Eq.(8), which means that if G_5 exists, the double two-photon transparency cannot be achieved under this condition.

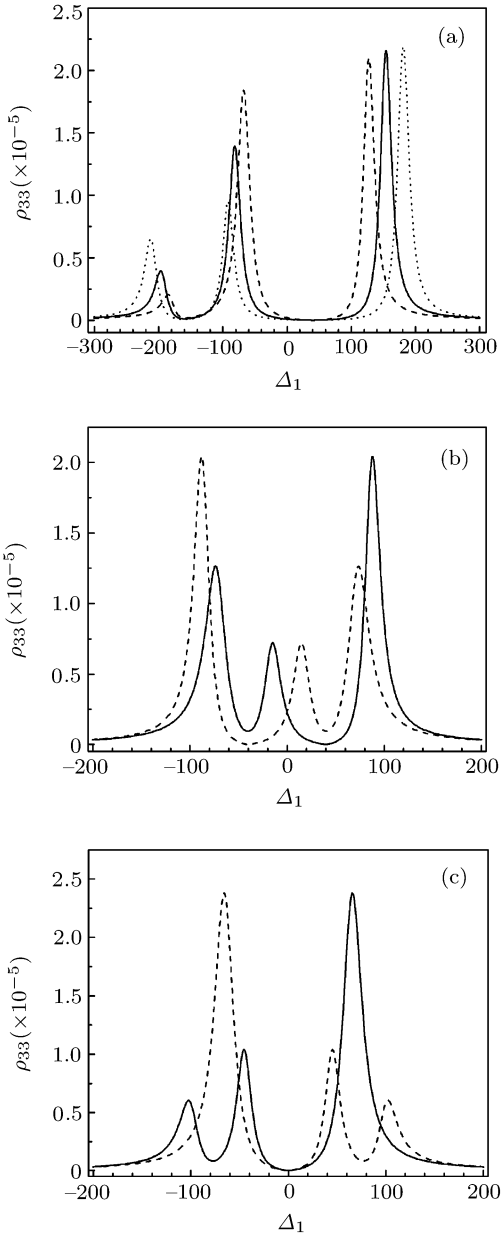


Fig.4. The two-photon absorption ρ_{33} as a function of the probe detuning Δ_1 with (a) fixed $G_5 = 100$ in all curves; $G_3 = G_4 = 100$ (solid line), $G_3 = G_4 = 80$ (dashed line) and $G_3 = G_4 = 120$ (dotted line), other parameters are the same as those in solid curve in Fig.3; (b) $\Delta_4 = \Delta_5 = 0$, $G_3 = G_4 = 50$, $G_5 = |\Delta_3| = 40$, $\Delta_3 = 40$ (solid line) and $\Delta_3 = -40$ (dashed line), other parameters are the same as those in Fig.3; and (c) $\Delta_3 = \Delta_5 = 0$, $G_3 = G_4 = 50$, $G_5 = |\Delta_4| = 40$, $\Delta_4 = 40$ (solid line) and $\Delta_4 = -40$ (dashed line), other parameters are the same as those in Fig.3.

4. Conclution

In conclusion, we have investigated the electromagnetically induced two-photon transparency in a six-level revised K-type atomic system. Numerical calculation and theoretical analysis show that the triple two-photon transparency can be realized in this system . The dependence of the two-photon transparency spectra on the Rabi frequencies and the detunings of the control fields is also investigated. By altering the detunings and Rabi frequencies of the control fields, the triple transparency window can change into a double one. The general condition of the appearance of double two-photon transparency has been given. This work may play an important role in two-photon lasing, pulse propagation,[10,11] and two-photon entanglement in the quantum information process.[13,14]

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