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Stimulated emission and multi-peaked absorption in a four level N-type atom*

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Absorption and refraction of the inner transition $F_2 \leftrightarrow F_3$ of the closed four level N-type atom have been investigated under a weak field. The outer transitions $F_1 \leftrightarrow F_3$ and $F_2 \leftrightarrow F_4$ are resonantly interacted with drive field with frequency ω_c and Rabi frequency Ω_c, and saturation field with ω_s and Ω_s, respectively. For the suitable Rabi frequencies Ω_c and Ω_s, we obtain the Mollow absorption spectrum of probe field. The reason is that the drive field excites the atom to the upper level F_3 and simultaneously the saturation field takes the atom out of the lower level F_2, leading to the stimulated emission. Meanwhile, due to the dynamic energy splitting induced by the drive and saturation fields, the two- and four-peaked absorption spectra are observed. At the zero off-resonance detuning of probe field, we also find the transfer of dispersion from negative to positive with an increment of Ω_s. Finally, the refractive index enhancement is predicted for a wide spectral region.

Keywords: stimulated emission, multi-peaked absorption
PACC: 4250, 4265

1. Introduction

Quantum coherence effects of two- and three-level atomic systems are widely studied for potential applications. In the pure two-level atom, the Mollow absorption spectrum (MAS),[1] enhanced four-wave mixing and resonance fluorescence are demonstrated.[2,3] The refractive index enhancement (RIE) with vanishing absorption is predicted.[4] Compared with a two-level atom, a three-level atomic system exhibits more complicated coherence properties since in this system two laser fields coherently couple with three levels. The typical phenomena include Hanle effects,[5] electromagnetically induced transparency (EIT),[6] coherent population trapping (CPT),[7] lasing without inversion (LWI)[8] and RIE.[9] EIT and CPT occur under the two-photon resonance condition[6] and are fundamentals of other coherent properties. The studies on the absorption and refraction spectra of two- and three-level atoms are helpful in the investigation of the quantum nonlinear optical properties,[10] quantum information, etc.[11]

There have been many investigations on multi-level atomic systems as well. The four-level atomic systems can be sorted according to the different schemes, such as N-type, double-Λ, which have different coherent effects.[10,12−29] Some complex systems can be simply looked on as a combination of various two-level and three-level atoms, such as the treatment of the degenerate systems.[12−14] However, the four-level double-Λ or N-type atom would not be a combination of the simple atomic systems. The double-Λ atomic medium was first used on the optical phase conjugation.[17] Subsequently, efficient frequency conversion,[18,19] high-resolution laser spectroscopy,[20] and efficient coherence Raman scattering in hydrogen[21] have been successfully obtained. Now nonlinear quantum optics based on the double-Λ atom has become an active area.[10] Very recently, the absorption and refraction of four-level N-type atoms have attracted great interest. The concept of photon switching was proposed[22] and was further investigated experimentally and theoretically.[23,24] Electromagnetically induced absorption (EIA) in the open four-level N-type atom is predicted,[25,26] while, for a cycling system, there appear the gain[27,28] and dispersion transition of the probe field,[28] as well as the superluminal propagation.[29] However, the absorption properties of inner transition in N-type atom have not

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been clarified. The main goal of this paper is to investigate the absorption spectra of inner transition in a four-level N-type atomic system.

As shown in Fig.1(a), for a closed four-level N-type atom, the drive field with frequency ω_c, Rabi frequency Ω_c and saturation field with ω_s, Ω_s resonantly act on the outer transitions $F_1 \leftrightarrow F_3$ and $F_2 \leftrightarrow F_4$, respectively. The drive field with Ω_c pumps the population to accumulate at the upper level F_3. Simultaneously, the saturation field with Ω_s takes out the population from F_2. So under suitable conditions, the absorption of probe field shows stimulated emission, similar to what is found in a two-level atomic system.[1]

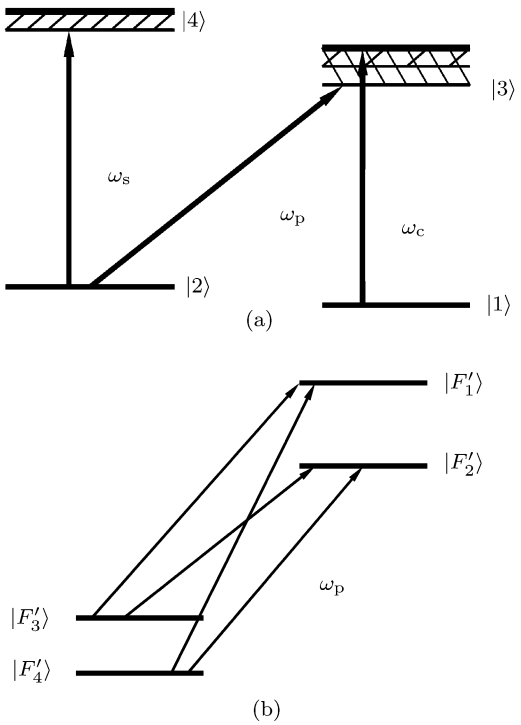


Fig.1. (a) N-type scheme of four-level atomic system coupled by the drive field with frequency ω_c, Rabi frequency Ω_c, and the saturation field with ω_s, Ω_s. The probe field is ω_p with Rabi frequency Ω_p. (b) Dressed energy structure (dressed energy level F_1', F_2', F_3', and F_4') of two subsystems. There are four transition channels for the probe field ω_p.

In the following, when the Rabi frequencies Ω_c and Ω_s are much stronger than the decay rates of the four-level system, on condition that there exists resonant coupling, we can obtain the MAS of the probe field, resembling the case of the two-level system. Meanwhile, due to the dynamic splitting of energy levels induced by the drive field and saturation field, there exist four transition channels, so the absorption spectrum exhibits a four-peaked feature. At the zero off-resonance detuning of the probe field, we also find the transfer of dispersion from negative to positive with the increase of Ω_s,[28] which did not appear in the two-level system.[3] Further numerical simulations indicate that the absorption and refraction spectra would be modified greatly by the off-resonance detunings $\Delta_s = \omega_{42} - \omega_s$ and $\Delta_c = \omega_{31} - \omega_c$. Finally, the refractive index enhancement at the vanishing of the absorption is found in a wide spectral region.

This paper is organized as follows. In the next section, we set up a four-level N-type atomic model, give the optical Bloch equations, and introduce the dressed state analysis to explain the multi-peaked spectra of absorption. In Section 3, numerical calculations are performed and the results are discussed, then the possible real atom is proposed. Finally, the main results are summarized in Section 4.

2. Theoretical approach

Consider a closed four-level N-type atom. As shown in Fig.1(a), the drive field with frequency ω_c interacts with the transition $F_1 \leftrightarrow F_3$, while the saturation field with ω_s interacts with the transition $F_2 \leftrightarrow F_4$. These two channels are called outer transitions. We use the probe field with ω_p to scan the inner transition $F_2 \leftrightarrow F_3$. The dipole moments of the different transitions are μ_{31}, μ_{42}, μ_{32}. Moreover, in the calculation, we would use the magnitude values of Rabi frequencies as $\Omega_{ij} = \mu_{ij}E_k/\hbar$, where E_k is the field at the atom interacting with different transitions. If only the decay Γ_{ij} of the atomic levels due to the spontaneous emission, and the collisions that result in dephasing of the coherence and exchange of population between the ground state levels is considered, in the rotating-wave and dipole approximations, the system is governed by the optical Bloch equations:

$$\dot{\rho}_{11} = \frac{\mathrm{i}}{\hbar}(\Omega_{13}^*\rho_{31} - \Omega_{31}\rho_{13}) + \Gamma_{21}\rho_{22} - \Gamma_{12}\rho_{11} + \Gamma_{41}\rho_{44} + \Gamma_{31}\rho_{33}, \quad (1)$$

$$\dot{\rho}_{22} = \frac{\mathrm{i}}{\hbar}(\Omega_{23}^*\rho_{32} + \Omega_{24}^*\rho_{42} - \Omega_{32}\rho_{23} - \Omega_{42}\rho_{24}) - \Gamma_{21}\rho_{22} + \Gamma_{12}\rho_{11} + \Gamma_{42}\rho_{44} + \Gamma_{32}\rho_{33}, \quad (2)$$

$$\dot{\rho}_{33} = \frac{\mathrm{i}}{\hbar}(\Omega_{31}\rho_{13} + \Omega_{32}\rho_{23} - \Omega_{23}^*\rho_{32} - \Omega_{13}^*\rho_{31}) + \Gamma_{43}\rho_{44} - (\Gamma_{34} + \Gamma_{31} + \Gamma_{32})\rho_{33}, \quad (3)$$

$$\dot{\rho}_{44} = -\frac{\mathrm{i}}{\hbar}(\Omega_{24}^{*}\rho_{42} - \Omega_{42}\rho_{24}) - (\Gamma_{43}+\Gamma_{41}+\Gamma_{42})\rho_{44} + \Gamma_{34}\rho_{33}, \tag{4}$$

$$\dot{\rho}_{12} = \frac{\mathrm{i}}{\hbar}(\Omega_{13}^{*}\rho_{32} - \Omega_{32}\rho_{13} - \Omega_{42}\rho_{14}) + (\mathrm{i}\omega_2 - \mathrm{i}\omega_1 - \gamma_{12})\rho_{12}, \tag{5}$$

$$\dot{\rho}_{13} = \frac{\mathrm{i}}{\hbar}(\Omega_{13}^{*}\rho_{33} - \Omega_{23}^{*}\rho_{12} - \Omega_{13}^{*}\rho_{11}) + (\mathrm{i}\omega_3 - \mathrm{i}\omega_1 - \gamma_{13})\rho_{13}, \tag{6}$$

$$\dot{\rho}_{14} = \frac{\mathrm{i}}{\hbar}(\Omega_{13}^{*}\rho_{34} - \Omega_{24}^{*}\rho_{12}) + (\mathrm{i}\omega_4 - \mathrm{i}\omega_1 - \gamma_{34})\rho_{14}, \tag{7}$$

$$\dot{\rho}_{23} = \frac{\mathrm{i}}{\hbar}(\Omega_{23}^{*}\rho_{33} + \Omega_{24}^{*}\rho_{43} - \Omega_{23}^{*}\rho_{22} - \Omega_{13}^{*}\rho_{21}) + (\mathrm{i}\omega_3 - \mathrm{i}\omega_2 - \gamma_{23})\rho_{23}, \tag{8}$$

$$\dot{\rho}_{24} = \frac{\mathrm{i}}{\hbar}(\Omega_{23}^{*}\rho_{34} + \Omega_{24}^{*}\rho_{44} - \Omega_{24}^{*}\rho_{22}) + (\mathrm{i}\omega_4 - \mathrm{i}\omega_2 - \gamma_{24})\rho_{24}, \tag{9}$$

$$\dot{\rho}_{34} = \frac{\mathrm{i}}{\hbar}(\Omega_{31}\rho_{14} + \Omega_{32}\rho_{24} - \Omega_{24}^{*}\rho_{32}) + (\mathrm{i}\omega_4 - \mathrm{i}\omega_3 - \gamma_{34})\rho_{34}, \tag{10}$$

$$\dot{\rho}_{ij} = \dot{\rho}_{ji}^{*}\,. \tag{11}$$

Ignoring the effect of spatial amplitude, the interacting energy Ω_{ij} can be expressed as $\Omega_{32} = \hbar\Omega_{\mathrm{p}}(\omega_{\mathrm{p}})\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{P}}t}$, $\Omega_{42} = \hbar\Omega_{\mathrm{s}}(\omega_{\mathrm{s}})\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{s}}t}$ and $\Omega_{31} = \hbar\Omega_{\mathrm{c}}(\omega_{\mathrm{c}})\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{c}}t}$. Here, $\Omega_{\mathrm{c}}(\omega_{\mathrm{c}}) = \mu E_{\mathrm{c}}/\hbar$, $\Omega_{\mathrm{s}}(\omega_{\mathrm{s}}) = \mu E_{\mathrm{s}}/\hbar$ and $\Omega_{\mathrm{p}}(\omega_{\mathrm{p}}) = \mu E_{\mathrm{p}}/\hbar$ are defined as the drive Rabi frequency, saturation Rabi frequency and probe Rabi frequency, respectively. Let $\omega_{ij} = \omega_i - \omega_j$ and Γ_{ij} is the decay rate from state $|i>$ to $|j>$. According to Ref.[30], we let $\Gamma_{31} = \Gamma_{32} = \Gamma_{41} = \Gamma_{42} = \Gamma$, which is the decay rate from the upper level to the lower level and $\Gamma_{12} = \Gamma_{21} = \Gamma_{34} = \Gamma_{43} = \Gamma_0$, which is the decay rate among lower levels or upper levels. Ignoring the rate of dephasing collisions, we have $\gamma_{13} = \gamma_{14} = \gamma_{23} = \gamma_{24} = \gamma = (\Gamma + \Gamma_0)$ and $\gamma_{34} = \gamma_0 = (2\Gamma + \Gamma_0)$. Here γ and γ_0 are the dephasing rates for the off-diagonal density matrix elements. The drive field E_{c} and the saturation field E_{s} are extended to all orders, and the probe field E_{p} to the first order. In order to form the coherence effect among levels, we always make the Rabi frequencies larger than the decay rate Γ. Although the assumption seems simple and unpractical, it is rational for the simulation of the coherence effect of atoms. In the steady state ($\dot{\rho}_{ij} = 0$), the elements of the density matrix are expressed as the terms of Fourier amplitudes. Each Fourier amplitude can be used to represent a kind of photonic process. For example, the third-order nonlinear term $\rho_{41}(\omega_{\mathrm{c}}+\omega_{\mathrm{s}}-\omega_{\mathrm{p}})$ means a three-photon process from the state F_1 to F_4, where the atom in the state F_1 absorbs an ω_{c} photon and an ω_{s} photon and simultaneously emits an ω_{p} photon, and as a result the atom transfers to the state F_4. Considering various photonic processes and the Fourier amplitudes, we have the following expressions: $\rho_{ii} = \rho^{dc}$ with $i = 1, 2, 3, 4$, $\rho_{31} = \rho_{31}(\omega_{\mathrm{c}})\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{c}}t}$, $\rho_{32} = \rho_{32}(\omega_{\mathrm{p}})\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{p}}t}$, $\rho_{42} = \rho_{42}(\omega_{\mathrm{s}})\mathrm{e}^{-\mathrm{i}\omega_{\mathrm{s}}t}$, $\rho_{21} = \rho_{21}(\omega_{\mathrm{c}} - \omega_{\mathrm{p}})\mathrm{e}^{-\mathrm{i}(\omega_{\mathrm{c}}-\omega_{\mathrm{p}})t}$, $\rho_{43} = \rho_{43}(\omega_{\mathrm{s}} - \omega_{\mathrm{p}})\mathrm{e}^{-\mathrm{i}(\omega_{\mathrm{s}}-\omega_{\mathrm{p}})t}$,and $\rho_{41} = \rho_{41}(\omega_{\mathrm{c}} + \omega_{\mathrm{s}} - \omega_{\mathrm{p}})\mathrm{e}^{-\mathrm{i}(\omega_{\mathrm{c}}+\omega_{\mathrm{s}}-\omega_{\mathrm{p}})t}$. Moreover, the closed relation $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1$ is satisfied and $\rho_{ij}(\omega_k) = \rho_{ji}^{*}(-\omega_k)$. Then without further approximation, the linear equations of Fourier amplitudes $\rho_{ij}(\omega_k)$ are readily solved.

The probe refraction and absorption are proportional to the real and imaginary parts of the susceptibility, i.e., $\chi(\omega_{\mathrm{p}}) \propto \rho_{32}(\omega_{\mathrm{p}})/(\Omega_{\mathrm{p}}\gamma)$. The dispersion D is proportional to $\mathrm{d}[\mathrm{Re}[\rho_{32}(\omega_{\mathrm{p}})]/(\Omega_{\mathrm{P}}\gamma)]/\mathrm{d}(\delta/\gamma)$. Generally, the dispersion of the group velocity is ignored. In steep dispersion, the relation is given by[31]

$$\frac{c}{V_{\mathrm{g}}} = 1 + 2\pi\mathrm{Re}\chi(\omega_{\mathrm{p}}) + 2\pi\omega_{\mathrm{P}}\mathrm{Re}\Big(\frac{\partial\chi}{\partial\omega_{\mathrm{p}}}\Big). \tag{12}$$

In a real atomic system, $c/V_{\mathrm{g}} = 1 + \Pi D(\delta = 0)$,where $\Pi = \pi\omega_{\mathrm{P}}N\mu_{32}^2/\gamma^2\hbar$.[32] For a normal positive dispersion, i.e., $D > 0$, we have a subluminal light propagation $V_{\mathrm{g}} < c$. While, for a negative dispersion, i.e., $D < 0$, we have a superluminal light propagation $V_{\mathrm{g}} > c$.

As a complement, we employ the dressed state theory to explain the coherent effect of the atomic system.[33,34] In the semiclassical picture, the dressed atom is a combination of the atom and the coupling fields. Then the energy levels should be rearranged in the direct product space. In this four-level N-type atomic system, when the weak probe field is added to the inner transition $F_2 \leftrightarrow F_3$, it is reasonable that the whole system is separated into two independent subsystems, but it must satisfy the closed relation: $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1$. The drive field ω_{c} interacts with the transition $F_1 \leftrightarrow F_3$, while saturation field ω_{s} interacts with the transition $F_2 \leftrightarrow F_4$, forming two outer arms. Each arm is a subsystem. Their interaction Hamiltonians read

$$\boldsymbol{H}_{\mathrm{s}} = -\Delta_{\mathrm{s}}|2\rangle\langle 2| - (\Omega_{\mathrm{s}}|2\rangle\langle 4| + \mathrm{H.c.}), \tag{13}$$

and

$$\boldsymbol{H}_{\mathrm{c}} = -\Delta_{\mathrm{c}}|1\rangle\langle 1| - (\Omega_{\mathrm{c}}|1\rangle\langle 3| + \mathrm{H.c.}), \tag{14}$$

where $\Delta_s = \omega_{42} - \omega_s$ and $\Delta_c = \omega_{31} - \omega_c$. They have the eigenvalues $\lambda_c = -\Delta_c \pm \sqrt{\Delta_c^2 + 4\Omega_c^2}/2$ and $\lambda_s = -\Delta_s \pm \sqrt{\Delta_s^2 + 4\Omega_s^2}/2$, respectively.

Then the dressed levels are obtained. The original two subsystems now correspond to four 'virtual' states F_1', F_2', F_3', and F_4' respectively as shown in Fig.1(b). For the scanning probe field, there are four transition channels to choose. Thus in the absorption spectrum, we observe at most four peaks as shown in Fig.2. If the two coupling fields Ω_c and Ω_s have the same detunings and equal Rabi frequencies, the splittings of the two levels would be equal, so the four-peaked spectra become two-peaked ones as in Fig.3. It is different from what is found in the two-level system, where only one-peak and three-peak structures of the absorption spectra are found.[3] More details can be found in the next section.

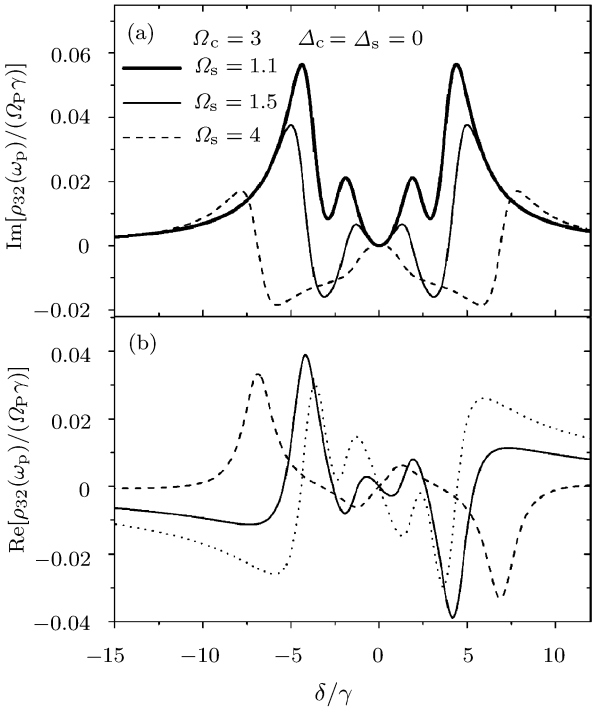


Fig.2. Quantum coherence effects for an inner transition $F_2 \leftrightarrow F_3$. Here $\Omega_c = 3$ and $\Delta_s = \Delta_c = 0$. $\Omega_s = 1.1, 1.5, 4$. $\delta = \omega_{32} - \omega_p$. (a) Absorption spectra. Stimulated emission and four-peaked structure in the absorption spectra appear. (b) Refraction spectra. The dispersion is changed from negative to positive at $\delta = 0$.

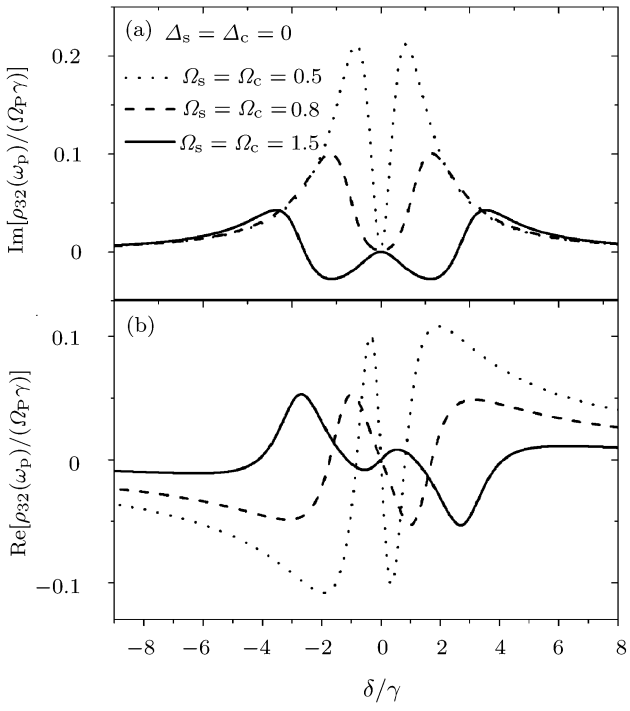


Fig.3. Quantum coherence effects for an inner transition $F_2 \leftrightarrow F_3$ with $\Omega_c = \Omega_c = \Omega$ and $\Delta_s = \Delta_c = 0$. Here $\Omega = 0.5, 0.8, 1.5$. (a) Absorption spectra. MAS and two-peaked structure appear. (b) Refraction spectra. The dispersion is transferred from positive to negative at $\delta = 0$.

3. Numerical results and discussions

Using the steady state approximation $\dot{\rho}_{ij} = 0$, we model the system shown in Fig.1. First we define the parameters in Bloch equations, $\Gamma = 1.0$, $\Gamma_0 = 0.01$, referring to Ref.[30]. The off-resonance probe detuning is $\delta = \omega_{32} - \omega_p$. To satisfy the condition that the probe Rabi frequency $|\Omega_p|$ is much smaller than the drive Rabi frequency $|\Omega_c|$ and the saturation field Rabi frequency $|\Omega_s|$, we always let $|\Omega_p| = 0.01|\Omega_c|$. For simplicity, we suppose Ω_c, Ω_s and Ω_p are real, and calculate the real and imaginary parts of the normalized Fourier coefficient $\rho_{32}(\omega_p)/(\Omega_p\gamma)$, which are proportional to the refraction and absorption of the probe field.

Figure 2 first displays the quantum coherence effects of the N-type atom with fixed drive Rabi frequency $\Omega_c = 3$ and $\Delta_s = \Delta_c = 0$. The multi-peaked scheme and MAS in the absorption spectra

are obtained by varying the saturation Rabi frequency Ω_s. In Fig.2, we find the negative absorption of the probe field from the figures. This means that, in these spectral regions, the probe field is not absorbed but amplified due to the coherence effect, which is also called stimulated emission. Moreover, as shown in Fig.2(a), when $\Omega_s = 1.1$, four absorption peaks appear at $\delta = -4.38, -1.9, 1.9, 4.38$. Now we use the dressed theory to predict their positions. The system is separated into two subsystems. With the above parameters, the eigenvalues are $\lambda_c = \pm 3$ and $\lambda_s = \pm 1.1$. By combining the two sets of dressed levels, four resonant transitions occurs at $\delta = \pm 4.1$, and ± 1.9. In the figure, the derivations from the predictions come from the decay rates among the energy levels, which are not included in the dressed theory. From the figure, the four-peaked structure of absorption will appear in a wide region of Ω_c and Ω_s. This result is different from the two-level system where at most three-peaked structures are observed.[1]

With increasing saturation Rabi frequency Ω_s, the gain curve of the probe field starts to appear, as shown by the solid curve in Fig.2(a). Simultaneously, the dispersion changes its sign from negative to positive at $\delta = 0$, which results in the superluminal propagation.[35] The dispersion transition accompanying the gain in the N-type scheme was experimentally demonstrated in Ref.[28]. Here we must emphasize that δ has an opposite sign to that of Ref.[28]. When Ω_s is increased to 4.0, the typical MAS effect are seen, similar to the result reported in the two-level system.[3] This emission effect is stimulated by the collaborating action of the coupling fields. The drive field pumps the atom to the state F_3, while the saturation field takes the atom out of F_2, leading to the stimulated emission. Here decay effects are worth to be emphasized. Only when the saturation Rabi frequency Ω_s is large enough, at least a bit larger than the decay rates between excited and ground levels, should there be a stimulated emission. In this case $\gamma = 1.01$. When $\Omega_s(= 1.5) > \gamma$, there appears the gain in the absorption profile, which does not appear when $\Omega_s = 1.1 - \gamma$.

Then we investigate the quantum coherences when the drive Rabi frequency equals saturation Rabi frequency, i.e., $\Omega_c = \Omega_s = \Omega$. We found that when $\Omega(= 0.5\,, 0.8)$ is smaller than the decay rate $\gamma(= 1.01)$, the four-peaked scheme of the absorption spectra become two-peaked ones, as shown in Fig.3(a). When Ω is increased to 1.5, MAS appears, with a shape just similar to that found in the two-level system.[1] However, the refraction of the four-level atom is different from that of the two-level one. As in Fig.3(b), with increasing Ω from 0.5 to 1.5, there is a sign change of dispersion from negative to positive[28] and it would lead to the superluminal propagation.[35] In a two-level system, only positive dispersion is found.[3] Here the eigenvalues of interaction Hamiltonian only approximately predict the positions of the above absorption peaks since in the dressed state theory the decay rates are not included. Besides, in the four-level system, only half of the population joins the transition $F_2 \leftrightarrow F_3$. Hence the magnitudes of absorption and refraction would be smaller than those of the two-level atom.

Next, we will discuss the influence of the coupling field detunings Δ_s and Δ_c on the absorption and refraction spectra. Our numerical calculations indicate that, except for $\Delta_s = \Delta_c = 0$, the unsymmetrical absorption spectra are obtained under other conditions, as shown in Figs.4(a) and 5(a). In Fig.4, $\Omega_s = 2$ and $\Omega_c = 5$, the positive detunings of $\Delta_s(= 1)$ and $\Delta_c(= 1)$, and the detunings with different signs $\Delta_s(= 1)$ and $\Delta_c(= -1)$ can cause the phenomenon that the right and left absorption peaks do not have the same height. In Fig.5, with the parameters $\Omega_s = \Omega_c = 1.5$, when $\Delta_s = -0.5$ and $\Delta_c = 0.0$, the right peak is higher than the left in the absorption spectrum. While, for $\Delta_s = 0.0$ and $\Delta_c = 0.5$, we find the opposite case: i.e., the left peak is higher than the right. In Figs.4(b) and 5(b), we see that the refraction spectra changes accordingly. So the off-resonance detunings Δ_s and Δ_c modify the coherence properties of the N-type system greatly.

Finally, we find that the RIE with vanishing absorption exists everywhere in the N-type atomic system. The typical points include A and B in Fig.4(b), and C in Fig.5(b). Except for the unsymmetrical refraction spectra, in Fig.2(b), for $\Omega_s = 1.5$(solid-curve), there are RIE points, where subluminal light propagation happens.

This N-type four-level system could be made up from the atoms, such as in the four hyperfine levels of Cs D_2 line, where the states $|6^2S_{1/2},\ F = 3\rangle$ and $|6^2S_{1/2},\ F = 4\rangle$ are used as two ground states of $|1\rangle$ and $|2\rangle$, then states $|6^2P_{3/2},\ F' = 3\rangle$ and $|6^2P_{3/2},\ F' = 4\rangle$ serve as two upper states $|3\rangle$ and $|4\rangle$, respectively. For these hyperfine levels, the decay rates from the upper states of $|6^2P_{3/2},\ F' = 3\rangle$ and $|6^2P_{3/2}, F' = 4\rangle$ to lower states $|6^2S_{1/2},\ F = 3\rangle$ and

$|6^2S_{1/2},\ F = 4\rangle$ are almost the same as those considered in theoretical discussion. In this situation Γ takes the value of 5.2 MHz. For convenience, in numerical calculation, the decay rate of Γ is normalized i.e. $\Gamma = 1$, thus the real Rabi frequencies of drive, saturation, and probe fields have the values of 5.2 times of Ω_c, Ω_s, Ω_p respectively. In this situation, the multi-peaked scheme, MAS, and RIE in Figs.2–5 should appear when the Rabi frequencies of drive and saturation fields take their values from several MHz to several tens of MHz.

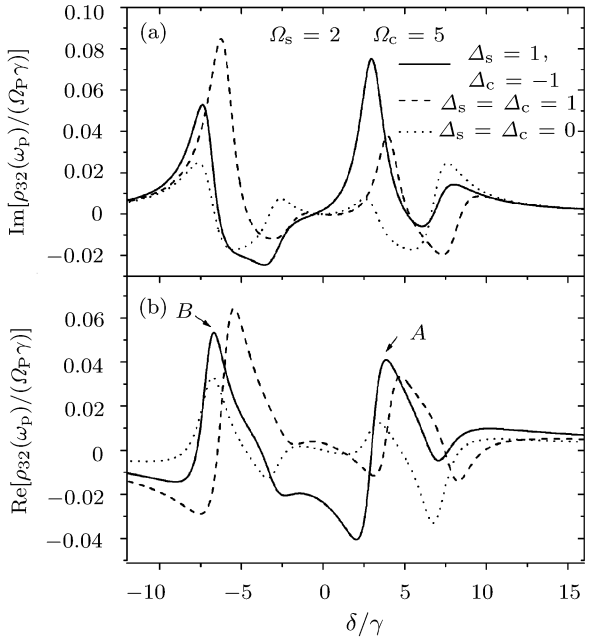


Fig.4. Quantum coherence effects for the inner transition $F_2 \leftrightarrow F_3$ with $\Omega_s = 2$, $\Omega_s = 5$ when coupling fields have detunings. (a) Absorption spectra. The left absorption peak is not symmetrical to the right. (b) Refraction spectra. RIE is displayed at points A and B.

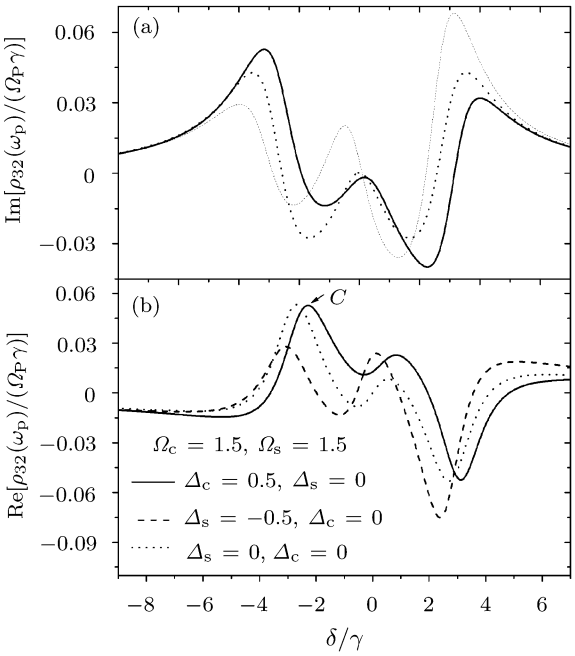


Fig.5. Quantum coherence effects for the inner transition $F_2 \leftrightarrow F_3$ with $\Omega_c = \Omega_s = 1.5$ when coupling fields have detunings. (a) Absorption spectra. (b) Refraction spectra. RIE is displayed at point C.

4. Summary

In this paper, the quantum coherence effects of an inner transition $F_2 \leftrightarrow F_3$ in the four-level N-type system have been investigated. For the suitable Rabi frequencies Ω_c and Ω_s, we obtain the Mollow absorption spectrum of probe field, as well as the multi-peaked scheme of absorption field. With varying the drive and saturation Rabi frequencies, the transfer of dispersion from negative to positive is also found. For a wide spectral region the RIE without absorption exists. These results are the important supplements to the coherence properties of the four-level atoms.

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