Quantum coherence in a degenerate two-level atomic ensemble: for a transition $F_e = 0 \leftrightarrow F_g = 1$

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Abstract

For a transition $F_e = 0 \leftrightarrow F_g = 1$ driven by a linearly polarized light and probed by a circularly light, quantum coherence effects are investigated. Due to the coherence between the drive Rabi frequency and Zeeman splitting, electromagnetically induced transparency, electromagnetically induced absorption, and the transition from positive to negative dispersion are obtained, as well as the populations coherently oscillating in a wide spectral region. At the zero pump-probe detuning, the subluminal and superluminal light propagation is predicted. Finally, coherent population trapping states are not highly sensitive to the refraction and absorption in such ensemble.

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I. INTRODUCTION

Quantum coherence or interference effectively influences the property of refraction and absorption in the phase-coherent atomic ensemble [1]. When laser resonantly interacts with atoms, the coherence can lead to electromagnetically induced transparency (EIT) [2], electromagnetically induced absorption (EIA) [3,4], coherent population trapping (CPT) [5] and the enhanced refractive index effect [6]. These phenomena have been widely studied in the typical Λ- and V-type three-level atomic systems. Recently, the coherently prepared degenerate atomic ensemble attracts great interest. The CPT in multilevel dark states was experimentally explored in the ground hyperfine states of ⁸⁷Rb atoms [7]. EIT and EIA have been observed in the degenerate systems due to the atomic coherence among Zeeman sublevels belonging to the same hyperfine splitting [3,8]. In this paper, we use the optical Bloch equations to study quantum coherence effects induced by the competition between the coupling field and Zeeman splitting in a degenerate two-level atomic ensemble.

Since quantum coherence greatly enhances the refractive index and induces the transparency, the study on the light propagation in a superluminal and subluminal group velocity is ignited. Wang et al. realized the superluminal and negative group velocity propagation of light pulses by using the lossless linear anomalous dispersion between two closely spaced gain lines [9]. The experiments have shown that light pulses were greatly slowed down, halted, and restarted in a coherently prepared atomic media [1,11,12,13,14]. Theoretically, by changing the intensity of the lower level coupling field in a Λ-type ensemble [15] and adjusting the phases of two weak optical fields in a V-type ensemble [16], the group velocity of a light pulse is controlled, so the transition from subluminal to superluminal light propagation is predicted. In a coherently prepared degenerate two-level atomic system, steep anomalous and normal dispersion were observed [8]. The degenerate systems should show more ability to adjust the sign of dispersion due to the coherence between the coupling field and Zeeman splitting. Motivated by that, in this work, we also investigate the positive and negative dispersion in a degenerate two-level ensemble.

In the following, the simplest degenerate two-level atomic system is considered. For a transition \( F_e = 0 \leftrightarrow F_g = 1 \) driven by a circularly polarized light with frequency \( \omega_c \), positive and negative dispersions of a circular probe light with \( \omega_p \) are investigated [17]. At this case, it is still a Λ-type system but with a population decay to the state \( M_{F_g} = 0 \). Instead of adding a circularly polarized pumping light, we drive the atomic system by a linear polarized π light with frequency \( \omega_c \) and probe it by a left and right circularly polarized \( \sigma_{\pm} \) light with \( \omega_p \). Now the system becomes a double Λ-type one. In the presence of the magnetic field, EIT, EIA, and the transition from positive to negative dispersion are obtained due to the coherence between the drive Rabi frequency and Zeeman splitting. Moreover, when the drive Rabi frequency \( |V_c| \) equals to \( \omega_{1-1} \) (where \( \omega_{1-1} = \omega_1 - \omega_{-1} \) and the frequencies \( \omega_1 \) and \( \omega_{-1} \) correspond to the Zeeman sublevels \( M_{F_g} = 1 \) and \( M_{F_g} = -1 \)), we observe that populations \( \rho_{11} \) and \( \rho_{-1-1} \) oscillate at about 0.5 with two-cycle. At the zero detuning, \( \delta = \omega_p - \omega_c = 0 \), the subluminal and superluminal light dispersion is predicted due to the steep normal and anomalous dispersion. In contrast, when \( |V_c| << \omega_{1-1} \) or \( |V_c| >> \omega_{1-1} \), the coherence between the coupling field and Zeeman splitting becomes weak, the results of degenerate two-level systems appear, and only EIT and positive dispersion are observed. Finally, we find that CPT is not highly sensitive to the refraction and absorption in such two-level
systems.

The paper is organized as follows. In the next section, we set up the model and present its optical Bloch equations, which can be expressed as a set of linear equations of Fourier amplitudes. In Section III, we solve these linear equations numerically and discuss the quantum coherence effects due to the competition between the coupling field and Zeeman splitting. Finally, we summary the main results in Section IV.

II. OPTICAL BLOCH EQUATIONS

Consider the simplest degenerate two-level system. As shown in Fig. 1, a $F_e = 0 \leftrightarrow F_g = 1$ transition is set up. This transition can be experimentally realized by using the $4f^66s^2{}^7F_1 \leftrightarrow 4f^66s6p^5D_0$ transition of Sm [18,19] and the $2p^53s^3\,^3P_1 \leftrightarrow 2p^53p^3\,^3P_0$ transition of Ne* [20]. The atoms are driven by a linear polarized $\pi$ light with frequency $\omega_c$ and probed by a left and right circularly polarized light $\sigma_\pm$ with frequency $\omega_p$, where $\pi$ light interacts with the transition $M_{F_e} = 0 \leftrightarrow M_{F_g} = 0$ and $\sigma \pm$ component of circular light interacts with the transition $M_{F_g} = \mp 1 \leftrightarrow M_{F_e} = 0$. In the presence of magnetic field, the system is a closed four-level one, but can be looked as a double $\Lambda$-type ensemble. All transitions have the same magnitude of dipole moments, but with the different sign, i.e. $\mu_e1 = \mu_c-1 = -\mu_c0 = \mu$. Considering the decay of the atomic levels due to the spontaneous emission and the collisions that result in dephasing of the coherences and exchange of population between the ground state levels, in the rotating-wave approximations, we write the optical Bloch equations as:

$$\dot{\rho}_{ee} = \frac{i}{\hbar}(V_{e-1}\rho_{-1e} - \rho_{e-1}V_{-1e}) + \frac{i}{\hbar}(V_{e1}\rho_{1e} - \rho_{e1}V_{1e}) + \frac{i}{\hbar}(V_{e0}\rho_{0e} - \rho_{e0}V_{0e}) - (\Gamma_{e-1} + \Gamma_{e1} + \Gamma_{e0})\rho_{ee}$$

(1)

$$\dot{\rho}_{-1-1} = -\frac{i}{\hbar}(V_{e-1}\rho_{-1e} - \rho_{e-1}V_{-1e}) - (\Gamma_{-10} + \Gamma_{-11})\rho_{-1-1} + \Gamma_{e-1}\rho_{ee} + \Gamma_{0-1}\rho_{00} + \Gamma_{1-1}\rho_{11}$$

(2)

$$\dot{\rho}_{11} = -\frac{i}{\hbar}(V_{e1}\rho_{1e} - \rho_{e1}V_{1e}) - (\Gamma_{10} + \Gamma_{1-1})\rho_{11} + \Gamma_{e1}\rho_{ee} + \Gamma_{01}\rho_{00} + \Gamma_{-11}\rho_{-1-1}$$

(3)

$$\dot{\rho}_{00} = -\frac{i}{\hbar}(V_{e0}\rho_{0e} - \rho_{e0}V_{0e}) - (\Gamma_{0-1} + \Gamma_{01})\rho_{00} + \Gamma_{e0}\rho_{ee} + \Gamma_{-10}\rho_{-1-1} + \Gamma_{10}\rho_{11}$$

(4)

$$\dot{\rho}_{e-1} = -\frac{i}{\hbar}[V_{e-1}(\rho_{ee} - \rho_{-1-1}) - V_{e1}\rho_{1-1} - V_{e0}\rho_{0-1}] - (i\omega_{e-1} + \gamma_{e-1})\rho_{e-1}$$

(5)

$$\dot{\rho}_{e1} = -\frac{i}{\hbar}[V_{e1}(\rho_{ee} - \rho_{11}) - V_{e-1}\rho_{-11} - V_{e0}\rho_{01}] - (i\omega_{e1} + \gamma_{e1})\rho_{e1}$$

(6)

$$\dot{\rho}_{e0} = -\frac{i}{\hbar}[V_{e0}(\rho_{ee} - \rho_{00}) - V_{e-1}\rho_{-10} - V_{e1}\rho_{10}] - (i\omega_{e0} + \gamma_{e0})\rho_{e0}$$

(7)
\[ \dot{\rho}_{1-1} = \frac{-i}{\hbar} (V_{e-1}\rho_{1e} - \rho_{e-1}V_{1e}) - (i\omega_{1-1} + \gamma_{1-1})\rho_{1-1} \quad (8) \]

\[ \dot{\rho}_{10} = \frac{-i}{\hbar} (V_{e0}\rho_{1e} - V_{1e}\rho_{e0}) - (i\omega_{10} + \gamma_{10})\rho_{10} \quad (9) \]

\[ \dot{\rho}_{-10} = \frac{-i}{\hbar} (V_{e0}\rho_{-1e} - V_{-1e}\rho_{e0}) - (i\omega_{-10} + \gamma_{-10})\rho_{-10} \quad (10) \]

\[ \dot{\rho}_{ij} = \dot{\rho}_{ji}^* \quad (11) \]

Ignoring the effect of spatial amplitude, the interacting energy \( V_{ei} \) for the \( |e\rangle \rightarrow |i\rangle \) transition can be expressed as \( V_{e1} = V_{e-1} = \hbar V_p(\omega_p)e^{-i\omega_pt} \) and \( V_{e0} = \hbar V_c(\omega_c)e^{-i\omega_ct} \). Here the magnitude values of \( 2V_p(\omega_p) = \mu_E/\gamma_p \) and \( 2V_c(\omega_c) = -\mu_E/\gamma_c \) are defined as the probe Rabi frequency and drive Rabi frequency respectively. Let \( \omega_{ij} = \omega_i - \omega_j \) and \( \omega_{1-1} = 2g\mu_B\mu/h \) denotes the Raman detuning induced by the static magnetic field of strength \( B \) applied in the atoms, where \( g \) is the Lande-factor and \( \mu_B \) the Bohr magneton. \( \Gamma_{ij} \) is the decay rate from state \( |i\rangle \) to \( |j\rangle \). Here we let \( \Gamma_{e1} = \Gamma_{e-1} = \Gamma_{e0} = \Gamma \). The decay rate among three lower levels is small and same, i.e., \( \Gamma_{ij} = \Gamma_0 \) for \( i,j = 1,0,-1 \). Ignoring the rate of dephasing collisions, \( \gamma_{e-1} = \gamma_{e0} = \gamma_{e1} = \gamma = (3\Gamma + 2\Gamma_0)/2 \) and \( \gamma_{1-1} = \gamma_{10} = \gamma_{1-0} = \gamma_0 = 2\Gamma_0 \).

We treat the drive field to all orders in \( E_e \) and the probe field to the first order in \( E_p \), then \( \rho_{ei} \) with \( i = 1,0,-1 \) is dominated by three main frequencies: \( \omega_c, \omega_p, 2\omega_c - \omega_p \). In terms of the Fourier amplitudes \( \rho_{ei}(\omega_i) \), \( \rho_{ei} \) can be expressed as \( \rho_{ei} = \rho_{ei}(\omega_c)e^{-i\omega_ct} + \rho_{ei}(\omega_c)e^{-i\omega_p t} \). The system is assumed to satisfy the relation: \( \rho_{ee} + \rho_{11} + \rho_{00} + \rho_{-1-1} = 1 \). In the steady state, we obtain a set up closed linear equations for the Fourier amplitudes [21][22]:

\[ 3i\Gamma_0\rho_{ee}^{dc} = [V_p^*\rho_{e-1}(\omega_p) - V_p\rho_{-1e}(-\omega_p)] + [V_p^*\rho_{e1}(\omega_p) - V_p\rho_{1e}(-\omega_p)] + [V_c^*\rho_{e0}(\omega_c) - V_c\rho_{0e}(-\omega_c)] \quad (12) \]

\[ 3i\Gamma_0\rho_{-1-1}^{dc} = -[V_p^*\rho_{e-1}(\omega_p) - V_p\rho_{-1e}(-\omega_p)] + i(\Gamma - \Gamma_0)\rho_{ee}^{dc} + i\Gamma_0 \quad (13) \]

\[ 3i\Gamma_0\rho_{11}^{dc} = -[V_p^*\rho_{e1}(\omega_p) - V_p\rho_{1e}(-\omega_p)] + i(\Gamma - \Gamma_0)\rho_{ee}^{dc} + i\Gamma_0 \quad (14) \]

\[ (\omega_{-11} - i\gamma_{0})\rho_{-11}^{dc} = [V_p^*\rho_{e1}(\omega_p) - V_p\rho_{1e}(-\omega_p)] \quad (15) \]

\[ (\omega_c - \omega_{e0} + i\gamma)\rho_{e0}(\omega_c) = V_c(2\rho_{ee}^{dc} + \rho_{-1-1}^{dc} + \rho_{11}^{dc} - 1) - V_p[\rho_{-10}(\omega_c - \omega_p) + \rho_{10}(\omega_c - \omega_p)] \quad (16) \]

\[ (\omega_p - \omega_{e-1} + i\gamma)\rho_{e-1}(\omega_p) = -V_p(\rho_{-1-1}^{dc} - \rho_{ee}^{dc} + \rho_{11}^{dc} - 1) - V_c\rho_{0-1}(\omega_p - \omega_c) \quad (17) \]

\[ (\omega_p - \omega_{e1} + i\gamma)\rho_{e1}(\omega_p) = -V_p(\rho_{11}^{dc} - \rho_{ee}^{dc} + \rho_{-1-1}^{dc}) - V_c\rho_{01}(\omega_p - \omega_c) \quad (18) \]
\[
(\omega_c - \omega_p - \omega_{10} + i \gamma_0)\rho_{10}(\omega_c - \omega_p) = -[V_p^* \rho_{e0}(\omega_c) - V_c \rho_{1e}(\omega_p)]
\]  
(19)

\[
(\omega_c - \omega_p - \omega_{-10} + i \gamma_0)\rho_{-10}(\omega_c - \omega_p) = -[V_p^* \rho_{e0}(\omega_c) - V_c \rho_{-1e}(\omega_p)]
\]  
(20)

\[
\rho_{ij}(\omega_k) = \rho_{ji}^*(\omega_k)
\]  
(21)

Taking account of Eq. (21), we are readily to solve these linear equations.

Since both transitions \(M_{Fg} = 1 \leftrightarrow M_{F_e} = 0\) and \(M_{Fg} = -1 \leftrightarrow M_{F_e} = 0\) have the same dipole moment and transverse and longitudinal decay rates, the probe refractive index and absorption are proportional to the real and imaginary part of the susceptibility, i.e., \(\chi(\omega_p) \propto [\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p)]/(V_2/\gamma)\). Because the dispersion \(D\) is proportional to \(d[\text{Re}(\chi(\omega_p))] / d(\omega_p)\), at the zero detuning, \(\delta = 0\), the dispersion can be written as \(D = d[\text{Re}(\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p))]/(V_2/\gamma)]/d(\delta/\gamma)\). In the steep dispersion, ignoring the dispersion of group velocity, we have [23]

\[
\frac{c}{V_g} = 1 + 2\pi \text{Re} \chi(\omega_p) + 2\pi \omega_p \text{Re}\left(\frac{\partial \chi}{\partial \omega_p}\right).
\]  
(22)

In the real atomic system, \(c/V_g = 1 + \Omega D(\delta = 0),\) where \(\Omega = \pi \omega_p N \mu_{el}^2/\gamma^2 \hbar\) [16]. For a positive dispersion, i.e. \(D > 0, V_g < c\), which is a subluminal light propagation. While, for a negative dispersion, i.e. \(D < 0, V_g > c\), a superluminal light propagation.

### III. NUMERICAL RESULTS AND DISCUSSIONS

To model the system shown in Fig. 1, we first define the parameters in the Bloch equations, \(\gamma = 1.0, \Gamma_0 = 0.001 \gamma, \Gamma = 2(\gamma - \Gamma_0)/3\) and \(\gamma_0 = 2\Gamma_0\), which are referred to Ref. [17,21]. We let \(\omega_c \simeq \omega_0\). Here the Zeeman splitting \(\omega_{1-1}\) between \(M_{Fg} = 1\) and \(M_{Fg} = -1\) is set up 5.0, so that \(\omega_{10} = \omega_{0-1} = 2.5\). To satisfy that the probe Rabi frequency \(2|V_p|\) is great smaller than the drive Rabi frequency \(2|V_c|\), we always let \(|V_p| = 0.01|V_c|\). For simplicity, we set \(V_c\) and \(V_p\) real. We plot the real and imaginary parts of \([\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p)]/(V_2/\gamma)\), which can be used to represent the refraction and absorption.

In order to study the refraction and absorption in a transition \(F_g = 1 \leftrightarrow F_e = 0\), we first consider the quantum coherence effects of a degenerate two-level atomic ensemble. It is a superposition of two \(\Lambda\)-type systems: \(M_{F_g} = -1 \leftrightarrow F_e = 0 \leftrightarrow M_{F_g} = 0\) and \(M_{F_g} = 1 \leftrightarrow F_e = 0 \leftrightarrow M_{F_g} = 0\), where the state \(M_{F_g} = 0\) shares the common transition: \(F_e = 0 \leftrightarrow M_{F_g} = 0\). The same results as what found in a typical \(\Lambda\)-type system, EIT and positive dispersion are shown as in Fig. 2. When the pump-probe detuning \(\delta\) is changed at a large spectral region, the populations are almost trapped in the two ground states \(M_{F_g} = \pm 1\), namely, \(\rho_{11} = \rho_{-1-1} = 0.5\). Note here EIT, positive dispersion and CPT effects are purely induced by the linearly polarized coupling \(\pi\) light. In the presence of the magnetic field, the degenerate state \(F_g = 1\) with the energy level \(\hbar \omega_0\) splits into three ones: \(M_{F_g} = \pm 1\) with \(\hbar \omega_0 \pm g \mu_B B\) and \(M_{F_g} = 0\) with \(\hbar \omega_0\). When the intensity of the drive field is varied, due to the existence of Zeeman splitting, it will experience a great changes in the refraction, absorption and CPT. The subsequent numerical calculations are performed to discuss the
quantum coherence effects, which are induced by the competition between the drive Rabi frequency and Zeeman splitting.

It is known that in many ensembles the intensity of coupling field can be used to control the quantum coherence effects [8,15,17,21]. In the subsequent figures, by means of changing the intensity of the coupling field, the quantum coherence effects between the drive Rabi frequency and the Zeeman splitting are shown. When $|V_c|$ is very small compared with the Zeeman splitting $\omega_{10} = 2.5$, i.e., $|V_c| = 1.0 << \omega_{10}$, the existence of the coupling field will not be enough to influence the properties of the ensemble. As shown in Fig. 3, at zero detuning, EIT and positive dispersion are found. The populations $\rho_{11}$ and $\rho_{-1-1}$ are little deviated from 0.5 at the small spectral region $\delta \in [-5, 5]$ due to the existence of the Zeeman splitting. When $|V_c|$ equals to Zeeman splitting $\omega_{10}$, due to the coherence between $|V_c|$ and Zeeman splitting, as shown in Fig. 4, not only EIA occurs, but also the dispersion is exhibited to be negative. Simultaneously, there are larger changes in CPT states comparing with the previous case. When we continue to increase $|V_c|$, let it be two times of Zeeman splitting, i.e. $V_c = 5.0$, we find that EIT and positive dispersion occurs at three frequencies: $\omega_p = \omega_c$, and $\omega_p = \omega_c \pm 5.0$. These results are shown in Fig. 5. The corresponding populations $\rho_{11}$ and $\rho_{-1-1}$ oscillate at 0.5 in a wide spectral region of the detuning $\delta$. The cycle of oscillation is 2. This phenomenon results from the coherence effect between the drive filed and the Zeeman splitting [24]. This kind of coherence has been discussed in the Ref. [24], while the oscillation of populations was not mentioned. At last, when the drive Rabi frequency $|V_c|$ is great larger than the Zeeman splitting, i.e., $|V_c| = 10.0 >> \omega_{10}$, the coupling field dominates the ensemble, so the results of a degenerate system appear. As shown in Fig. 6, EIT and positive dispersion are exhibited in a wide spectral region of $\delta$ [24]. Therefore, in the presence of the magnetic field, both EIT and EIA arise due to the coherence between $|V_c|$ and Zeeman splitting.

Here positive and negative dispersions at the zero detuning, $\delta = 0$, are emphasized. We observe the transition from positive, via negative, to positive dispersion from the features of refraction in Figures 3, 4 and 5. Since the group velocity $V_g$ can be expressed as $c/V_g = 1 + \Omega D(\delta = 0)$ [16], the transition from subluminal to superluminal light propagation is predicted. We have noted this transition in a $\Lambda$-type ensemble by changing the intensity of the lower level coupling field [13] and in a $V$-type ensemble by adjusting the phases of two weak optical fields [14]. In the presence of magnetic field, the ensemble becomes a real four-level system, or a superposition of two $\Lambda$-type ensembles. Due to the existence of Zeeman sublevel $M_{F_g} = 0$, the system becomes more adjustable, so that the changing of $V_c$ can lead to the positive and negative dispersions. Therefore this kind of system is suitable to unify the subluminal and superluminal light propagation.

CPT states in the excited level and Zeeman sublevels are shown in these figures. In all figures, at $\delta = 0$, the populations $\rho_{11}$ and $\rho_{-1-1}$ approximately equal to 0.5 while $\rho_{ee}$ and $\rho_{00}$ are approximately zero. The pump effect of a linearly polarized light results in populations trapping in the Zeeman sublevels $M_{F_g} = 1$ and $M_{F_g} = -1$. In the ensemble driven and probed by a circular polarized light [17], the quantum coherent result is different, in that, at the detuning center the ratio $\rho_{ee}/\rho_{11} + \rho_{-1-1}$ is large and can reach the maximum $\frac{1}{2}$. Finally, we find that CPT states are not sensitively related to the refraction and absorption in such ensemble.

The opposite case is complemented, where the atomic system is driven by a left and
right circularly polarized $\sigma_\pm$ light with $\omega_{c\pm}$ and probed by a linear polarized $\pi$ light with $\omega_p$. Analogous to the system driven by a $\pi$ light and probed by a $\sigma_\pm$ light, it is also a double $\Lambda$-type ensemble. At the degenerate case, it should exhibit the same property as what found in previous, i.e., EIT and positive dispersion, which have been verified by further numerical calculations. However, when the magnetic field is added to the ensemble, there exist more than three dominant frequencies: $\omega_{c+}, \omega_{c-}, \omega_p, 2\omega_{c+} - \omega_p, 2\omega_{c-} - \omega_p$ and so on, so that it is very difficult to obtain the Fourier amplitudes. For this system, it should exhibit the same quantum coherence effects as what discussed in the previous part of the paper. In ref. [17], a transition $F_g = 1 \leftrightarrow F_e = 0$ driven and probed by a circularly polarized light is investigated. At that case, though the existence of the state $M_{F_g} = 0$ the system is still a $\Lambda$-type one, so only positive or negative dispersion and EIT are found. Finally, for a transition $F_e = 0 \leftrightarrow F_g = 1$ driven and probed by a linearly polarized light, only transition $M_{F_e} = 0 \leftrightarrow M_{F_g} = 0$ exists, it corresponds to a two-level atomic ensemble.

IV. CONCLUSION

In summary, we investigate the quantum coherence effects in a degenerate two-level atomic system. For a transition $F_e = 0 \leftrightarrow F_g = 1$ driven by a linearly polarized light and probed by a circularly polarized light, a double $\Lambda$-type ensemble is set up. In the presence of the magnetic field, due to the coherence between the drive Rabi frequency and Zeeman splitting, EIT, EIA, and the transition from positive to negative dispersion are obtained. When the drive Rabi frequency $|V_c|$ equals to Zeeman splitting, we observe that the populations $\rho_{11}$ and $\rho_{-1-1}$ oscillate at about 0.5 with two-cycle. At the zero detuning, the subluminal and superluminal light propagation is predicted due to the steep normal and anomalous dispersion. While, when drive Rabi frequency is great larger than or smaller than Zeeman splitting, the action of Zeeman splitting becomes weak, the results of degenerate two-level systems appear, namely, only EIT and positive dispersion are observed. Finally, CPT is not highly sensitive to the refraction and absorption as we expected.

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FIG. 1. Schematic diagram of energy-level for a transition $F_e = 0 \leftrightarrow F_g = 1$ driven by a linearly polarized $\pi$ light and probed by a circularly polarized $\sigma_{\pm}$ light.

FIG. 2. Quantum coherence effects of a degenerate two-level atomic ensemble. The transition is $F_e = 0 \leftrightarrow F_g = 1$. Here $|V_e| = 1.0$ and $|V_p| = 0.01|V_e|$. (a) CPT for four populations $\rho_{ee}, \rho_{11}, \rho_{00}$ and $\rho_{-1-1}$. The atoms are trapped in the Zeeman sublevels $M_{F_g} = 1$ and $M_{F_g} = -1$ with the same probability $\rho_{11} = \rho_{-1-1} = 0.5$. (b) Real and imaginary parts of $[\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p)]/(V_2/\gamma)$, which are proportional to refraction and absorption. EIT and positive dispersion are shown at the zero detuning $\delta = 0.0$.

FIG. 3. Quantum coherence effects for a transition $F_e = 0 \leftrightarrow F_g = 1$ with Zeeman splitting $\omega_{10} = 2.5$ and drive Rabi frequency $|V_e| = 1.0$. (a) CPT for four populations $\rho_{ee}, \rho_{11}, \rho_{00}$ and $\rho_{-1-1}$. Most atoms are trapped in the Zeeman sublevels $M_{F_g} = 1$ and $M_{F_g} = -1$, but with a little oscillation around 0.5. (b) Real and imaginary parts of $[\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p)]/(V_2/\gamma)$, which are proportional to refraction and absorption. Due to the coherence between drive Rabi frequency and Zeeman splitting, EIA and negative dispersion are exhibited at the zero detuning $\delta = 0.0$.

FIG. 4. Quantum coherence effects for a transition $F_e = 0 \leftrightarrow F_g = 1$ with Zeeman splitting $\omega_{10} = 2.5$ and drive Rabi frequency $|V_e| = 2.5$. (a) CPT for four populations $\rho_{ee}, \rho_{11}, \rho_{00}$ and $\rho_{-1-1}$. Most atoms are trapped in the Zeeman sublevels $M_{F_g} = 1$ and $M_{F_g} = -1$, but with a two-cycle oscillation around 0.5. (b) Real and imaginary parts of $[\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p)]/(V_2/\gamma)$, which are proportional to refraction and absorption. Due to the coherence between drive Rabi frequency and Zeeman splitting, EIT and positive dispersion occur at three frequencies: $\omega_p = \omega_e$, and $\omega_p = \omega_c \pm 5.0$.

FIG. 5. Quantum coherence effects for a transition $F_e = 0 \leftrightarrow F_g = 1$ with Zeeman splitting $\omega_{10} = 2.5$ and drive Rabi frequency $|V_e| = 10.0$. (a) CPT for four populations $\rho_{ee}, \rho_{11}, \rho_{00}$ and $\rho_{-1-1}$. Most atoms are trapped in the Zeeman sublevels $M_{F_g} = 1$ and $M_{F_g} = -1$, but with a large deviation from 0.5 far from the pump-probe detuning center. (b) Real and imaginary parts of $[\rho_{e1}(\omega_p) + \rho_{e-1}(\omega_p)]/(V_2/\gamma)$, which are proportional to refraction and absorption. The results of a degenerate ensemble appear, and EIT and positive dispersion are found at a large spectral region.
Fig. 1/By Gu and Gong
Fig. 3 / By Gu, Sun and Gong
Absorption, Refraction

| $V_c| = 2.5$
| $|V_p| = 0.01|V_c|$

Fig. 4 /By Gu, Sun and Gong
Fig. 5 /By Gu, Sun and Gong
Fig. 6 / By Gu, Sun and Gong