Coherent hole burning and Mollow absorption effects in the cycling transition $F_e=0 \leftrightarrow F_e=1$ subject to a magnetic field

Ying Gu,* Qingqing Sun, and Qihuang Gong†

State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University, Beijing 100871, China

(Received 4 January 2004; published 7 June 2004)

With saturation and probing by circularly polarized fields, quantum coherence effects are investigated for the cycling transition $F_e=0 \leftrightarrow F_e=1$, which is subject to a linearly polarized field and a magnetic field. The saturation field is applied to the case of maximum coherence between the drive Rabi frequency and magnetic field, corresponding to the electromagnetically induced absorption (EIA) with negative dispersion found by Gu et al. For a small saturation Rabi frequency, holes are burned in two Autler-Towns peaks outside two symmetric electromagnetically induced transparency windows due to the two-photon resonance. However, when the saturation Rabi frequency is comparable with the drive Rabi frequency, holes caused by the coherent population oscillation appear in the EIA spectrum. Finally, when the saturation Rabi frequency is large enough, several emission peaks are observed due to the Mollow absorption effects. Furthermore, the dispersion at the pump-probe detuning center is kept negative with an increase in saturation field, which is a precursor of superluminal light propagation.

DOI: 10.1103/PhysRevA.69.063805 PACS number(s): 42.50.Gy, 32.80.Qk, 42.25.Kb

I. INTRODUCTION

Recently, quantum coherence effects in degenerate atomic systems have attracted great interest. On the one hand, they possess the general features of the $\Lambda$- and V-type systems, such as electromagnetically induced transparency (EIT) [1], coherent population trapping (CPT) [2], and the enhanced refractive index effect [3]. On the other hand, the degeneracy of atomic energy influences the refraction and absorption in the phase-coherent atomic ensemble. EIT and electromagnetically induced absorption (EIA) have been predicted and observed in the degenerate systems due to the atomic coherence among Zeeman sublevels belonging to the same hyperfine splitting [4–7]. Absorption spectra of the degenerate two-level atomic system driven by optical fields are different from the classical Mollow absorption spectrum (MAS) [8–10]. With the Zeeman splitting, the two-level degenerate atomic system also shares the properties of the multilevel atom. In this paper, we investigate the quantum coherence effects of a degenerate atomic system for the transition $F_e=0 \leftrightarrow F_e=1$ driven by a linearly polarized field and saturated by the circularly polarized fields.

Hole burning in homogenous and inhomogeneous Doppler-broadened atoms was studied since the 1960s [11–14]. The saturation spectra can be used to study the collision process in atomic and molecular systems [15], as well as the writing and reading of optical data [16,17]. Recently, hole burning and anti-hole-burning caused by the coherent population oscillations are used to demonstrate the subluminal and superluminal light propagation in solids [18,19]. In the degenerate two-level atomic system for a transition $F_e=0 \leftrightarrow F_e=1$, when the coherence between the drive Rabi frequency and Zeeman splitting reaches the maximum, the EIA with negative dispersion is reported [20]. Also for this transition, in this work, the saturation fields are added (detailed description in Sec. II). We find coherent hole burning and Mollow absorption in the original EIA spectra [20] with varying the saturation field.

In the following, we will investigate the quantum coherence effects for the cycling transition $F_e=0 \leftrightarrow F_e=1$ driven by a linearly polarized field, saturated and probed by the circular polarized field, and in a magnetic field. Without the saturation field, when the drive Rabi frequency equals the Zeeman splitting, the quantum coherence reaches the maximum, namely, EIA with negative dispersion has been obtained due to the shifting of EIT windows [20]. Then, for the fixed drive Rabi frequency where EIA occurs, the saturation field is added. In a small saturation Rabi frequency, the holes are burned in the Autler-Towns peaks outside the two symmetric EIT windows due to the two-photon resonance [21]. When the saturation Rabi frequency is matching with the drive Rabi frequency, the holes caused by the coherent population oscillation [22,23] appear in the original EIA spectrum [20]. When we continue to increase the saturation field, several emission peaks are observed due to the Mollow absorption effects [9,10]. With the increment of the saturation field, the dispersion at the pump-probe detuning center is kept to be negative, which predicts the superluminal light propagation. Finally, the situations beyond the EIA are discussed. When the drive Rabi frequency is very small, first four EIT windows, then Mollow absorption appears in the absorption spectrum with increasing the saturation Rabi frequency. However, when the drive Rabi frequency is very large, the intensive saturation field only leads to the widening of the EIT window at the zero pump-probe detuning.

The paper is organized as follows. In the next section, we set up the theoretical model for the transition $F_e=0 \leftrightarrow F_e=1$ in the drive, saturation and probe fields, and write out its optical Bloch equations. Considering various photonic processes of the transitions, we express the Bloch equations as a
set of linear equations of Fourier amplitudes. Then, in Sec. III, we solve these linear equations numerically and discuss the quantum coherence effects with varying the drive Rabi frequency and saturation Rabi frequency. Finally, a summary is given in Sec. IV.

II. THEORETICAL APPROACH

The simplest degenerate two-level system is considered. As shown in Fig. 1, a degenerate two-level transition $F_e=0\leftrightarrow F_e=1$ is set up, which is used to represent a set of transitions $F_e=0\leftrightarrow F_e=1$. The atomic system is driven by a linearly polarized $\pi$ field with frequency $\omega_s$, saturated and probed by the circularly polarized fields $\sigma_i$ with frequency $\omega_i$ and $\omega_p$. Note that the polarization of the saturation fields and probe fields is orthogonal to the linear polarization of the drive field and magnetic field. If the magnetic field is defined as the quantization axis. The saturation and probe field propagation direction and drive field polarization direction are parallel to quantization axis, while the saturation and probe field oscillations are orthogonal to the quantization axis. Here $\pi$ field interacts with the transition $M_{F_e}=i\rightarrow M_{F_e}=i$, and $\sigma_i$ field interacts with the transition $M_{F_e}=i\rightarrow M_{F_e}=i\pm1$ with $i=0, \pm1$. In the presence of magnetic field, the system is a closed four-level one. A transition $F_e=0\leftrightarrow F_e=1$ can be experimentally realized by using the 4f$^6$6s$^2$ $^7F_{1\pm} \leftrightarrow 4f^66p$ $^3D_0$ transition of Sm [24,25] and the $2p^33s^3 P_1 \leftrightarrow 2p^33p$ $^3P_0$ transition of Ne$^+$ [26]. A transition $5S_{1/2}(F=1) \leftrightarrow 5P_{3/2}(F=0)$ in the D$_2$ line of $^{87}$Rb [27] is also a good example, however, in that case, the $M_{F_e}=1$ level is higher in energy than the $M_{F_e}=1$ level. All transition have the same magnitude of dipole moments, but with the different sign, i.e., $\mu_{c1}=\mu_{c-1}=-\mu_{e0}=\mu$.

Now we consider only the decay 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. In the rotating-wave approximations, the system is governed by the optical Bloch equations:

\[
\dot{\rho}_{1-1} = -\frac{i}{\hbar} (V_{e1} \rho_{1e} - \rho_{1e} V_{e1}) - (V_{e0} + V_{e1}) \dot{\rho}_{1e} - (\Gamma_{e-1} + \Gamma_{e0}) \rho_{1e},
\]

\[
\dot{\rho}_{01} = -\frac{i}{\hbar} (V_{c1} \rho_{c1} - \rho_{c1} V_{c1}) - (V_{c0} + V_{c1}) \dot{\rho}_{c1} - (\Gamma_{c-1} + \Gamma_{c0}) \rho_{c1},
\]

\[
\dot{\rho}_{c0} = -\frac{i}{\hbar} [V_{c0} \rho_{c0} - \rho_{c0} V_{c0}] - (V_{c1} + V_{c0}) \dot{\rho}_{c1} - (\Gamma_{c+1} + \Gamma_{c0}) \rho_{c0}.
\]

\[
\dot{\rho}_{p0} = -\frac{i}{\hbar} (V_{p0} \rho_{p0} - \rho_{p0} V_{p0}) - (V_{p1} + V_{p0}) \dot{\rho}_{p1} - (\Gamma_{p-1} + \Gamma_{p0}) \rho_{p0}.
\]

FIG. 1. Diagram of the energy levels for a cycling transition $F_e=0 \leftrightarrow F_e=1$. It is driven by a linearly polarized $\pi$ field with frequency $\omega_s$, saturated and probed by the circularly polarized fields $\sigma_i$ with $\omega_i$ and $\omega_p$.

Ignoring the effect of spatial amplitude, the interaction energy $V_{ci}$ for the $|e\rangle \rightarrow |i\rangle$ transition can be expressed as $V_{c1} = V_{c-1} = hV_{c}(\omega_s)e^{-i\omega_s t} + hV_{p}(\omega_p)e^{-i\omega_p t}$ and $V_{p0} = hV_{p}(\omega_p)e^{-i\omega_p t}$. Here the magnitude values of $2V_{c}(\omega_s) = -\mu E_i/2\hbar^2$, $2V_{p}(\omega_p) = \mu E_i/2\hbar^2$ and $2V_{p}(\omega_p) = \mu E_p/2\hbar^2$ are defined as the drive Rabi frequency, saturation Rabi frequency and probe Rabi frequency, respectively. Let $\omega_j = \omega_s - \omega_p$ and $\omega_{j-1} = 2g \mu_j B / \hbar$ denotes the Raman detuning induced by the static magnetic field of strength $B$ applied in the atoms, where $g$ is the Lande factor and $\mu_j$ is the Bohr magneton. $\gamma_{ij}$ is the decay rate from state $|i\rangle$ to $|j\rangle$. Here we set $\gamma_{c1} = \gamma_{c-1} = \gamma_{c0} = \gamma = (3\Gamma + 2\Gamma_0)/2$ and $\gamma_{i-1} = \gamma_{i0} = \gamma_{i+1} = \gamma = 2\Gamma_0$. 

063805-2
We treat the drive field to all orders in $E_d$ and $E_a$, and the probe field to the first order in $E_p$. In the steady state, the elements of the density matrix are expressed as the terms of Fourier amplitudes [22,28]. Each Fourier amplitude can be used to represent a photonic process. For example, the third order nonlinear term $\rho_{01}(\omega_a+\omega_p-\omega_s)$ means a three-photon process from the state $|0\rangle$ to $|e\rangle$, where the atom in the state $|0\rangle$ absorbs a $\omega_s$ photon to $|e\rangle$, and simultaneously emits a $\omega_s$ photon to the state $|1\rangle$ or $|-1\rangle$ and absorbs a $\omega_p$ photon back to $|e\rangle$. Considering various photonic processes, in terms of the Fourier amplitudes $\rho_{ic}(\omega_i)$, we express $\rho_{ii}$ as

$$\rho_{ii} = \rho_{i0} + \rho_{i1}(\omega_p - \omega_i)e^{-i(\omega_p - \omega_i)t} + \rho_{i2}(\omega_s - \omega_p)e^{-i(\omega_s - \omega_p)t}$$

Subject to $i = e, 1, 0, -1$;

$$\rho_{00} = \rho_{00}(\omega_p) = e^{-i\omega_p t} + \rho_{01}(\omega_s + \omega_p - \omega_i)e^{-i(\omega_s + \omega_p - \omega_i)t} + \rho_{02}(\omega_s - \omega_p)e^{-i(\omega_s - \omega_p)t}$$

$$\rho_{11} = \rho_{11}(\omega_s) = e^{-i\omega_s t} + \rho_{10}(\omega_p) + \rho_{12}(2\omega_s - \omega_p)e^{-i(2\omega_s - \omega_p)t}$$

$$\rho_{-11} = \rho_{-11}(\omega_s) = e^{-i\omega_s t} + \rho_{00}(\omega_p) + \rho_{12}(2\omega_s - \omega_p)e^{-i(2\omega_s - \omega_p)t}$$

The system is assumed to satisfy the relation $\rho_{i0}(\omega_i) = \rho_{ji}(-\omega_i)$. For example, $\rho_{i1}(\omega_i)$ has the form

$$[i(\omega_p - \omega_s) - \chi_{c1}]\rho_{i1}(\omega_i) = [(V_{g0}^d) + V_p\rho_{-11}(\omega_p - \omega_s) + V_g\rho_{01}(\omega_p - \omega_s) - V_p\rho_{-12}(\omega_p - \omega_s)] \rho_{i1}(\omega_i) - \rho_{-11}(\omega_p - \omega_s) = 0.$$

In Eq. (17), by exchanging $1$ and $-1$, $\rho_{i1}(\omega_i)$ can be obtained. The linear equations of Fourier amplitudes are ready to be solved.

The probe refraction and absorption are proportional to the real and imaginary part of the susceptibility, i.e., $\chi(\omega) \propto [\rho_{11}(\omega_p) + \rho_{-11}(\omega_p)]/(V_g/\gamma)$. Since both transitions $M_f = 1 \leftrightarrow M_f = 0$ and $M_f = -1 \leftrightarrow M_f = 0$ have the same dipole moment, $\chi(\omega) \propto \rho_{11}(\omega_p) + \rho_{-11}(\omega_p)/(V_g/\gamma)$. The pump-probe detuning $\delta = \omega_p - \omega_s$. The dispersion $D$ is proportional to $d^2[\rho_{11}(\omega_p) + \rho_{-11}(\omega_p)]/(V_g/\gamma)/d(\delta/\gamma)$. Generally, the dispersion of group velocity can be ignored. In the steep dispersion, we have [29]

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

In the real atomic system, $c/V_g = 1 + \Omega D(\delta = 0)$, where $\Omega = \pi \omega_p N \mu_e^2 / \gamma^2 \hbar$ [30]. At $\delta = 0$, for a positive dispersion, $V_g < c$, which corresponds to a subluminal light propagation, while, for a negative dispersion, $V_g > c$, a superluminal light propagation or even a propagation with negative group velocity.

### III. Quantum Coherence Effects

In order to investigate the effects of saturation field, we first review the quantum coherence effects in a transition $F_e = 0 \leftrightarrow F_g = 1$ driven by a linearly polarized field and probed by the circular polarized fields [20]. In this case, the system can be seen as a superposition of two $\Lambda$-type systems: $M_g = -1 \leftrightarrow F_e = 0 \leftrightarrow M_f = 0$ and $M_f = 1 \leftrightarrow F_e = 0 \leftrightarrow M_f = 0$, where the state $M_f = 0$ shares the common transition: $F_e = 0 \leftrightarrow M_g = 0$. In a moderate magnetic field, the coherence between the drive Rabi frequency and Zeeman splitting reaches the maximum, leading to the EIA. When the saturation field is added, besides the original two $\Lambda$-type systems (where the $M_f = 1 \leftrightarrow F_e = 0 \leftrightarrow M_f = 0$, there are two other $\Lambda$-type systems $M_f = 1 \leftrightarrow F_e = 0 \leftrightarrow M_f = 1$, and they are identical each other), and two pure two-level systems ($M_f = 1 \leftrightarrow F_e = 0$ and $M_f = -1 \leftrightarrow F_e = 0$). The main photonic processes include two types of two-photon resonance (which leads to the EIT) [21] and two-photon gain (which leads to the MAS) [9,10]. In the original EIA spectrum [20], with varying the saturation Rabi frequency, the system experiences first two EIT windows and two coherent hole burning, then the coherent hole burning in the EIA peak, and at last several emission peaks. Simultaneously, by the Kramers-Kronig relations, the refraction changes correspondingly. The following Figs. 2, 3, and 5 illustrate the above coherence between the EIA [20] and saturation Rabi frequency.

To model the system shown in Fig. 1, we first define the parameters in the optical Bloch equations, $G = 1.0$, $G_0 = 0.01$, $\gamma_{c0} = \gamma_{c1} = (3\Gamma + 2\Gamma_0)/2$ and $\gamma_{01} = \gamma_{01} = 2\Gamma_0$, which are referred to Ref. [28]. We set $\omega_s = \omega_{g0}$ and $\omega_p = \omega_{ep}$. Here the Zeeman splitting $\omega_{g1}$ between $M_f = 1$ and $M_f = -1$ is set to 5.0, so that $\omega_{01} = \omega_{01} = 2.5$. To satisfy that the probe Rabi frequency $2|V_p|$ is much smaller than the drive Rabi frequency $2|V_g|$ and saturation Rabi frequency $2|V_e|$, we always set $|V_p| = 0.01|V_g|$. In the following Figs. 2, 3, and 5, $|V_p| = \omega_{01} = 2.5$, where the EIA happens. For simplicity, we set $V_c$, $V_e$, and $V_p$ real. We plot the real and imaginary parts of $[\rho_{11}(\omega_p) + \rho_{-12}(\omega_p)]/(V_g/\gamma)$, which are used to represent the refraction and absorption.

When the saturation Rabi frequency $V_g$ is small, the two-photon resonance dominates. At $\delta = \pm 2.5$, we observe two main EIT windows due to the two-photon resonance condition of the original drive field and probe field, as shown in Fig. 2. Since $V_g$ is small, the EIA spectrum is preserved [20]. Outside two EIT windows, Butler-Towns peaks at $\delta = \pm 5.0$ are still preserved [31], but where two holes are coherently
The holes in the EIA peak are decreased and the holes are burned deeper when treated as the pump field. It is also found that the intensity of the Rabi frequency $V_s$ with increasing $V_c$ drive Rabi frequency $= 0$ originate in the coherent population oscillations. Figure 3 illustrates the evolution of the holes with increasing $V_c$. The holes in the EIA originates in the coherent population oscillations, reported in Refs. [22,23]. The details about this will be explained in the next paragraph. At the same time, increasing the saturation field leads to the decrease of the absorption. However, at $\delta=\pm 2.5$, two EIT windows are very stable due to the two-photon resonance condition. But at $\delta=\pm 5.0$, the transparency points of the original two EIT windows become deeper, until $V_c=0.9$ in Fig. 3(c), and two emission peaks start to appear. In this case, the coupling among the four EIT systems and two pure two-level systems begins to increase, so the multipole structures appear. In this process, the dispersions also exhibit the complex features. It is noted that, at $\delta=0$, the dispersion is always negative.

Now we consider the influence of the population oscillations $\rho_{ee}(\omega_p-\omega_v)$ and $\rho_{11}(\omega_p-\omega_v)$ on the absorption spectrum. Since $\omega_v = \omega_0$ and $\omega_v = \omega_0$, in Eq. (17), $\rho_{ee}(\omega_p-\omega_v)$ becomes $\rho_{ee}(\delta) - \rho_{11}(\delta)$. When the drive Rabi frequency $V_c = 2.5$, Fig. 4 displays the absorptive response $-i V_s^2 \rho_{ee}(\delta) - \rho_{11}(\delta) / [(i \omega_p - \omega_v) - \gamma_1]$ with varying the saturation Rabi frequency $V_c$. When $V_c$ is small, i.e., $V_c=0.2$, the gain at $\delta=0.2$ is also very small. This gain induces only a small decrease in the original EIA peak [20], as shown in Fig. 2. When $V_c$ is moderate, say, $V_c=0.8$, there is a large gain in the absorption spectrum. Hence, the coherent population oscillations $[\rho_{ee}(\delta) - \rho_{11}(\delta)]$ with a beat frequency $\delta$ cause the holes in the original EIA peak [20]. However, when $V_c=1.6$, the large gain is obtained at $\delta=2.5$. Combined with the EIT effect, in the following Fig. 5, emission peaks are observed.

When we continue to increase the saturation Rabi frequency $V_c$, Mollow absorption effects play an important role and several emission peaks appear in the absorption spectrum. When $V_c=1.4$, as shown in Fig. 5(a), the absorption at $\delta=0$ starts to disappear, where the transition from absorption to emission takes place [32,33]. We also observe four emission peaks in this figure. When $V_c=2.5$ in Fig. 5(b), the gain appears in a wide spectral region. At $\delta=\pm 2.5$, there exist two
large emission peaks. These two emission peaks come from a combination of Mollow absorption effects [9,10] and coherent population oscillations [22,23], shown as the dotted line in Fig. 4. At $\delta=0$, the negative dispersion with gain is obtained. Hence, when $V_g \gg 1.4$, the zero pump-probe detuning should be a suitable point to perform the experiment of superluminal light propagation.

In the above Figs. 2, 3, and 5, the refractions also exhibit very fruitful features with varying the saturation Rabi frequency $V_s$. It is noted that, for any values of $V_s$, the dispersion at $\delta=0$ is kept to be negative, but its absolute value of dispersion is decreasing. Furthermore, in the region of gain, not only the negative dispersion, but also the positive dispersion are obtained, as shown in Fig. 5. These results come from the coherence among the drive Rabi frequency, saturation Rabi frequency, and the Zeeman splitting.

We also investigate the quantum coherence effects of the saturation field when the drive Rabi frequency $V_c$ is very small or very large. When $V_c=0.5$, the system first experiences four EIT windows, then MAS with varying the saturation Rabi frequency $V_s$. When $V_c=5.0$, the spectra of absorption and refraction are very stable for a small saturation Rabi frequency $V_s=1.0$, as shown in Fig. 7(a). While, for a large $V_s=5.5$, two outside EIT windows are preserved, but moving away from the detuning center.

IV. SUMMARY

In this paper, we have investigated the quantum coherence effects for a transition $F_e=0 \leftrightarrow F_g=1$. When the atom is driven by a linearly polarized field, probed by the circularly quantum profiles of the FWM will be found. Further discussion about this will appear in another publication.
polarized fields, without the saturation field. EIA with negative dispersion is obtained in the moderate drive Rabi frequency and magnetic field [20]. Then the drive Rabi frequency is fixed at the point of EIA occurring. For a small saturation Rabi frequency, the holes in the Autler-Towns peaks outside the two EIT windows are burned due to the two-photon resonance. When the saturation Rabi frequency matches with the drive Rabi frequency, the hole burning in the EIA spectrum is found due to the coherent population oscillations. When the saturation Rabi frequency is large enough, several emission peaks are observed due to the Mollow absorption effects. With the increment of the saturation Rabi frequency, the dispersion at the pump-probe detuning center is kept negative, which predicts the superluminal light propagation. Finally, in the saturation field, the quantum coherence effects for a very small or large drive Rabi frequency are also discussed.

ACKNOWLEDGMENTS

The work was supported by National Natural Science Foundation of China under Grant Nos. 10334010, 10304001, 10328407, and 90101027. The work was also supported by the special fund from Ministry of Science and Technology of China, the National Key Basic Research Special Foundation under Grant No. TG1999075207. The project was partly sponsored by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry. We thank Professor Z. J. Xia and Professor H. B. Jiang for stimulating and helpful discussions.