Transient responses of transparency in a far-off resonant atomic system*

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Transient coherent oscillations in a closed Λ system under far-off resonant Raman fields were investigated theoretically. It has been found that the coherent superposition of the ground states can be formed due to the absorption even for initial maximal mixed ground states. The absorption oscillates with a period depending on the two-photon detuning when the system is initially in a transparent state and the two-photon Raman detuning is suddenly changed. The amplitude of the absorption decays with the decay rate of the ground states, which is different from the case when the lasers are applied resonantly. These transient coherent oscillations can be used to measure the relaxation rate of the ground states.

Keywords: laser atom interaction, coherent population trapping, transient coherent oscillation, three-level system

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1. Introduction

The quantum coherent phenomena are very interesting and have many important applications in many fields.[1–3] In order to generate the quantum coherent phenomena in atomic media, usually the atoms should be prepared by the laser or microwave fields so that the atomic media under these fields are changed into a coherent system. Electromagnetically induced transparency (EIT)[4] and coherent population trapping (CPT)[5] are typical quantum coherent processes.[1–3] Some very interesting phenomena can be produced in these processes, such as slow light,[6] very narrow spectral lines,[7,8] light storage in atomic medium,[9,10] and light switch.[11] It is well-known that in the EIT (or CPT) process, the applied laser lights are usually near resonant with the respective transitions. However, when there is a large one-photon detuning, the so-called Raman process can also generate phenomena similar to those of the EIT process.[12] Based on the far-off resonant three-level Λ-configuration atom ensemble, slow light and high-speed broadband optical quantum memory have been experimentally demonstrated.[13–17]

In recent years, the dynamical formation and disappearance of EIT (or CPT) have attracted a lot of attention. In a three-level Λ-structure atom–field interaction system, the transient processes can exhibit the formations of EIT and electromagnetically induced absorption (EIA). It can tell us how the atomic system was evolving before the steady state has been reached. The transient processes of the three-level Λ-configuration atom–light interacting system have been investigated under the condition of near one-photon resonance experimentally and theoretically.[18–20] In Refs. [18] and [19], the transient responses were induced by changing the frequencies of the laser beams, which was the change of the Raman detuning. However, in Ref. [20], the dynamic responses were induced by changing the magnetic field. The Raman detuning was generated by the shifts of the levels induced by the Zeeman effect. However, the transient responses related to the far-off resonant Raman process have not been investigated up to date. In the case of far-off resonance, the influence of the spontaneous emission of the excited state is diminishing and the relaxation of the ground states has an effect on the transient processes. Because the relaxation rates of the ground states are much smaller than the relaxation rate of the excited state, the transient processes are slow. Therefore, the relaxation rates of the ground states can be easily measured by using those far-off resonant transient processes. This is an alternative method to detect the decay rates of the ground states.

2. Theory and numerical calculations

In this paper, we consider the transient responses of a Λ system when far-off resonant Raman lasers are applied. The laser–atom interaction system is shown in Fig. 1. The three atomic energy levels form a Λ configuration and are labeled as $|a\rangle$, $|b\rangle$, and $|c\rangle$, where $|a\rangle$ is an excited state and $|b\rangle$, $|c\rangle$ are the ground states. Laser 1 with angular frequency ω_1 drives the transition $|a\rangle \leftrightarrow |b\rangle$. The transition of $|a\rangle \leftrightarrow |c\rangle$ is driven by another laser with angular frequency ω_2. The Hamiltonian

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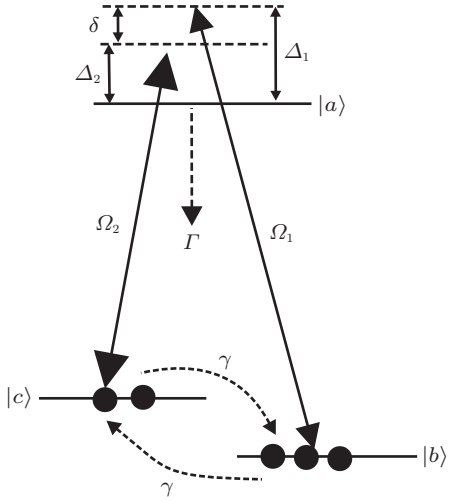


Fig. 1. The atomic system levels in Λ configuration. Here $|a\rangle$ is an excited state and $|b\rangle$, $|c\rangle$ are the ground states. Laser 1 with frequency ω_1 and laser 2 with frequency ω_2 drive the transitions $|a\rangle \leftrightarrow |b\rangle$ and $|a\rangle \leftrightarrow |c\rangle$, respectively. The excited state spontaneous emission rate is Γ. The one-photon detunings of lasers 1 and 2 are Δ_1 and Δ_2, respectively. The two-photon detuning is δ.

of the system reads

$$H = H_{\rm A} + H_{\rm AL}, \tag{1}$$

where $H_{\rm A}$ is the atomic Hamiltonian, and $H_{\rm AL}$ is the Hamiltonian of the light–atom interaction. The free part of the atomic Hamiltonian is

$$H_{\rm A} = \hbar\omega_a|a\rangle\langle a| + \hbar\omega_b|b\rangle\langle b| + \hbar\omega_c|c\rangle\langle c|, \tag{2}$$

and the interaction part of the Hamiltonian is

$$H_{\rm AL} = -\hbar\Omega_1 \,{\rm e}^{-{\rm i}\omega_1 t}|a\rangle\langle b| - \hbar\Omega_2 \,{\rm e}^{-{\rm i}\omega_2 t}|a\rangle\langle c| + {\rm h.c.}, \tag{3}$$

where $\hbar\omega_a$, $\hbar\omega_b$, $\hbar\omega_c$ are the energies of the atomic states; Ω_1 and Ω_2 are the Rabi frequencies of the laser–atom interaction defined as $\Omega = Ed_{\mu\nu}/\hbar$ $(\mu, \nu = a, b, c)$, with E being the intensity of the electric field and $d_{\mu\nu}$ the atomic dipole moment. The differential equation of the density matrix is given as follows:

$$\frac{{\rm d}\rho}{{\rm d}t} = -\frac{\rm i}{\hbar}[H, \rho] - \frac{1}{2}\{\Gamma, \rho\}. \tag{4}$$

Under the rotating wave approximation, we obtain

$$\dot{\rho}_{aa} = -\Gamma\rho_{aa} + {\rm i}(\Omega_2^*\rho_{ca} - \Omega_2\rho_{ac}) + {\rm i}(\Omega_1^*\rho_{ba} - \Omega_1\rho_{ab}), \tag{5}$$

$$\dot{\rho}_{bb} = \frac{\Gamma}{2}\rho_{aa} - \gamma(\rho_{bb} - \rho_{cc}) + {\rm i}(\Omega_1\rho_{ab} - \Omega_1^*\rho_{ba}), \tag{6}$$

$$\dot{\rho}_{cc} = \frac{\Gamma}{2}\rho_{cc} - \gamma(\rho_{cc} - \rho_{bb}) + {\rm i}(\Omega_2\rho_{ac} - \Omega_2^*\rho_{ca}), \tag{7}$$

$$\dot{\rho}_{ab} = -\Gamma_{ab}\rho_{ab} + {\rm i}\Omega_2^*\rho_{cb} + {\rm i}\Omega_1^*\rho_{bb} - {\rm i}\Omega_1\rho_{aa}, \tag{8}$$

$$\dot{\rho}_{ac} = -\Gamma_{ac}\rho_{ac} + {\rm i}\Omega_2^*\rho_{cc} - {\rm i}\Omega_2\rho_{aa} + {\rm i}\Omega_1^*\rho_{bc}, \tag{9}$$

$$\dot{\rho}_{bc} = -\Gamma_{bc}\rho_{bc} - {\rm i}\Omega_2^*\rho_{ba} + {\rm i}\Omega_1\rho_{ac}, \tag{10}$$

$$\dot{\rho}_{\mu\nu} = \dot{\rho}_{\nu\mu}^*, \tag{11}$$

where

$$\Gamma_{ab} = (\Gamma + \gamma)/2 + {\rm i}\Delta_1, \tag{12}$$

$$\Gamma_{ac} = (\Gamma + \gamma)/2 + {\rm i}\Delta_2, \tag{13}$$

$$\Gamma_{bc} = {\rm i}\delta + \gamma, \tag{14}$$

$$\Delta_1 = \omega_{ab} - \omega_1, \tag{15}$$

$$\Delta_2 = \omega_{ac} - \omega_2, \tag{16}$$

$$\delta = \Delta_1 - \Delta_2. \tag{17}$$

Here Γ is the decay rate of the excited state, Δ_1 and Δ_2 are the detunings of the lasers, γ is the relaxation rate of the ground states (we have assumed that the decay rates of the two ground states are the same), and δ is the two-photon detuning. According to the differential equations of the density matrix elements, under certain approximations, we can obtain the analytical solutions of the density matrix elements. We solve ρ_{bc} in zero order, which means that the population of the excited state $\rho_{aa}^{(0)}$ is zero and the Raman coherences between the excited and the ground states, $\rho_{ab}^{(0)}$ and $\rho_{ac}^{(0)}$, are zero. We assume that the initial atomic population is equally distributed in the two ground states in thermal equilibrium, that is $\rho_{bb}^{(0)} = \rho_{cc}^{(0)} = 1/2$. By solving Eqs. (8) and (9), we obtain

$$\rho_{ab} = ({\rm i}\Omega_2^*\rho_{cb} + {\rm i}\Omega_1/2)/\Gamma_{ab}, \tag{18}$$

$$\rho_{ac} = ({\rm i}\Omega_1^*\rho_{bc} + {\rm i}\Omega_2^*/2)/\Gamma_{ac}. \tag{19}$$

By substituting Eqs. (18) and (19) into Eq. (10), $\dot{\rho}_{bc}$ can be rewritten as

$$\begin{aligned}\dot{\rho}_{bc} \;=\; & -\Gamma_{bc}\rho_{bc} + {\rm i}\Omega_1({\rm i}\Omega_2^*/2 + {\rm i}\Omega_1^*\rho_{bc})/\Gamma_{ac} \\ & -{\rm i}\Omega_2^*(-{\rm i}\Omega_2\rho_{bc} - {\rm i}\Omega_1^*/2)/\Gamma_{ab}^*.\end{aligned} \tag{20}$$

Firstly, we consider the formation of the transparency in the Raman process. Initially, the atom ensemble is in thermal equilibrium. The atomic population distributes between the ground states equally. At this stage, there is no coherence of the ground states, that is $\rho_{bc}(t = 0) = 0$. For the large one-photon detuning Raman process, $\Delta_1 \simeq \Delta_2 = \Delta$ and $\Delta \gg \Gamma \gg \delta$. We assume $\Omega_1 = \Omega_2 = \Omega$. From Eqs. (19) and (20), we obtain the imaginary part of the coherence as

$$\begin{aligned}&{\rm Im}(\rho_{ac}) \\ &= {\rm Im}(\rho_{ac}^{\rm s}) + \frac{{\rm e}^{-\left(\gamma + \Gamma\Omega^2/\Delta^2\right)t}\Gamma\Omega^3}{4\Delta^2\left[\left(\gamma^2 + \delta^2\right)\Delta^4 + 2\gamma\Gamma\Delta^2\Omega^2 + \Gamma^2\Omega^4\right]} \\ &\quad \times\left[\left(\gamma\Gamma\Delta^2 - 2\delta\Delta^3 + \Gamma^2\Omega^2\right)\cos(\delta t)\right. \\ &\quad \left. - \Delta\left(\Gamma\delta\Delta + 2\delta\Delta^3 + 2\Gamma\Omega^2\right)\sin(\delta t)\right],\end{aligned} \tag{21}$$

where the steady state solution is

$${\rm Im}(\rho_{ac}^{\rm s}) = \frac{\Gamma\Omega\Delta^2\left[\left(\gamma^2 + \delta^2\right)\Delta^2 + \left(\gamma\Gamma + 2\delta\Delta\right)\Omega^2\right]}{4\Delta^2\left[\left(\gamma^2 + \delta^2\right)\Delta^4 + 2\gamma\Gamma\Delta^2\Omega^2 + \Gamma^2\Omega^4\right]}. \tag{22}$$

From Eq. (21), we can see that when the one-photon detuning is very large, the absorption is smaller compared with that in the case of no one-photon detuning, and the time of the CPT

formation in this case is mainly dependent on the relaxation rate of the ground states. This decay rate is much smaller than the spontaneous decay rate of the excited state. Therefore, the mechanism for the formation of the CPT in our scheme is different from that in the resonant case. In this system, the transient process can be easily detected. By measuring the absorption, the decay rate of the ground states can be determined. We numerically calculate the absorptions of the atoms when there is no initial coherence of the ground states. The results are shown in Fig. 2.

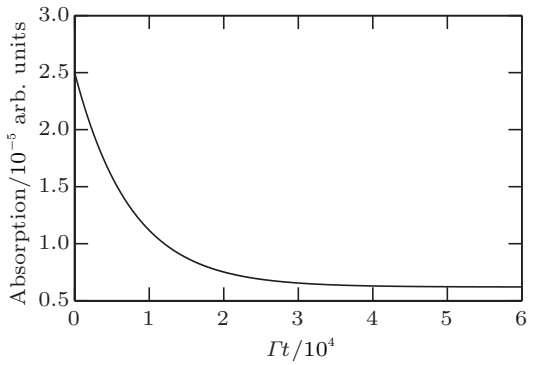


Fig. 2. The absorption of the atoms in the process of the CPT formation when the lasers are applied far-off resonant and there is no two-photon detuning. The parameters are $\Omega = 1.0\Gamma$, $\gamma = 3.3\times10^{-5}\Gamma$, $\delta = 0$, and $\Delta = 10^2\Gamma$.

It is seen clearly from Fig. 2 that the absorption of the atoms is very small and the amplitude of the absorption is decreasing gradually with time. The above results are for the case without two-photon detuning. The results also show that the atoms will be changed into a coherent superposition state due to the absorption although the atoms initially are in a maximal mixed state. This means that the coherence is transferred from the lasers to the atoms in the absorption process.

We also consider the case with a two-photon detuning. From Eq. (21), we can see that the absorption periodically oscillates with time when there is a two-photon detuning and the period is $2\pi/\delta$. The numerical results are shown in Fig. 3.

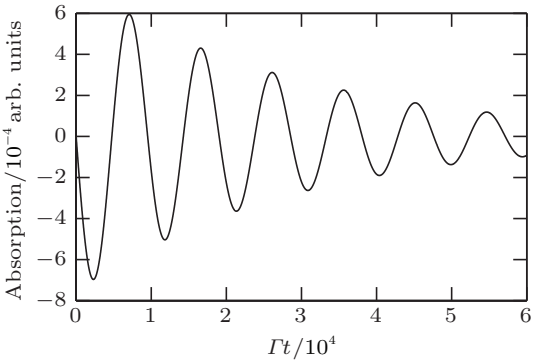


Fig. 3. The absorption of the atoms when the lasers are applied far-off resonant, a two-photon detuning is included, and there is no coherence between the ground states initially. The parameters are $\Omega = 1.0\Gamma$, $\gamma = 3.3\times10^{-5}\Gamma$, $\delta = 6.6\times10^{-4}\Gamma$, and $\Delta = 10^3\Gamma$.

Figure 3 clearly shows that the absorption has a periodical oscillation with time and the amplitude of the oscillation is decreasing with time. Due to the existence of the two-photon detuning, the CPT cannot be formed steady.

Secondly, we consider the transient process of the breakup of the CPT state. In this process, the ground states of the atoms are initially in coherent superposition. When the two-photon detuning increases suddenly from zero to a non-zero value, the atoms will absorb the light. As $(\Delta_1,\Delta_2) \gg \Gamma \gg \gamma$, the initial stationary solution is

$$\begin{aligned}
&\rho_{bc}(t=0)\\
&= -\{\Omega_1\Omega_2\left[\Gamma^2+2\Delta_1\left(\Delta_1-\Delta_2\right)\right]\Omega_1^2\\
&\quad+\left[\Gamma^2+2\Delta_2\left(\Delta_2-\Delta_1\right)\right]\Omega_2^2\}/[\left(\Gamma^2+4\Delta_1^2\right)\Omega_1^4\\
&\quad+2\left(\Gamma^2-4\Delta_1\Delta_2\right)\Omega_1^2\Omega_2^2+\left(\Gamma^2+4\Delta_2^2\right)\Omega_2^4]\\
&\quad-\mathrm{i}[\Gamma\left(\Delta_1+\Delta_2\right)\Omega_1\Omega_2\left(\Omega_1^2-\Omega_2^2\right)]/[\left(\Gamma^2+4\Delta_1^2\right)\Omega_1^4\\
&\quad+2\left(\Gamma^2-4\Delta_1\Delta_2\right)\Omega_1^2\Omega_2^2+\left(\Gamma^2+4\Delta_2^2\right)\Omega_2^4]. \qquad (23)
\end{aligned}$$

Under the conditions $\Delta_1 \simeq \Delta_2 = \Delta$ and $\Delta \gg \Gamma \gg \gamma$, the imaginary part of ρ_{ac} is

$$\begin{aligned}
&\mathrm{Im}(\rho_{ac})\\
&= \mathrm{Im}(\rho_{ac}^{\mathrm{s}})+\frac{\Omega\,\mathrm{e}^{-(\gamma+\Gamma\Omega^2/\Delta^2)t}}{4\left[(\gamma^2+\delta^2)\Delta^4+2\gamma\Gamma\Delta^2\Omega^2+\Gamma^2\Omega^4\right]}\\
&\quad\times\{\Gamma\left[\left(\gamma^2+\delta^2\right)\Delta^2+(\gamma\Gamma+2\delta\Delta)\Omega^2\right]\cos(\delta t)\\
&\quad+\left[2\left(\delta^2+\gamma^2\right)\Delta^3+\Gamma\left(-\Gamma\delta+2\gamma\Delta\right)\Omega^2\right]\sin(\delta t)\}, \qquad (24)
\end{aligned}$$

where the steady part of ρ_{ac} is

$$\mathrm{Im}(\rho_{ac}^{\mathrm{s}}) = \frac{\Gamma\Omega\Delta^2(\gamma^2+\delta^2)+\Gamma\Omega^3(\gamma\Gamma+2\delta\Delta)}{4\left[(\gamma^2+\delta^2)\Delta^4+2\gamma\Gamma\Delta^2\Omega^2+\Gamma^2\Omega^4\right]}. \qquad (25)$$

From Eq. (24), we can see that the absorption will appear when the two-photon detuning suddenly becomes non-zero. The absorption will oscillate and the amplitude will reduce gradually with time. Finally, the absorption will reach a steady value. The numerical result is shown in Fig. 4. Similar to the process of the CPT formation when the two-photon detuning is not zero, the absorption oscillates with period δ and the amplitude decreases gradually with time at the decay rate of the ground states. Finally, the absorption reaches a steady value. According to these results, we can also measure the decay rate of the ground states by suddenly changing the two-photon detuning when the atoms are initially in a CPT state.

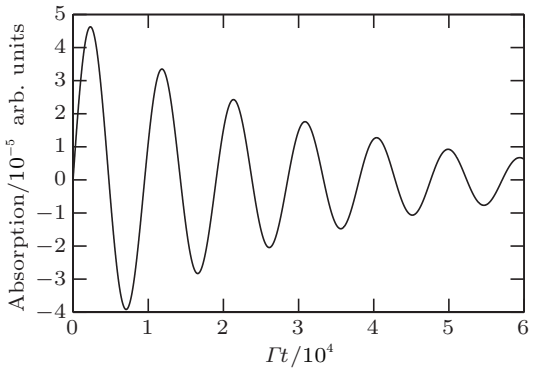


Fig. 4. The absorption of the atoms when laser lights are applied far-off resonant and the Raman coherence between the ground states is existence. The parameters are $\Omega = 1.0\Gamma$, $\gamma = 3.3 \times 10^{-5}\Gamma$, $\delta = 6.6 \times 10^{-4}\Gamma$, $\Delta = 10^3\Gamma$.

3. Conclusion

We have investigated the transient processes of the CPT theoretically under the condition of far-off resonant Raman process and analytically obtained the expressions of the absorption in the processes of the CPT formation and the breakup of the CPT. When there is a two-photon detuning, the absorption oscillates with reducing amplitude at the period of the two-photon detuning. The transient processes are different from those of the one-photon resonance, as the processes depend on the relaxation rate of the ground states. It is interesting to find that the ground state atoms can be driven into a coherent superposition due to the absorption. Compared to the resonant process, the transient processes of the far-off resonant Raman process are very slow. Therefore, these transient processes can be detected easily and the decay rate of the ground states can be measured by using this method.

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