Absorption Changes Induced by Off-Resonance Driving a Degenerate Two-Level System *

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The alteration of atomic absorption via quantum coherence is observed in the degenerate two-level atomic system. It is shown that when the detuning of coupling field equals to that of probe light, i.e. two-photon resonance, the reduction of atomic absorption via electromagnetically induced transparency occurs. However, when we tune the coupling field to two-photon off-resonance, the enhancement of absorption is obtained for the probe field. The influences of one-photon detuning and intensity of coupling field on absorption are also experimentally demonstrated.

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Quantum coherence in multilevel atomic system induced by monochromatic fields can lead to interesting phenomena, such as coherence population trapping (CPT),[1] electromagnetically induced transparency (EIT),[2] electromagnetically induced absorption (EIA),[3] lasing without inversion (LWI).[4] These properties have many interesting applications in subluminal and 'superluminal' propagation of light pulse,[5,6] nonlinear optics,[7,8] highly sensitive magnetometers,[9] reducing the line width of a cavity[10] and quantum information processing.[11]

Up to now, there are a large number of experiments and theoretical modelling on EIT in different atomic systems.[12,13] An enhancement of the absorption termed EIA resulting from atomic coherence has also been reported.[3,14] Later it was theoretically shown that the EIA resonance has also been caused in four level systems by the spontaneous transfer of the light-induced low-frequency coherence from the excited level to the ground level state.[15] A theoretical and experimental investigation of the Hanle EIT/EIA resonances have also been presented.[16,17] It was theoretically found that EIT and EIA can be altered due to the competition between the driver Rabi frequency and the Zeeman splitting in a degenerate two-level system.[18] Very recently, it was demonstrated that the light pulse speed can be changed from subluminal to superluminal resulted from the quantum coherences of EIT and EIA in degenerate two-level atomic system.[19]

On the other hand, the absorption of probe light in a medium can also be influenced by the off-resonance interaction. The enhanced absorptions for the probe laser appear in a ladder-type three-level system when the pump field is tuned off resonance.[20] A theoretical analysis has shown that when a Raman atomic system is tuned from two-photon resonance to far-off two-photon resonance, the group velocity of the light pulse can be switched dramatically from subluminal to superluminal.[21] All these investigations show that the atomic medium has abundant effects under the interaction of light fields at the condition of resonance or off-resonance. In this Letter, we report the observation of absorption modification from electromagnetically induced transparency to enhanced absorption by tuning the detuning of coupling light from two-photon resonance to near-off two-photon resonance in a degenerate two-level atomic system, which may be used as a new scheme to propagate pulse light from subluminal to superluminal velocity by controlling the detuning of coupling light.

The experiment is perform with caesium atoms at room temperature. The transition between $6S_{1/2}$, $F = 3$ and $6P_{3/2}$, $F' = 2$ within the D2 line of Cs atoms is served as degenerate two-level system, which is a closed transition system. It should be noted that the total angular momentum of the excited level F_e (F_e=2) is smaller than that of the ground level F_g ($F_g = 3$). Under the condition of two-photon resonance, the absorption reduction of EIT effect should be occurred when both the coupling and probe laser beams are interacting with the transition of $F_g \leftrightarrow F_e$. However, when the frequency of the coupling laser is tuned from on-resonance to off-resonance, the enhancement of absorption is obtained.

Figure 1 shows the experimental setup for measurement of the absorption reduction and absorption enhancement of the probe beam. Both the coupling

and probe laser are diode lasers with external cavity, which are frequency and temperature stabilized to provide a narrow linewidth less than 2 MHz. Faraday rotation isolators are used to prevent any back reflections from surfaces of the optics. Small fractions of the coupling and probe beams separated respectively by PBS2 and PBS1 are employed to monitor the laser frequency. Two standard saturated absorption spectroscopy are used for stabilizing the frequency of the coupling laser beam to the transition of $F = 3$ ($6S_{1/2}$) $\leftrightarrow F' = 2$ ($6P_{3/2}$) and scanning the frequency of the probe laser beam through the transition $F = 3 \leftrightarrow F' = 2$. The Fabry–Perot cavity is served as the monitor of the laser frequency detuning, meanwhile the other Fabry–Perot cavity is applied for locking the coupling laser beam to a suitable detuning frequency to obtain the modification effects from EIT to absorption enhancement. The remaining parts of both laser beams are brought together by PBS3 as the coupling and probe beams and propagate orthogonally through a 30-mm-long caesium vapour cell to create effective atomic coherence. The cell kept at the room temperature is shielded with metal to avoid the magnetic field splitting of sublevels caused by surrounding magnetic field. Two lens of $f = 100$ mm and $f = 60$ mm are located at the two sides of the cell for mode matching between the coupling and probe beams in the cell and for collimating the output power into the detectors. The transmitted probe beam is detected by a silicon photodiode and recorded by a digital oscilloscope.
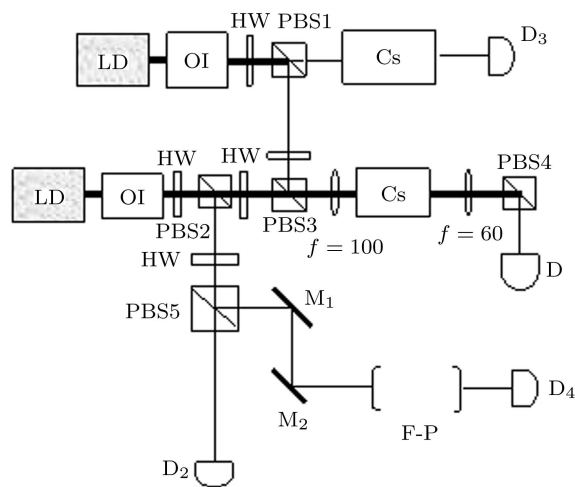

Fig. 1. Schematic of the experimental setup. LD: laser diode, OI: optical isolator, HW: half wave plate, PBS: polarized beam splitter, F-P: monitoring Fabry–Perot cavity, M: reflecting mirror. Cs: caesium atom vapour. D: detector.

We lock the coupling laser to the transition line of $F = 3$ ($6S_{1/2}$) $\leftrightarrow F' = 2$ ($6P_{3/2}$), and meanwhile the probe laser is scanned across the transition

of $F = 3 \leftrightarrow F' = 2$. As is expected, we obtain the EIT effect as shown in Fig. 2. The power of coupling laser and probe laser are 2.1 mW and 50 μW, corresponding to the Rabi frequency of $\Omega_c = 2\pi \times 28.5$ MHz, $\Omega_p = 2\pi \times 4.4$ MHz.
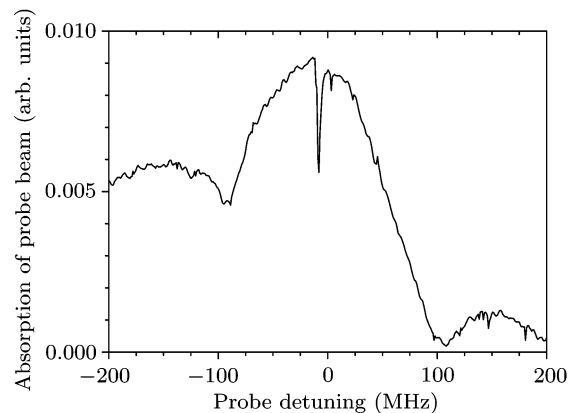

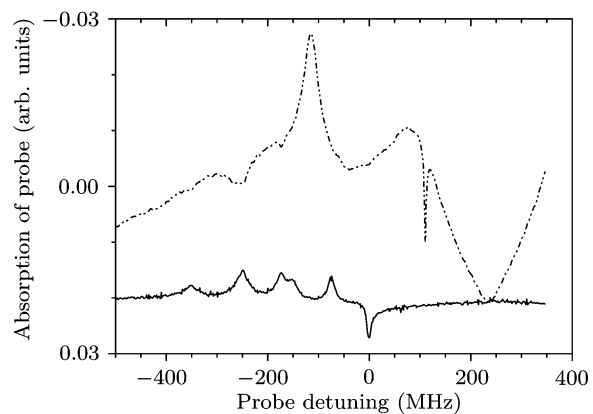**Fig. 2.** Absorption spectrum vs probe detuning at the resonance pumping.

Fig. 3. Transmission of probe beam vs. probe detuning with an off-resonance coupling beam. Dot-dot-dashed line: the changes of electromagnetically induced reduction and enhancement of probe absorption. Solid line: saturated absorption spectra for the transition of $F = 3$ ($6S_{1/2}$) $\leftrightarrow F' = 2, 3, 4$ ($6P_{2/3}$).

On the other hand, when the coupling laser beam is tuned to off-resonance at the red side of the transition of $F = 3 \leftrightarrow F' = 2$, the absorption spectrum of the probe beam is changed from EIT to a peak of enhanced absorption. Figure 3(a) shows both the absorption reduction and absorption enhancement effects when the probe laser is scanned continuously through the transition of $F = 3 \leftrightarrow F' = 2$, and meanwhile the detuning of the coupling beam (i.e. one photon detuning) is $\Delta = -109.7$ MHz, which is locked and recorded by a confocal Fabry–Perot cavity. Figure 3(b) shows the saturated absorption spectra of the transition of $F = 3$ ($6S_{1/2}$) to $F' = 2, 3, 4$ ($6P_{2/3}$). It is obvious that the absorption dip of

EIT appears on the right side of Fig. 3(a), and meanwhile the absorption peak on the opposite side of EIT peak demonstrates the absorption enhancement for the probe beam, where the probe light detuning is $\delta = 120\,\mathrm{MHz}$, which is much larger than the Rabi frequency of coupling and probe beam ($\Omega_c = 28.5\,\mathrm{MHz}$ and $\Omega_p = 4.4\,\mathrm{MHz}$) for a condition to reach the superluminal propagation of pulse light.[28] The absorption enhancement appears in the case of both the one photon detuning Δ and two-photon detuning $\delta - \Delta$ are very large. Thus it is demonstrated that the probe absorption changes from electromagnetically induced reduction to absorption enhancement when the coupling laser beam is tuned from two-photon resonance to two-photon off-resonance.
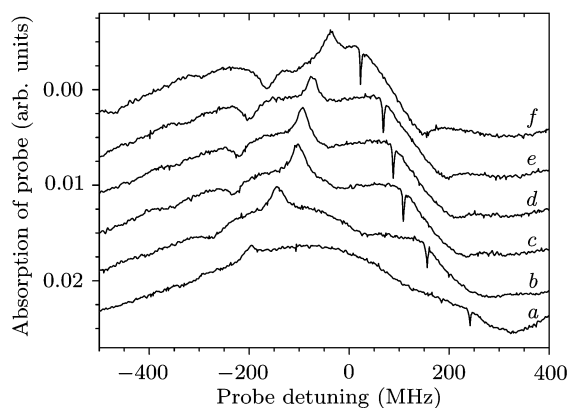

Fig. 4. Dependence of the probe absorption on the detuning of coupling beam for the coupling laser detunings: (a) $\Delta = 40\,\mathrm{MHz}$, (b) $\Delta = 70\,\mathrm{MHz}$, (c) $\Delta = 90\,\mathrm{MHz}$, (d) $\Delta = 105\,\mathrm{MHz}$, (e) $\Delta = 150\,\mathrm{MHz}$, (f) $\Delta = 240\,\mathrm{MHz}$.

Figure 4 shows the absorption reduction and enhancement at different pumping detuning. As the coupling detuning is changed, EIT dips move to the positions where the probe-beam frequency exactly equals to that of the coupling beam, i.e. the condition of two-photon resonance. Meanwhile, the enhancement absorption peaks are moved with the detuning of coupling beam changing. When the coupling detuning increases, the peak of absorption moves to the position where the detuning of probe frequency is larger, and its height becomes smaller as shown in Figs. 4(a)–4(f). The larger the detuning of the coupling beam, i.e. one photon detuning is, the larger the two photon detuning for absorption enhancement is. However, the maximum enhancement of absorption is observed at a suitable coupling detuning of $\Delta = 90\,\mathrm{MHz}$ as shown in Fig. 4(c), in this case the two photon detuning is $189\,\mathrm{MHz}$. To reach the maximum absorption, the power of the coupling and probe laser is carefully chosen to be $2.1\,\mathrm{mW}$ and $50\,\mu\mathrm{W}$. In this experiment, in order to improve long term frequency stability, the coupling laser frequency is always locked to an external tunable $100\,\mathrm{mm}$ long confocal Fabry–Perot cavity by a lock-in amplifier and a proportional and integrating amplifier, and meanwhile the other Fabry–Perot cavity is used to monitor its detuning.

Figure 5 gives the probe absorption with different coupling power. The detuning of coupling beam is fixed at $\Delta = 109.7\,\mathrm{MHz}$. All these curves are given for the same probe power $50\,\mu\mathrm{W}$. The largest enhancement of absorption is obtained for $2.3\,\mathrm{mW}$ (Fig. 5(c)). Because the condition of two-photon resonance is independent of coupling power, the EIT dips do not change its position, but the position of absorption enhancement peaks have a small displacement when the coupling detuning increases, The peak of absorption becomes larger with the increasing power of coupling laser.
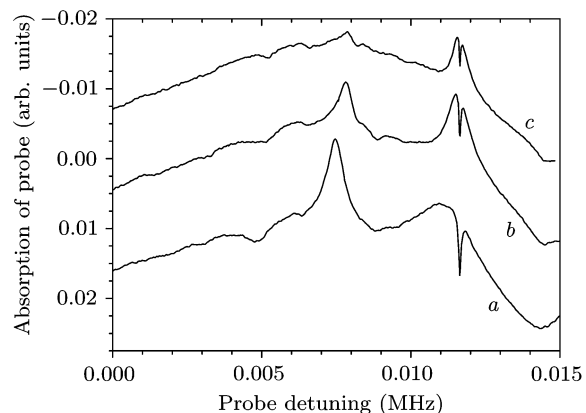

Fig. 5. Absorption spectrum for probe beam as the power of coupling light changes: (a) $P_c = 0.8\,\mathrm{mW}$, (b) $P_c = 1.6\,\mathrm{mW}$, (c) $P_c = 2.3\,\mathrm{mW}$.

In conclusion, we have demonstrated absorption changes in the situation of two-photon on-resonance and two-photon off-resonance. It is shown that both the reduction and enhancement in absorption can be obtained when a big detuning of the coupling light is employed. The alteration from EIT to absorption enhancement can be controlled by changing the two-photo detuning from on-resonance to off-resonance. It is expected that this simple system may be developed to accomplish the subluminal and superluminal propagation of pulse light in a degenerate two-level atomic system.

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