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Observation of EIA in closed and open caesium atomic system*

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We present an experimental study on electromagnetically induced absorption (EIA) in the closed transition of a degenerate two-level Cs atomic system. The coupling and probe lasers coupled with the transition $6S_{1/2}F=4 \rightarrow 6P_{3/2}F'=5$ of caesium atom. The signal of EIA was obtained and the frequency detuning and intensity effect of the pumping laser were experimentally investigated. The EIA signal in $6S_{1/2}$ F=4 $\rightarrow$ $6P_{3/2}$ F'=4 and $6S_{1/2}$ F=4 $\rightarrow$ $6P_{3/2}$ F'=3 open transitions was also obtained. As the repumping laser couples with the transition of $6S_{1/2}$ F=3 $\rightarrow$ $6P_{3/2}$ F'=4, the EIA signal is increased due to the hyperfine optical pumping.

Keywords: EIA, caesium atom, degenerate, two-level system
PACC: 3280, 4225K

1. Introduction

The interaction of laser beam with an atomic system has attracted much attention in recent years.[1] The coupling laser that resonates with the transition line of the atom can make the absorption of the resonant probe laser decrease (electro-magnetically induced transparency: EIT)[2] in a three-level atomic system or increase (electro-magnetically induced absorption: EIA)[3−4] in a degenerate two-level system. EIA, as a counterpart of EIT, is caused by quantum destructive interference. EIA receives much interest in a coherently prepared medium. It has recently been demonstrated that degenerate two-level systems may exhibit some new interesting coherent spectroscopic effects.[5] The properties of EIA, which depend upon the coupling laser intensity, magnetic field and laser beam polarizations, were analysed in the rubidium atomic system.[6,7] Kazantsev *et al*[8] proposed the theoretical prediction about EIA, and Lipsich *et al*[9] demonstrated EIA by using two coherent laser fields in a Rb atomic vapour cell. However, the investigations about EIA were almost done in $F_g \leftrightarrow F_e = F_g + 1$ transition, which was one of the three conditions that must be satisfied to observe an EIA signal. [5] Another important condition is that the system must be closed. Reference [7] reported the observation of EIA signal in the Rb atomic system not satisfying the above two conditions.

In this paper, we present the experimental demonstration of EIA induced by two co-propagating laser fields in closed and open hyperfine transitions in the caesium D_2 line. The effects of intensity and detuning of the coupling laser are systematically investigated. Due to the hyperfine optical pumping effect, atomic population of the $6S_{1/2}F=4$ is partially transferred to $6S_{1/2}F=3$ and influence the further experiment. So, in order to reduce the pumping effect of the coupling laser, a repumping laser which is resonant with $6S_{1/2}$ F=3$\rightarrow$$6P_{3/2}$ F'=4 or $6S_{1/2}$ F=3$\rightarrow$$6P_{3/2}$ F'=3 transition is introduced. The experimental results are in agreement with the theoretical analysis in Ref.[10].

2. Experiment

The relevant energy levels of a caesium atom are shown in Fig.1. According to the dipole transition selection rule, the $6S_{1/2}$ F=3$\rightarrow$$6P_{3/2}$ F'=5 transition is forbidden, so the $6S_{1/2}$ F=4$\rightarrow$$6P_{3/2}$ F'=5 transition is a closed transition of caesium atoms. C and

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P indicate the coupling laser and the probe laser, respectively. R denotes the repumping laser which is resonant with the transition of the $6S_{1/2}$ F=3→$6P_{3/2}$ F'=4 or $6S_{1/2}$ F=3→$6P_{3/2}$F'=3.

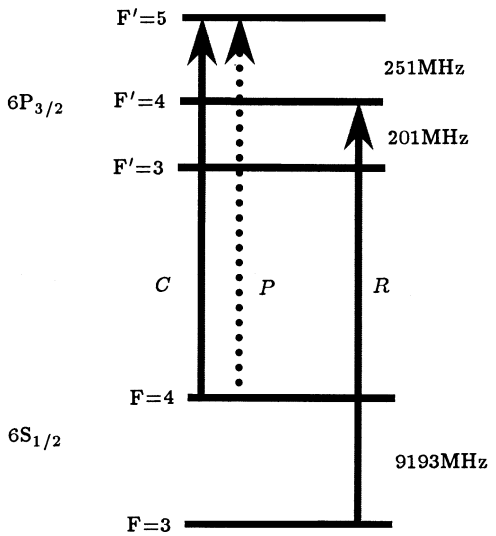


Fig.1. Relevant energy levels of caesium atom. C and R are coupling laser and repumping laser, respectively; P denotes the probe laser.

The experimental setup is schematically shown in Fig.2. The pumping laser is a frequency-stabilized Ti:sapphire laser (Coherent, MBR-110), with frequency stabilized to the $6S_{1/2}$ F=4→$6P_{3/2}$ F'=5 transition by using a saturated absorption spectrum. The probe laser is an external-cavity diode laser (New Focus, model 6017), which is temperature-stabilized and can be tuned to the D_2 line of caesium atoms. Probe frequency is scanned across the whole D_2 transition. The coupling and probe lasers are arranged to have orthogonal linear polarization and propagate in the same direction through a 3-cm-long caesium vapour cell that is kept at room temperature. Transmissions of the coupling and probe beams are separated by a polarization beam splitter cube placed after the vapour cell, and the absorption of the weak probe beam is measured by an avalanche photodiode (Hamamatsu Si APD, S3884) and recorded by a digital oscilloscope. The saturation absorption spectrum for another caesium vapour cell is used for frequency calibration of probe absorption spectrum. The repumping laser is another external-cavity diode laser (not shown in Fig.2), the frequency of which is locked to the transition of $6S_{1/2}$F=3 to $6P_{3/2}$ F'=4. This makes the atoms populated in the $6S_{1/2}$F=3 level back into the F=4 level.

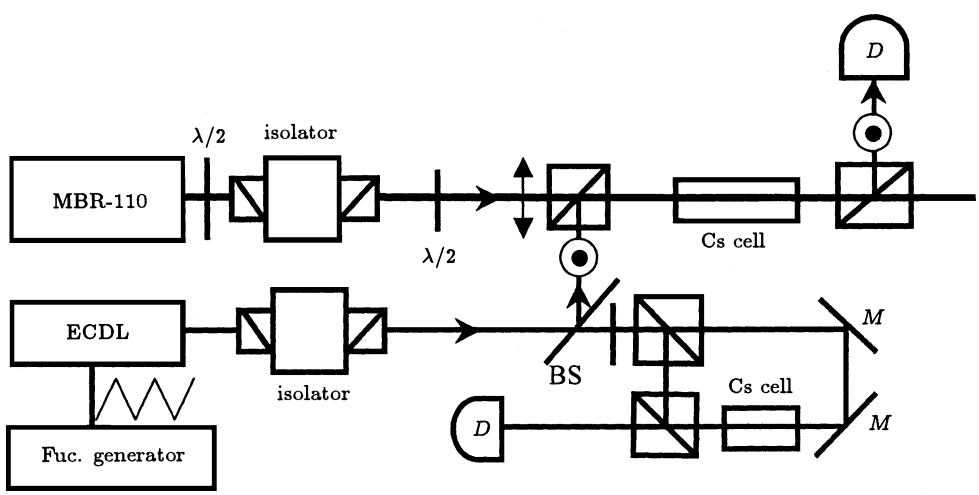


Fig.2. Schematic diagram of EIA experimental setup. MBR-110: Model MBR-110 Ti:sapphire laser; ECDL: external-cavity diode laser; M: reflection mirror; D: photo-detector.

The diameter of the probe laser beam is about 1mm, smaller than that of the coupling laser beam (about 3mm) for a good overlapping. The power of the probe beam in front of the caesium vapour cell is 200μW, whereas the power of the pumping laser is changed with a polarizer, a $\lambda/2$ plate and a neutral density filter. The caesium cell is wrapped in μ-metal to minimize the effect of earth magnetic field so that all the magnetic sublevels in the hyperfine states of caesium atoms are degenerate.

When the probe frequency is scanned across the $6S_{1/2}$ F=4 → $6P_{3/2}$ transition, and the coupling laser is stabilized to the transition of $6S_{1/2}$F=4→ $6P_{3/2}$F'=5, the probe absorption curve is measured, as shown in Fig.3. Curve b presents the Doppler broadened single-photon absorption of the probe in

the absence of the coupling laser. As the power of the coupling laser is lowered (to less than 200μW), the saturation peak of the probe at $6S_{1/2}$ F=4→$6P_{3/2}$ F'=5 cycling transition can be observed, as shown by curve *c* in Fig.3. When the coupling power increases, a narrow dip (EIA signal) appears at the absorption profile, as shown by curves *d* and *e* in Fig.3. Figures 3 *d* and *e* correspond to the coupling laser power of 3.4 and of 14mW, respectively. We find that an EIA spectrum shows a profile with a linewidth about 2.3MHz, which is narrower than the natural linewidth of 5.2MHz. With increasing intensity of coupling laser, the linewidth of EIA signal becomes broader, which is increased to about 5.3MHz as the coupling power becomes 40mW. By further increasing the coupling intensity, the linewidth of the EIA signal becomes much broader and breaks up into two dips, and EIT appears in its central region.[11]

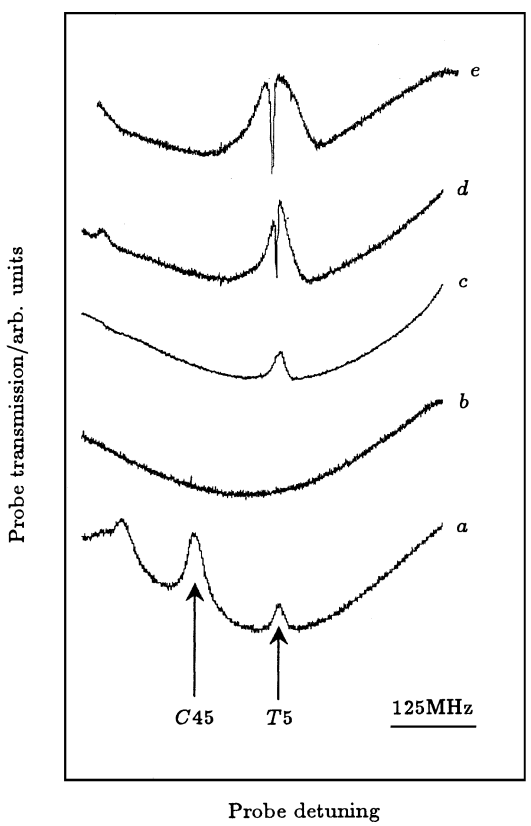


Fig.3. The EIA spectra with the different pumping laser intensity. The curves *b*, *c*, *d* and *e* correspond to the optical powers of the coupling laser of 0, 0.24mW, 3.4mW and 14mW, respectively. Curve *a* is the saturated absorption spectrum.

EIA is explained by the density matrix equations of motion for the N-type four-state system. The theoretical simulation based on the N-type four-state system has been carried out by Scully's group,[10] and our experimental result is in agreement with the theoretical analysis.

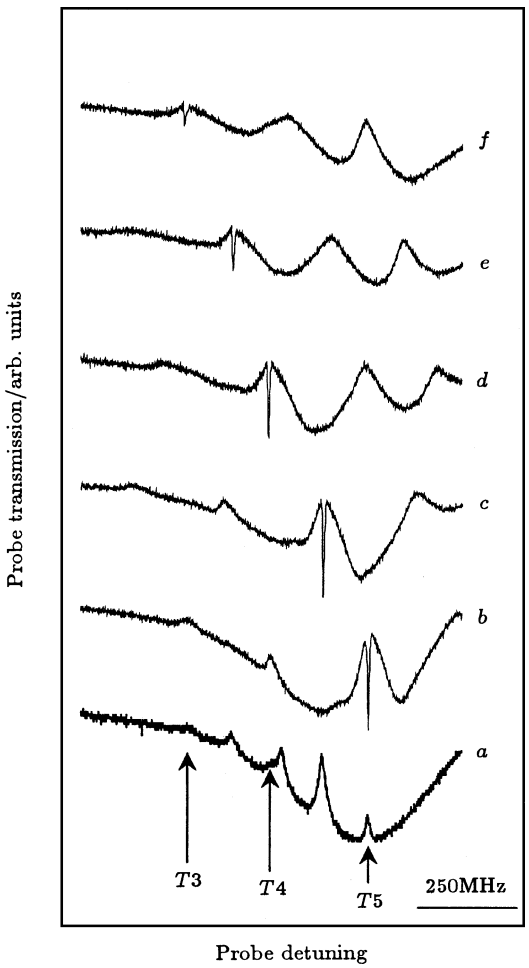


Fig.4. EIA signals for various coupling detunings. The coupling intensity is 14mW and the diameter is about 3mm. The coupling laser is tuned to $6S_{1/2}$ F=4→$6P_{3/2}$ F'=5 cycling transition with a detuning of 0, −125MHz, −250MHz, −350MHz and −450MHz for curves *b*, *c*, *d*, *e* and *f*, respectively. Curve *a* is the saturated absorption spectrum.

The effect of detuning of the coupling laser on EIA signal has been investigated experimentally, and the experimental result is shown in Fig.4. When the frequency of the coupling laser decreases from the transition of $6S_{1/2}$ F=4→$6P_{3/2}$ F'=5, the depth of the EIA signal is reduced and the position of the EIA dip shifts. The frequency of the coupling laser is red detuned by 250 and 450MHz corresponding to the transition of $6S_{1/2}$ F=4→$6P_{3/2}$ F'=5, namely the coupling laser is resonant with the $6S_{1/2}$ F=4→$6P_{3/2}$ F'=4 and $6S_{1/2}$ F=4→$6P_{3/2}$F'=3 hyperfine transitions, respectively. The two transitions are not a closed system and do not satisfy the third one of the three EIA conditions.[5] The EIA signals in an open system $6S_{1/2}$ F=4 to $6P_{3/2}$ F'=4 and F'=3 are also obtained and shown in Fig.4

by curves d and f, respectively. The EIA signal intensity in the open system is much less than that in the closed system.

Since $6S_{1/2}$ F=4 $\rightarrow$ $6P_{3/2}$ F'=4 and $6S_{1/2}$ F=4$\rightarrow$$6P_{3/2}$ F'=3 are open systems, Ref.[5] indicates that EIT would be expected rather than EIA. Absorption spectra should show EIT because the coupling field is pumping the atoms optically into other magnetic sublevels uncoupled with the probe field. The atoms are then transferred into dark states, which are coupled coherently with two fields. However, the observed signal is EIA even though it is small compared to that of the closed system. In Ref.[12] the possibility of observing EIA in an open system is analysed theoretically. In this system, atoms excited to the state F_e by the coupling laser not only can decay to the pumped ground state F_g, but also decay to other hyperfine ground states. The latter decay makes the population in the original F_g and F_e states less then unity, meanwhile the probability for transfer of coherence from the excited state to the ground state decreases, so the EIA signal is decreased.

As described above, we used the repumping laser to bring the population of the $6S_{1/2}$ F=3 back into the level of $6S_{1/2}$ F=4. The repumping laser was stabilized to the $6S_{1/2}$ F=3$\rightarrow$$6P_{3/2}$ F'=4 transition, which was arranged to have the same linear polarization and propagate nearly the same as the coupling laser through the caesium atomic vapour cell. Figure 5 shows that the effect of the repumping laser on the absorption of the weak probe light, where lines in Figs.5 b and a denote the absorption of the probe with and without repumping laser of 5.2mW (the diameter of the repumping laser beam is about 2mm), respectively. From Fig.5 the absorption coefficient of the probe in $6S_{1/2}$ F=4$\rightarrow$$6P_{3/2}$ F'=5 with repumping is about four times larger than that without repumping.

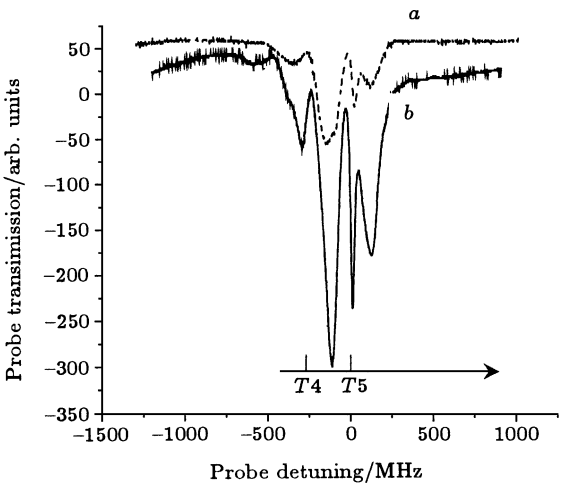


Fig.5. The effect of the repumping laser on EIA. Curves b and a correspond to the cases with and without the repumping laser. Intensities of the coupling and probe lasers are 44 and 1.5mW, respectively.

3. Conclusion

In summary, we have investigated experimentally the effect of EIA in the closed and open caesium atomic systems. The enhanced absorption signal has been obtained. The effect of the intensity and detuning of the coupling laser on EIA are experimentally studied. Repumping laser is resonant with the transition of the $6S_{1/2}$ F=3$\rightarrow$$6P_{3/2}$ F'=4, and the absorption coefficient of EIA signal is larger than the case without repumping laser. The narrow and steep dispersion of the EIA peak can find practical application in observing anomalous dispersion. According to the formula $v_g = \dfrac{c}{n + \omega_0 \mathrm{d}n/\mathrm{d}\omega}$, the superluminal light could be obtained. The EIA signal in a closed two-level system has an important significance for superluminal light.

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