

# Observation of the Electromagnetically Induced Transparency and Dispersion-like Structure in Trapped Cs Atoms

Kyungdae Kim, Mirang Kwon, and Jung Bog Kim\*

*Dept. of Physics Education, Korea National University of Education, Chungbuk 363-791, KOREA*

Han Seb Moon

*Center for Information and Telecommunication Standards,  
Research Institute of Standards and Science, Daejeon 305-600, KOREA*

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We report experimental results demonstrating the electromagnetically induced transparency (EIT) in trapped Cs atoms. EIT occurs at the  $\Lambda$ -type configuration where the re-pumping laser simultaneously plays a role as the coupling laser in the presence of a magneto-optical trapping and weak magnetic fields. Dependences of EIT signal on both the intensity and the detuning of the coupling laser were investigated. Linear absorption spectra for cold cesium atoms in the magneto-optical trap have been observed and shown the pronounced dispersion-like structure with sub-natural linewidth of 1 MHz due to the cooling laser.

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## I. INTRODUCTION

A cold atomic sample prepared by laser cooling is useful for nonlinear, quantum optical experiments or high resolution laser spectroscopy. Cold atoms in a MOT have several merits as an atomic sample. The most important one of them is that a cold atom sample in an MOT is the most suitable material for investigating the coherent interaction between matter and light. Furthermore, high atomic densities can be useful in order to obtain highly efficient nonlinear susceptibilities. Strong nonlinear effects such as Raman gain and the Autler-Townes doublet have been observed in cold atoms in the magneto-optical trap [1]. Also the pronounced dispersion-like structure, the very narrow gain, and absorption peak have been observed and explained theoretically by many groups [2,3]. Mitsunaga et al. [2] explained qualitatively the sign-changing structure due to a  $\Lambda$ -type stimulated Raman process with a small splitting in the ground state,  $F = 4$ . In addition, Chen et al. [3] have carried out the pump-probe spectroscopy in cold  $^{87}\text{Rb}$  atoms with various polarization configurations.

When two lasers are tuned near to atomic transitions which share the common level, the atomic states can be coupled by two lasers. Coherent inter-

actions such as a two-photon transition in the  $\Lambda$ -type three-level energy configuration occurs between atoms and light. Electromagnetically induced transparency (EIT) is a coherent effect that can occur when a weak probe light field propagates through the medium with reduced absorption due to the presence of a strong coupling field. The first observation of EIT in the  $\Lambda$ -system was in strontium vapor in 1991 by Boller et al. [4] using high-power pulsed lasers to overcome the inhomogeneous broadening. Many EIT experiments with cw lasers were carried out in various media including solids, vapor cells, atomic beams, and recently laser-cooled atoms [5]. Recently Clarke et al. [6] have carried out the EIT experiments in cold atoms and the vapor cell and compared EIT signals. Many EIT experiments in three-level or four-level systems have been demonstrated in atomic media or solid media. These studies of EIT have opened new roads toward many possible applications including lasing without inversion, nonlinear optics, or designing a high-sensitivity magnetometer. In addition, the dispersive properties can generate an ultra-slow light or halted light pulses in EIT material [7,8]. Several groups have proposed optical switches and wavelength converters based on EIT for possible telecommunication applications [9,10].

Our group has previously studied EIT in an ideal three-level system and the dependences of EIT signal on the laser linewidth, Rabi frequency and detuning of the coupling laser beam in  $^{87}\text{Rb}$ , and we have measured the dispersion of EIT in Cs atomic vapor [11–13]. With the weak probe laser and the strong coupling laser arranged in a Doppler-cancellation configuration, reduction of Doppler-free absorption was observed. We have built an MOT setup to compare the experimental results in Doppler-free atoms with those accomplished in Doppler broadened vapors, and investigate coherent interactions between atoms and light. We have measured absorption spectra of the probe laser beam under the influence of the trapping laser beam for MOT, and the signal of electromagnetically induced transparency in cooled cesium atoms in the presence of the MOT trapping and weak magnetic fields.

## II. EXPERIMENTAL SETUP

A schematic diagram of the relevant energy levels is shown in Fig. 1. The energy-level configurations for absorption spectra and the EIT in a  $\Lambda$ -type three-level system are as shown in Figs. 1 (a) and (b), respectively. The laser  $\omega_c$  plays dual roles in cooling atoms and dressing atoms due to strong fields, and the weak probe laser  $\omega_b$  is used to observe the transmission through the MOT. For the EIT experiment, as shown in Fig. 1 (b), the coupling laser frequency  $\omega_p$  is applied to the  $F = 3 \rightarrow F' = 4$  transition and the probe laser frequency  $\omega_b$  is scanned over the range of the  $F = 4 \rightarrow F' = 4$  transition which makes a  $\Lambda$ -type three-level system.

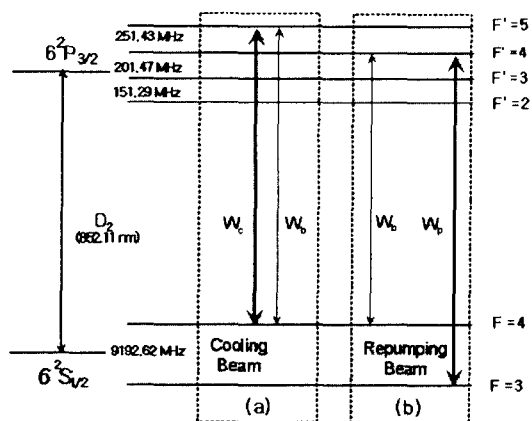


FIG. 1. Schematic diagram of relevant energy levels for the D2 line in Cs atoms. Energy-level configurations for (a) probing a MOT and (b) EIT in a  $\Lambda$ -type system.  $\omega_p$  is the coupling laser frequency and  $\omega_b$  is the probe laser frequency.

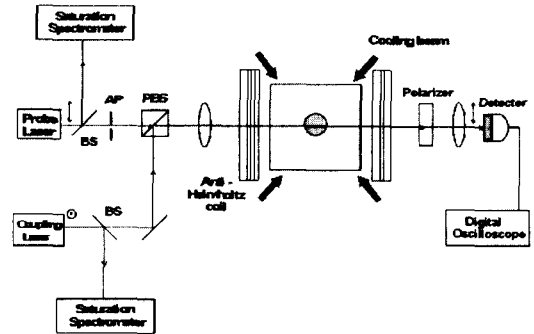


FIG. 2. Schematic diagram of the experimental setup for pump-probe spectroscopy of cold cesium atoms in a MOT. DL1 and DL2 are diode lasers, BS denotes a beam-splitter, PBS is a polarized beamsplitter and AP is a aperture stop.

The diagram of the experimental setup is shown in Fig. 2. The vapor pressure in the quartz cube was kept at  $2.2 \times 10^{-9}$  torr by the ion pump of 100 l/min. The cesium atoms were trapped in a conventional MOT consisting of a quadrupole magnetic field produced by a pair of anti-Helmholtz coils and three pairs of counter-propagating circular polarized lights. The magnetic field gradient is 2.6 G/cm along the symmetry axis. Three diode lasers were used for a trapping laser, a re-pumping laser and a probe laser. The frequency of the trapping laser was locked within the range of 100 kHz to the transition,  $F = 4 \rightarrow F' = 5$  by using a Lock-in amplifier (Tuioptics Lock-In Regulator LIR 100) and then red-detuned about 15 MHz from the 852 nm  $D_2$  transition  $6S_{1/2} (F=4) \rightarrow 6P_{3/2} (F'=5)$  by shifting the resonant frequency with a Zeeman-shifter in the saturated absorption spectrometer. Circular polarization of each beam was produced by the quarter wave retardation plate and retro-reflection of a linearly polarized 5 mW beam of 1.5 cm diameter. The frequency of the re-pumping laser was fixed at the transition  $F = 3 \rightarrow F' = 4$ . The linewidth and the frequency stability of the re-pumping laser was improved by using a grating external cavity DBR diode laser (SDL-5712-H1). The laser linewidth was reduced to less than 1 MHz. The power of re-pumping laser was about 1 mW and the diameter was 2 mm. The optical isolators were used in front of the lasers to get rid of unwanted optical feedback.

For the EIT experiment, the probe beam was sent through a circular aperture with a diameter of 1 mm, before it interacted with cold atoms. The power of the probe laser beam was  $30 \mu\text{W}$ . The re-pumping beam, which was also playing a coupling role, and the probe beams were linearly polarized perpendicularly to each other. The coupling and the probe beams copropagate in the same direction. The angle between

the propagation direction of the coupling beam and the probe beam was about 3 mrad. The overlap of the two laser beams was accomplished by optimizing the observed EIT signal. Neutral density filters were inserted in the laser beam paths to change the powers of the diode laser beams. The EIT signal was observed by detecting the transmission of the probe laser beam through the cold atoms in a MOT. The coupling laser beam was blocked by the analyzer in front of the photo-diode detector. The photo-diode signal was sent to a digital oscilloscope (Tektronix TDS 360).

To obtain the absorption spectra of the probe, the re-pumping laser was overlapped with the trapping laser and the transmission of the probe laser alone was measured. We will denote this case as the absence of the external coupling laser field.

### III. RESULTS AND DISCUSSION

Fig. 3 shows signals obtained when the re-pumping laser was tuned to the  $6S_{1/2}$  ( $F=3$ )  $\rightarrow$   $6P_{3/2}$  ( $F=4$ ) and the probe laser was scanned from  $6S_{1/2}$  ( $F=4$ )  $\rightarrow$   $6P_{3/2}$  ( $F'=3,4,5$ ). Typical probe absorption spectra in the absence of the coupling laser, as shown in Fig. 3 (a), and the EIT signal (c) in the presence of the coupling laser appear at the frequency for the  $F = 4$  to  $F' = 4$  transition.

We can see the several spectral features in the absorption spectra (a): (i) a blue shift of the absorption peaks for three transitions due to a ac-Stark effects,

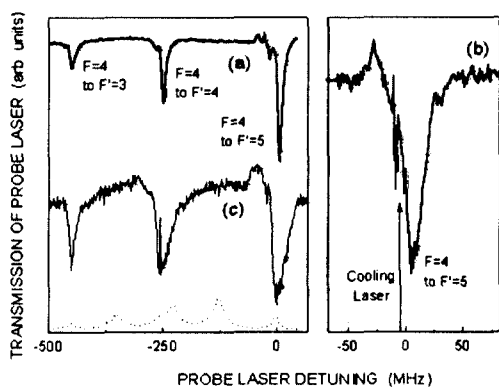


FIG. 3. (a) Probe absorption spectra of cold Cs atoms dressed by cooling laser photons for  $F = 4 \rightarrow F' = 3, 4, 5$  transitions. Cooling laser detuning is indicated by the arrows. The vertically dashed lines indicate the absorption frequencies. The bottom dashed spectrum a saturated absorption spectrum of probe laser beam, (b) probe absorption spectra including Raman gain and sub-natural dispersion-like structure, (c) absorption spectra including the EIT signal in cold Cs atoms.

(ii) secondary absorption peaks for negative detuning of the  $F = 4$  to  $F' = 3, 4$  lines (the Autler-Townes doublets), (iii) strong broad gain due to amplification of the probe beam in the  $F = 4$  to  $F' = 5$  line (the dressed-atom gain) and a pronounced dispersion-like structure with narrow linewidth at the trapping laser frequency due to a  $\Lambda$ -type stimulated Raman process with a small splitting in the ground-state, when the detuning of the trapping beam was about -20 MHz from the  $F = 4 \rightarrow F' = 5$  transition line. Mitsunaga and his coworkers were able to explain the absorption spectra, with the dressed-atom model, due to  $\Lambda$ -type stimulated Raman process with small splitting in the ground-state  $F = 4$  level [3].

The spectrum in Fig. 3 (b) shows the dispersion-like profile with sub-natural linewidth (1.2 MHz; peak to peak) at the -10 MHz from the  $F = 4 \rightarrow F' = 5$  transition. In spectra (a) and (b), the dispersion-like structure profiles indicate the frequency of the trapping laser. There are some differences between spectra (a) and (b), because these are obtained with different detunings of the trapping laser frequency from resonant transition  $F = 4$  to  $F' = 5$ . The detuning from the resonant transition,  $F = 4$  to  $F' = 5$ , and the amplitude of the dispersion-like structures, the Raman gain (broad gain), and the absorption peak are slightly different.

For the  $\Lambda$ -type EIT experiments, the re-pumping laser of the trap served as a coupling laser. MOT trapping and magnetic fields were not switched off because of the experimental limitations. The EIT signal with linewidth of 3 MHz, in Fig. 3 (c) is obtained where the probe laser is resonant to the  $F = 4$  to  $F' = 4$  transition when the power of coupling laser was 1.1 mW (re-pumping laser) and the power of the probe laser was  $4 \mu\text{W}$ . We did not consider the field effect of the trapping laser because of the lower intensity of the trapping beam compared to that of the coupling beam. A consideration of the trapping laser in the experiment for EIT produces an N-type configuration consisting of two coupling lasers and a probe laser scheme, so we have analyzed the EIT results under that consideration.

Fig. 4 shows the dependence of the EIT signal on the detuning of the coupling diode laser beam. Figs. 4 (a), (b), (c), (d), (e), and (f) show EIT signal for the -14 MHz, -5 MHz, 0 MHz, 2 MHz, 17 MHz, and 27 MHz detuning, respectively. All six scans were taken with the coupling laser frequency tuned to the center of the  $6S_{1/2}$  ( $F=4$ )  $\rightarrow$   $6P_{3/2}$  ( $F'=4$ ) transition. The experimental results in Fig. 4 (c) show the typical EIT signal for zero detuning, evolving into a normal absorption line at large detunings. The power of coupling laser was 1 mW and the power of probe laser was  $30 \mu\text{W}$ . The observed depth of the EIT window for zero detuning corresponds to a reduction of the

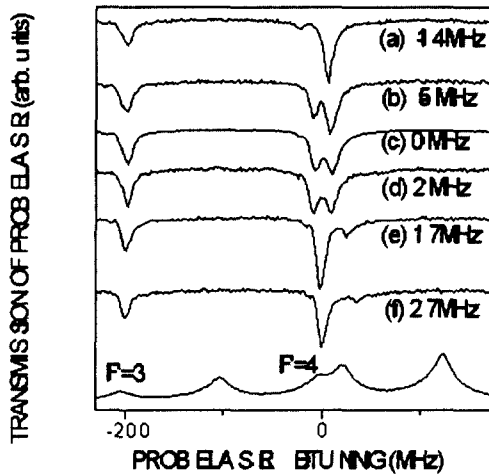


FIG. 4. Detuning Effects of the coupling laser. The probe laser was scanned across the  $6S_{1/2}(F=4) \rightarrow 6P_{3/2}$  transition while the coupling laser was detuned from  $F = 3 \rightarrow F' = 4$  transition center by (a) -14 MHz, (b) -5 MHz, (c) 0 MHz, (d) 2 MHz, (e) 17 MHz, (f) 27 MHz.

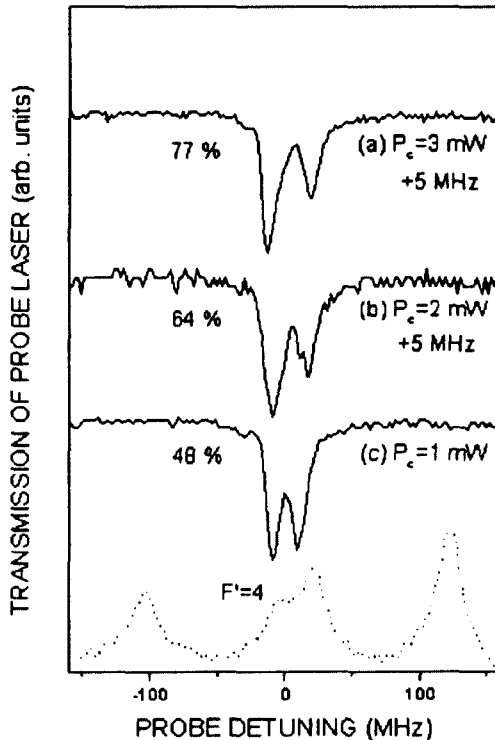


FIG. 5. Effect of various coupling laser powers. The probe laser was scanned across the  $6S_{1/2}(F=4) \rightarrow 6P_{3/2}$  transition while the coupling laser resonant with  $F = 3 \rightarrow F' = 4$  transition was varied as follows: (a) 3 mW, (b) 2 mW, (c) 1 mW. Detuning of the coupling laser frequency was denoted as "+ 5 MHz" in spectra (a), (b).

absorption by about 50 % at line center. The bottom spectrum shows saturated absorption spectrum of the probe laser scanned from  $F = 4$  to  $F' = 3$  to  $F = 4$  to  $F' = 4$ . We can see the EIT signal and the side-band absorption peak at red detuned frequency of the  $F = 4$  to  $F' = 4$  in Figs. 4 (b), (c), (d), (e), and (f).

We also investigated the dependence of the EIT signal on the power of the coupling beam as shown in Fig. 5. The amplitude of each spectrum was normalized for comparison. Really the amplitude of the absorption peaks and the number of trapped atoms was varied according to the coupling beam power because the repumping laser served as coupling laser in our experiments. The depth of reduction of absorption in the observed EIT window was nearly 80 % when the power of the coupling beam was 3 mW. All three scans were taken with the coupling laser frequency tuned to the  $F = 3$  to  $F' = 4$  and the power of the coupling laser was 1 mW. The coupling laser beam made the cold cesium atoms increase the transmission of the probe laser beam from 48 % to 77 %.

In the presence of the trapping light beams and the magnetic fields, the analysis of the experimental results is complicated because of the perturbation of the ground-state sublevels governed by Zeeman effect and the various polarization of the lasers. The EIT signal of cold cesium atoms in a magneto-optical trap depends on a coupling laser, and the sub-natural dispersion-like structure of absorption spectra depends strongly a cooling laser.

#### IV. CONCLUSION

We have demonstrated electromagnetically induced transparency produced by coherences among the Zeeman sublevels of the  $F = 4$  hyperfine level of cold cesium atoms in a magneto-optical trap and investigated systematically the dependences of the EIT signal on the power and the detuning frequency of the coupling laser in the presence of the MOT trapping laser and the weak magnetic fields. Absorption spectra of cold cesium atoms in a magneto-optical trap have been observed and show the known dispersion-like structure with sub-natural linewidth of 1 MHz. Although the present work is concerned with the observation of EIT resonances in an operating MOT, it would have been interesting to study the corresponding effect in a cold atomic sample without the perturbing presence of the trapping fields.

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\*Corresponding author : jbkim@cc.knue.ac.kr.

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