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Electromagnetically induced transparency in a three-level Λ -type system in rubidium atoms

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An electromagnetically induced transparency is observed at one arm of a three-level Λ -type system in a rubidium D1 line (794.8 nm) with an 85% reduction in absorption, when a pumping field is present at the other arm. This reduction in absorption for the weak probe field is due to the atomic coherence produced by the strong pumping field. This experiment is done in a Rb vapor cell at room temperature with cw diode lasers for both pumping and probe beams in a Doppler-free configuration. A simple theoretical treatment including Doppler broadening is in good qualitative agreement with the experimental measurement.

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Electromagnetically induced transparency (EIT) in multilevel atomic systems has attracted great attention in recent years due to its possible applications in nonlinear optics [1-3]. The EIT effect is also the mechanism behind the recently demonstrated gain without population inversion in multilevel atomic systems [4]. Although many theoretical papers have been published in recent years, only a few experimental demonstrations of the EIT effect in simple atomic systems have been reported [1-3]. Among them, the only experiment done in a Λ -type system was by Harris and coworkers [1]. In their experiment, a heated Sr atomic vapor was used and all the relevant levels were excited states. Due to the requirement for very high pumping power to overcome the collisional and Doppler broadenings, a pulsed laser was used as the pumping beam. The existence of gain is predicted when both coherent and incoherent pumping fields are present [5]. Population trapping states [6] have been observed in an atomic beam experiment [7] and an atomic vapor experiment [8]. Quantum-statistical properties were calculated with 50% squeezing predicted in the output beam of an inversionless laser built in such a system [9]. Matched photon statistics and correlation effects have also been predicted [10]. However, due to the complication of the optical pumping and nonlinear Faraday effects in real atomic systems, to our knowledge, experimental demonstration of the EIT effect has not been reported in an ideal closed Λ -type system until now.

In this work, we have chosen a closed three-level Λ -type system in 87 Rb atoms to show the EIT effect. The D1 line of the 87 Rb is shown in Fig. 1. The hyperfine level F'=2 of $5P_{1/2}$ serves as excited state $|2\rangle$. The hyperfine levels F=1 and F=2 of the ground state $5S_{1/2}$ serve as two ground states $|1\rangle$ and $|3\rangle$ of the Λ -type system, respectively. Another hyperfine level F' = 1 of the excited states $5P_{1/2}$ is 812 MHz away (outside the Doppler width of the transition line) and can be neglected. The atoms are pumped between the $5S_{1/2}$, F=2 and $5P_{1/2}$, F'=2 states by a pumping laser with Rabi frequency Ω_2 (solid lines) and probed between the $5S_{1/2}, F=1$ and $5P_{1/2}, F'=2$ states by a weak probe laser with Rabi frequency Ω_1 (dotted lines). The EIT effect means that, when the pumping laser is present, the weak probe laser is affected by reduced absorption at the resonant frequency, although almost all the atoms are optically pumped to populate the $5S_{1/2}$, F = 1 state. This pump-probe experiment in a three-level system is different from the previous experiments in a two-level system [11], where a strong laser resonantly dresses a two-level system via the ac Stark effect, a weak probe laser probes the sideband transitions, and then Mollow-sideband gain is found.

Although there are many degenerate magnetic sublevels in each of these hyperfine levels, they can be considered simply as an effective three-level Λ -type system for the EIT effect. This can be understood as follows: the strong pumping laser pumps all the populations from state $|3\rangle$ to the sublevels of state $|1\rangle$, and the probe laser is weak enough so that its effect on atomic populations can be neglected. Assuming that the pumping and probe lasers are orthogonally linearly polarized, it is easily shown that each probed transition (π transition on the right-hand side of Fig. 1) from a sublevel of state $|1\rangle$ to state $|2\rangle$ is coupled to a σ^+ - or a σ^{-} -pump transition from a sublevel of state $|3\rangle$ to state $|2\rangle$ with an effective Rabi frequency. Due to the fact that the atomic population of state $|3\rangle$ is small and can be neglected, the coherence between the magnetic sublevels of state $|3\rangle$ is unimportant for the transparency of the probed transitions. Due to the weakness of the probe laser, the probed transitions can be thought of as being independent. Thus this system really can be considered as an ideal closed three-level Λ -type system for the purpose of EIT. Similarly, F'=1 of the $5P_{1/2}$ excited state can serve as the upper level $|2\rangle$, which is also a closed Λ -type system.

For a closed three-level Λ -type system, the equations of motion for the slowly varying off-diagonal matrix elements



FIG. 1. Relevant energy diagram of the D1 line in the ⁸⁷Rb atom. Solid line, pump transition; dotted line, probe transition. The right-hand part is the diagram with magnetic sublevels.

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of the atomic density operator take the form [3,6]

$$\dot{\rho}_{21} = (i\Delta_1 - \gamma)\rho_{21} + i\frac{\Omega_1}{2}(\rho_{22} - \rho_{11}) - i\frac{\Omega_2}{2}\rho_{31},$$
 (1a)

$$\dot{\rho}_{23} = (i\Delta_2 - \gamma)\rho_{23} + i\frac{\Omega_2}{2}(\rho_{22} - \rho_{33}) - i\frac{\Omega_1}{2}\rho_{31}^*,$$
 (1b)

$$\dot{\rho}_{31} = [i(\Delta_1 - \Delta_2) - \Gamma_3]\rho_{31} - i\frac{\Omega_2^*}{2}\rho_{21} + i\frac{\Omega_1}{2}\rho_{23}^*, (1c)$$

where $\gamma \equiv (\Gamma_1 + \Gamma_2 + \Gamma_3)/2$; Γ_1 and Γ_2 are the spontaneous decay rates of the excited state $|2\rangle$ to the ground states $|1\rangle$ and $|3\rangle$, respectively; Γ_3 is the nonradiative decay rate between two ground states; Δ_1 is the detuning of the probe field from the atomic transition ω_{12} and Δ_2 is the detuning of the pumping beam from the atomic transition ω_{32} ; $\Omega_1 = -\mu_{21}E_1/\hbar$ and $\Omega_2 = -\mu_{23}E_2/\hbar$ are the Rabi frequencies of the probe laser (with amplitude E_1) and pumping laser (with amplitude E_2); and μ_{21} and μ_{23} are the relevant dipole moments. Let us assume that the pumping field is strong and the probe field is very weak, i.e., $\Omega_2 \ge \Omega_1$. Then, it is expected that, in the steady state, all the atoms will be optically pumped into state $|1\rangle$ and no atoms will populate states $|2\rangle$ and $|3\rangle$, so that $\rho_{11} \approx 1$, $\rho_{22} \approx \rho_{33} \approx 0$. This approximation is valid only if the pumping Rabi frequency is much smaller than the separation of states $|1\rangle$ and $|3\rangle$, i.e., $\Omega_2 \ll \omega_{12} - \omega_{32}$, which is about 6.8 GHz in Fig. 1. Since the intensity of the probe laser is very weak, we can neglect the second order in Ω_1 and solve Eqs. (1) in the steady state to get

$$\rho_{21} \approx -\frac{i\Omega_1/2}{\gamma - i\Delta_1 + \frac{\Omega_2^2/4}{\Gamma_3 - i(\Delta_1 - \Delta_2)}}.$$
 (2)

The linear susceptibility of the atomic system can be written as [3]

$$\chi = \frac{N\mu_{21}^*\rho_{21}}{E_1/2} = -\frac{2N\mu_{21}^2}{\hbar\Omega_1}\rho_{21},$$
(3)

where N is the density of the atoms.

We consider the pumping laser and probe laser passing through a Doppler-broadened atomic cell in the same direction. An atom moving towards the probe beam (with frequency ω_p) with velocity v is affected by the probe frequency detuning upshifted to $\Delta_1 + \omega_p v/c$ and the frequency detuning of the pumping beam (with frequency ω_c) upshifted to $\Delta_2 + \omega_c v/c$. The atomic density with velocity v is $N(v)dv = (N_0/u\sqrt{\pi})\exp(-v^2/u^2)dv$ in the Maxwellian approximation, with $u/\sqrt{2}$ being the root-mean-square atomic velocity, depending on the temperature of the cell; N_0 is the atomic density. In the case of $\omega_p \approx \omega_c$, the integral of Eq. (3) over velocities results in the following compact form:



FIG. 2. Experimental arrangement. DL1, diode laser for probe beam; DL2, diode laser for pumping beam; BS1, BS2, polarization cube beam splitter; Det, photodetector; $\lambda/2$, half-wave plate. An aperture 0.8 mm in diameter is used in front of the focus lens.

$$\chi = \frac{i c \,\mu_{21}^2 N_0 \sqrt{\pi}}{\hbar \,\omega_p u} \, e^{z^2} [1 - \text{erf}(z)], \qquad (4)$$

with the argument

$$z = \frac{c}{\omega_p u} \left[\gamma - i\Delta_1 + \frac{\Omega_2^2/4}{\Gamma_3 - i(\Delta_1 - \Delta_2)} \right],\tag{5}$$

where $\operatorname{erf}(z)$ is the error function with complex argument z. When the laser line shape can be considered to be a Lorentzian shape (which is a good approximation in our case), the effect of the finite laser linewidth can be included in the decay rates, so that $\gamma \rightarrow \gamma + \delta \omega_1$, $\Gamma_3 \rightarrow \Gamma_3 + \delta \omega_1 + \delta \omega_2$, where $\delta \omega_1$ and $\delta \omega_2$ are half linewidths of the probe laser and pumping laser, respectively [3,12]. The imaginary part Im(χ) of Eq. (4) is proportional to the absorption coefficient of the atomic medium for a weak probe beam.

The experimental arrangement is given in Fig. 2. The Doppler-free configuration for coherence effects in the Λ -type system is that the pumping beam and the probe beam propagate colinearly, because the Doppler shifts of the probe laser and pumping laser for the same group of atoms with velocity v can be canceled, as shown in Eq. (2). This configuration can reduce the requirement for the pumping intensity to create effective atomic coherence. The probe beam and pumping beam are orthogonally polarized and are separated with a polarization cube beam splitter after passing through the rubidium cell. The 76-mm-long rubidium vapor cell is kept at a room temperature of about 20 °C and shielded with μ -metal from the surrounding magnetic field. The natural linewidth of the excited state is 6 MHz. The Doppler-broadened linewidth is about 530 MHz. The DL2 laser is the pumping laser and the DL1 laser is the probe laser. Both diode lasers are current and temperature stabilized to give a linewidth of about 4.7 to 7.5 MHz over a time period of 50 ms, which is measured by the linewidth of the beating frequency between the two lasers. Both lasers have negligibly slow frequency drifts during a single scanning time (~ 10 ms). Both diode lasers have wavelengths near 794.8 nm. The probe laser beam is about 0.9 μ W, with a beam size of 0.80 mm in diameter. The pumping beam is about 5.6 mW with the same beam size as the probe beam. Both of these beams are focused with a (f=15-cm) lens before entering the cell, which gives a pumping intensity of about 19.6 W/cm^2 at the cell center. The frequency of the probe beam is scanned over 10 GHz by the current without



FIG. 3. Absorption coefficient of the probe beam versus probe frequency for the entire range of the *D*1 lines in ⁸⁵Rb and ⁸⁷Rb for (a) no pumping field and (b) pumping field tuned to the $5S_{1/2}, F=2 \rightarrow 5P_{1/2}, F'=2$ transition of ⁸⁷Rb atoms.

mode hopping, while the frequency of the pumping beam is tuned to a fixed resonant frequency.

When the pumping beam is blocked, a typical absorption curve from rubidium D1 lines (including both ⁸⁵Rb and ⁸⁷Rb atoms) is recorded, as shown in Fig. 3(a). There are six distinguishable peaks within the 10-GHz range scanned. The middle two big peaks are the ⁸⁵Rb lines, with all the hyperfine structures falling into the Doppler width. Due to the large hyperfine separation (812 MHz) of the excited levels in the D1 line of ⁸⁷Rb atoms, the influence of the F'=1hyperfine level to the F'=2 level can be neglected. When the pumping laser is tuned to the transition $5S_{1/2}, F=2 \rightarrow 5P_{1/2}, F'=2$, almost all the atoms in the $5S_{1/2}, F=2$ state are pumped into the $5S_{1/2}, F=1$ state, as shown in Fig. 3(b). Now, looking at the absorption of the $5S_{1/2}(F=1)$ state, other than the increased absorption due to the increase in the atomic population, there is a sharp dip in the middle of the peak. This means that the probe field is not absorbed at the center frequency, although all the atoms are in that state. This absorption reduction at resonant frequency is the result of the atomic coherence between the two ground states induced by the pumping field. The sharp spike at the pumping frequency in Fig. 3(b) is due to the optical interference between the scattered pumping beam (from windows of the cell and resonant atoms) or polarization-rotated pumping beam (due to the nonlinear Faraday effect [13] for the resonant pumping beam by the atomic medium) and the probe beam as the probe frequency is tuned to exactly the same frequency as the pumping beam. The residual magnetic field in the shielded vapor cell will cause the rotation of the polarization angle for a very small portion of the resonant pumping beam, which will reach the detector and interfere with the probe beam. This optical interference on a relatively slow photodetector (with bandwidth about 100 kHz in our



FIG. 4. Absorption coefficient for the probe beam versus probe frequency for the $5S_{1/2}$, $F = 1 \rightarrow 5P_{1/2}$ transition of ⁸⁷Rb. The lower solid curve is for no pumping field. The upper solid curve is for the pumping field tuned at the $5S_{1/2}$, $F = 2 \rightarrow 5P_{1/2}$, F' = 2 transition with intensity $I_c = 19.6$ W/cm² at the cell center. The dotted curve is the theoretical result for $\Gamma_1 + \Gamma_2 = 6.0$ MHz, $\Gamma_3 = 0.1$ MHz, $\delta\omega_1 = \delta\omega_2 = 2.5$ MHz, $\Delta\omega_D = 530$ MHz, and an effective pumping Rabi frequency $\Omega_2 = 105$ MHz.

case) causes the signal to suddenly increase as the probe frequency is tuned to the same frequency as the pumping frequency.

Figure 4 is an expanded curve for the absorption peak of the $5S_{1/2}, F = 1 \rightarrow 5P_{1/2}F' = 2$ transition. The lower solid curve with no dip is without the pumping field and the upper solid curve with a dip is when the pumping field is present. The absorption coefficient is $\alpha = 0.92 \times 10^{-2}$ cm⁻¹ at the absorption peak without the pumping field. With the pumping field present, the probe absorption coefficient changes to $\alpha' = 0.56 \times 10^{-2} \text{ cm}^{-1}$. When measuring relative to the new absorption peak after taking into account the absorption increase due to optical pumping ($\alpha = 1.92 \times 10^{-2}$ cm⁻¹), the absorption reduction is 70.8%. The fact that the dip is below the unpumped level is a clear indication that this is not an optical pumping effect, but the result of the atomic coherence. The dotted curve is the theoretical calculation from Eq. (4) with $\Gamma_1 + \Gamma_2 = 6.0$ MHz, $\Gamma_3 = 0.1$ MHz, $\delta \omega_1 = \delta \omega_2 = 2.5$ MHz, $\Delta \omega_D = 530$ MHz, and $\Omega_2 = 105$ MHz, where $\Delta \omega_D$ is the Doppler width. As can be seen from Fig. 4, the theoretical calculation is in good qualitative agreement with the experimental measurement. The only adjustable parameter in this comparison is the pumping power Ω_2 , because our theoretical calculation does not take into account the spatial variation of the pumping beam in the vapor cell and the sublevel effect. The selection of the theoretical effective Rabi frequency ($\Omega_2 = 105$ MHz) in Fig. 4 is a reasonable parameter for the experimental condition (the pumping intensity of 19.6 W/cm² at the cell center). The fitted and experimental values agree within uncertainty, and the main source of uncertainty is due to measuring the beam sizes and calibrating the saturation intensities.

When the pumping beam is tuned to the $5S_{1/2}, F = 2 \rightarrow 5P_{1/2}, F' = 1$ transition, the EIT effect is also observed in the $5S_{1/2}, F = 1 \rightarrow 5P_{1/2}, F' = 1$ transition, as

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FIG. 5. Absorption coefficient for the probe beam versus probe frequency for the $5S_{1/2}$, $F=1 \rightarrow 5P_{1/2}$, F'=1 transition of ⁸⁷Rb. The lower curve is for no pumping field present, and the upper curve with a narrow dip in the resonance frequency of $F=1 \rightarrow F'=1$ is for the pumping field tuned at the $5S_{1/2}$, $F=2 \rightarrow 5P_{1/2}$, F'=1 transition with intensity $I_c=560$ mW/cm².

shown in Fig. 5. In this case, the pumping intensity is 560 mW/cm^2 . The absorption reduction is measured to be about 85.4%.

In conclusion, we have demonstrated the EIT effect in a

closed three-level Λ -type atomic system with cw diode lasers as both pumping and probe beams. The Rabi frequency of the pumping beam (about 100 MHz), although much larger than the natural linewidth of the excited state, is much smaller than the Doppler width (530 MHz) of the atomic system. The absorption reduction of more than 85% is quite significant and is below the unpumped absorption level. We are currently limited by the laser linewidths of both pumping and probe lasers. A theoretical calculation including the Doppler effect is presented and compared with our experimental results, yielding good qualitative agreement. We emphasize that the EIT effect is a single-atom effect. Our demonstration of this EIT effect at room temperature with low atomic density has the same physical significance and can be directly applied to the high-density situation. This system is relatively simple in comparison with the previous experiments with pulsed lasers, and it offers some advantages, such as frequency tunability, frequency resolution, and considerably lower power (only a few milliwatts). The closed three-level Λ -type system provides an ideal experimental testing ground for some very interesting theoretical predictions [9,10], such as phase correlation and quantum noise reduction.

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