Sub-Doppler linewidth with electromagnetically induced transparency in rubidium atoms

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We report the experimental observation of steady-state electromagnetically induced transparency and sub-Doppler linewidth in a Doppler-broadened Λ-type Rb atomic system formed on the ^{87}Rb D_2 transitions. The Λ system is coupled on one transition by a strong laser and probed on the other transition by a weak laser. The observed sub-Doppler linewidth decreases with the increasing detuning of the strong-coupling laser from the atomic transition frequency and is in good agreement with the theoretical calculations of G. Vemuri, G. S. Agarwal, and B. D. N. Rao [Phys. Rev. A **53**, 2842 (1996)]. [S1050-2947(96)10810-6]

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I. INTRODUCTION

Control of atomic response with an intense coupling laser has been a subject of many recent studies [1–5]. Typically, the atomic system consists of an ensemble of three-level atoms. The coupling laser is applied to one transition and modifies the atomic response on the other transition. The optical nonlinearity and the coherence induced in the atomic system by the strong-coupling laser in the presence of other laser fields may lead to a variety of physical phenomena for fundamental studies and practical applications, such as electromagnetically induced transparency (EIT) [1], lasing without population inversion (LWI) [6,7], enhancement or suppression of atomic refractive index [4,8], enhanced third harmonic generation [3], and correction of optical self-focusing and self-defocusing [5].

In electromagnetically induced transparency (EIT), an absorbing atomic medium is rendered transparent to a probe laser tuned *on resonance* with the atomic transition while a strong-coupling laser is applied to the other transition. Practical applications of EIT and the related refractive index change have been explored in a number of publications [1,2,4,5]. Experimental observation of EIT was made in a Λ-type atomic system in the time-dependent transient regime [1]. Subsequently, steady-state EIT was observed experimentally with continuous-wave lasers both in a ladder-type atomic system [9,10] and a Λ-type atomic system [11,12].

Previous theoretical and experimental studies of EIT were under the condition of a resonant coupling laser; thus a weak probe laser experiences transparent window at the line center of the atomic transition. In a Doppler-broadened atomic system, the absorption spectrum of the weak probe laser shows the familiar Autler-Townes' doublet structure and the spectral linewidth is Doppler broadened. Recently, Vemuri, Agarwal, and Rao pointed out that it is possible to obtain sub-Doppler resolution in an EIT system if the strong-coupling laser is sufficiently detuned from the atomic transition [13]. Thus EIT can be extended to a class of phenomena in nonlinear optics, where the atomic coherence induced by the coupling laser is used to influence inhomogeneous broadening. Here, following their theoretical paper, we present experimental measurements of sub-Doppler linewidth and EIT in an effective Λ-type three-level system formed on the ^{87}Rb D_2 transitions.

II. EFFECTIVE ^{87}Rb THREE-LEVEL Λ SYSTEM

The Rb effective Λ-type three-level system is formed with the laser coupled D_2 transitions and is depicted in Fig. 1. A strong-coupling laser of frequency ω_c drives the ^{87}Rb $5S_{1/2}(F=2)\leftrightarrow 5P_{3/2}$ transition and generates a pair of dressed states. A weak probe laser of frequency ω_p drives the ^{87}Rb $5S_{1/2}(F=1)\leftrightarrow 5P_{3/2}$ transition and experiences modified absorption due to the ac stark shift and interference in the Autler-Townes' doublet transitions induced by the coupling laser. We note that EIT with a *resonant* coupling laser has been observed previously in a Λ-type system formed on the Rb D_1 transition [11,12]. Differing from the previous work, our study here will be on the behavior of the effective Rb Λ-type system formed on the D_2 transition and the emphasis will be on the sub-Doppler linewidth in the probe laser absorption spectrum when the frequency of the strong-coupling laser is tuned away from the atomic transition frequency. In the bare-atomic-state picture, EIT can be viewed as induced by the two-photon coherence ρ_{12} and as a direct consequence of the resulting population trapping in the Λ system [14]. In a Doppler broadened Λ system, if the coupling laser and the probe laser propagate in the same direction and $\omega_p \sim \omega_c$, the two-photon scattering process $|2\rangle \leftrightarrow |3\rangle \leftrightarrow |1\rangle$ will be kept near resonance. The near cancellation of the Doppler shifts in the two-photon scattering process gives rise to a resonantly enhanced two-photon coher-

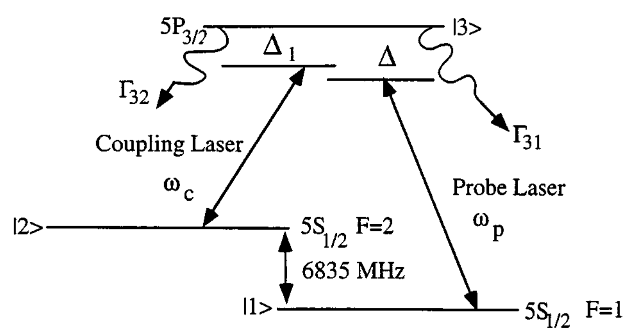

FIG. 1. The energy level structure of ^{87}Rb D_1 transition and the laser coupling scheme, which forms an effective three-level Λ-type sytem. $\Delta_1=\omega_c-\omega_{32}$ ($\Delta=\omega_p-\omega_{31}$) is the coupling (probe) laser detuning. Γ_{31} (Γ_{32}) is the spontaneous decay rate from state $|3\rangle$ to state $|1\rangle$ ($|2\rangle$). ω_c (ω_p) is the coupling (probe) laser frequency.

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ence ρ_{12} and preserves the suppressed absorption at the line center of the probe transition. Using a semiclassical density-matrix analysis, it has been shown by Gea-Banacloche *et al.* [9] that the steady-state contribution of the atoms with velocity v to the complex susceptibility of the probe transition $|1\rangle\leftrightarrow|3\rangle$ in the Λ-type system is given by

$$\chi(\nu)d\nu=\frac{4i\hbar g_{13}^2N(\nu)d\nu}{\epsilon_0\{\Gamma_{31}/2-i\Delta-i(\omega_p\nu/c)+\Omega^2/[\Gamma_{31}/2-i(\Delta-\Delta_1)-i((\omega_p-\omega_c)\nu/c)]\}},\qquad(1)$$

where $N(\nu)=(N_0/u\sqrt{\pi})e^{-\nu^2/u^2}$ (u is the root-mean-square atomic velocity and N_0 is the total atomic number density) is the atomic number density of Maxwellian velocity distribution in a Doppler-broadened system, $\Omega=D_{23}E_c/\hbar$ is the Rabi frequency of the coupling laser ($D_{23}=\langle 2|D|3\rangle$ is the dipole matrix element and E_c is the electric field amplitude of the coupling laser), g_{13} is the probe laser Rabi frequency, and Γ_{31} is the population decay rate from state $|3\rangle$ to state $|1\rangle$. In deriving Eq. (1), a weak probe laser is assumed so that only the terms up to the first order in the probe field amplitude are retained. The probe and the pump are assumed to propagate in the same direction. After integration over the Maxwellian velocity distribution, one obtains the atomic susceptibility $\chi=\int\chi(\nu)d\nu$ and the intensity absorption coefficient is given by $\alpha=(\omega_p n_0/c)\mathrm{Im}(\chi)$ (n_0 is the background index of refraction). The probe absorption spectrum consists of two peaks (Autler-Townes' doublet) located at the probe frequency detuning $\Delta_\pm=\Delta_1/2\pm\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$. The analytical expression for the spectral linewidth of the two absorption peaks has been derived by Vemuri, Agarwal, and Rao [13] and is given by

$$\Gamma_\pm=\frac{\Gamma_{31}+\Gamma_{32}+2D}{4}\left(1\mp\frac{\Delta_1}{\sqrt{\Delta_1^2+4\Omega^2}}\right).\qquad(2)$$

Here D is the full Doppler width of the thermal atomic system. Equation (2) shows that the width for one of the two lines (at Δ_+) is reduced by a factor $1-\Delta_1/\sqrt{\Delta_1^2+4\Omega^2}$. Thus, by choosing appropriate values of the coupling laser Rabi frequency (Ω) and frequency detuning (Δ_1), the linewidth of the atomic transition $|3\rangle\leftrightarrow|1\rangle$ can be manipulated and reduced to sub-Doppler value. As a matter of fact, when $\Delta_1\gg\Omega$, the linewidth Γ_+ can become subnatural, i.e., $\Gamma_+<\Gamma_{31}$. Of course, at such large detunings Δ_1, the absorption coefficient at $\Delta=\Delta_+$ becomes very small.

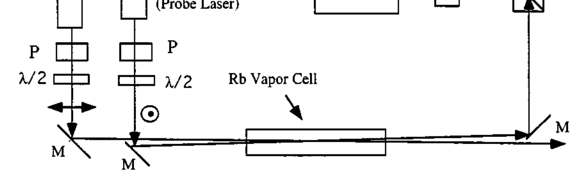

FIG. 2. Schematic drawing of the experimental apparatus. M's: mirrors; P's: polarizers; $\lambda/2$'s: half-wave plates; PB: polarizing beam splitter; D: photodiode detector.

III. EXPERIMENTAL RESULTS

The experimental apparatus is shown schematically in Fig. 2. The experiment was done in a 75 mm Rb vapor cell magnetically shielded by a μ-metal tube and kept at room temperatures. No buffer gas was added in the vapor cell. A cw single frequency Ti:sapphire laser (Coherent 899-21) was used as the strong-coupling laser, and a cw external-cavity diode laser (Sharp LTO-24MD) with grating feedback was used as the probe laser. The linewidth of the diode laser was about 1 MHz and that of the Ti:sapphire laser was about 5 MHz. The coupling laser and the probe laser had linear orthogonal polarizations, were made to propagate in the same direction, and were overlapped in the Rb cell with a relative angle of $\sim 2\times10^{-3}$ rad. After passing through the Rb cell, the probe laser beam was directed to a photodiode, and its output was recorded by a digital oscilloscope (Lecroy 9310A) and then transferred to a personnel computer. The collimated coupling laser had a beam diameter of $\sim$2 mm, while the beam diameter of the collimated probe laser was $\sim$1 mm. The probe laser power was $\sim$5 μW and the maximum power of the coupling was about 600 mW. During the experiment, the coupling laser frequency was kept at appropriate detunings Δ_1 from the Doppler-broadened ^{87}Rb $5S_{1/2}(F=2)\leftrightarrow 5P_{3/2}$ transition, while the probe laser was scanned across the ^{87}Rb $5S_{1/2}(F=1)\leftrightarrow 5P_{3/2}$ transition, and the probe laser absorption spectrum was recorded. Under our experimental conditions, the collisional broadening (estimated to be <10 KHz) in the Rb vapor cell is negligible, and the radiative relaxation rate of $\Gamma_{31}+\Gamma_{32}\approx 6$ MHz. The full Doppler width is $\sim$540 MHz. When the coupling laser was blocked, the normal Doppler-broadened absorption spectrum was observed as shown in Fig. 3 and the maximum absorption was about 25% at the line center ($\Delta=0$) of the ^{87}Rb $5S_{1/2}(F=1)\leftrightarrow 5P_{3/2}$ transition. Figure 4 shows a series of

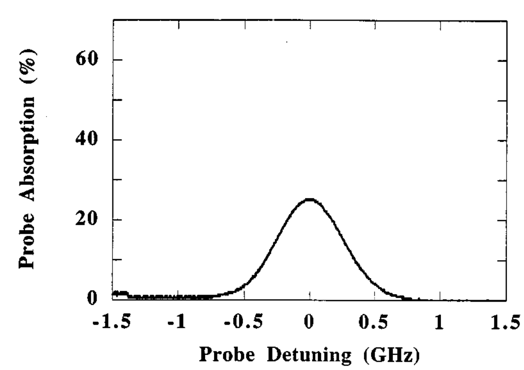

FIG. 3. Measured probe absorption spectrum versus the probe detuning Δ without the coupling laser, which shows a normal Doppler-broadened line profile.

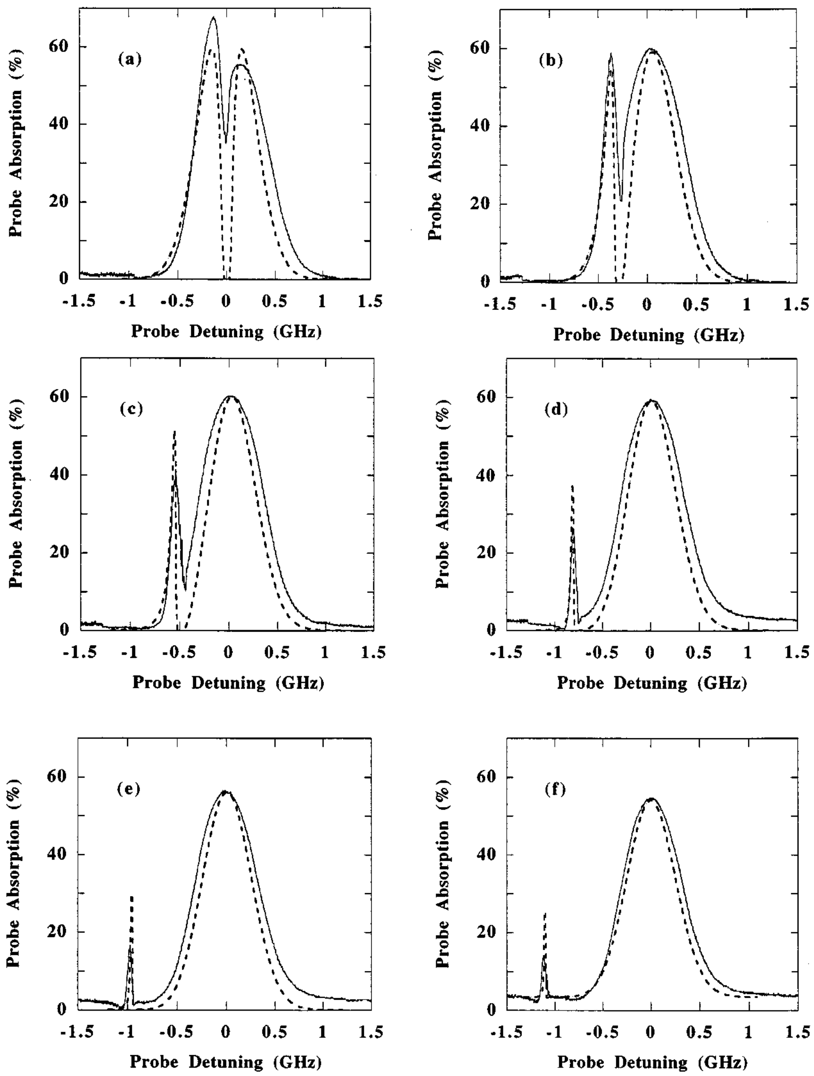

FIG. 4. Measured (solid lines) and calculated (dashed lines) probe absorption spectra versus the probe laser detuning Δ. (a) The coupling laser detuning $\Delta_1 \approx 0$. (b) The coupling laser detuning $\Delta_1 = -300$ MHz. (c) The coupling laser detuning $\Delta_1 = -450$ MHz. (d) The coupling laser detuning $\Delta_1 = -780$ MHz. (e) The coupling laser detuning $\Delta_1 = -1$ GHz. (f) The coupling laser detuning $\Delta_1 = -1.1$ GHz. During the experiment, the coupling laser power was about 600 mW (the estimated Rabi frequency $\Omega \sim 250$ MHz). The theoretical calculation is based on a simple three-level Λ system and the parameters are chosen according to the experimental conditions for the Rb Λ-type system depicted in Fig. 1: $\Gamma_{31} + \Gamma_{32} = 6$ MHz, the probe Rabi frequency g_{13} is $0.1\Gamma_{31}$, the full Doppler width is 540 MHz, and the coupling laser Rabi frequency is 250 MHz.

the probe absorption spectrum versus the probe laser detuning Δ under different coupling laser detunings Δ_1. The solid lines are the experimental data and the dashed lines are the theoretical simulation results derived from an ideal three-level Λ system. When the strong-coupling laser is on, the optical pumping induced by the coupling laser transfers most of the Rb atoms from the $5S_{1/2}$ $F=2$ state to the $5S_{1/2}$ $F=1$ state, and the maximum probe absorption is increased by about 2.4 times as shown in Fig. 4. Due to the resonance EIT effect, the line center absorption was reduced by about 40% for a resonant coupling laser as shown in Fig. 4(a). Figures 4(b)–4(f) show the measured (solid lines) and the calculated (dashed lines) probe absorption spectra when the coupling laser was detuned from the ^{87}Rb $5S_{1/2}(F=2) \leftrightarrow 5P_{3/2}$ transition. As expected from Eqs. (1) and (2), the Autler-Townes' doublet becomes asymmetrical, and the spectral line at the probe detuning $\Delta = \Delta_+ = \Delta_1/2 + \frac{1}{2}\sqrt{\Delta_1^2 + 4\Omega^2}$ becomes narrower when the coupling laser detuning Δ_1 increases; the other spectral line at the probe detuning $\Delta = \Delta_- = \Delta_1/2 - \frac{1}{2}\sqrt{\Delta_1^2 + 4\Omega^2}$ has a Doppler-broadened linewidth and is located approximately at the line center of the atomic transition frequency. We note that the agreement between the experimental measurements and the theoretical simulation based on an ideal three-level Λ system is only qualitative. This is expected since the effective Λ system formed from the ^{87}Rb D_2 transition is not a simple three-level system: the upper $5P_{3/2}$ state contains the hyperfine states with $F=0$, 1, 2, and 3; furthermore, each F (for the $5S_{1/2}$ ground state) and F' (for the $5P_{3/2}$ state) contain $2F+1$ and $(2F'+1)$ magnetic sublevels, respectively. More importantly, note that according to the selection rule $\Delta_{FF'} = F - F' = 0, \pm 1$; therefore, the coupling laser connects the $5S_{1/2}$ $F=2$ state to $5P_{3/2}$ $F'=1$, 2, and 3 states, while the probe laser connects the $5S_{1/2}$ $F=1$ state to $5P_{3/2}$ $F'=0$, 1, and 2 states. The atomic coherence exists between the $5S_{1/2}$ $F=2$ and $5S_{1/2}$ $F=1$ state only through the intermediate $5P_{3/2}$ $F'=1$, 2 states, but not the $5P_{3/2}$ $F'=0$ and 3 states. The $5P_{3/2}$ $F'=3$ state only participates in the optical pumping process and the probe laser experiences usual bare-states absorption on the transition $5S_{1/2}$ $F=1 \leftrightarrow 5P_{3/2}$ $F=0$. The processes associated with the $5P_{3/2}$ $F'=3$ and $F'=0$ can be viewed as incoherent processes in the multilevel Rb system. These facts may explain the following discrepancies between the theoretical simulation and the experimental measurements: first, the absorption at the line center is reduced by only about 40% instead of 100% when the coupling laser detuning $\Delta_1=0$; second, with $\Delta_1 \neq 0$, the ratio of the probe absorption at the probe detunings $\Delta = \Delta_+ = \Delta_1/2 + \frac{1}{2}\sqrt{\Delta_1^2 + 4\Omega^2}$ and $\Delta = \Delta - = \Delta 1/2$

$-\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$ is smaller in the experimental measurement than in the theoretical simulation [in Figs. 4(a)–4(f), the calculated probe absorption is normalized to the measured probe absorption at $\Delta=\Delta_-=\Delta_1/2-\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$, so the measured probe absorption at the narrower sideband is smaller than the calculated probe absorption. But at small Δ_1 values in Figs. 4(a) and 4(b), the absorption at the left (red) sideband is greater in the experimental measurements than in the theoretical simulation, apparently due to the probe absorption contributed by the $5S_{1/2}$ $F=1\leftrightarrow 5P_{3/2}$ $F'=0$ transition]; third, the measured spectral linewidth for the probe absorption at $\Delta=\Delta_-=\Delta_1/2-\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$ is markedly broader than that of the calculation. Nevertheless, when the coupling detuning Δ_1 is sufficiently large, the probe absorption at the smaller sideband ($\Delta=\Delta_+=\Delta_1/2+\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$) should be affected less by the incoherent processes than the main probe absorption at $\Delta=\Delta_-=\Delta_1/2-\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$. Therefore, the reduced linewidth due to the EIT effect at sufficiently large coupling-laser detunings should not be influenced strongly by the incoherent processes. Figure 5 shows the measured (dots) and calculated [from Eq. (2), solid line] sub-Doppler linewidth Γ_+ versus the coupling laser detuning Δ_1. Considering the intrinsic laser linewidth of a few MHz (for both the coupling laser and the probe laser), the agreement between the measurement and the theory is satisfactory.

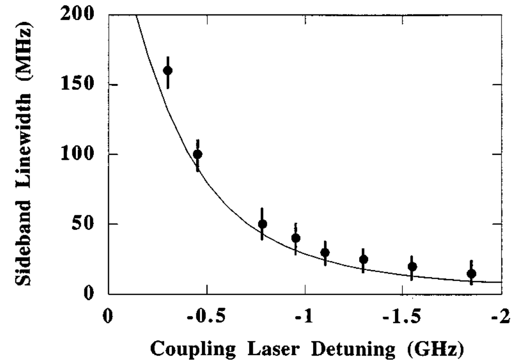

FIG. 5. Measured (dots) and calculated [from Eq. (2), solid line] linewidths of the probe absorption line at the probe detuning $\Delta=\Delta_+=\Delta_1/2+\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$ versus the probing detuning Δ_1. For the experimental measurements, the coupling laser power was about 600 mW. The parameters used in Eq. (2) are $\Gamma_{31}+\Gamma_{32}=6$ MHz, $D=540$ MHz, and $\Omega=250$ MHz.

IV. CONCLUSION

In summary, we have studied steady-state EIT and observed sub-Doppler linewidth behavior in a Doppler-broadened effective Λ-type Rb system. The sub-Doppler resolution was obtained at the probe absorption line located at $\Delta=\Delta_+=\Delta_1/2+\frac{1}{2}\sqrt{\Delta_1^2+4\Omega^2}$ when the coupling laser detuning $\Delta_1\neq 0$. The sub-Doppler linewidth approaches the natural linewidth when Δ_1 is sufficiently large as shown by the data in Fig. 5]. Qualitative agreement between the measured probe absorption spectra and the calculated spectra based on a simple three-level Λ-type system was obtained. The measured sub-Doppler linewidth agrees with the theoretical predictions of Vemuri, Agarwal, and Rao [13].

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