Experimental observation of the linewidth narrowing of electromagnetically induced transparency resonance

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We report an experimental observation of the variation in linewidth of the electromagnetically induced transparency (EIT) resonance in a three-level Λ-type system for several laser bandwidths in a Rb vapor cell, with and without a buffer gas. It is found, using narrow bandwidth (about 20 kHz) diode laser for both coupling and probe beams, that the linewidth of the EIT resonance can be significantly narrowed in the Rb vapor cell with the buffer gas. The results are in good qualitative agreement with a simple theoretical calculation.

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Many theoretical and experimental works show that the effect of electromagnetically induced transparency (EIT) is becoming an important tool for implementation of quantum information science. Nevertheless, EIT is a fragile quantum interference effect; the ideal transparency is achieved at exactly the two-photon resonance condition, i.e., when the frequency detuning of two photons is zero. If the frequency detuning of two photons is slightly nonzero, the interference is destroyed and the medium becomes absorbing. So the EIT linewidth is very narrow and accompanied by a very steep dispersion[1,2]. The steepness of the dispersion function with respect to the frequency detuning of the two photons plays a key role in applications of EIT such as providing an effective technique for slowing down the group velocity of light[3,4], trapping and manipulating photon states in atoms[5,6], obtaining high-resolution spectroscopy[7], enhancing nonlinear optical processes[8−11], and narrowing the linewidth of an optical cavity[12,13].

Because the steep dispersion in an EIT system is directly related to the EIT linewidth, it is of a great practical interest. Theoretical and experimental studies show that the EIT linewidth depends on such parameters as the atomic nonradiative decay rate between the two ground states, the bandwidth of the coupling and probe laser beams, the Rabi frequency of coupling light field[14−18], etc.. In the past few years, several experimental demonstrations of linewidth narrowing of a coherent dark resonance in Λ-type three-level atoms were reported[19]. The dependence of the EIT linewidth on the bandwidth of the coupling laser also has been studied theoretically[15] and experimentally[16,17]. However, the dependence of the EIT linewidth on experimental parameters is not completely understood. For example, to our knowledge, there have been no reports directly comparing the EIT linewidth in a Rb vapor cell without a buffer gas to that in a Rb vapor cell with a buffer gas, where the atomic nonradiative decay rate between two ground states is far smaller than the bandwidth of the commercial laser diode.

In this paper, we observe variation in the EIT linewidth of a three-level Λ-type atomic system for several laser bandwidths in a Rb vapor cell, both with and without a buffer gas (30-Torr Ne). Using narrow bandwidth diode lasers with optical feedback from confocal Fabry-Perot (CFP) cavities for both the coupling and probe beams, the EIT linewidth can be significantly narrowed in the Rb vapor cell with buffer gas, and is measured as a function of the Rabi frequency of the coupling beam. The results agree qualitatively with simple theoretical calculations.

The experiment is performed in a three-level Λ-type system of ^{87}Rb atoms using D_2 lines of the $5S_{1/2} \rightarrow 5P_{3/2}$ transition, as shown in Fig. 1. The hyperfine levels $F = 1$ and $F = 2$ of the ground state $5S_{1/2}$ serve as the two lower states $|1\rangle$ and $|3\rangle$ of the Λ-type system, respectively. The hyperfine level $F' = 1$ of the excited state $5P_{3/2}$ serves as the common upper state. A strong coupling laser beam with frequency ω_c and Rabi frequency $\Omega_c = -\mu_{23}E_c/\hbar$ couples states $|3\rangle$ and $|2\rangle$ while a weaker beam with frequency ω_p and Rabi frequency $\Omega_p = -\mu_{21}E_p/\hbar$ interacts with states $|1\rangle$ and $|2\rangle$. E_c and E_p are the amplitudes of the coupling and probe fields, μ_{23} and μ_{21} are the relevant dipole transition moments. The coupling frequency detuning is defined as $\Delta_c = \omega_c - \omega_{23}$ and the probe frequency detuning as $\Delta_p = \omega_p - \omega_{21}$, where ω_{23} and ω_{21} are the atomic transition frequencies of $|2\rangle$ to $|3\rangle$ and $|2\rangle$ to $|1\rangle$, respectively.

For a three-level Λ-type Rb atomic system in a warm vapor cell, the Doppler-broadening effect will modify the atomic susceptibility. If the coupling and probe beams

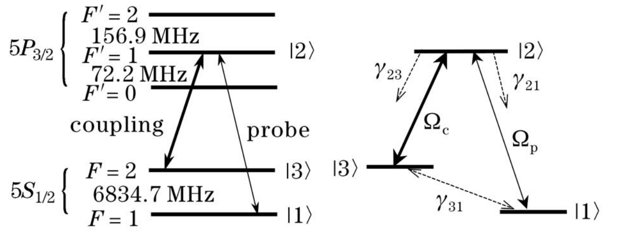

Fig. 1. Three-level Λ-type system in the D_2 line of ^{87}Rb atom.

have nearly the same wavelength and propagate collinearly through the atomic vapor cell, the one-photon absorption is Doppler-broadened, while the two-photon transition is Doppler-free[20]. In that case, the absorption spectrum of probe laser beam will be a transparency spike within a certain frequency width around the two-photon resonance ($\Delta_c = \Delta_p$) due to atomic quantum interference. The frequency width of the transparency spike is so-called EIT linewidth Γ_{EIT}, which depends on parameters[14−18] such as the Rabi frequency of the coupling laser beam Ω_c, the dephasing rate for the two lower states of the Λ-type system γ_{31}, and the bandwidth of the probe and coupling beams etc.. An explicit analytical expression of the linewidth of the EIT resonance Γ_{EIT} is difficult to be obtained in a Doppler-broadened three-level Λ-type system. Recently, using a Lorentzian profile as the velocity distribution function, Javan *et al.*[14] gave an expression for evaluating the EIT linewidth

$$\Gamma_{EIT} \propto \sqrt{\frac{2\gamma_{31}}{\gamma}}\Omega_c, \quad \chi \ll 1, \qquad (1)$$

where $\chi = \Omega_c^2\gamma/(2\gamma_{31}W_D^2)$ in the range of $(\gamma/W_D)^2 \ll \chi \ll \gamma/\gamma_{31}$. The decay rate $\gamma = (\gamma_{21} + \gamma_{23} + \gamma_{31})/2$, where γ_{23} and γ_{21} are decay rates from the upper state to the two lower states, respectively. W_D is the Doppler width; when the Rb cell is kept at room temperature, $W_D \approx 540$ MHz.

The above formula must be modified to account for the finite linewidth of the coupling and probe laser beams. In practice, we can consider the line shapes of the probe and coupling beams to be Lorentzian, so one can change the effective decay rate as[16]

$$\gamma_{31}^e \rightarrow \gamma_{31} + \gamma_p + \gamma_c, \qquad (2)$$

where, $2\gamma_p$ and $2\gamma_c$ are the full-widths at half-maximum (FWHMs) of the probe and coupling lasers, respectively. Combining Eqs. (1) and (2), one can see that the EIT linewidth Γ_{EIT} will become wider with increasing the linewidths of the coupling and probe lasers. To obtain a narrower EIT linewidth Γ_{EIT}, the bandwidths of coupling and probe lasers must be narrowed.

Our experimental setup is shown in Fig. 2. The probe laser (CLD1) and the coupling laser (CLD2) are single-mode tunable Hitachi HL7851G diode lasers which are current and temperature stabilized. The frequencies of these two lasers can be independently locked to the resonances of their respective CFP cavities which provide weak optical feedback. Their bandwidths can be narrowed from 10 MHz at free running to about 20 kHz with optical feedback from the CFP cavities[21]. The configuration of both lasers is shown in the bubble of Fig. 2. Parts of the coupling laser beam and probe laser beam are split off by beam splitters BS1 and BS2 to saturation absorption spectroscopy setups (SAS1 and SAS2) which are used to monitor the frequencies of the two lasers. The probe and coupling beams are combined with a polarizing beam splitter (PBS1) and co-propagate through the vapor cell containing three-level Λ-type Rb atoms so as to achieve a two-photon Doppler-free configuration. The Rb cell is 5 cm long and is kept at room temperature (about 20 °C) and wrapped in μ-metal for magnetic shielding. The probe and coupling beams are focused onto the Rb cell by lenses with focal lengths of 15 and 20 cm respectively, and their respective beam radii at the center of the Rb cell are 0.35 and 0.4 mm. For the Rb cell without buffer gas, the dephasing rate for the two lower states of the Λ-type system γ_{31} is determined by the time-of-flight of atoms through the laser beam[22], which is about $\gamma_{31} = u/2\pi\omega_0 \approx 0.1$ MHz, where ω_0 is the radius of the probe light at the center of the Rb cell. For the Rb cell with 30-Torr Ne buffer gas, γ_{31} is reduced to below 1 kHz. The probe power entering into the Rb cell is about 15 μW, corresponding to a Rabi frequency of $\Omega_p = 5$ MHz. The coupling power entering into the Rb cell is about 240 μW, corresponding to a Rabi frequency of $\Omega_c = 20$ MHz. The probe and coupling beams are orthogonally polarized and are separated with a polarizing beam splitter (PBS3) after passing through the Rb cell. The transmission of the probe beam was recorded with an avalanche photodiode.

In this experiment, the frequency of the coupling laser is tuned to the atomic transition $|2\rangle$ to $|3\rangle$, while the frequency of probe laser is scanned across the transition from $5S_{1/2}(F = 1)$ to $5P_{3/2}(F' = 1)$. We tune or scan either laser frequency by varying the injection current when laser is free running or by changing the length of the CFP cavities when the laser is locked to the CFP cavity resonance. When both lasers are free running, the transmission signals of the probe beam passing through

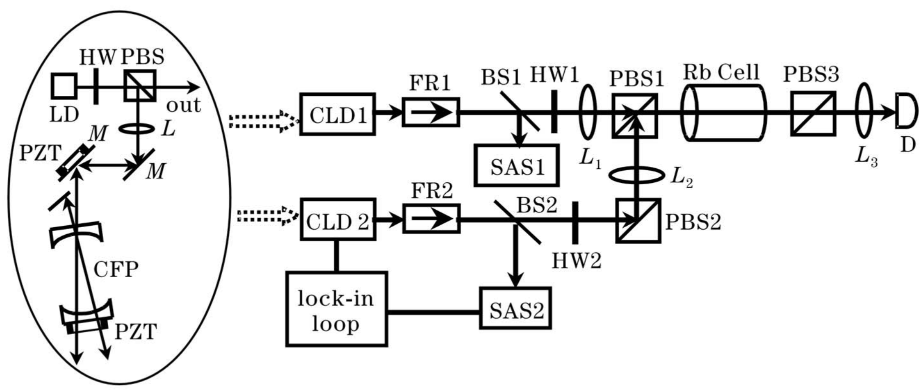

Fig. 2. The experimental setup. LD: laser diode; PZT: piezoelectric transducer; CLD1 and CLD2: probe and coupling lasers, respectively; FR: Faraday rotator; SAS: saturation absorption spectroscopy setup; BS: beam splitter; HW: half-wave plate; PBS: polarizing beam splitter; *L*: lens; *M*: mirror; D: detector.

the Rb cell with and without buffer gas are shown in Figs. 3(a) and (b), respectively. The EIT linewidths from the Rb cell with and without buffer gas are both about 7 MHz. This result shows that, as the linewidths of the lasers are far bigger than the dephasing rate for the two lower states γ_{31}, i.e., $\gamma_p + \gamma_c \gg \gamma_{31}$, decreasing γ_{31} does not significantly influence the EIT linewidth. When coupling laser is locked to its CFP cavity resonance frequency while the probe laser is free running, the probe transmission signals passing through the Rb cell with and without buffer gas are shown in Figs. 3(c) and (d), respectively. The EIT linewidths from the cell with and without buffer gas are still nearly the same (about 2.7 MHz) since we still have $\gamma_p + \gamma_c \gg \gamma_{31}$. However, the EIT linewidths becomes smaller with decreasing the coupling laser bandwidth, as shown in Figs. 3(a)—(d). When both lasers are independently locked to their CFP cavity resonance frequencies, the transmission signals of the probe beam passing through the Rb cell with and without buffer gas are shown in Figs. 3(e) and (f), respectively. The EIT linewidth from the cell with buffer gas $\Gamma_{\rm EIT} = 0.6$ MHz is noticeably smaller than that from the cell without buffer gas $\Gamma'_{\rm EIT} = 1.8$ MHz with a ratio of $\Gamma'_{\rm EIT}/\Gamma_{\rm EIT} \approx 3$. This indicates that, as the bandwidth of the lasers $(\gamma_p + \gamma_c)$ approaches the dephasing rate for the two lower states γ_{31}, decreasing γ_{31} will obviously reduce the EIT linewidth as shown in Eq. (1). In the case where the bandwidths of the lasers are very small $(\gamma_p + \gamma_c \approx 20$ kHz), the value of χ can satisfy the range given by $(\gamma/W_D)^2 \ll \chi \ll \gamma/\gamma_{31}$, so the EIT linewidth could be simply calculated from Eqs. (1) and (2). For

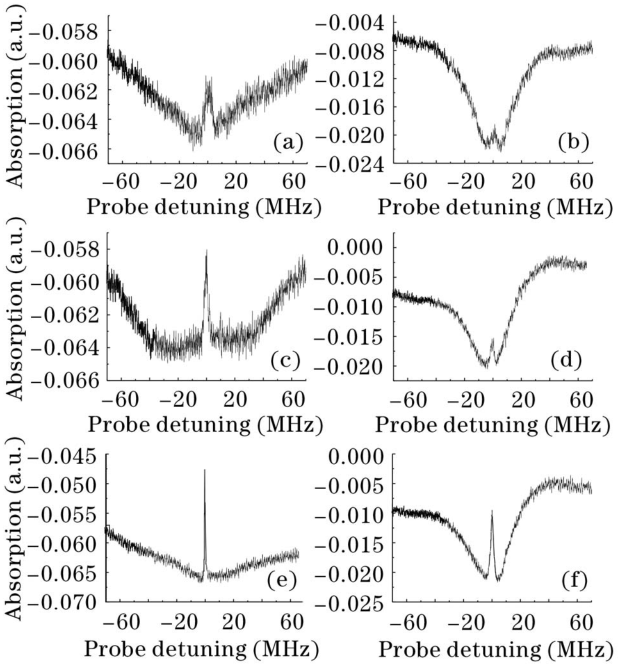

Fig. 3. The signals of transmitted probe beam passing through the Rb cell with (left) and without (right) buffer gas for variance laser bandwidth. (a) and (b): Both lasers are free running; (c) and (d): the frequency of coupling laser is locked to the CFP cavity while the probe laser is free running; (e) and (f): the frequencies of both lasers are independently locked to the CFP cavity respectively.

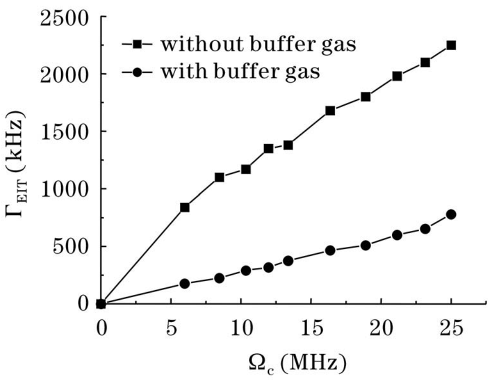

Fig. 4. The EIT linewidth versus the Rabi frequency of the coupling laser.

the Rb cell with buffer gas, $\gamma_{31} = (1 \text{ kHz}) + \gamma_p + \gamma_c \approx 21$ kHz, while for the Rb cell without buffer gas, $\gamma'_{31} = (100 \text{ kHz}) + \gamma_p + \gamma_c \approx 120$ kHz. The spontaneous rates γ and Rabi frequency of coupling light Ω_c are equal for both Rb cells. So $\Gamma'_{\rm EIT}/\Gamma_{\rm EIT} = \sqrt{\gamma'_{31}/\gamma_{31}} \approx 2.5$. The above theoretical result shows that our experimental results are in good qualitative agreement with simple theoretical calculations.

As shown in Fig. 4, the observed EIT linewidth is found to be linearly proportional to the Rabi frequency of the coupling laser beam. As the Rabi frequency of the coupling laser beam is decreased, the linewidth of the EIT resonance becomes smaller and EIT changes into CPT.

We have observed experimentally how the EIT resonance linewidth varies for a three-level Λ-type atomic system over several laser bandwidths in a Rb vapor cell, with and without a buffer gas (30-Torr Ne). We found, using narrow bandwidth diode lasers with optical feedback from Fabry-Perot cavities for both coupling and probe lasers, the EIT linewidth can be significantly narrowed in Rb vapor cell with buffer gas compared with that in the Rb vapor cell without buffer gas. The EIT linewidth was measured as a function of the Rabi frequency of the coupling beam for Rb vapor cells with and without buffer gas and the results are consistent with simple theoretical calculations.

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