Observation of Electromagnetically Induced Transparency in a Zeeman-Sublevel System in Rubidium Atomic Vapour

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(Received 10 March 2003)

We observed electromagnetically induced transparency (EIT) in a Zeeman-sublevel system using rubidium atomic vapour at the temperature of 75° C, in which the width of the EIT signal is only 0.6 MHz. Two different methods were performed to observe the EIT signal in our experiment.

PACS: 42. 50. Gy, 42. 50. Hz, 42. 62. Fi

Electromagnetically induced transparency (EIT) is a quantum interference effect which eliminates the absorption of a medium on a propagating weak probe field in resonance of an atomic transition, with a strong coupling field on another linked transition.[1] Three levels involved can be in cascade, Λ, or V configurations. Many theoretical and experimental studies have been carried out since Boller *et al.*[2] observed the EIT phenomenon with high-power pulsed lasers in atomic vapour of neutral strontium in 1991. In their work, how the EIT depends on some experimental parameters, such as coupling laser intensity and detuning, the condition of medium,[3–8] etc., has been well studied. Meanwhile, some fundamental work about EIT was performed theoretically.[9–13] In recent years, great progress was made in the field of EIT, owing to its several potential applications. Especially in 1999, Hau *et al.*[14] slowed the speed of light to 17 m/s. Two years later, Liu *et al.*[15] stopped the light in cooled atom cloud of sodium, based on the mechanism of EIT, which made the EIT a highlight in the field of quantum coherence and interference. Except for the studies mentioned above, there are other important works on EIT applications, such as high-resolution spectroscopy, high-precision magnetometry,[16–21] and sub-recoil laser cooling,[22,23], etc. In general, EIT has been studied with cw lasers in various media, including vapour cell, solids, laser-cooled atoms, and even Bose–Einstein condensate,[24] with most of them carried out in the fine and hyperfine levels of alkali atoms. However, there are few experiments of EIT reported in the Zeeman-sublevel structure, for example, Phillips *et al.*[25] scanned an externally applied magnetic field to the vapour cell of ^{87}Rb to check the transparent rate of EIT in their light-storage experiment, Andreeva *et al.*[26,27] studied the EIT of Zeeman-sublevels in the fluorescence.

In this Letter, we report an experimental study on EIT in a Zeeman-sublevels system using atomic vapour of rubidium. We tried to use two different schemes to observe the EIT signal. One is a general method, in which we fixed the frequency of coupling laser and scanned the frequency of probe one. To the best of our knowledge, there is no report on using this scheme to investigate the properties of the Zeeman-sublevel EIT. In the other scheme, we fixed both the frequencies of coupling and probe, and changed the splitting between ($5S_{1/2}$, $F = 1$, $m_F = +1$) and ($5S_{1/2}$, $F = 1$, $m_F = -1$) by scanning a bias magnetic field on the cell with the same direction as light propagation. In other words, we scanned the detuning of the coupling and probed to their respectively resonant transitions, which means that the transparent rate of the probe beam can change periodically even if its frequency is fixed, due to the fact that the efficiency of the EIT can change periodically. Although this method was rarely used to study EIT,[25–27] it is still worth studying in details. In our experiment, we obtained the similar EIT signal in this scheme as in general way, and its linewidth is 0.5 MHz, which is comparable to 0.6 MHz in the general method.

Figure 1 shows the schematic energy levels in our experiment, in which a -type three-level system is used with the two ground states degenerated. The calculation was performed by a semi-classical theory.[28] A strong coupling laser with frequency ν_2 corresponding to the Rabi frequency Ω_2 drives the $|c\rangle \rightarrow |a\rangle$ transition, and a weak probe laser with frequency ν_1 corresponding to the Rabi frequency Ω_1 couples the $|b\rangle \rightarrow |a\rangle$ transition. Equations of motion under the electric dipole and rotating-wave approximations read

$$\begin{aligned}\dot{\rho}_{ab} = &-(\mathrm{i}\omega_{ab}+\gamma_1)\rho_{ab} - \frac{\mathrm{i}\Omega_1 \mathrm{e}^{-\mathrm{i}\phi_1}\mathrm{e}^{-\mathrm{i}\nu_1 t}}{2}(\rho_{aa}-\rho_{bb}) \\ &+ \frac{\mathrm{i}\Omega_2 \mathrm{e}^{-\mathrm{i}\phi_2}\mathrm{e}^{-\mathrm{i}\nu_2 t}}{2}\rho_{cb}, \qquad (1)\\ \dot{\rho}_{cb} = &-(\mathrm{i}\omega_{cb}+\gamma_3)\rho_{cb} - \frac{\mathrm{i}\Omega_1 \mathrm{e}^{-\mathrm{i}\phi_1}\mathrm{e}^{-\mathrm{i}\nu_1 t}}{2}\rho_{ca}\end{aligned}$$

* Supported by the National High Technology Research and Development Programme of China under Grant No 2001CB309308, and the Key Project of Ministry of Education of China under Grant No 00-09.

$$+\frac{\mathrm{i}\Omega_2 \mathrm{e}^{\mathrm{i}\phi_2}\mathrm{e}^{\mathrm{i}\nu_2 t}}{2}\rho_{ab},$$

$$\dot{\rho}_{ac} = -(\mathrm{i}\omega_{ac}+\gamma_2)\rho_{ac} - \mathrm{i}\Omega_2 \mathrm{e}^{-\mathrm{i}\phi_2}\mathrm{e}^{-\mathrm{i}\nu_2 t}(\rho_{aa}-\rho_{cc}) + \frac{\mathrm{i}\Omega_1 \mathrm{e}^{-\mathrm{i}\phi_1}\mathrm{e}^{-\mathrm{i}\nu_1 t}}{2}\rho_{bc},$$

where γ_1, γ_2, and γ_3 are the delay rates of ρ_{ab}, ρ_{ac}, and ρ_{cb} respectively; and $\gamma_1 \approx \gamma_2 \approx 6\,\mathrm{MHz}$. We simply consider that the coupling field is resonant ($\nu_2 = \omega_{ac}$), and the detuning of probe field is $\Delta = \omega_{ab} - \nu_1$. In addition, we assume that the probe field is weak enough and it does not significantly populate the level $|a\rangle$, and the atoms initially are in the ground level $|b\rangle$. Then Eq. (1) can be solved and we obtain

$$\rho_{ab}(t) = \frac{\mathrm{i}\mu_{ab}E_{10}(\mathrm{i}\Delta\gamma_3)\mathrm{e}^{-\mathrm{i}\nu_1 t}}{2\hbar[(\mathrm{i}\Delta+\gamma_1)(\mathrm{i}\Delta+\gamma_3)+\Omega_2^2/4]}. \quad (2)$$

From Eq. (2), χ' and χ'', which correspond to dispersive and absorptive distributions of probe field respectively, can be written as

$$\chi' = \frac{N|\mu_{ab}|^2\Delta}{\hbar\varepsilon_0 Z}\Big[\gamma_3(\gamma_1+\gamma_3) + \Big(-\gamma_1\gamma_3 - \frac{\Omega_2^2}{4} + \Delta^2\Big)\Big], \quad (3a)$$

$$\chi'' = \frac{N|\mu_{ab}|^2}{\hbar\varepsilon_0 Z}\Big[\Delta^2(\gamma_1+\gamma_3) - \gamma_3\Big(-\gamma_1\gamma_3 - \frac{\Omega_2^2}{4} + \Delta^2\Big)\Big], \quad (3b)$$

where

$$Z = \Big(\gamma_1\gamma_3 + \frac{\Omega_2^2}{4} - \Delta^2\Big)^2 + \Delta^2(\gamma_1+\gamma_3)^2.$$

Owing to the probe and the coupling laser beams deriving from one laser in our experiment, the laser linewidth has a less influence on EIT. This is just a simple model, we do not consider the Doppler effect in the process.

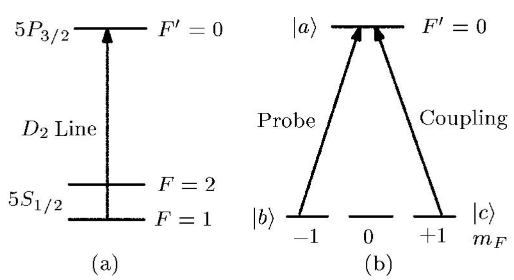

Fig. 1. Relevant energy levels of rubidium atom: (a) Hyperfine level of the D$_2$ line of ^{87}Rb; (b) Λ-type three-level system employed in the experiment. The transition of $5S_{1/2}, F=1, m_F=+1 \rightarrow 5P_{3/2}, F=0$ is for the coupling, and $5S_{1/2}, F=1, m_F=-1 \rightarrow 5P_{3/2}, F=0$ is for the probe.

The experiment was performed in an ^{87}Rb atomic vapour cell at the temperature of 75°C, which corresponds to the atomic densities of 10^{11}–$10^{12}\,\mathrm{cm}^{-3}$. As the schematic diagram shown in Fig. 1, we employed the transition of ^{87}Rb ($5S_{1/2}$, $F=1$, $m_F=+1$) $\rightarrow$ ($5P_{3/2}, F=0$) for coupling, and ($5S_{1/2}, F=1$, $m_F=-1$) $\rightarrow$ ($5P_{3/2}, F=0$) for probe. Only one laser was used in our experiment. We locked the laser to the transition of ($5S_{1/2}, F=1$) $\rightarrow$ ($5P_{3/2}, F=2$) and then shifted the frequency to the transition of ($5S_{1/2}, F=1$) $\rightarrow$ ($5P_{3/2}, F=0$) by acoustic-optic modulation (AOM), for the reason that the saturated absorption peak corresponding to the transition of ($5S_{1/2}, F=1$) $\rightarrow$ ($5P_{3/2}, F=0$), which is used to lock the frequency, is very small and is not easy to lock directly. The coupling field is always much stronger than the probe field, and both the coupling and the probe are circularly polarized. Our two different schemes are described in detail in the following.

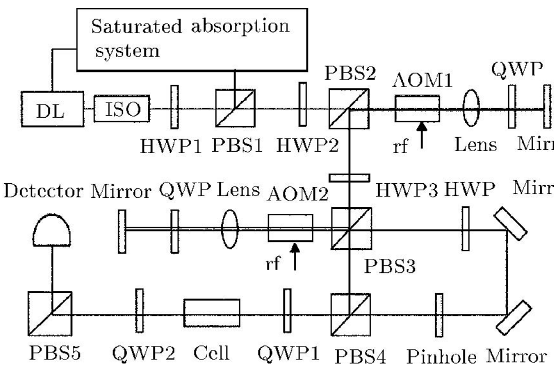

Fig. 2. Experimental set-up for the scheme of scanning the frequency of probe laser beam. DL: external cavity diode laser; HWP: half-wave plate, QWP: quarter-wave plate, PBS: polarized beamsplitter, AOM: acoustic-optic modulation. A pinhole is used to reshaping the probe beam, a fixed amplified rf signal is used to drive the AOM1, and a scanning amplified rf signal is used to drive the AOM2.

Figure 2 shows the first experimental set-up. Both the coupling laser beam and the probe laser beam come from one external-cavity diode laser that is temperature stabilized and can be tuned to the D_2 line of rubidium atom. The linewidth of the laser is about 1 MHz. The laser beam is separated into two orthogonally linearly polarized laser beams by using a half-wave plate and polarizing beamsplitter (PBS2). The vertically polarized part serves as coupling, whose frequency shifted through a double pass by the AOM1 from the transition of ($5S_{1/2}, F=1$) $\rightarrow$ ($5P_{3/2}, F=2$) to the transition of ($5S_{1/2}, F=1$) $\rightarrow$ ($5P_{3/2}, F=0$), which is about -229 MHz. The horizontally polarized part serves as probe, whose frequency shifted by 229 MHz and synchronously scanned by the AOM2. Then put the two parts together and make them circularly polarized by the PBS4 and a quarter-wave plate. The two laser beams propagate in the same direction through a 8-cm-long rubidium vapour cell that is kept at the temperature of 75°C and shielded by μ-metal to protect from the earth magnetic field. The weak probe laser beam is monitored by a photodiode after PBS5. In this experiment, the power of the coupling and probe laser beam are 0.376 mW and 0.022 mW, respectively.

Figure 3 shows the experimental result. When we scan the frequency of the probe laser beam with the coupling beam turned off, we can only observe the absorption background. However, when the coupling laser beam is turned on, the rubidium atomic vapour becomes transparent to the probe laser beam, and the width of the EIT signal is 0.6 MHz. The EIT signal is shown in Fig. 3, whose background has been removed and the original signal is shown in the inset, which shows an absorptive background. It is emphasized that, when the vapour cell is kept at room temperature, the signal-to-noise (SNR) ratio of the EIT signal we observed in the experiment is very low, until we heat the vapour cell to 60°C.

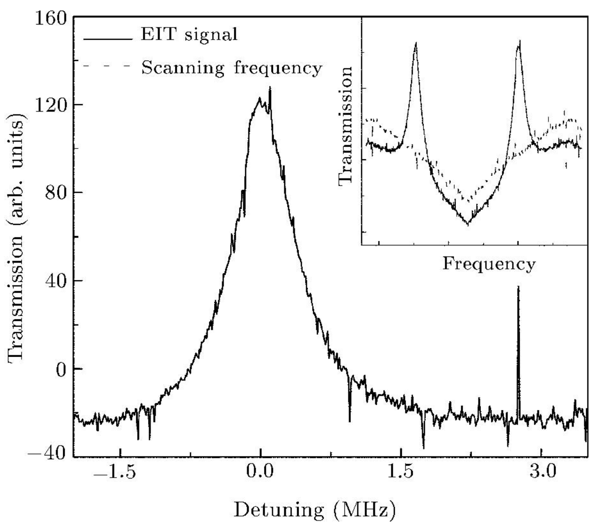

Fig. 3. Electromagnetically induced transparency (EIT) signal observed in the scheme of scanning the probe frequency. This EIT signal is a part of the original one that shown in the inset with the same units, in which the absorptive background is removed.

Furthermore, when we try to increase the power of coupling laser beam and keep the power of the probe laser beam unchanged, we find that the intensity of the EIT signal increases. The experimental result indicates how the intensity of the EIT signal depends on the coupling power, as shown in Fig. 4.

In addition, when we increase the power of the coupling laser beam with the power of the probe laser beam unchanged, we found that the width of the EIT signal would increase, as shown in Fig. 5.

The geometric configuration for the second experiment is shown in Fig. 6. In this case, the coupling laser beam and the probe laser beam have the same frequency corresponding to the transition from $(5S_{1/2}, F = 1)$ to $(5P_{3/2}, F = 0)$, after a double pass by using the AOM2 that shifts a frequency of -229 MHz. Both the beams are left circularly polarized and right circularly polarized, respectively, when they pass through the Rubidium vapour cell. Without the magnetic field, the hyperfine level of $(5S_{1/2}, F = 1)$ is triply degenerated. This implies that the coupling and probe are in the resonance of $(5S_{1/2}, F = 1)$ to $(5P_{3/2}, F = 0)$, so EIT occurs. If we put a magnetic field in the rubidium vapour cell, the three sublevels of $(5S_{1/2}, F = 1)$ will split, which causes both the coupling and the probe beams to have a detuning to the resonances of $(5S_{1/2}, F = 1, m_F = +1)$ and $(5S_{1/2}, F = 1, m_F = -1)$ to $(5P_{3/2}, F = 0)$ respectively. In this case, the EIT occurs with less efficiency, even no EIT occurs if the detuning is large enough. One interesting point is, while we periodically scan detuning of the coupling laser to the transition of $(5S_{1/2}, F = 1, m_F = +1) \to (5P_{3/2}, F = 0)$, the position of EIT signal is unchanged, because of the Doppler effect. In this experiment, we observed the EIT signal by scanning the magnetic field, and its width is about 0.5 MHz, as shown in Fig. 7.

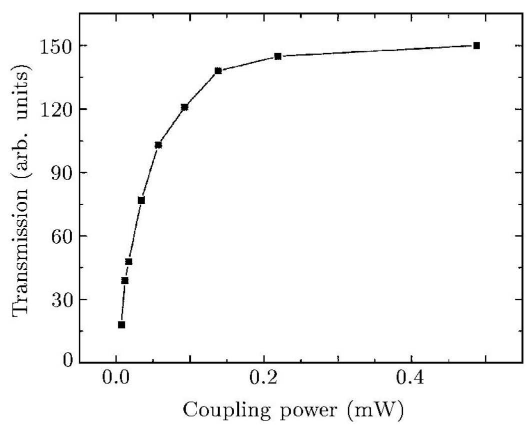

Fig. 4. Transparency of EIT signal versus coupling laser power, with the probe laser intensity unchanged.

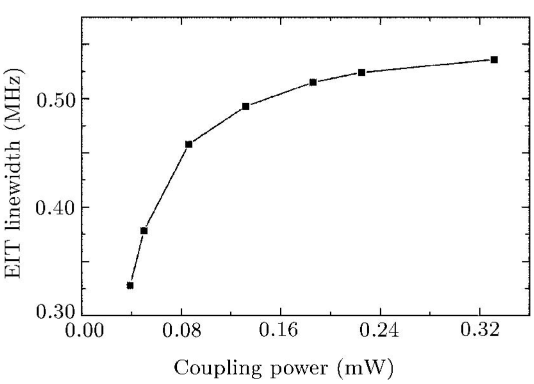

Fig. 5. Width of the EIT signal versus the coupling power, with the power of the probe laser beam unchanged.

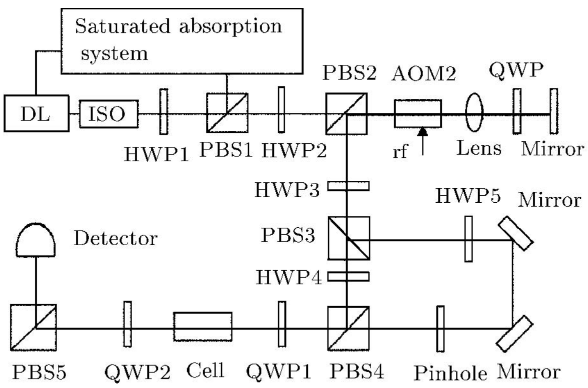

Fig. 6. Experimental set-up in the scheme of scanning the magnetic field. A scanning magnetic field is applied to the vapour cell by using a solenoid with a μ-metal shelter.

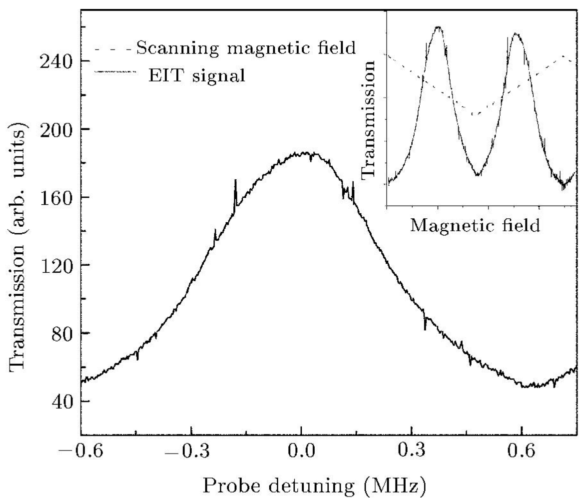

Fig. 7. EIT signal observed in the scheme of scanning the magnetic field. This signal is a part of the original one that is shown in the inset, from which we performed a treatment with the horizontal ordinate from magnetic units to frequency units, by multiplying the magnetic field with 1.4 MHz/G.

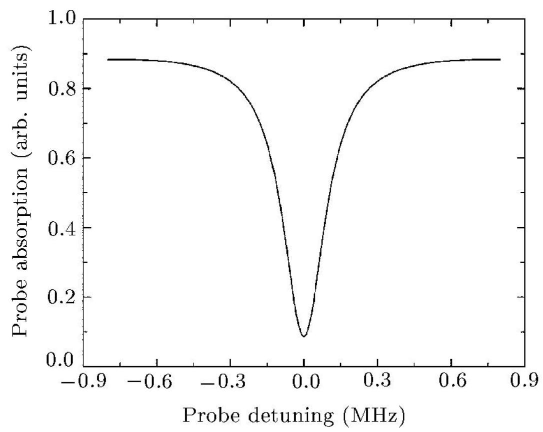

Fig. 8. Theoretical absorption of probe beam for $\gamma_1 \approx \gamma_2$=6 MHz, γ_3=0.01 MHz, Ω_2=1.2 MHz. The linewidth is about 0.4 MHz, comparable to 0.6 MHz in Fig. 3 and 0.5 MHz in Fig. 7.

We try to numerically simulate the spectra of EIT in the Zeeman-sublevel structure from Eq. (3b), the result as shown in Fig. 8 agrees well with what we obtained by the two methods. In this theoretical calculation, $\gamma_1 \approx \gamma_2 = 6$ MHz, $\gamma_3 = 0.01$ MHz, $\Omega_2 = 1.2$ MHz.

In summary, we have reported the experiment of EIT in the Zeeman sublevels using hot Rb vapour and a diode laser with external cavity, and the latter is not often used to study EIT. It provides new scheme to modulate the light intensity using a magnetic field, and it can be used to detect the magnetic field sensitively. On the other hand, the width of the EIT signal is very narrow, which has potential applications in optic switch, high-resolution spectroscopy, slowing light, and even light storage.

We thank Professor Jung Bog Kim for helpful discussion.

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