Cavity linewidth narrowing by means of electromagnetically induced transparency in Rb with a longitudinal magnetic field

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We demonstrate a method for further reducing the cavity linewidth by the application of a small longitudinal magnetic field on the Rb cell. Because of the magnetic field multiple electromagnetically induced transparencies (EITs) are observed. The center EIT linewidth is measured as a function of the magnetic field. By utilizing the center EIT we narrow the cavity linewidth to 2 MHz which is half of the cavity linewidth without magnetic field.

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Electromagnetically induced transparency (EIT) is a quantum interference effect which eliminates the absorption of a propagating weak probe field in resonance of an atomic transition, with a strong coupling field on another linked transition[1,2]. Meanwhile, the dispersive properties of the weak probe field near the atomic transition frequency can be greatly modified owing to the quantum interference. Because of its useful features it has attracted great attention since it was first observed by Boller *et al.*[3]. After two decades of study, many theoretical and experimental studies have been carried out and great progresses have been made in the field of EIT. In early works, the study of EIT mainly focused on lasing without population inversion[4,5], enhancement of nonlinear optical effects[6,7], enhancement of refraction[8,9], etc. One of the most important achievements is that Hau *et al.*[10] slow the speed of light to 17 m/s in 1999. Two years later, Liu *et al.*[11] stopped the light in cooled atom cloud of sodium. In recent years, there are many works in the above research areas[12–18]. What is more, combined with other areas EIT is still a research hotspot of quantum optics. For instance, associating EIT with Rydberg atoms has showed great potential applications in quantum information processing[19] and merging EIT with cavity quantum electrodynamics is another hot point[20].

Optical cavity is a major component of laser, optical parametric oscillator, and interferometer. The transmission properties of an optical cavity containing an atomic medium are highly dependent on the atomic absorption and dispersive. Because of the properties of large dispersion and almost vanishing absorption, it is naturally thought that placing an EIT medium into an optical cavity to modify the cavity response. Lukin *et al.*[21] first pointed out that making use of EIT medium to narrow cavity linewidth in theory, that is, intracavity EIT. Before long, Wang *et al.*[22] experimentally demonstrated cavity linewidth narrowing by means of EIT with hot atomic-Rb vapor and then they did a series of research works on the intracavity EIT[23–27]. Later, Hernandez *et al.*[28] observed a narrowed cavity linewidth in a cold atomic-Rb system. Our research group has also proposed a theoretical scheme for obtaining a tunable ultra-narrow cavity linewidth with two interacted dark resonances[29] and this phenomenon has been observed in experiment very recently[30]. At the same time we observed a narrowed cavity linewidth which could keep at 1.2 MHz in a wide frequency range of 100 MHz by the optical pumping-assisted V-type EIT[31].

Although EIT has been observed, a lot of theoretical and experimental works on EIT under the effect of magnetic field have been carried out. Wei *et al.*[32] investigated both in theory and in experiment the EIT phenomenon in ^{87}Rb atoms at 58 °C with a 50 G static magnetic field being parallel or perpendicular to the laser beam direction. Their study result showed that the orientation of magnetic field could play important roles in the EIT effects. Later, Iftiquar *et al.*[33] studied the impact of a small longitudinal magnetic field (0–5 G) on the EIT in Rb atoms at room temperature. They demonstrated that the EIT width could be further reduced by the application of a small longitudinal magnetic field and pointed that the narrow feature implied the dispersion near the resonance was more pronounced.

Inspired by Iftiquar *et al.*[33] work, we feel that if we apply a small longitudinal magnetic field on the intracavity EIT, the EIT linewidth can be reduced and a larger dispersion will be created. Then a substantial narrowing of the cavity linewidth can be expected.

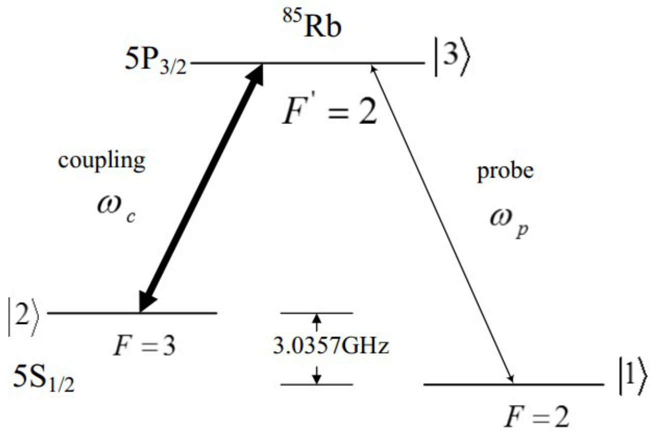

Fig. 1. Energy level configuration of the ^{85}Rb D_2 line for our experiment.

Here, we experimentally demonstrate the above idea by ^{85}Rb atoms at room temperature. The cavity linewidth can be narrowed to about 2 MHz, which is half of the case without the magnetic field. The dependences of the EIT linewidth and the narrowed cavity linewidth on the strength of magnetic field are also studied.

The EIT system used in our experiment is the D_2 line (780 nm) of ^{85}Rb. A strong coupling laser and a weak probe laser are both applied between the ground state $5^2S_{1/2}$ and the excited state $5^2P_{3/2}$, as shown in Fig. 1. A diagram of the experimental setup is shown in Fig. 2. The ^{85}Rb atomic vapor contained in a 10 cm long and 2.5 cm diameter cylindrical Brewster-cut cell is at room temperature. The cell is placed in a solenoidal coil that can produce a magnetic field up to 5 G. Both the coupling and the probe lasers are external cavity diode lasers (ECDLs) (New Focus TLB-6900) with a linewidth of 300 kHz, as well as current and temperature stabilized. Polarizing beam splitter (PBS)2 separates 10% of the coupling beam into another Rb cell for frequency stabilization using saturation absorption spectrum. The remaining beams are brought together by PBS3 and focused at the center of the Brewster-cut Rb cell. Both the cavity mirrors M1 and M2 are concave mirrors with a 550 mm radius of curvature and the transmittance of them is 99.5%. At the same time, mirror M2 is controlled by a piezoelectric driver (PZT). The cavity length L is 550 mm. The coupling and probe beams are orthogonally polarized in the cavity and propagate collinearly. Both of them are focused into the cavity by lenses with focal length of 15 cm. Their respective beam diameters at the center of the Rb vapor cell are about 250 and 150 μm. The coupling beam is rejected by PBS4 before reaching detector D1. The finesse of the cavity is 30 after the Rb cell and PBS3 is inserted.

We remove mirrors M1 and M2 to observe the free-space EIT under the magnetic field. The probe beam frequency is scanned near ω_{31} with a zigzag voltage driver operating with a peak-to-peak value of 450 mV. The frequency of the coupling field is locked to the $F = 3 \to F' = 2$ transition. Then turning on the power to drive the solenoidal coil, we can get a static magnetic field. Figure 3 shows the probe field absorption spectra in ^{85}Rb atom with different strengths of magnetic field. As the magnetic field is 0 G we can observe a typical EIT dip from the line center. When the magnetic field increases from 1 to 3.5 G, multiple EITs begin to appear which are equally separated from the line center. According to Ref. [33] when a magnetic field is used, the degeneracy of all three involved hyperfine levels will be broken so that the ^{85}Rb atom has to be treated as a complicated system with 17 nondegenerate magnetic sublevels. In this case, the coherently driven ^{85}Rb atom can be regarded as the superposition of five independent three-level subsystems, each of which is shifted slightly from the line center. The combined effect of these is to create multiple EIT dips.

Since the central EIT dip is much deeper and narrower than the other EIT dips around it, we will utilize it to narrow the cavity linewidth. Before doing this, it is necessary to make clear how the center EIT linewidth changes with the magnetic field. We measure the center EIT linewidth with the increase in magnetic field, as shown in Fig. 4. In the range of 0–3 G, there is a reduction in the center EIT linewidth. But if the magnetic field continues to increase, the center EIT linewidth will broaden. This phenomenon can be explained using Fig. 5, which is taken from Ref. [33]. As mentioned

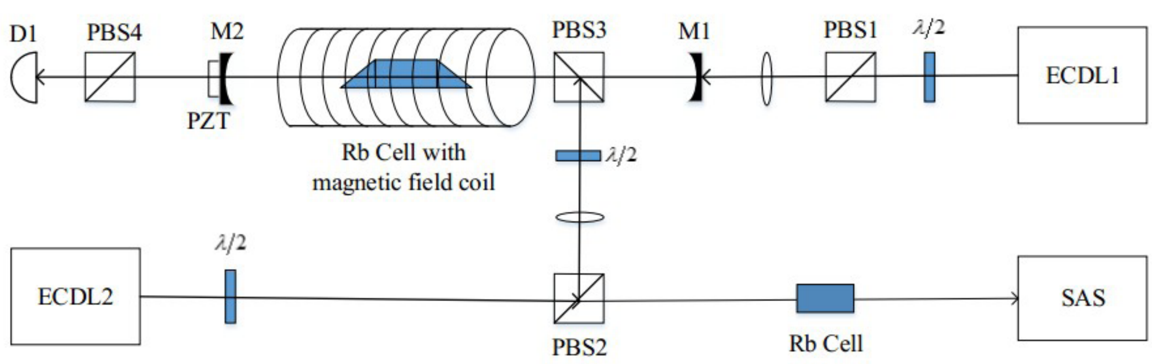

Fig. 2. Experimental setup: D1 and D2, detectors; λ/2, half-wave plate.

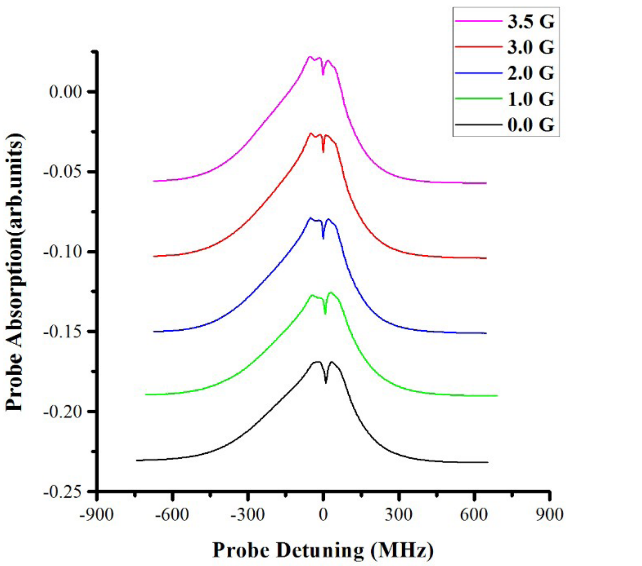

Fig. 3. Probe field absorption spectra in ^{85}Rb with increasing magnetic field.

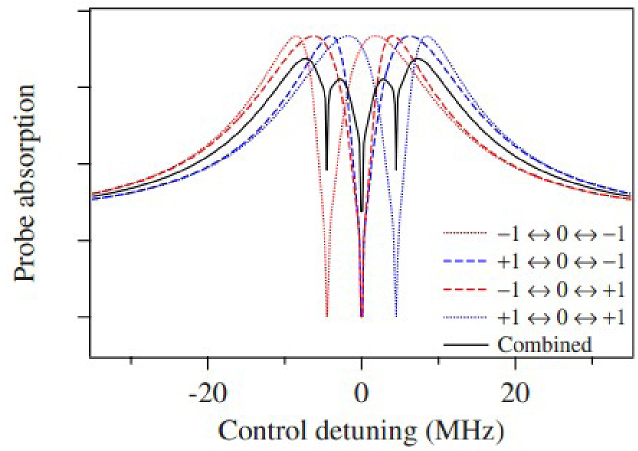

Fig. 5. Different subsystems showing how the shifted EIT fill in the transparency window. Cited from Ref. [31].

above, multiple EIT dips appear when a magnetic field is used. Meanwhile, the transparency region of the EIT will be overlapped in the center EIT, which will have significant influence on the center EIT width. When a very weak magnetic field is applied (<3 G), a part of the transparency region in the center EIT is covered by the absorption region of the adjacent EITs, which reduce the scale of transparency region in the center EIT. As the magnetic field continues to increase (>3 G), the influence of the multiple EIT dips on the EIT width would not be significant. This is why the EIT linewidth reaches a minimum value at 3 G and widen again. In the following, the cavity linewidth narrowing under magnetic field 3 G is studied.

Mirrors M1 and M2 are put back to form the cavity. As the probe field is circulating in the cavity, both co-propagation and counter-propagation of the probe and coupling field exist in the cavity. Then, there will be a Doppler-broadened and a Doppler-free EIT dips with a frequency separation of about 300 MHz. In our experiment, the cavity frequency is adjusted near the Doppler-free EIT dip, therefore, the influence of the Doppler-broadened EIT dip can be ignored. Lock the frequency of the coupling field to the $F = 3 \rightarrow F' = 2$ transition and make the probe field scan near ω_{31}. We adjust the cavity length to match resonant frequency ω_r of the cavity plus medium to resonant frequency ω_{31} of the Rb atoms by changing the driving voltage of the PZT-mounted mirror. When this condition ($\omega_{31} = \omega_r$) is met, the transmission peak is highest and narrowest. Figure 6 shows a comparison of the cavity linewidth under different conditions. Here, the probe and coupling field power is kept at 30 μW and 8.2 mW, respectively. When the magnetic field reaches a value of 3 G, the narrowest cavity linewidth is 2 MHz, which is half as much as the cavity linewidth without magnetic field.

We measure the dependence of the cavity linewidth on the strength of the magnetic field, as shown in Fig. 7. At each point we measure five values and take an average. As the magnetic field increases, the cavity

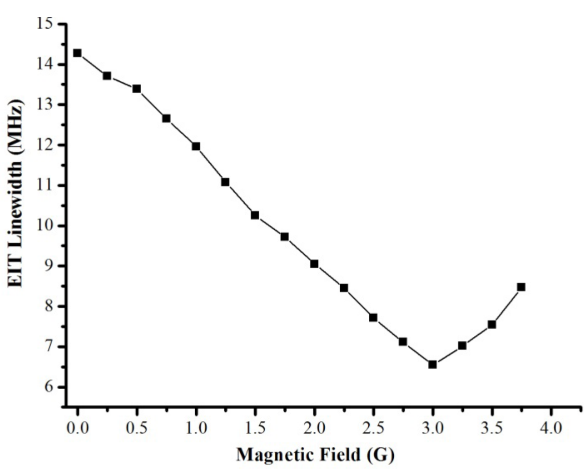

Fig. 4. EIT linewidth versus the strength of magnetic field.

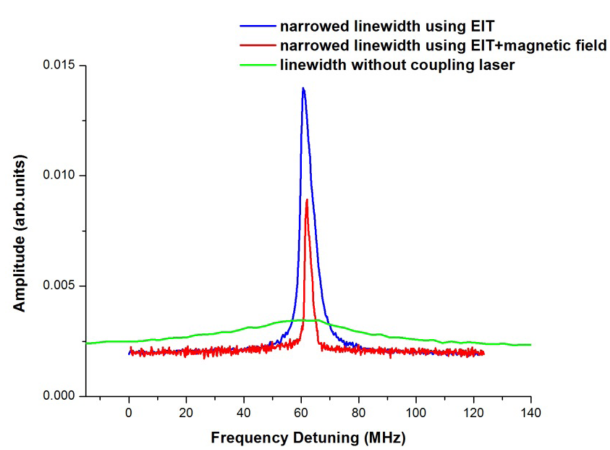

Fig. 6. Cavity output versus probe frequency detuning, showing cavity linewidth narrowing in different conditions.

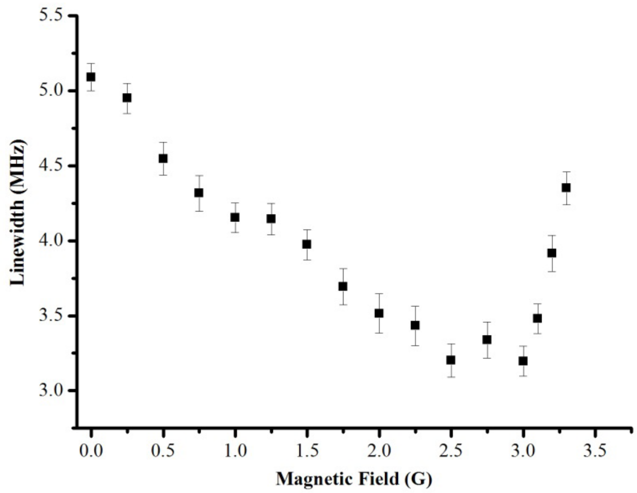

Fig. 7. Cavity linewidth versus the strength of magnetic field.

linewidth narrows until it reaches a minimum at approximately 3 G. When the strength of the magnetic field is increased further, the cavity linewidth broadens again. This curve matches the profile in Fig. 4. It indicates that the EIT linewidth is dominated in this process.

In conclusion, we experimentally demonstrate a further reduction in the cavity linewidth under the EIT condition by the application of a small longitudinal magnetic field. The narrowest cavity linewidth 2 MHz is observed when the static magnetic field reaches 3 G. The cavity linewidth is narrower a half than the case without the magnetic field. Then the cavity linewidth broadens because of the widened EIT linewidth. This technique has potential applications in high-resolution spectroscopy and laser frequency stabilization.

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