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Double EIT and enhanced EIT signal in a combination of Λ- and V-type system of Rb-D_2 transition

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Abstract We report the experimental observations of double EIT and enhanced EIT signal in a combination of Λ- and V-type multi-level system of the D_2 transition of ^{85}Rb atoms interacting with three laser fields. The EIT formation under a Λ-type and V-type systems is also observed separately. It is found that the EIT width in a V-type system becomes narrower than the Λ-type system. Also the effect of frequency detuning of the control laser on the probe absorption profile is studied in presence of Λ- and V-type EIT systems.

1 Introduction

Coherent population trapping (CPT) and electromagnetically induced transparency (EIT) in an atomic media have been studied extensively [1–12] in recent times due to their many potential applications in non-linear and quantum optics. In case of CPT in a three-level Λ-type system driven by two laser fields, the atomic population is accumulated into a coherent superposition of two ground states called a dark state, which is decoupled from the laser fields. As a result, the absorption in the medium by the probe laser field is reduced over a narrow spectral region near two photon resonance for the effect of CPT. EIT also makes an atomic absorbing medium transparent to a weak probe field due to the presence of a strong coupling field and this kind of reduced absorption in a Λ-type system can be explained with the idea of CPT. The formation of EIT in an atomic medium is strongly dependent on the coherence dephasing rate of the atomic state. This dephasing rate for a pure Λ-type system can be assumed as zero ideally; therefore the Λ-type system may produce the best EIT resonance. In a V-type system when two upper levels are coupled to a common lower level with two optical fields, EIT is obtained by the destructive interference of the two absorption pathways from the common lower level. CPT cannot be established in a V-type system due to the spontaneous decays from the upper levels and an ideal V-type system will produce the poorest EIT signal due to the higher rate of coherence dephasing induced by the spontaneous decays of the upper levels [3]. The EIT formation in a V-type system is solely based on the quantum coherence effect in an atomic system in absence of the CPT effect. The observation of an enhanced EIT signal in a V-type system is useful in many applications where the atomic coherence effect is utilized. In an atomic medium, if the Λ- and V-type systems act together in presence of three laser fields, then two EIT windows are formed in the common probe transmission spectrum by the contribution of two individual EIT systems. The separation of two EIT peaks is dependent on the frequency position of the two coupling lasers. More recently, the formation of double EIT window [13–16] is also gaining enough interest for its applications in four-wave and six-wave mixing processes [14], storage of light pulse in two channels [17], quantum switching [18], entanglement generation [19, 20], etc.

In this paper, we report an experimental observation on the formation of double EIT and enhancement of EIT signal in a combination of Λ- and V-type system of the D_2 transition of ^{85}Rb atoms interacting with three laser fields. The effect of frequency detuning of the control laser on the probe transmission profile is also studied in presence of Λ- and V-type EIT systems. To the best of our knowledge, such

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an experiment consisting of both Λ- and V-type system in the D_2 hyperfine transition of ^{85}Rb atoms and considering all possible allowed transitions, which produces the double EIT and enhanced EIT signal due to the overlapping of two EIT, has not been reported earlier. The formation of EIT in a Λ-type and V-type system is also represented here considering all possible hyperfine levels. In our experiment, we observe a very narrow EIT signal in a V-type system where the EIT formation is mainly caused by the quantum coherence effect between two transition pathways.

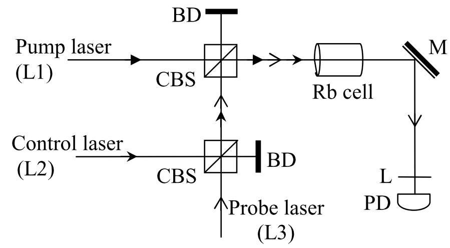

Fig. 1 Schematic diagram of the experimental setup, *CBS*: cubic beam splitter, *M*: mirror, *L*: convex lens, *PD*: photo detector, *BD*: beam dump

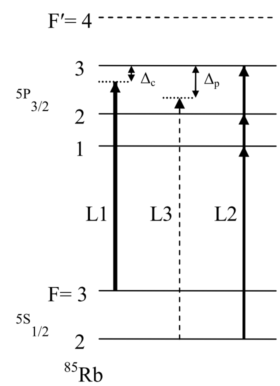

Fig. 2 Energy level scheme for the combination of Λ- and V-type system of ^{85}Rb-D_2 transition. L1 and L3 form the Λ-type system, whereas L2 and L3 form the V-type system. Δ_c and Δ_p are the pump and probe laser detuning, respectively

2 Experiment

The schematic of the experimental setup is shown in Fig. 1. Three external cavity diode lasers (ECDLs) operating at ∼780 nm have been used to generate the pump (Toptica, DL 100), control (TEC 100, Sacher Lasertechnik) and probe (New Focus-6312) fields. Both the pump (L1) and probe (L3) lasers have the same elliptical beam shape with size ∼3 mm × 2 mm and the control (L2) laser has nearly circular beam shape with size ∼2 mm × 2 mm. All three laser beams are linearly polarized. A rubidium vapor cell of length 5 cm and diameter 2.5 cm is used to observe the EIT resonance signals and an identical cell is used for frequency locking purpose. Each of the cells is sealed at a pressure of 10^{-6} Torr at room temperature and contains both isotopes of Rb in their natural abundances: ^{85}Rb (72%) and ^{87}Rb (28%). The laser beams are adjusted to overlap by using a cubic beam splitter (CBS) and co-propagate through the experimental cell. The transmitted probe laser beam is fed to the photo detector (New Focus-2307) and the photo diode output is recorded by a digital storage oscilloscope of 200 MHz bandwidth (Yokogawa, Japan).

Figure 2 shows the energy level diagram and three laser coupling schemes for the Λ-type, V-type and the combination of Λ- and V-type i.e. the (Λ+V) configuration. In the absence of L2 laser, the L1 and L3 lasers are making the Λ-type system where the common level is one of the upper hyperfine level ($F' = 2$ or 3). On the other hand, L2 and L3 lasers (in absence of L1 laser) form the V-type system with a common ground level ($F = 2$) and two excited levels $F' = 1$ and 2. The L3 laser is a common probe field in presence of both L1 and L2 lasers. The L1 laser is frequency locked and its frequency position is kept fixed throughout the whole experiment. The control laser (L2) is frequency detuned over the probe Doppler spectrum of $F = 2 \to F' = 1, 2, 3$ transitions. The effect of frequency locked pump laser and frequency detuned control laser on the probe transmission is obtained when the probe laser scans the transitions $F = 2 \to F' = 1, 2, 3$. The intensities of pump, control and probe lasers through the Rb vapor cell are 60 mW/cm^2, 26 mW/cm^2 and 10 mW/cm^2, respectively. The intensities are measured by an optical power meter (Thorlabs, PM100A). All intensity values are kept unchanged throughout the experiment.

3 Results and discussion

3.1 Λ-type system

The Λ-type system is formed with two ground levels ($^5S_{1/2}$, $F = 2, 3$) and three closely spaced excited levels ($^5P_{3/2}$, $F' = 1, 2, 3$) of ^{85}Rb-D_2 transition (Fig. 3). Since the probe laser (from $F = 2$ level) cannot couple with the $F' = 4$ level, this is a five-level system. To observe the EIT signal, we have used the L1 and L3 laser as a pump and probe field, respectively (L2 laser is turned off). The pump laser is frequency locked at the transition $^5S_{1/2}, F = 3 \to {}^5P_{3/2}, F' = 3$ with a small red detuning Δ_c ($\Delta_c = \omega_{33} - \omega_c$), where ω_c is the laser frequency, ω_{33} is the transition frequency between $F = 3 \to F' = 3$. The probe laser is scanned across all possible transitions $F = 2 \to F' = 1, 2, 3$. Now for a Λ-type system, the EIT resonance occurs at the Raman resonance condition of pump-probe fields. In our experiment, the EIT signal is observed with a narrow peak at the center of the probe's Doppler transmission profile when the detuning of the probe laser (Δ_p) reaches $\Delta_c = \Delta_p$. Figure 3 shows the EIT signal along with the velocity-selective optical pumping (VSOP) dips [9–12], which are marked by vertical arrows. The observed EIT signal sits on one of the VSOP dips. The VSOP dips are formed due to the optical pumping of

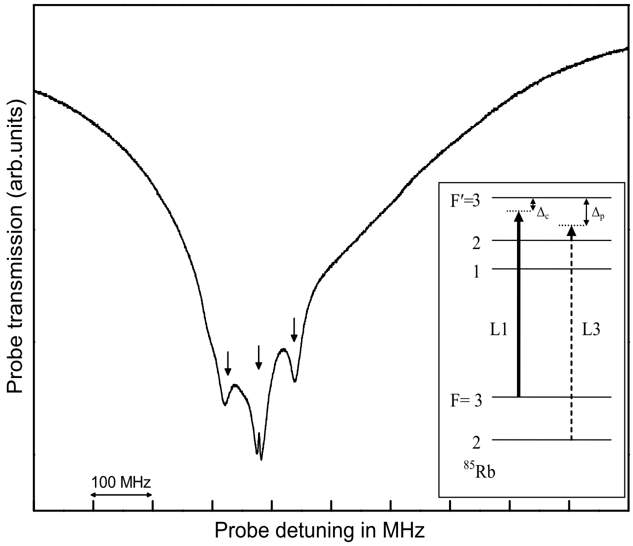

Fig. 3 Observed probe transmission versus probe detuning in a Λ-type system of ^{85}Rb-D$_2$ transition. The corresponding *level scheme* is shown on the *right side*. EIT signal is observed with VSOP dips. Intensities of pump and probe lasers are 60 mW/cm^2 and 10 mW/cm^2, respectively

non-zero velocity group of atoms to the lower level of probe transmission profile via all possible excited levels. The measured EIT width (FWHM) is 3.85 ± 0.40 MHz. Theoretical simulation of this type of single EIT in a five-level system was carried out in Refs. [10–12], where we had set up the density matrix for a five-level system in the rotating wave approximation (RWA), which is obtained from Liouville's equation:

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[(H_0 + H_I), \rho] + \xi \rho$$

where ρ is the density matrix operator, H_0 is the unperturbed Hamiltonian of the system and H_I is the perturbation or atom-field Hamiltonian, ξ is the decay or relaxation matrix. The first term of the right hand side corresponds to the coherent interaction of atom-laser fields and the second term represents relaxation and all other dephasings.

3.2 V-type system

We consider a V-type system with a common ground level $F = 2$ and two excited levels $F' = 1$ and 2 interacting with the laser fields L2 and L3. In case of V-type system, the strong control laser (L2) can cause non-resonant excitations to all the possible upper levels $F' = 1, 2, 3$ from the lower level $F = 2$ and it works as a four-level system. These excitations will cause population holes for the three velocity groups v_1, v_2 and v_3 in the lower level population distribution curve. So the probe laser transmission will show peaks at the corresponding frequencies when it is scanned from $F = 2 \rightarrow F' = 1, 2, 3$. These peaks are called velocity-selective resonances (VSR) and they are solely based on saturating effect of the control laser. These VSR peaks may be very strong, depending on the power of the control laser. On the other hand the formation of EIT in a V-type system is purely based on the coherence effect in the atomic system interacting with the laser fields and it is perturbed by higher rate of coherence dephasing of the upper levels. As a result, the EIT in a V-type configuration of pump and probe fields is difficult to isolate from the VSR peaks. Except a few works [14, 21], most of the works on EIT in V-type system were done on three- or four-level configuration where the common ground level is one of the $^5S_{1/2}$ state and the other upper levels are taken from $^5P_{1/2}$ (D$_1$ transition) and $^5P_{3/2}$ (D$_2$ transition) [3, 22, 23]. But here we consider the D$_2$ transition of ^{85}Rb ($^5S_{1/2} \rightarrow {}^5P_{3/2}$) only and we have taken all possible transitions of the excited levels of $^5P_{3/2}$ ($F' = 1, 2, 3$) from the ground state $^5S_{1/2}$ ($F = 2$). We use the L2 laser as a control field and L3 laser as a probe field (L1 laser is turned off). When the L2 laser is set at a frequency detuned position in the Doppler profile of $F = 2 \rightarrow F' = 1, 2, 3$ transitions and the probe laser frequency is scanned over the Doppler spectrum of $F = 2 \rightarrow F' = 1, 2, 3$ transitions, we observe the VSR peaks (marked by vertical arrows in Fig. 4). In addition to these VSR peaks, we have been able to record a sharp and narrow EIT transmission peak on the probe Doppler spectrum for the highlighted portion shown in inset of Fig. 4. We obtain the narrow EIT peak when the transition $F = 2 \rightarrow F' = 1$ is coupled by the control laser and the probe laser connects the transition $F = 2 \rightarrow F' = 2$. Among the three excited levels ($F' = 1, 2, 3$), the depopulation of atoms from the $F' = 1$ level to the ground level $F = 3$ is not possible as per selection rule ($\Delta F = 0, \pm 1$) and therefore the transition $F = 2 \rightarrow F' = 1$ is not influenced by the saturating effect of the control laser. As a result, the EIT peak corresponding to the transition ($F = 2 \rightarrow F' = 1$) is resolved from the VSR peaks on the probe Doppler spectrum. It is found that the VSR peaks are broadened due to the saturation of atoms in the excited states by both the laser fields. In a three-level V-type system, the theoretical modeling and the details of EIT formation were carried out by Fulton et al. in Ref. [3]. The theoretical simulation of our experimental results also can be carried out using the standard density matrix analysis taking into account the four hyperfine levels (one common ground level and three upper levels). In our experiment, the observed EIT peak is very narrow due to formation of EIT mainly caused by the atomic coherence phenomena. The measured EIT width (FWHM) is 1.12 ± 0.11 MHz, which is much narrower than the natural line-width (~6 MHz) as well as Λ-type EIT line-width (3.85 ± 0.40 MHz).

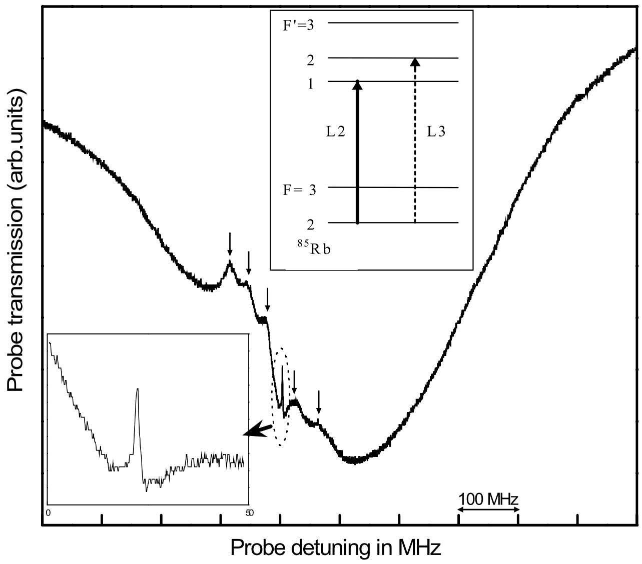

Fig. 4 Probe transmission versus probe detuning spectrum in a V-type system of ^{85}Rb-D$_2$ transition. The corresponding *level scheme* is shown *above*. VSR peaks are marked by *vertical arrows* and the highlighted narrow peak shown in the *inset* is the EIT signal. Control and probe laser intensities are 26 mW/cm^2 and 10 mW/cm^2, respectively

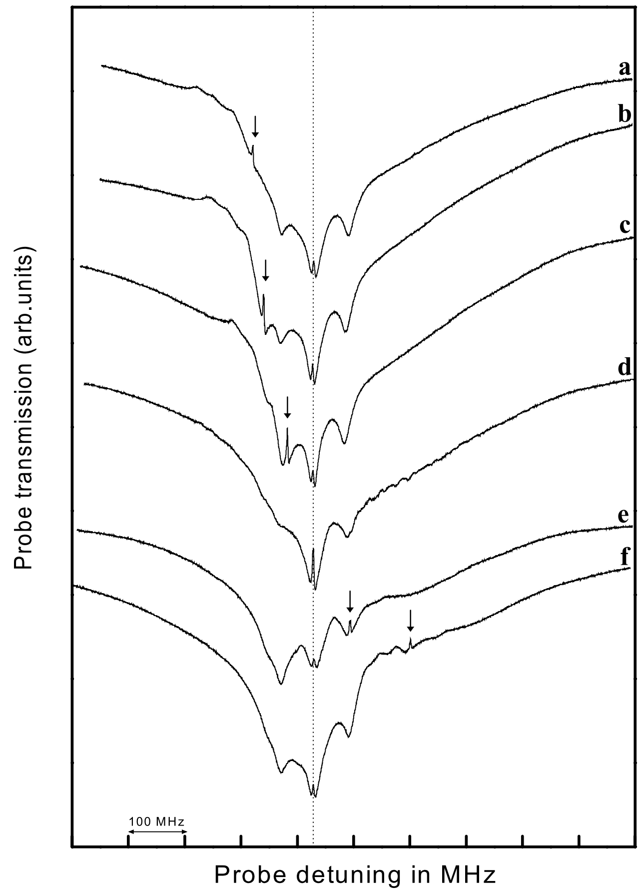

Fig. 5 Observed probe transmission spectra versus the probe detuning when the control laser (L2) frequency is tuned over the probe Doppler profile in presence of Λ- and V-type EIT systems. (**a**)–(**f**) represent the shift of the V-type EIT signal due to frequency tuning of control laser over the probe Doppler profile. (**d**) is the enhanced EIT signal when the two EIT peaks are merged together. The intensities of the pump, control and probe lasers are 60 mW/cm^2, 26 mW/cm^2 and 10 mW/cm^2, respectively

3.3 (Λ+V)-type system

In this section, we observe the probe transmission spectra when both the Λ-type system (formed by L1 and L3 laser) and V-type system (formed by L2 and L3 laser) act together. The L1 laser is used as a pump with frequency ω_c and it is frequency locked to the transition $F = 3 \rightarrow F' = 3$ with a small red detuning Δ_c. The L2 laser is used to generate the control field and it is frequency detuned over the probe Doppler spectrum for the allowed transitions ($F = 2 \rightarrow F' = 1, 2, 3$). When the probe laser scans $F = 2 \rightarrow F' = 1, 2, 3$ transitions in presence of both the L1 and L2 lasers, we observe two EIT peaks along with the broadened VSR peaks formed by the V-type system and VSOP dips formed by the Λ-type system. Figure 5 represents the observed probe transmission spectra at a fixed locked frequency of L1 and with the frequency detuning of L2 over the Doppler-broadened probe spectrum. When the pump laser is locked and the probe laser is scanned, we get the EIT resonance in a Λ-type system only when the probe frequency satisfies the Raman resonance condition with the pump frequency, i.e. $\Delta_c = \Delta_p$. The dotted vertical line in Fig. 5 shows the EIT in a Λ-type system when $\Delta_c = \Delta_p$.

The EIT in a V-type system is also shown in Fig. 5 by a solid vertical arrow and it is found that the EIT peak moves over the probe spectrum with the detuning of the control laser. The control laser frequency is red detuned in Figs. 5a, b, c and it is observed that at the far red detuned position of L2 laser, the EIT peak is weak. The strength of the peak gradually increases as L2 is tuned close to the center of the probe transmission profile. Figure 5d represents the formation of enhanced EIT resonance when L2 is tuned at the center. At this position, the two EIT signals corresponding to Λ- and V-type systems are merged together and only one enhanced EIT signal is obtained. We observe that the individual Λ- and V-type EIT signals are not much stronger in height, but due to the overlapping of these two EIT signals the resultant signal shows a significant enhancement in height. It may be due to the fact that the coherency of the combined system is enhanced significantly by the three laser fields. We also see in Fig. 5d that both of VSOP dips and VSR peaks are reduced in magnitude due to their coexistence in same probe frequency range.

Figure 5e and 5f are the EIT spectra where the frequency of L2 laser is blue detuned from the center of the probe Doppler profile and the EIT peak is relatively weak in this case. It is seen that the EIT can be moved over the entire probe Doppler spectrum with the shift of the control laser

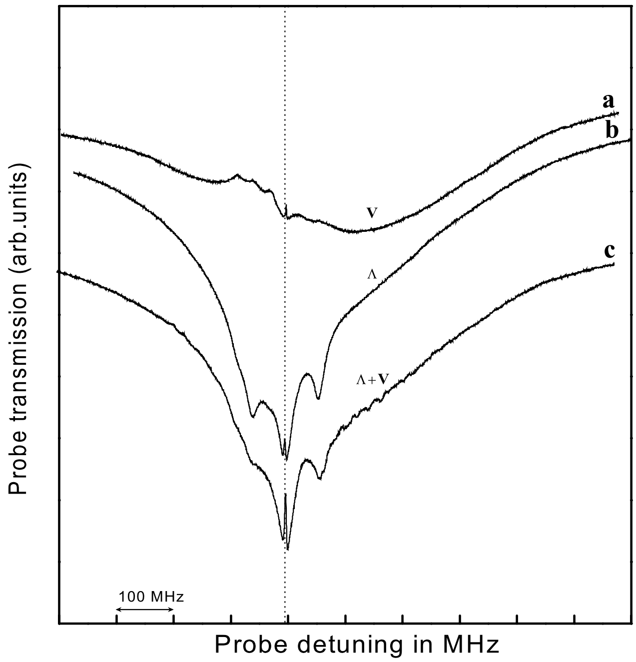

Fig. 6 Effect on EIT signal due to the combination of Λ- and V-type system of ^{85}Rb-D$_2$ transition in presence of L1, L2 and L3 lasers. (**a**) and (**b**) represent the probe transmission due to pure V-type system and pure Λ-type system, respectively. (**c**) represents the enhanced EIT signal

frequency, but its strength first increases gradually when L2 is tuned from the far red detuned position to the center and then the strength decreases when L2 is tuned from the center to the blue side. When the control laser (L2) is tuned to the blue side, it goes far away from the $F = 2 \to F' = 1$ transition, which is responsible for the EIT formation in the V-type system. As a result a very small number of off-resonance atoms contribute to form the EIT, and the EIT becomes very weak.

Theoretically, the total interaction Hamiltonian of the above (Λ+V)-type system, which is formed by the pump (L1), control (L2) and a common probe (L3) lasers can be written as $H_\mathrm{I} = H_\mathrm{IV} + H_{\mathrm{I}\Lambda}$, where H_IV is due to the four-level pure V-type system formed by the L2 and L3 lasers and $H_{\mathrm{I}\Lambda}$ is due to the five-level pure Λ-type system formed by the L1 and L3 lasers. Using this total interaction Hamiltonian in the Liouville equation under RWA, one can get the theoretical probe transmission profile containing double EIT along with VSR peaks and VSOP dips. The position shifting of the V-type EIT peak (marked by vertical arrows in Fig. 5) can also be obtained by the variation of different frequency detuning of the control laser (L2). A similar type of theoretical simulation of double EIT along with VSOP dips and VSR peaks was done in detail in Refs. [13, 14], which had a good agreement with the experimental results.

Figure 6 shows the resultant EIT resonance due to the effect of combination of Λ-type EIT (Fig. 6b) and V-type EIT (Fig. 6a). It is found that the EIT signal strengths in both Fig. 6a and 6b are small compared to the combined EIT signal (Fig. 6c). So the combination of two EIT signals produces a much-enhanced EIT signal. Here the height of the enhanced EIT signal is five times higher than the pure V-type EIT signal and around three times higher than the pure Λ-type EIT signal. The measured EIT widths of Fig. 6a and 6b are 1.12 ± 0.11 MHz and 3.85 ± 0.40 MHz, respectively. Also the EIT width of the enhanced EIT signal is 3.80 ± 0.26 MHz, which is nearly equal to the EIT width in Λ-type system. It shows that the overlapping of two individual EIT signals does not give any extra broadening in the measured EIT line-width. This type of enhanced EIT signal may be very useful to store the light pulse and also to reduce the velocity of light. It is well known that the height of the EIT signal can be increased by increasing the pump/control laser intensity, but at the same time the width of the EIT signal also increases linearly with the pump/control laser intensity. This is a disadvantage in the applications where a narrow and enhanced signal is required. The enhancement of EIT peak height due to the combination of two systems may be useful since this gives only the enhancement of height keeping the EIT width unchanged. It is to be noted that the use of buffer gas in a pure atomic vapor cell can increase the coherent interaction time between atoms and laser fields without destroying the ground state coherence. As a result, the EIT width becomes narrower and the EIT height is also increased [24–26]. So the Rb vapor cell with buffer gas (such as He, Ne, Ar, N_2, etc.) can be used for further improvement of the EIT peak height and narrowing of width in addition to the above advantage of three lasers application in a (Λ+V)-type system.

4 Conclusions

We have experimentally observed the double EIT and enhanced EIT signal in a combination of Λ- and V-type system of the D$_2$ transition of ^{85}Rb. The EIT resonances in Λ- and V-type systems are also observed separately. In a Λ-type system, the EIT signal is produced along with VSOP dips. For the V-type system, the narrow EIT peak is obtained along with the broadened VSR peaks. In a (Λ+V)-type system which is formed by the three laser fields acting simultaneously, we obtain two EIT peaks along with both the VSR peaks and VSOP dips. The frequency detuning of the control laser field shifts the position of the V-type EIT peak along the Doppler-broadened probe transmission profile. It is also observed that the frequency detuning of the control laser over the probe Doppler spectrum produces a different strength of V-type EIT at different position of the probe frequency scale. The EIT peak height of the V-type system is more pronounced when it is close to the Doppler line center and when it goes to the wings of the Doppler profile, the strength of the EIT peak is decreased. It may be due to the fact that at far detuning position of the control laser from the possible transition region ($F = 2 \rightarrow F' = 1, 2, 3$), a small number of atoms are available to form the EIT signal under off-resonant condition. When the control laser is tuned near resonance, maximum numbers of atoms participate in the EIT formation and the corresponding EIT is more enhanced than the off-resonant condition. The Λ-type EIT is formed in a fixed frequency position of the probe profile and the V-type EIT is shifted around the same probe transmission profile. When the V-type EIT signal merges with the Λ-type EIT signal, a significant enhancement of EIT peak height is observed without any broadening of EIT line-width. In the coherent spectroscopic measurement, the saturating effect induced by the pump and control lasers in the probe transmission profile may complicate the coherent measurement process. In a (Λ+V)-type configuration we can minimize the saturating effects by suitable choices of the pump and control laser frequencies. This type of observation of double EIT and enhanced EIT signal would be useful in applications of slow light propagation, logic gate for an optical quantum computer, four-wave and six-wave mixing processes.

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