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Comparison of Electromagnetically Induced Transparency (EIT) Spectra for Six-level Lambda (Λ) and Five-level V-type Systems

Research Article

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Abstract. *Electromagnetically induced transparency* (EIT) is experimentally studied in a rubidium vapour cell (without buffer gas, both ^{87}Rb and ^{85}Rb present according to their natural abundance) kept within two-layers of mu(μ)-metal shields to avoid the effect of Earth's magnetic field on the energy levels of atomic rubidium. An external cavity diode laser (ECDL), used as a low power probe laser, is locked to the hyperfine cross-over peak of $F = 2 \to F' = 2,3$ transitions of ^{87}Rb. The frequency of another ECDL, the pump laser, is set to scan the $F = 1 \to F' = 0,1,2$ transitions of ^{87}Rb. These form the Λ-type six level system. In the V-type system, both the pump and the probe lasers share the same $F = 2$ ground level. The probe beam coming out of the cell is detected by a low noise fast photodetector. The resulting spectra show signature of EIT in the "peak" for the Λ-type system and in the "dip" for the V-type system. Numerical calculation based simulated spectra are also compared with the experimental spectra. In both the cases very narrow EIT linewidth ($\Gamma_t < \Gamma$) is observed even at high value of pump Rabi-frequency ($\Omega_c \gg \Gamma$). Narrower value of EIT linewidth is due to Doppler averaging phenomena.

Keywords. Electromagnetically Induced Transparency (EIT); Coherent control; Sub-natural linewidth

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1. Introduction

Coherent effects generated due to interaction of atomic levels with laser radiation has drawn tremendous attention in the recent years. *Coherent population trapping* (CPT) [1], *Electromagnetically induced transparency* (EIT) [2,3], *Lasing without inversion* (LWI) [4] etc., occur due to coherent interaction of atoms and laser fields. EIT transforms an initially absorbing medium into a transparent medium for a weak field (commonly known as a probe or signal beam) in the presence of a much stronger coupling field (known as a pump or control beam) which shares a common level with the probe field but is connected to some other upper or lower hyperfine level of the atomic system. A *three-level system* (TLS), such as Λ-type, V-type and Λ-type is the simplest level scheme for studying this effect. Many interesting studies have been carried out using EIT in applications such as slow light generation, light storage in hot or cold atomic system, optical switching, quantum information processing, magnetometery and atomic clock etc. The study of EIT is not only limited to three-level systems a lot of work has been done on four-level and five-level [5,6] systems also. The results obtained from the multi-level atomic system shows new features in the experimental spectra due to the presence of optical pumping.

In a three-level system, the medium becomes transparent only at the center frequency of the probe transition, and no extra dip can be generated. But in case of multi-level systems, due to the presence of extra upper levels with spacing smaller than the Doppler width of the transition, extra velocity-selective dips or satellite dips are also expected along with the EIT peak [6]. The separations between the satellite dips are exactly equal to the upper level hyperfine spacing. The optical pumping process can affect all multi-level pump-probe experiments. It can modify the results of saturation spectroscopy [7], as well as EIT and also the laser cooling process [8]. In this paper we present our experimental measurements on ^{87}Rb atoms for both Λ-type six-level and V-type five level systems. We also present a density-matrix based theoretical formulation for Λ-type six-level system and compare our experimental results with our theoretical simulation. In Figure 1(a) and 1(b) we present Λ-type six-level and V-type five level systems. They have two ground levels $F = 1$ and 2 (for ^{87}Rb) and four closely spaced upper levels $F' = 0,1,2,3$.

The density matrix equations are solved numerically under the steady state condition and Doppler shifts are taken into account in the lineshape calculation. The simulated spectra agree fairly well with the experimental spectra.

2. Experimental

We used two independent external cavity diode lasers from Toptica Photonics operating at 780 nm with no phase matching. Their linewidths are about 1 MHz. One laser acts as pump and the other one as probe. The probe laser is locked to the crossover peak of the $F = 2 \to F' = 2,3$ transitions by standard saturation absorption spectroscopy and pump laser scans the $F = 1 \to F' = 0,1,2$ transitions of ^{87}Rb. The error signal generated by a proportional amplifier + integrator based servolock circuit is fed to the Piezoelectric transducer (PZT) that moves the grating element of the ECDL1 (*probe laser*) as shown in Figure 2. Diameters of both the pump and probe beams are about 2 mm and have opposite linear polarizations with respect to each other. They are sent through the Rb-cell in a co-propagating manner using a *polarizing*

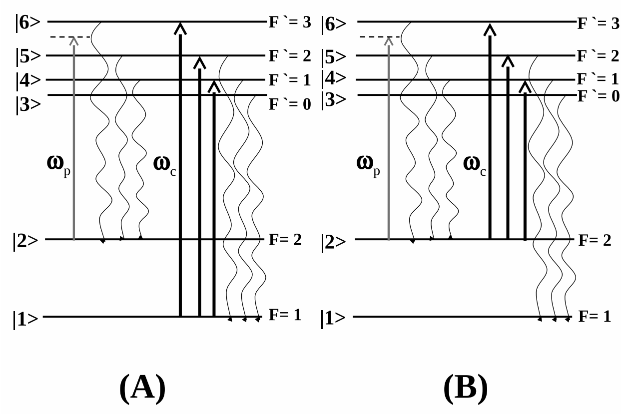

Figure 1. (Colour online) A) Energy level diagram of a Λ-type six-level atomic system interacting with two radiation fields. B) Energy level diagram of a five level V-type atomic system. The bold solid (black colored) line indicates the pump beam scanning and weak (red colored) line indicates the probe beam fixed. The corresponding hyperfine levels are for ^{87}Rb.

cube beam splitter (PBS). The intensity of the pump beam is controlled by a variable neutral density filter. After coming out of the cell, the pump and probe beams are separated by another PBS. Probe beam is detected by a fast photo detector (New Focus) and the resulting signal is recorded by a digital storage oscilloscope. In the V-type system, pump and probe lasers act from the same ground level $F = 2$ of ^{87}Rb atoms, probe laser is locked to the cross-over peak of $F' = 2,3$ and pump laser frequency is scanned through $F = 2 \rightarrow F' = 1,2,3$ hyperfine transitions. All the experiments are done in the Laser Spectroscopy Laboratory of Saha Institute of Nuclear Physics, Kolkata.

2.1 Experimental Results

Figure 3 and Figure 4 show the measured probe absorption signals vs pump detuning for Λ and V-type systems for ^{87}Rb atoms. Five velocity selective absorption dips are observed in the Λ-type system and five velocity selective peaks are observed in the V-type system. We clearly observed signature of EIT in the Λ-type system on a velocity selective absorption dip as a “peak”. Whereas an absorption dip in the V-type system on the background of a “peak”. EIT signal has appeared in the 2nd dip (b in Figure 3) for Λ-type system and field induced dip occurred in the 2nd peak (b in Figure 4) in V-type system. With increase in the pump beam power, EIT signal as well as the field induced dip are enhanced. We fitted the EIT linewidth of ^{87}Rb atoms with the Lorentzian profile $\left(\frac{\frac{\Gamma_t}{2}}{(\frac{\Gamma_t}{2})^2+\delta v^2}\right)$ where Γ_t is the *full width at half maximum* (FWHM) of the Lorentzian profile and δv is the detuning parameter. Our measured EIT width is much less than the natural linewidth (Γ = 6 MHz) of the Rb-D_2 transitions. Similar is the case with the field induced dip. Observation of this narrow or sub-natural EIT linewidth is due to thermal averaging [9, 10]. This is confirmed in the simulated spectra in the next section. It is observed that the EIT linewidth remains sub-natural ($\Gamma_t < \Gamma$) even at higher pump power.

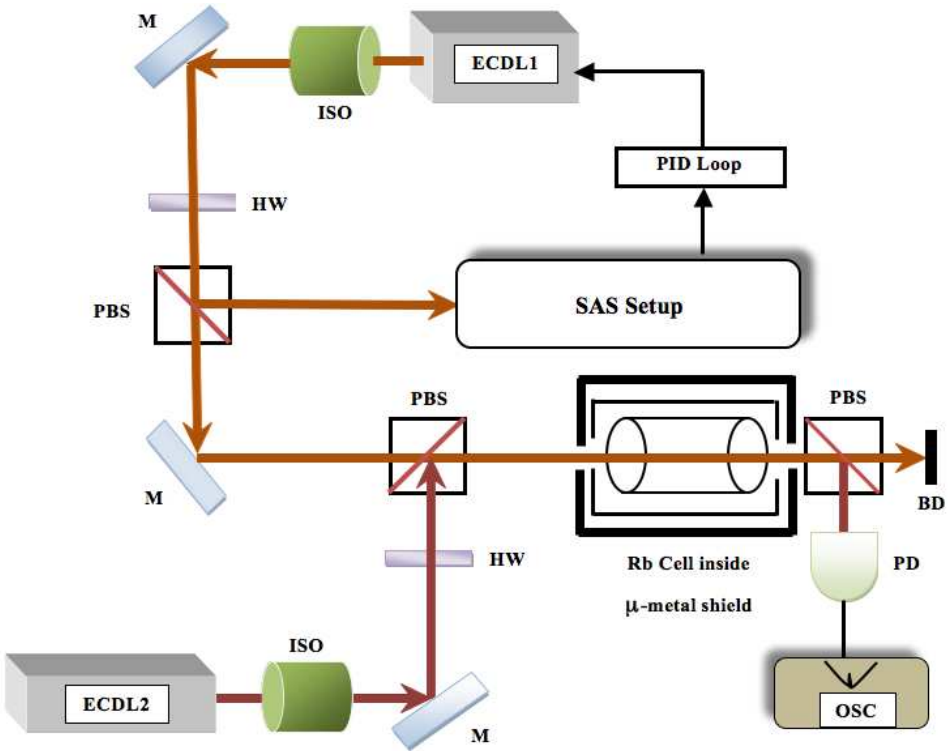

Figure 2. (Colour online) Schematic drawing of the experimental setup. ECDL: external cavity diode laser, ISO: optical isolator, M: Mirror, HW: half wave plate, PBS: polarizing beam splitter, PD: photo-detector, BD: beam dump, OSC: digital storage oscilloscope, SAS setup: saturation absorption spectroscopy setup.

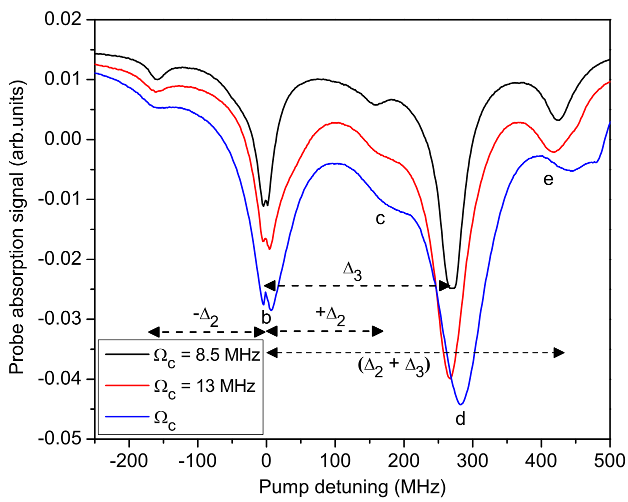

Figure 3. (Colour online) Measured probe absorption signal vs. pump detuning spectra with variation of pump beam power for *Lambda*-type six level system. Probe Rabi-frequency (Ω_p) is 1 MHz and values of pump Rabi-frequencies (Ω_c) are shown in the figure.

2.2 Numerical Simulation of Line-Shape

The time evolution of the atomic density matrix of an atom moving with a velocity v (along the z-direction) can be derived from the Liouville equation (popularly known as the master-equation)

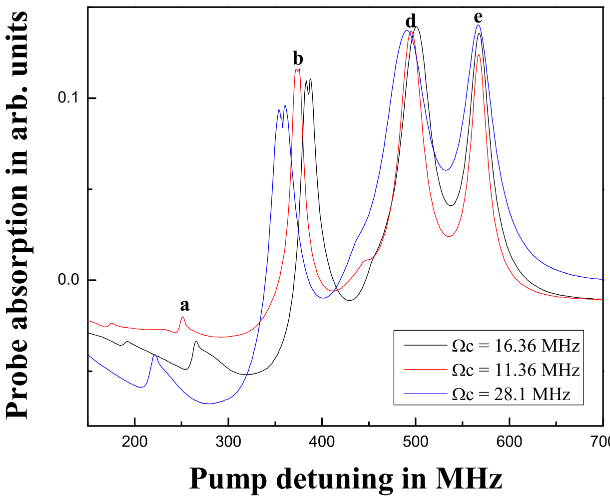

Figure 4. (Colour online) Measured probe absorption signal vs. pump detuning spectra with variation of pump beam power for V-type five level system. Probe Rabi-frequency (Ω_p) is 1 MHz and values of pump Rabi-frequencies (Ω_c) are shown in the figure.

by including the decay terms phenomenologically;

$$\frac{\partial\rho}{\partial t} = -\frac{\mathrm{i}}{\hbar}[H,\rho] + \Lambda_{relax}\rho \tag{2.1}$$

Here Λ_{relax} is the relaxation operator and ρ is the density matrix operator. In a six-level atomic system the density matrix equations of motion for an atom, interacting with two co-propagating laser radiations, may be obtained from the Liouville equation under the *rotating wave approximations* (RWA) [11, 12]. To study the probe absorption line shape theoretically we have used six-level and five-level (Figure 1(a) and Figure 1(b)) atomic system interacting with two laser fields. By using the Master equation (Eqn.1) we can derive detail density matrix equations of motion of an atom interacting two co-propagating laser-radiation [6]. By solving the set of Optical Bloch equations numerically in steady state we will get the probe absorption signal. The probe absorption coefficient(α) of the medium at the frequency ω_p is proportional to the imaginary part of ρ_{2j} ($j = 4,5,6$) for six level λ-type system, so we may write them as:

$$\alpha = \frac{4\pi\omega_p}{c}\sum_{j=4}^{6}\mathrm{Im}(\rho_{2j}) \tag{2.2}$$

To calculate the probe absorption in a Doppler broadened background we have to integrate the probe absorption over the whole velocity range. If we assume that atoms have a Maxwell velocity distribution then the distribution function can be written as,

$$f(v)dv = (u\sqrt{\pi})^{-1}\exp(-\mathrm{v}^2/\mathrm{u}^2)dv \tag{2.3}$$

where u is the most probable velocity of the atoms at a temperature 'T' K. The total probe absorption signal in a Doppler broadened background can be written as:

$$\alpha_d = \int_{-\infty}^{\infty} \alpha \mathrm{W(v)} dv. \tag{2.4}$$

In Figure 5 we show the plot of probe absorption signal (Eqn. 4) versus pump detuning for different values of pump power by keeping the probe frequency fixed at $(\omega_{25} + \frac{\Delta_3}{2})$. We define our pump and probe Rabi frequencies as $\Omega_c = \Omega_{13} = \Omega_{14} = \Omega_{15}$ and $\Omega_p = \Omega_{24} = \Omega_{25} = \Omega_{26}$. The probe Rabi frequency is kept fixed at 1 MHz and the pump Rabi-frequency is assigned three different values of 8.5, 13 and 19 MHz. All five velocity selective dips along with EIT signal appear in the simulated spectra which reproduces our experimentally observed spectra (Figure 3) of ^{87}Rb.

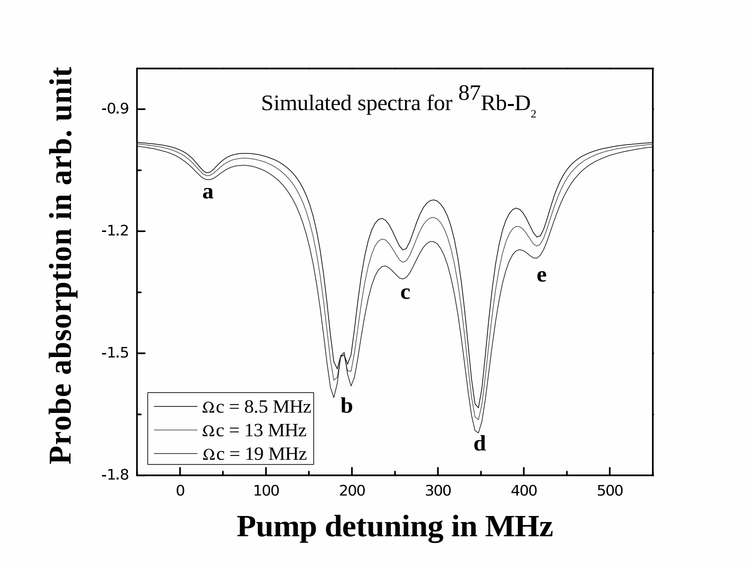

Figure 5. (Colour online) Simulated probe absorption signal (α_d) vs. pump detuning curve for Λ-type six level system with ^{87}Rb atom. Probe laser frequency is $\omega_p = (\omega_{25} + \frac{\Delta_3}{2})$ MHz. In the simulation we have used probe Rabi-frequency(Ω_p) as 1 MHz. The values of the pump Rabi frequency have been mentioned in the figure.

3. Conclusion

We have measured EIT and field induced absorption spectra of ^{87}Rb atoms at room temperature for Λ-type six and V-type five level systems respectively and compared them. Λ-type system shows EIT peaks whereas V-type system shows field induced absorption dips. We also measured the pump power dependence of the EIT signal. We have developed a theoretical model based on density matrix formulation to simulate the experimental results theoretically as shown in Figure 5 for Λ-type six-level system.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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