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Formation of field induced absorption in the probe response signal of a four-level 'V' type atomic system: a theoretical study

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Abstract – A density matrix based analytical model is developed to study the coherent probe field propagation through a four-level 'V' type system in presence of a coherent control field. The four-level system comprises of two ground levels and two upper levels. The model allows coupling of the probe field from the upper ground level to both of the excited levels whereas the control field is kept locked from the upper ground level to one of the excited levels. The addition of an extra ground level to a conventional three-level 'V' type system creates extra decay paths to the ground levels from the upper levels. A set of sixteen density matrix based equations are formed and then solved analytically under rotating wave approximation to study the probe response under steady state condition. Under Doppler free condition the simulated probe absorption shows EIT but under thermal averaging the EIT window displays signature of absorption at its middle. The absorption dip exhibits shift as well as broadening with variation in the control Rabi frequency. This is termed as field induced absorption.

Keywords: Four-level; V-type system; Density matrix; EIT; Field induced absorption;

I.

INTRODUCTION

Electromagnetically induced transparency (EIT) [1-5], a prime example of quantum interference effect, has been the centre of attraction to a large section of researchers who are engaged in the field of quantum optics. When the frequency difference between the control and the probe beams is set equal to the separation between the ground states of multi-level system, EIT occurs [2] and an otherwise absorptive medium becomes transparent to a low power coherent probe beam in presence of a coherent high-power control beam due to the formation of 'dark state'. The reason behind the interest of the researchers with EIT is the potential application of EIT in developing future optical devices that are supposed to be used in optical logic gates, all optical switches [6, 7], optical delay generators [8]etc. In addition to this, pure academic interest is also driving researchers to investigate this effect using various level schemes like inverted-Y [9, 10], cascade [10], M and N-type systems [11, 12] etc. The effect of thermal averaging also influences the EIT line shape by reducing its width compared to the Doppler free condition. Thermal averaging affects the dispersive properties of a medium substantially. The extremely low line width of the EIT window under this condition corresponds to a very steep dispersion that results in very low group velocity of a probe pulse passing through a medium in presence of high power control field. This phenomenon points towards a possibility to manipulate the probe pulse propagation through an atomic vapour medium. In fact, the theoretical prediction [13] has been well supported by the experimental demonstration of reduction of the group velocity of a probe pulse propagating through hot 87 Rb vapour [14]. The deceleration and storage of a light pulse in an atomic vapour and then its release on demand ultimately fulfilled the dream of stopping and storage of light. The observation of EIT is most easily realized in a three-level Λ type system [15] although in reality it is very difficult to form a true three-level Λ type system even in the alkali atomic vapour medium. Almost all alkali atoms have complex multi-level atomic structure. Many reports in this regard can be found in the literature. Iftiquar et. al. [16] has demonstrated experimentally how the thermal averaging in a rubidium vapour cell at room temperature reduces the EIT line width to sub-natural value for a Λ type system. They have also presented a simple theoretical model in this connection. Very recently D. Bhattacharyya et. al. [17] showed the formation of EIT with sub-natural line width in a sixlevel Λ type system in ⁸⁷Rb as well as ⁸⁵Rb vapour at room temperature. An analytical model has been presented there to explain the sub-natural line width of the observed EIT signal. But in three-level 'V' and cascade type systems too EIT can be produced. D. J. Fulton et. al. [15] reported a comparative study of EIT in 'V', Λ and cascade (Ξ) type systems along with their experimental findings. They have explained why the Λ type system is the most well suited to study EIT on the basis of coherence dephasing rate between the dipole-forbidden transitions. There has been very large number of reports on both the theoretical and experimental studies on EIT [15-17 and the references in 17] as well as electromagnetically induced absorption (EIA) [18, 19] using Λ type level scheme. Although the three-level systems serve well in understanding the physical picture behind formation of EIT, these are hard to be found in reality. Formation of hyperfine levels in atoms almost everywhere makes the level scheme complicated enough to consider more than three energy levels in the theoretical models in order to explain the experimentally observed spectra. In this report, we shall present a theoretical investigation on the propagation of a resonant weak probe field through a four-level 'V' type atomic system in presence of a strong coupling field known as the pump field or control field. The treatment is completely

analytic and the simulated probe absorption spectra exhibits formation of a field induced absorption dip on the background of an EIT peak under the thermal averaging whereas under Doppler free condition an electromagnetically induced transparency window in the probe absorption profile is created.

II. THEORETICAL MODEL

We shall now describe the chosen four-level system in which there are two ground levels (|1>, |2>) and two upper levels (|3>, |4>) (Fig. 1). The separation between the two excited states |3> and |4> is set equal to 816.656 MHz and that between the ground levels as 6.8 GHz following the energy level of ⁸⁷Rb [20]. The frequency of the probe beam is scanned from the upper ground state |2> to the excited states |3> and |4>. The frequency of the pump beam is kept locked between the levels |2> and |3>. The coupling of the probe beam to both the upper levels makes the formulation different from the conventional 'V' type system where the probe field couples one of the upper states from the ground level and the control (pump) field acts between the ground level and the other upper level. The spontaneous decay of the population from the uppermost level |4> to the ground levels |1> and |2> is dipole-allowed. We assume that the population transfer between the two ground levels has been kept in the theoretical formulation so that the collision induced transfer of population among the ground levels may be taken into consideration if so desired. Figure 1 below shows the level diagram schematically. The population decay rates of the level |*i*> (*i* = 3, 4) to level |*j*> (*j* = 1, 2) have been represented by γ_{ij} whereas the circular frequencies of probe and control fields are symbolized by ω_p and ω_c respectively.



of the level scheme. The dotted lines represent the decay of population. The frequencies of the control and probe fields are represented by ω_c and ω_n .

The Hamiltonian of the above level scheme can be written in the following form, $H = H_0 + H_I$(1) Here H, H_0 and H_I represent the total Hamiltonian, unperturbed Hamiltonian and the interaction Hamiltonian of the system.

$$H_{0} = \hbar \sum_{i=1}^{4} \omega_{i} |i\rangle \langle i| = \hbar \omega_{1} |1\rangle \langle 1| + \hbar \omega_{2} |2\rangle \langle 2| + \hbar \omega_{3} |3\rangle \langle 3| + \hbar \omega_{4} |4\rangle \langle 4| \dots (2)$$

$$H_{I} = -x_{1} \frac{\hbar \Omega_{c}}{2} \{|2\rangle \langle 3| e^{i\omega_{c}t} + \text{c.c.} \} - x_{1} \frac{\hbar \Omega_{p}}{2} \{|2\rangle \langle 3| e^{i(\omega_{p} - \Delta/2)t} + \text{c.c.} \}$$

$$-x_{2} \frac{\hbar \Omega_{p}}{2} \{|2\rangle \langle 4| e^{i(\omega_{p} + \Delta/2)t} + \text{c.c.} \} \dots (3)$$

Here the control and probe Rabi frequencies are defined by $\Omega_c = \mu_{ij}E_c/\hbar$ and $\Omega_p = \mu_{ij}E_p/\hbar$. The transition $(|i\rangle \rightarrow |j\rangle)$ dipole matrix element is μ_{ij} . $E_{c(p)}$ is the amplitude of the applied control (probe) field. $\Delta = (\omega_4 - \omega_3) = 816.656$ MHz, where $\hbar\omega_i$ corresponds to the energy of the *i*th level (*i* = 1, 2, 3, 4). The relative strengths of the two transitions $|2\rangle \rightarrow |3\rangle$ and $|2\rangle \rightarrow |4\rangle$ have been taken care of in the simulation by the factors x_1 and x_2 respectively. This makes $\mu_{42}/\mu_{32} = x_2/x_1$. A set of sixteen density matrix equations involving the population and coherence terms of the four-level system are derived by using the Liouville's equation of motion after adding the decay terms phenomenalogically [21, 22] -

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{\mathrm{i}}{\hbar} [H, \rho] + \Lambda....(4)$$

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With $\Lambda = \frac{\Gamma}{2}[\sigma_+\sigma_-\rho + \rho\sigma_-\sigma_+ - 2\sigma_+\rho\sigma_-]$, Γ stands for the atomic decay rates. The atomic transition operators are given by σ_+ and σ_- and they are complex conjugate of each other [21, 22]. The population and the coherence terms are (diagonal and off-diagonal elements of the density matrix respectively) obtained by solving the following equations and their complex conjugates analytically following rotating wave approximation [21, 22]:

We have considered, $\rho_{23}(t) = \rho_{23}^c e^{i\omega_c t} + \rho_{23}^p e^{i\omega_p t}$, $\rho_{24}(t) = \rho_{24}^p e^{i\omega_p t}$ [23], subject to the boundary condition $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1$. The probe absorption and dispersion are determined by using the imaginary and real parts of the coherence terms induced by the probe between the levels |2> and |3> (ρ_{23}^p), |2> and |4> (ρ_{24}^p) [17, 21, 22]. The analytical expression of ρ_{23}^p and ρ_{24}^p can be obtained by solving sixteen optical Bloch equations (OBE) under steady state condition.

$$\rho_{23}^{p} = \frac{\left[-x_{1}x_{2}^{2}\frac{n}{b}(\alpha_{p}+\alpha_{c})\right]}{\left[a_{1}\Gamma_{32}+a_{2}A_{32}^{p}+x_{2}^{2}\frac{n}{b}^{2}}A_{1}r_{42}+i\left\{a_{1}A_{32}^{p}-a_{2}\Gamma_{32}-x_{2}^{2}\frac{n}{b}^{2}}A_{42}^{p}\right\}}\left(\rho_{44}-\rho_{22}\right) \\
+ \frac{x_{1}\frac{(a_{c}+\alpha_{p})}{2}(a_{2}+ia_{1})}{\left[a_{1}\Gamma_{32}+a_{2}A_{32}^{p}+x_{2}^{2}\frac{n}{b}^{2}}\Gamma_{42}+i\left\{a_{1}A_{32}^{p}-a_{2}\Gamma_{32}-x_{2}^{2}\frac{n}{b}^{2}}A_{42}^{p}\right\}}\left(\rho_{33}-\rho_{22}\right) \\
+ \frac{a_{1}\Gamma_{32}+a_{2}A_{32}^{p}+x_{2}^{2}\frac{n}{b}^{2}}{\left[a_{1}\Gamma_{32}+a_{2}A_{32}^{p}+x_{2}^{2}\frac{n}{b}^{2}}\Gamma_{42}+i\left\{a_{1}A_{32}^{p}-a_{2}\Gamma_{32}-x_{2}^{2}\frac{n}{b}^{2}}A_{4}^{p}\right\}}{\left[a_{1}\Gamma_{32}+a_{2}A_{32}^{p}+x_{2}^{2}\frac{n}{b}^{2}}\Gamma_{42}+i\left\{a_{1}A_{32}^{p}-a_{2}\Gamma_{32}-x_{2}^{2}\frac{n}{b}^{2}}A_{4}^{p}\right\}\right]}.$$

$$(12)$$

$$\rho_{24}^{p} = \frac{x_{2}\frac{n}{a_{2}}(a_{3}+ia_{4})}{\left[a_{3}\Gamma_{42}-a_{4}A_{42}^{p}+x_{1}^{2}\frac{\left(\left(n_{p}+\alpha_{c}\right)^{2}\right)}{4}\Gamma_{32}+i\left\{a_{3}A_{42}^{p}+a_{4}\Gamma_{42}-x_{1}^{2}\frac{\left(\left(n_{p}+\alpha_{c}\right)^{2}\right)}{4}A_{32}^{p}\right\}\right]}}\left(\rho_{44}-\rho_{22}\right) \\
- \frac{x_{1}^{2}x_{2}\frac{n}{a}\left[a_{2}\Gamma_{42}-a_{4}A_{42}^{p}+x_{1}^{2}\frac{\left(\left(n_{p}+\alpha_{c}\right)^{2}\right)}{4}\Gamma_{32}+i\left\{a_{3}A_{42}^{p}+a_{4}\Gamma_{42}-x_{1}^{2}\frac{\left(\left(n_{p}+\alpha_{c}\right)^{2}\right)}{4}A_{32}^{p}\right\}}}{\left[a_{3}\Gamma_{42}-a_{4}A_{42}^{p}+x_{1}^{2}\frac{\left(\left(n_{p}+\alpha_{c}\right)^{2}\right)}{4}\Gamma_{32}+i\left\{a_{3}A_{42}^{p}+a_{4}\Gamma_{42}-x_{1}^{2}\frac{\left(\left(n_{p}+\alpha_{c}\right)^{2}\right)}{4}A_{32}^{p}\right\}}\right]}\left(\rho_{33}-\rho_{22}\right)$$

$$+ \frac{x_1 x_2 \frac{\alpha_p}{2} (\frac{\alpha_c}{2} + \frac{\alpha_p}{2}) (\Delta_{32}^c - \Delta_{32}^p) \{ Re(\rho_{23}^c) - ilm(\rho_{23}^c) \}}{2}$$

$$+\frac{x_{1}x_{2}}{[a_{3}\Gamma_{42}-a_{4}\Delta_{42}^{p}+x_{1}^{2}\frac{((a_{p}+a_{c})^{2})}{4}\Gamma_{32}+i\{a_{3}\Delta_{42}^{p}+a_{4}\Gamma_{42}-x_{1}^{2}\frac{((a_{p}+a_{c})^{2})}{4}\Delta_{32}^{p}\}]}$$
....(13)

Here, $Im(\rho_{23}^c) = \frac{x_1 \frac{\alpha_c}{2} (\Gamma_{32})}{[\Gamma_{32}^2 + (\Delta_{32}^c)^2]} (\rho_{33}^0 - \rho_{22}^0), Re(\rho_{23}^c) = \frac{x_1 \frac{\alpha_c}{2} (\Delta_{32}^c)}{[\Gamma_{32}^2 + (\Delta_{32}^c)^2]} (\rho_{33}^0 - \rho_{22}^0)$ $a_1 = \Gamma_{42} \Gamma_{43} - \Delta_{42}^p (\Delta_{42}^p - \Delta_{32}^c) + \frac{x_1^2}{4} (\Omega_p + \Omega_c)^2, \quad a_2 = \Gamma_{42} (\Delta_{42}^p - \Delta_{32}^c) + \Gamma_{43} \Delta_{42}^p$ $a_3 = \Gamma_{32} \Gamma_{43} + \Delta_{32}^p (\Delta_{42}^p - \Delta_{32}^c) + \frac{x_2^2}{4} \Omega_p^2, \quad a_4 = \Gamma_{32} (\Delta_{42}^p - \Delta_{32}^c) - \Gamma_{43} \Delta_{32}^p$

The nature of probe absorption and probe dispersion can be obtained by simulating $(\rho_{23}^p + \rho_{24}^p)$ and then plotting its imaginary and real parts separately as functions of probe detuning (Δ_{42}^p) . The probe absorption coefficient (α) and dispersion coefficient (β) of the medium at a frequency ω_p can be written in the following forms:

$\alpha = \frac{4\pi\omega_P}{\alpha}$	$\frac{P}{2}\sum_{i=3}^{4}Im(\rho_{2i}^{P})$	(14)
$\beta = \frac{4\pi\omega_P}{c}$	$\sum_{i=3}^{P} \sum_{i=3}^{4} Re(\rho_{2i}^{P})$	(15)

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In this article we shall concentrate on the probe response under Doppler free condition as well as under thermal averaging. Assuming the atoms to follow Maxwell velocity distribution, the probe absorption signal at a temperature 'T' K with can be written as

 $\alpha_d = \int_{-\infty}^{+\infty} \alpha W(v) dv.$ (16)

Here $W(v) = (u\sqrt{\pi})^{-1}exp(-v^2/u^2)$ with 'u' standing for the most probable velocity of the atoms at a temperature 'T'. We can determine the probe absorption under Doppler free condition from Eq.(14) and that under thermal averaging from Eq.(16).

III. SIMULATION

The analytical expressions for $(\rho_{23}^p + \rho_{24}^p)$ given in Eq.(12) and Eq.(13) have been used to simulate the probe absorption under different conditions. We have noticed distinctly different absorptive properties of the atomic system under Doppler free situation compared to that under thermal averaging. We have used the data available in the literature for the D₁ transition of ⁸⁷Rb [20] atoms in the simulation in order to make the theoretical study realistic and useful to the experimentalists as well. The spontaneous decay rates (γ_{ii} , i = 3, 4; j = 1, 2) of population from both the upper levels to the ground levels have been taken to be 6 MHz each. The control field has been kept locked to the transition from $|2\rangle \rightarrow$ $|3\rangle$, hence the corresponding detuning of the control field (Δ_{32}^c) is equal to zero during the entire simulation process. The probe Rabi frequency (Ω_p) has been kept equal to 1 MHz whereas the Rabi frequency (Ω_c) of the control field has been varied from 20 MHz to 60 MHz in steps of 10 MHz. We get two absorption lines at $\Delta_{42}^p = 0$ and $\Delta_{42}^p = -816.656$ MHz. At zero probe field detuning ($\Delta_{42}^p = 0$, with $\Delta_{42}^p = \omega_p - \omega_{42}$, $\omega_{42} = \omega_4 - \omega_2$, so at zero probe detuning $\omega_p = \omega_4 - \omega_2$), the control and the probe fields are on resonant to the transitions $|2 \rightarrow |3 \rangle$ and $|2 \rightarrow |4 \rangle$ respectively. A 'V' type system is formed and under Doppler free condition the transparency signal is seen to appear around $\Delta_{42}^p = 0$ in the absorption line shape as expected (Fig. 2). But the absorption signal at $\Delta_{42}^{p} = -816.656$ MHz is created when the probe field, along with the pump field, becomes on resonant with the $|2\rangle \rightarrow |3\rangle$ transition. There is no question of fulfilling Raman resonance condition or anything else under this situation. We just observe an absorption line at this condition under Doppler free regime without any EIT like peak (Fig. 2) around $\Delta_{42}^p = -816.656$ MHz. The simulated line shape under thermal averaging shows two transmission peaks in the two Doppler broadened curves (Fig. 3), one around $\Delta_{42}^p = 0$ and another around $\Delta_{42}^p = -816.656$ MHz.But in addition to a transparency peak, signature of an absorption dip at the middle of the transparency window is also visible at $\Delta_{42}^p = 0$ under thermal averaging (Fig.3). We shall term this as field induced absorption. We have kept the temperature of the ensemble fixed at 300 K while considering the thermal averaging. The population transfer rate among the ground hyperfine levels can influence the absorption line shape of the probe field in presence of perturbers (alkali vapour cells filled with N₂, inert gas like He, Ne, Ar etc.). We have not studied this case here although this can be done with the help of the present theoretical model.



Figure 2: Plot of imaginary part of $(\rho_{23}^p + \rho_{24}^p)$ vs. probe frequency detuning (Δ_{42}^p) under Doppler free condition. Values of the control (Ω_c) and probe (Ω_p) Rabi frequencies have been mentioned in the figure.

The thermal averaging process makes an absorption dip at $\Delta_{42}^p = -816.656$ MHz under Doppler free situation to appear with a transmission like peak at the centre of its Doppler broadened absorption line shape. At this condition, both the pump and the control fields are on-resonant with the $|2\rangle \rightarrow |3\rangle$ transition for the zero-velocity group of atoms. The probe absorption decreases here since the control field creates a hole in the population of the zero velocity group of atoms, leaving fewer atoms for the probe field to interact with. This is similar to saturation absorption spectroscopy and formations of Lamb dip [24]. The appearance of the transmission peak around $\Delta_{42}^p = 0$ in the Doppler broadened absorption background however is due to the formation of an EIT type signal for a typical 'V' type system as has already been explained in the last page. We have kept the value of control Rabi frequency far less than the Doppler width (~ 560 MHz) of the transition in order to eliminate the influence of Autler-Towns (AT) effect [25].



Figure 3: Plot of imaginary part of the $(\rho_{23}^p + \rho_{24}^p)$ vs. probe frequency detuning (Δ_{42}^p) under thermal averaging. The values of the control (Ω_c) and probe (Ω_p) Rabi frequencies have been mentioned in the figure.

We have shown the zoomed EIT peak around zero probe detuning in figure 4 in order to make the absorption dip clearly visible. At $\Omega_{\rm C} = 10$ MHz, clear signature of the absorption dip in the EIT background around zero probe detuning could not be seen. From $\Omega_{\rm c} = 20$ MHz and above, the field induced absorption on the background of an EIT window appears prominently. This absorption dip is found to enhance with increase in the Rabi frequency of the control field. Furthermore, a regular shift of the absorption dip with increase in the control Rabi frequency ($\Omega_{\rm c}$) can also be noticed (Fig.4). The formation of an absorption dip on the background of a transparency window in the probe absorption spectra and its shift with increase in the control Rabi frequency are present only under thermal averaging (please compare figure 2 and figure 4 around $\Delta_{42}^p = 0$). These features cannot be observed in the probe absorption spectra for a simple three-level 'V' type system [25]. We shall now quantitatively find out the dependence of this shift on the control Rabi frequency through a plot of the shift of the field induced absorption vs. control Rabi frequency (Fig.5). It is seen that the shift of the absorption dip, appearing in the EIT background around $\Delta_{42}^p = 0$, with respect to the control Rabi frequency is linear. The EIT window shows broadening with increase in the control Rabi frequency. This is also the case for the transparency window appearing around $\Delta_{42}^p = -816.656$ MHz. The shift noticed here is attributed to the AC Stark shift [26].



Figure 4: Plot of imaginary part of the $(\rho_{23}^p + \rho_{24}^p)$ around zero probe frequency detuning (Δ_{42}^p) under thermal averaging. The values of the control (Ω_c) and probe (Ω_p) Rabi frequencies have been mentioned in the figure.



Figure 5: Plot of the shift of the absorption dips (appearing in the EIT background) vs. control Rabi frequency.

We have also determined the full width at half maximum (FWHM) intensity of the absorption dips appearing in the background of the EIT peak by fitting them with Lorentzian line shape function. The variation of the fitted FWHM of the absorption dips with control Rabi frequency is given below (Fig. 6). It is evident from this plot that at lower values of the control Rabi frequency (Ω_C), the fitted FWHM of the absorption dip increases slowly with Ω_C . Only above $\Omega_C = 50$ MHz, the fitted FWHM of the absorption dip starts increasing faster with Ω_C .



Figure 6: Plot of the fitted FWHM of the absorption dips vs. control Rabi frequency.

The presence of an extra ground level (|1> in this case) provides an extra decay path for the population pumped to the upper levels. The coupling of the probe field to both the upper levels means when it is on resonant with the $|2> \rightarrow |4>$ transition ($\omega_p = \omega_4 - \omega_2$), it is still sending atoms with velocity 'v' (for which $\omega_4 - \omega_3 = \omega_p(v/c)$, here v takes a value of -648.38 m/s corresponding to the energy level separation of 816.656 MHz) [21] to level |3>. The atoms thus pumped to |3> are allowed to decay spontaneously to both the ground levels |2> and |1>. Under Doppler free situation this extra coupling is not possible. If we does not allow the probe field to couple both the excited states (|3> and |4>, Fig.1) to the ground level |2> in the theoretical model and allow it to couple |2> and |4> only, no such absorption dip in the EIT window at $\Delta_{42}^p = 0$ can be found. This has been shown in the figure 7 below for different values of the control Rabi frequency. Hence it is evident that the formation of the absorption dip, which we term as field induced absorption, is due to Doppler shifted absorption of atoms. We have tried to avoid the use of approximation throughout the treatment as far as possible and relied on the graphical representation of the analytically obtained probe response.



Figure 7: Plot of $Im(\rho_{24}^p)$ vs. probe frequency detuning Δ_{42}^p at different values of control Rabi frequency for 4-level V-type system. Pump field couples $|2 > \rightarrow |3\rangle$, probe couples $|2 > \rightarrow |4\rangle$.

Till now we have been interested in studying the probe response under both the Doppler free condition and thermal averaging by allowing the decay of the population from excited levels $|3\rangle$ and $|4\rangle$ to both the ground levels $|1\rangle$ and $|2\rangle$. Let us now try to find out the population distribution of various levels as a function of control Rabi frequency (Ω_C). This has been shown graphically in the figure 8 below for $\Omega_P = 1$ MHz at zero probe detuning ($\Delta_{42}^p = 0$) keeping all other parameters same. With increase in the value of the control Rabi frequency we can see that the initial equal distribution of population among the two ground levels gets altered. The population starts building up soon in the level $|1\rangle$ as the control

Rabi frequency keeps on increasing as if the population is getting trapped in this level at high values of the control Rabi frequency [25]. The population of the upper levels remain small, only that of level |3> increases with the control Rabi frequency, although insignificant compared to the ground levels.



Figure 8: Plot of population vs. control Rabi frequency at $\Omega_P = 1$ MHz.

IV. CONCLUSION

We have mainly investigated the probe response after adding an extra ground level in a three-level 'V' type system and checked with the role played by the non-zero velocity group of atoms when the probe field is allowed to couple both the upper levels from the ground level. The theoretical model has been developed to incorporate a control field locked to a specific transition. The treatment is completely analytic and no terms in any power of probe Rabi frequency has been omitted at any stage of the calculation to make the analysis easier. This allows us to reverse the choice of pump and probe fields as per the requirement. Although we have cited the example of D_1 transition of ⁸⁷Rb atoms, this model can be useful to study other alkali D_1 transitions under the v-type configuration. The simulation exhibits occurrence of field induced absorption on the EIT window at higher values of control Rabi frequency. The power dependent shift of this absorption dip has been quantitatively determined too. In fact, to the best of our knowledge, formation of an absorption dip on the transparency background in a four-level 'V' type system is shown here for the first time through a complete analytical treatment. We have tried to incorporate the experimental situation in the simulation and used standard values of spontaneous decay rates of different energy levels as well as transition strengths in order to make the result practically useful. It has also been shown that at zero frequency detuning of the probe field, steady increase in the control Rabi frequency leads to trapping of atoms in the lowest ground state which is not connected by any of the interacting laser fields. This leads to the formation of an EIT window in the simulated probe absorption spectrum around the zero detuning of the probe field. It has also been established that the creation of the field induced absorption in the EIT background is due to the contribution of the non-zero velocity groups of atoms towards the probe absorption through Doppler shifting. The model discussed here can also be used to study the effect of dephasing and other collision related population transfer phenomena among the ground levels on the probe response. The width of the filed induced absorption dip starts increasing at a higher rate when the control Rabi frequency is increased above 50 MHz, this is nothing but the consequence of thermal averaging and power broadening. At lower value of the control Rabi frequency the effect of thermal averaging is predominant, but with increase in the value of control Rabi frequency beyond a certain level the power broadening starts dominating. Experimental evidences of the narrowing of resonances due to thermal averaging have been reported many times by different groups. Our theoretical study confirms this for the filed induced absorption dips too. We believe that this simple analytical model will be useful in probing the 'V' type system in further details in the future and exciting new results can be obtained.

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