Pulse delay and group velocity dispersion measurement in V-type electromagnetically induced transparency of hot $^{85}$Rb atom

Bankim Chandra Das$^1$, Dipankar Bhattacharyya$^2$, Arpita Das$^1$, Satyajit Saha$^1$, Shrabana Chakrabarti$^1$ and Sankar De$^{1,3}$

$^1$ Saha Institute of Nuclear Physics, HBNI, 1/AF, Bidhannagar, Kolkata-700064, India
$^2$ Department of Physics, Santipur College, Santipur, Nadia, West Bengal, 741404, India

E-mail: bankim.das@saha.ac.in and sankar.de@saha.ac.in

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Abstract
Pulse delay with the group velocity dispersion (GVD) characteristics was studied in the V-type electromagnetically induced transparency in the hyperfine levels of $^{85}$Rb atoms with a closed system configuration. The phase coherency between the pump and the probe laser beams was maintained. We studied the pulse delay and the GVD characteristics with the variation of the pump Rabi frequency taking optical density (OD) as a parameter. We observed a maximum of 268 ns pulse delay for 21.24 MHz pump Rabi frequency at OD 5.04 of the Rb vapor cell. For a better understanding of the experimental results, we have derived an analytical solution for the delay characteristics considering the thermal averaging. The analytical solution was derived for a three level V-type system. The theoretical plots of the delay and the GVD show the same characteristics as we observed in the experiment. This analytical approach can be further generalized for the higher level schemes to calculate different quantities such as susceptibility, group velocity delay or GVD characteristics.

Keywords: pulse propagation and temporal solitons, coherent optical effects, electromagnetically induced transparency

(Some figures may appear in colour only in the online journal)

1. Introduction
Interaction of two coherent fields with the atomic media had led to many interesting phenomena like electromagnetically induced transparency (EIT) [1], coherent population trapping [2], lasing without inversion [3] etc. When a weak probe beam interacts with the atomic medium in the presence of a strong pump beam, a quantum interference phenomenon can happen. This leads to EIT, rendering the medium transparent to the field over a small frequency range. In this EIT region, the medium has high normal dispersion which creates a control over the group velocity of light.

To study the absorptive and the dispersive properties of the medium, a $\Lambda$-type and a cascade system were always preferred in comparison to the V-type system. The V-type system has higher EIT width compared to the former systems because it has higher decay rates of the two upper excited levels in addition to the optical pumping phenomena which degrades the EIT phenomena. There were several studies on the subluminal light propagation in the $\Lambda$-type system [4–7] whereas the V-type system needs to be explored further. V-type EIT can used as waveguide [8, 9]. It was assumed that the V-type EIT was due to the Aulter Townes splitting but a recent study showed that quantum destructive interference was behind the occurrence of EIT in the V-type system [10]. V-type system has importance in the generation of superluminal light with cold atomic ensembles without gain [11]. Beil et al showed that in Pr$^{3+}$ : Y$_2$SiO$_5$ with the V-type system, storage time can be increased as compared to the $\Lambda$-type system [12]. Using correlated light beams squeezing...
control was studied in the same system [13]. Studies showed that the velocity selective effect in the V-type EIT in Zeeman levels with a re-pumper configuration can change the time delay [14]. Apart from what is mentioned above, there are not much studies done on the absorptive and the dispersive properties in the V-type EIT in hyperfine levels, both experimentally and theoretically. In our earlier study we have shown that EIT will be formed for a V-type system in the closed transition [15].

In this article we have studied both experimentally and theoretically the dispersive property of $^{85}$Rb using a pulsed probe and a continuous pump beam. We observed subluminal light propagation in the V-type system with closed system configuration. We also studied the group velocity dispersion (GVD) characteristics and saturation intensity dependency with the variation of pump Rabi frequency taking OD as a parameter. We observed a maximum of 268 ns pulse delay with 21.24 MHz pump Rabi frequency for OD 5.04. It was observed that if we increase the OD, the delay will increase. The GVD characteristics was found to be opposite to the pulse delay characteristics. We also derived an analytical solution to study the characteristics of the slow light propagation and GVD characteristics taking account of the thermal averaging. The analytical solution was derived for a three level V-type system. We found out that these results were similar to the numerically solved results.

We have maintained phase coherence between the probe and the pump beams since the time delay is dependent on the phase coherence between the beams. The delay will be less if the phase coherence is not present [16]. We choose $^{85}$Rb $F = 3 \rightarrow F'$ transition to form a closed V-type system.

2. Experiment

The experimental setup to study slow light in a V-type EIT is shown in figure 1(a). We have generated both the pump and the probe beams from a single external cavity diode laser (ECDL) to preserve the phase coherence between the beams. The ECDL was lasing at 780 nm (TOPTICA DL100). The output laser beam had a diameter of $\sim 2$ mm and a line-width $\sim 1$ MHz. A small part of the ECDL output was used for saturation absorption spectroscopy (SAS) (CoSy, TEM Messtechnik) (not shown in the figure 1(a)). SAS was further used for locking the laser frequency with the help of a lock-in-amplifier (LIR) and proportional integrator differentiator loop (TOPTICA LIR110). The remaining part of the laser beam was incident on the beam splitter BS1. The reflected part from BS1 was used for the probe beam and the transmitted part was used for the pump beam. The pump beam was magnified by three times using a Galilean telescope so that the beam diameter becomes $\sim 6$ mm. The probe beam was incident on an acousto optic modulator (AOM, INTRACTION). We took the -1th order of the diffraction in order to make the probe frequency less than the pump, so that an EIT condition can be produced for the V-type system [17]. Now the -1th order of the AOM output was incident on beam splitter BS2. The reflected part was taken as the reference signal which is detected by photo-diode (Detector1). The transmitted part from BS2 was mixed with the pump beam in a polarizing beam splitter (PBS1). We took orthogonal polarizations for the pump and the probe beams. Both the beams were sent through a Rb cell co-linearly. After the cell they were...
The pump beam was locked to the closed transition $F = 3 \rightarrow F' = 4$ of $^{85}$Rb and the probe beam was down shifted by $-120$ MHz with the AOM so that it can be locked to the transition $F = 3 \rightarrow F' = 3$ (see figure 1(b)). In this way a V-type system was formed maintaining the phase coherence between the two laser beams. A 50 mm long and 25 mm diameter cylindrical Rb cell was used in the experiment containing both $^{87}$Rb and $^{85}$Rb atoms in their natural abundance and with no buffer gas. The pressure of the cell is of the order of $10^{-7}$ Torr at room temperature. The Rb cell was put inside a $\mu$-metal shield. The cell was heated with a home made double walled heating jacket in order to vary the temperature of water was controlled using a home made temperature controller circuit. The temperature fluctuation was maintained within $\pm 0.5$ °C. We have avoided the resistive heating techniques in order to avoid unwanted magnetic field effects. During the experiment when we had heated up the cell, a small portion of the Rb vapor had deposited on the cell windows. This could have been avoided by keeping the windows hot with extra heaters. To vary the pump power we have used variable neutral density filter. For our experiment, we have used the pump beam as a pulsed beam and the pump beam as a continuous beam. For generating the probe pulse an arbitrary function generator (Tektronix AFG3052C) was used to modulate the amplitude of the RF driver of the AOM. The probe pulse was chosen to be a Gaussian pulse of width 2.25 $\mu$s.

Throughout the experiment the probe Rabi frequency ($\Omega_p$) was fixed to 7.74 MHz. We have started the experiment with the pump Rabi frequency ($\Omega_r$) as 8.64 MHz which is comparable to the probe Rabi frequency and increased the pump Rabi frequency gradually.

3. Experimental results and discussion

We tuned the probe and the pump beams to get the EIT condition. Both the probe pulse, after passing through the cell, and the reference pulse were detected by a pair of photo detectors simultaneously. The initial mismatch between the peaks of the pulses in both the detectors was subtracted to get the correct delay values when the probe beam was in off resonant condition and the pump beam was switched off.

In figure 2, the reference pulse signal and a probe pulse output signal after the cell, is shown for 34.68 MHz pump Rabi frequency and OD 4.06. The observed delay is 154 ns. Here the data are normalized in order to visualize the delay and group frequency 34.68 MHz with 4.06. Observed delay is 154 ns. Here the data are normalized in order to visualize the pulse delay and group velocity dispersion. The orange and the blue curves are the fitted curves of the reference and the EIT signals respectively.

![Figure 2. Experimentally observed slow light pulse for pump Rabi frequency 34.68 MHz with 4.06. Observed delay is 154 ns. Here the data are normalized in order to visualize the pulse delay and group velocity dispersion. The orange and the blue curves are the fitted curves of the reference and the EIT signals respectively.](image)

2.62, 4.06 and 5.04. Corresponding maximum delays were 57 ns, 109 ns, 176 ns and 268 ns respectively as shown in figure 3(a). The OD was calculated using the Beer–Lambert law. We observed that for a particular OD, if we increase the pump Rabi frequency up to a certain value, the delay will start to increase but after reaching a maximum value, the delay will decrease if the pump Rabi frequency is increased further. It implied that if we increase the pump Rabi frequency till the saturation limit, the slope of the dispersion will increase and correspondingly the delay will increase. But after reaching the maximum delay, the pump power broadening starts to dominate resulting in a decreased slope of dispersion. Therefore the delay will be less if further pump Rabi frequency is increased. Theoretically we have derived an asymptotic solution for this phenomena (discussed in the theoretical section). When the pump Rabi frequency $\Omega_r \rightarrow 0$, we found that the pulse delay is increasing with a $\Omega_r^2$ dependency and when $\Omega_r \rightarrow \infty$, it decreases following a $\frac{1}{\Omega_r}$ relationship. In between these two limits, the delay is increasing almost linearly till it reaches the maximum value.

It was also observed that the pump Rabi frequency for which we got the maximum delay, was changing with the OD. This can be explained on the basis of saturation limits. As the OD increases, the pump power needed to reach the saturation limit will also increase. So with the increase of OD, the peak will shift. This can be seen in the delay versus pump Rabi frequency graph (figure 3(a)). We have shown later that our theoretical model also supports this statement. The maximum value of $\frac{d\lambda}{d\Omega_r}$ is dependent on the temperature which is related to the optical density (OD).

In figure 3(b), the GVD i.e. the variation of the pulse width (FWHM) of the output pulse is shown with the pump Rabi frequency taking OD as a parameter. It is noticed that the nature of the GVD with the variation of pump Rabi frequency is just opposite to the delay characteristics. The pulse...
distortion or the GVD can be understood in the following way. When a Gaussian pulse having an initial width \( \sigma_0 \) passes through a medium, its width is modified after interacting with the medium. From the response function formulation, it can be shown that (see the theory in section 4), the effective width can be determined by

\[
\sigma^2 = \sigma_0^2 + ik''_0 z. \tag{1}
\]

Here, \( k''_0 \) is the measure of GVD which occurs due to the coherent effect of the EIT. Now for a normal dispersion \( k''_0 > 0 \). But \( k''_0 \) is an imaginary quantity. Since in the EIT medium, the dispersion is normal, therefore \( \sigma < \sigma_0 \). It is expected that for higher delay, the pulse compression will be more. The experimentally observed FWHM curve of pulses shows the expected results. For higher OD, the delay is higher resulting in a higher GVD of the output pulse. For the maximum delay at a particular OD, the compression will be maximum which is also observed in figure 3(b). Our theoretical simulation shows the same GVD characteristics (see figure 6(b)).

4. Theoretical model

To support our experimental observations we have simulated the output pulse envelope. To analyze the nature of the pulse delay and the GVD we have calculated the response function of the atomic medium in the EIT condition.

Let us assume that the initial electric field of the probe is \( E_p(0, t) \). Now we need to calculate the final electric field after it has traveled a distance \( z \) through the atomic medium having a response function in frequency domain \( H(\omega, \omega') \). From the response theory we can calculate the final output as

\[
E_p(\omega, \omega') = H(\omega, \omega')E_p(0, \omega') \tag{2}
\]

or in the time domain

\[
E_p(\omega, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega\tau}H(\omega, \omega')E_p(0, \omega')d\omega. \tag{3}
\]

In this experiment we have send the probe beam as a pulsed beam. So, the initial pulse can be written in the time domain as

\[
F(0, t) = \exp \left[ -\frac{t^2}{2\sigma_0^2} \right] \tag{4}
\]

Here \( \sigma_0 \) is the initial width. The inverse Fourier transformation of the initial pulse can be written as

\[
F(0, \omega) = \sqrt{2\pi\sigma_0^2}e^{-\sigma_0^2\omega^2/2}. \tag{5}
\]

Now the frequency response function of the envelope can be written as

\[
G(z, \omega) = e^{-i(k-k_0)z}. \tag{6}
\]

Here \( k \) is the wave vector. If we assume that the medium is behaving like a 2nd order nonlinear medium, we can Taylor expand \( k(\omega) \) in the vicinity of the resonance frequency \( \omega_0 \) as

\[
k(\omega) = k_0 + k'_0(\omega - \omega_0) + \frac{1}{2}k''_0(\omega - \omega_0)^2 + \ldots, \tag{7}
\]

where, \( k_0 = k(\omega_0), k'_0 = \frac{dk}{d\omega}|_{\omega_0} \) and \( k''_0 = \frac{d^2k}{d\omega^2}|_{\omega_0} \). Furthermore, \( k_0 = \frac{dk}{d\omega}|_{\omega_0} = \frac{1}{v_g} \) where \( v_g \) is the group velocity. This is the main reason behind the pulse delay in the medium and \( k''_0 \) is related to the pulse distortion or the GVD [18]. Now we can calculate \( F(z, \omega) \) in the following way

\[
F(z, \omega) = G(z, \omega)F(0, \omega)
= \sqrt{2\pi\sigma_0^2}e^{-i(k-k_0)z-i\sigma_0^2\omega^2/2-i\sigma_0^2\omega^2/2}. \tag{8}
\]

Using the Fourier transformation, \( F(z, t) \) becomes

\[
F(z, t) = \sqrt{\frac{\sigma_0^2}{\sigma_0^2 + ik''_0 z}} \exp \left\{ -\frac{(t-k'_0z)^2}{2(\sigma_0^2 + ik''_0 z)} \right\}. \tag{9}
\]

This output pulse is detected by the detector. The above expression shows that the pulse will be delayed by a time \( k'_0z \) if it has traveled a distance \( z \) in a medium. The effective time delay \( \Delta t \) can thus be calculated by subtracting the time required to travel a distance \( z \) in the vacuum as given by \( \Delta t = z/v_g - z/c \approx \frac{2z}{v_g} \). The width is also modified after passing through the medium. The effective width can be determined by

\[
\sigma^2 = \sigma_0^2 + ik''_0 z. \tag{10}
\]

So the GVD is arising due to the \( k''_0 \) term. The wave vector \( k(\omega) \) is related to the refractive index i.e. \( k(\omega) = \frac{n\omega}{c} \) or more...
generally to the susceptibility of the medium, which can be calculated by the density matrix model. Now
\[ k' = (1 + \frac{\omega_1}{2} \frac{d_1}{2\Delta_0}) / c \] and \[ k'' = \frac{\omega_1}{2} \frac{d_1}{2\Delta_0} \]. Since in our experiment we are considering a three level V-type system as shown in figure 1(b), we have solved the master equation for a three level system. The master equation is given by [19]

\[ \frac{d}{dt} \rho = -\frac{i}{\hbar} [H, \rho]. \] (11)

Here \( H \) is the total Hamiltonian of the system and \( \rho \) is the density operator. These \( H \) and \( \rho \) are 3 x 3 matrices. We have added the decay terms phenomenologically. Since our pump beam was continuous we have solved the density matrix equation in the steady state condition. The probe pulse can be calculated using the coherence term i.e. \( \rho_{21} \). The coherence term \( \rho_{21} \) can be solved in steady state condition to get the susceptibility of the medium. \( \rho_{21} \) can be written as

\[ \rho_{21} = \frac{i\Omega_p}{2} \]
\[ \times \left( \Gamma^2 + 4(\Delta_p + kv)^2 + \Omega_p^2 \right) - \frac{\Omega_p^2}{4} \left( \Gamma^2 + 4(\Delta_p + kv)^2 + 2\Omega_p^2 \right) \]
\[ \times \left( \Gamma^2 - 2i(\Delta_p + kv) + \frac{\Omega_p^2}{4} \Gamma - i\Delta_p - \Delta_0 \right). \] (12)

Here \( \Omega_p, \Omega_c, \Gamma \) are the probe Rabi frequency, the pump Rabi frequency and the natural line-width respectively. \( \Delta_p \) is the probe detuning which is defined as \( \omega_2 - \omega_0 \), \( \omega_2 \) is the resonant frequency of the transition \( |2\rangle \rightarrow |1\rangle \) and \( \omega_0 \) is the field frequency. \( \Delta_c = \omega_2 - \omega \) is the pump detuning. \( \omega_2 \) is the resonant frequency of the transition \( |2\rangle \rightarrow |3\rangle \). The wave vector of the pump and the probe beams are almost equal. In a vapor cell we need to take care of the velocity of the atoms to get the total absorption or the dispersion. The atoms obey Maxwell–Boltzmann (M–B) velocity distribution. Considering all the possible velocities the susceptibility becomes

\[ \chi = \frac{\mu}{\epsilon_0 E_p} \int_{-\infty}^{\infty} N(kv) \rho_{21} d(kv). \] (13)

The distribution for a velocity \( v \) can be written as

\[ N(kv) = \frac{N_0}{\sqrt{\pi}k^2u^2} e^{-kv^2/(2u^2)}. \] (14)

Here \( u \) is the most probable velocity which is related to the Doppler width of the absorption. Equation (13) is not analytically solvable for the M–B velocity distribution. But instead of M–B velocity distribution which is a Gaussian distribution, if we assume the distribution to be a Lorentzian having the same FWHM as the Doppler i.e. \( 2\Gamma_0 = 2\sqrt{2\ln 2}ku \), then the above equation (13) can be solved analytically. The assumed Lorentzian velocity distribution [20] is

\[ N(kv) = N_0 \Lambda_0 \frac{W_d / \pi}{W_d^2 + (kv)^2}. \] (15)

Here \( N_0 \) is the number density of the atoms, \( k \) is the wave vector and \( \Lambda_0 \) is a constant. We observed that by taking \( \Lambda_0 \) to be \( \sqrt{\pi} \ln 2 \), if we solve equation (13) numerically assuming both the above mentioned distributions, the results are completely overlapped for both the absorption and the dispersion in the EIT region (figure 4). There is mismatch however on the outer side of the EIT i.e. the Doppler wing part of the simulated plots as shown in figure 4. In this way we showed that we can use the Lorentzian velocity distribution in order to calculate \( \chi \) and also to estimate the time delay and the GVD characteristics analytically.

The integral in equation (13) can be solved by contour integral method, considering the Lorentzian distribution. \( \chi \) has five poles, \( \pm i\omega_D, \pm \frac{i}{2} \sqrt{1 + 2\Omega_c^2} \) and \( -\left( \frac{i}{2} / + \Delta_p + \frac{i\Omega_p}{\Gamma - i\Delta_p} \right) \). We shall consider the contribution of two poles in the upper half plane \( +i\omega_D \) and \( \frac{i}{2} \sqrt{1 + 2\Omega_c^2} \). Here we assumed that the pump is on resonance i.e. \( \Delta_c = 0 \). Let us also assume that \( \chi = \chi_1 + \chi_2 \) where \( \chi_1 \) is the contribution of the pole \( +i\omega_D \) and \( \chi_2 \) is the contribution of the pole \( \frac{i}{2} \sqrt{1 + 2\Omega_c^2} \). Since we are interested in \[ \frac{d\chi_1}{d\omega} = \frac{d\chi_2}{d\omega}, \] the analytical expression for \[ \frac{d\chi_2}{d\omega} \] is shown below. Here we have assumed \( \omega_{21} = \omega_0 \) for simplicity.

The contribution of the pole \( kv = +i\omega_D \) in \[ \frac{d\chi_1}{d\omega} \] when the pump and the probe beams are on resonance, is given by

\[ \frac{d\chi_1}{d\omega}|_{\omega_0} = -\frac{\mu \Omega_p}{\epsilon_0 E_p} \times \frac{N_0 \Lambda_0}{4W_d^2 - \Gamma^2 - 2\Omega_c^2} \times \frac{2(4W_d \Gamma - 2\Omega^2 + \Omega_c^2)}{2\Gamma^2 + 4W_d \Gamma + \Omega_c^2}. \] (16)

The contribution of the pole \( kv = \frac{i}{2} \sqrt{1 + 2\Omega_c^2} \) in \( \frac{d\chi_2}{d\omega} \) when the pump and the probe beams are on resonance, is given by

\[ \frac{d\chi_2}{d\omega}|_{\omega_0} = -\mu \Omega_p \times \frac{N_0 \Lambda_0}{-4W_d^2 + \Gamma^2 + 2\Omega_c^2} \times \frac{4W_d \Omega_c^2 (2\Omega^2 + \Omega_c^2 + 4\sqrt{1 + 2\Omega_c^2})}{2\Gamma^2 + 2\Omega_c^2 (2\Omega^2 + \Omega_c^2 + 2\sqrt{1 + 2\Omega_c^2})}. \] (17)
The above equations (16) and (17) are the analytical solutions for the time delay characteristics. In figure 5(a), we have plotted the delay characteristics obtained from both the analytical solution following the Lorentzian distribution along with the numerically solved M–B distribution. Analytically obtained solution is completely overlapped with the numerical solution.

Now using the analytical solution the asymptotic behavior can be further solved. When $\Omega_c \to 0$, $\frac{d\chi}{d\omega}$ becomes

$$
\left. \frac{d\chi}{d\omega} \right|_{\omega_0} \to - \frac{2\Lambda_0}{(2W_D + \Gamma^2)} + 3 \left( \frac{W_D\Lambda_0}{\Gamma^4(4W_D^2 - \Gamma^2)} - \frac{2\Lambda_0}{(2W_D - \Gamma)(2W_D + \Gamma)^3} \right) \Omega_c^2.
$$

(18)

It can be observed that when $\Omega_c \sim 0$, $\frac{d\chi}{d\omega}$ increases as $\Omega_c^2$ (see figure 5(a)). But there is also a term $-\frac{2\Lambda_0}{(2W_D - \Gamma)}$ where the negative sign signifies that when $\Omega_c = 0$ it will reduce to one photon transition. In this case, the EIT will disappear giving a simple Doppler absorption profile. The slope of the dispersion will become negative here. Experimentally we have worked only in the EIT regime. So the lower pump Rabi frequency part is not observed in the experimental curves.

When $\Omega_c \to \infty$ it falls down as

$$
\left. \frac{d\chi}{d\omega} \right|_{\omega_0} \to \frac{\Lambda_0}{\Omega_c^2}.
$$

(19)

Overall the delay characteristics can be summarized as: when $\Omega_c \sim 0$, it increases as $\Omega_c^2$ and then it linearly increases till the saturation occurs where it becomes maximum. After that when the pump broadening starts dominating, the slope of the dispersion curve starts to decrease with $\frac{1}{\Omega_c^2}$. These theoretically simulated graphs support our experimental observations quite well. It can be seen from the analytical expression (equations (16) and (17)) that the maximum delay is dependent on the most probable velocity $u$, which is further related to the temperature and thus the OD of the system. So, if we increase the OD of the cell, the pump Rabi frequency for which the maximum delay was observed will change. This was also observed in the experiment.

From the analytical solution of $\chi$, we can calculate $\frac{d^2\chi}{d\omega^2}$ to get the GVD. In figure 5(b), we have shown both the numerically calculated values with the M–B distribution and the analytical solution with the Lorentzian distribution. This is showing the same feature as that of the experimentally observed spectrum. We mentioned earlier that for the highest delay, the GVD will be the maximum. Here also the analytically obtained results completely overlapped with the numerically solved results. The $\frac{d^2\chi}{d\omega^2}$ is itself imaginary and the modified width of the pulse $\sigma^2 = \sigma_0^2 + i\kappa_0\tau$ carries an imaginary $i$ before $\kappa_0\tau$. To avoid the confusion with the experimental plot (figure 3(b)) we have plotted $-\frac{d^2\chi}{d\omega^2}$ versus pump Rabi frequency ($\Omega_c$) in figure 5(b).
In order to compare the experimental features with the theoretical ones, we have calculated the time delay $\Delta t$ versus $\Omega$, and the FWHM versus $\Omega$, for different optical densities considering our analytical results of $\chi$. These are shown in figures 6(a) and (b). The time delay $\Delta t$ can be calculated from the equations (16) and (17). The time delay $\Delta t$ can be defined as $\Delta t \approx \frac{2}{v_g} = (1 + \frac{\omega_z}{\omega_0})z/c$. Here $z$ is the length of the medium and $c$ is the velocity of the light in vacuum. In figure 6(a), we have plotted the time delay characteristics as a function of pump Rabi frequency with OD as a parameter which shows similar results as in the experiment (figure 3(a)). Now the FWHM can be calculated from equation (10). The FWHM can be related with $\sigma$ by, FWHM $= 2\sqrt{2}\ln 2\sigma$. In figure 6(b), the FWHM is plotted as a function of pump Rabi frequency which shows similar features as observed in the experiment (figure 3(b)).

We observed a mismatch between the theory and the experiment because in the theoretical model the one photon Doppler absorption (absorptive part of wave vector) and the higher order GVD (e.g. $\frac{d^3\chi}{d\omega^3}$) terms were not considered which were present in the experiment. We have neglected these terms in order to make our theoretical model simple and analytically solvable. Apart from this mismatch, we can explain our experimental results and the characteristics in a clear manner with the help of our analytical solutions.

5. Conclusion

We experimentally observed subluminal light propagation in a V-type system under the EIT condition. Pulse delay and GVD characteristics of the input pulse were studied with the variation of the pump Rabi frequency taking OD as a parameter. It is observed that the pump Rabi frequency for which the maximum pulse delay is observed, is a function of OD. GVD is studied with the variation of the pump Rabi frequency. To support our experimental observations, we have formulated an analytical expression for the susceptibility considering thermal averaging. We have also compared the experimental results i.e. time delay and GVD with our analytical solutions. The simulated spectra shows the same nature as that of the experimentally observed results.

Although we have done the experiment in the closed transition, the Doppler effect of the hot atomic vapor would induce the non-closed transitions $F = 3 \rightarrow F' = 2, 3$ and pump population from the closed transition $F = 3 \rightarrow F' = 4$. Due to this optical pumping effect, the population will be reduced for the closed transition. Therefore the EIT effect will be diminished. This results in a further reduction of the slowing effect. The slow light and GVD measurements in this system has importance in making optical buffers [21], optical sensing memories [22], optical rotation sensing [23], telecommunications [24], etc. Furthermore in the V-type system, studies have shown that the storage time can be increased compared to the A-type system [12]. The subluminal to superluminal light propagation can also be observed in a V-type system with a repumper configuration. V-type system can be used for the quantum beat generation which is not possible in a A-type system [25]. Moreover our theoretical approach can be generalized further in the higher level systems to formulate an analytical solution and estimate the different quantities such as susceptibility, delay, GVD, etc and study their characteristic behaviors.

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ORCID iDs

Bankim Chandra Das @ https://orcid.org/0000-0002-4849-7138
Dipankar Bhattacharyya @ https://orcid.org/0000-0003-0403-2651
Arpita Das @ https://orcid.org/0000-0002-7753-3900
Sankar De @ https://orcid.org/0000-0002-3116-7271

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