A New Way of Broadening the EIT Window: control over Subluminal Group Velocity

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Abstract.

The broadening of the Electromagnetically induced transparency (EIT) window can be achieved in a three level closed \( \Lambda \) system by controlling the strength of incoherent pumping. It has been shown that the presence of homogeneous/inhomogeneous decay facilitates the EIT window broadening. Moreover control over the subluminal group velocity associated with EIT can be achieved by manipulating the number density of the molecules. This effect has been demonstrated in a heteronuclear molecule (e.g. LiH).

Keywords: Spontaneously Generated Coherence, EIT, Broadening of EIT Window

Electromagnetically induced transparency (EIT) has drawn tremendous attention both theoretically \([1, 2]\) and experimentally \([3, 4]\) due to its potential applications in many areas of quantum optics. In \( \Lambda \)-type three-level system the spontaneously generated coherence (SGC) due to the interaction with the vacuum bath of the radiation field has been investigated by Javanainen \([5]\). In the \( \Lambda \) systems observation of EIT can be explained with the help of a concept called coherent population trapping (CPT) \([6, 7]\). In our previous work, we have shown a new way of achieving EIT due to the destructive interference of spontaneously generated coherence and dynamically induced coherence, when the contribution to the probe response from two coherences are equal and opposite at resonance \([8, 9, 10]\). We have also shown that the broadening of the EIT window can be achieved by controlling the incoherent pumping rate \([11]\).

In the present work we have shown that the broadening of the EIT window is further enhanced in presence of the homogeneous/inhomogeneous decay and the subluminal group velocity of the probe light for a particular value of the EIT window width can be controlled by manipulating the number density of the molecules.
1. Theory

Our aim is to create a Λ system with parallel or antiparallel dipole moments. Let us apply a laser field between $X^1\Sigma^+(v = 0, j = 0)$ and $X^1\Sigma^+(v = 0, j = 1)$ states of LiH molecule. It then produces dressed states $|+\rangle = \sin \psi |j = 0\rangle + \cos \psi |j = 1\rangle$ and $|-\rangle = \cos \psi |j = 0\rangle - \sin \psi |j = 1\rangle$ with $\cos \psi = \frac{1}{2} + \frac{\Delta E}{2S'}$, where $\Delta E$ is the detuning of the laser frequency from the molecular transition frequency. The two dressed states are separated by an interval $S' h = h \sqrt{S^2 + \Delta L^2}$, where $S$ is the Rabi frequency of the transition. For LiH molecule the separation between $X^1\Sigma^+(v = 0, j = 0)$ and $X^1\Sigma^+(v = 0, j = 1)$ states is of the order of $10^2$ GHz [12]. Therefore to couple these two levels a maser emitting around $10^2$ GHz energy (some water masers, HCN maser [13]) should be used. The energy separation between $|+\rangle$ and $|-\rangle$ levels should be greater than the bandwidth ($<< 1$ GHZ) of the maser and it should be much less than $10^2$ GHz i.e. the separation energy between $X^1\Sigma^+(v = 0, j = 0)$ and $X^1\Sigma^+(v = 0, j = 1)$ states.

If $|\mu_{ij}|$ be the dipole moment matrix element for the transition, summed over the three perpendicular directions in space [14], we have $|\mu_{ij}|^2 = \mu^2 \frac{(j+1)}{(2j+1)}$ for the transition $j + 1 \leftarrow j$ and $|\mu_{ij}|^2 = \mu^2 \frac{(j+1)}{(2j+1)}$ for the transition $j + 1 \rightarrow j$. For $X^1\Sigma^+(v = 0, j = 0)$ to $X^1\Sigma^+(v = 0, j = 1)$ transition, $|\mu_{01}| = \mu$, where $\mu$ is the electric dipole moment of the LiH molecule ($\approx 5.866 D$) at equilibrium nuclear distance [15].

Let us consider $A^1\Sigma^+(v = 0, j = 2)$ state of LiH as the upper excited level of a Λ system and the dressed states $|+\rangle$, $|-\rangle$ are coupled with the upper excited level by a coherent field and a probe field respectively (see fig.1). We find that the dipole matrix elements between the dressed states and the upper excited level are $d_{2+} = d_{12} \cos \psi$ and $d_{2-} = d_{12} \sin \psi$, where $d_{12}$ is the dipole transition moment between $A^1\Sigma^+(v = 0, j = 2)$ and $X^1\Sigma^+(v = 0, j = 1)$ states. Thus, the system with upper state $A^1\Sigma^+(v = 0, j = 2)$ and the lower dressed states $|+\rangle$, $|-\rangle$ behaves as a Λ system with antiparallel dipole moments. The spontaneous decay widths ($\gamma_+$ and $\gamma_-$) can be calculated from the dipole transition moments ($d_{2+}$ and $d_{2-}$) and the frequencies of transition [10]. This system has the advantage that the magnitudes of the dipole transition moments ($d_{2+}$ and $d_{2-}$) and the energy separation between the dressed states ($S'$) can be controlled by the
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Figure 2. Dependence of FWHM (Full Width at Half Maximum) of the EIT window and \( (n_g - 1) \) on incoherent pumping rate for \( \Omega = 10^{-13} \) a.u. For FWHM curves, ———: \( \gamma_0 = 0 \), ······: \( \gamma_0 = 10^{-8} \) a.u., - - - -: \( \gamma_0 = 10^{-7} \) a.u. and — - ··: \( \gamma_0 = 10^{-6} \) a.u. For \( (n_g - 1) \) curves, ■: N=10^{16}/cm^{3} and ●: N=10^{18}/cm^{3}

Rabi frequency \( (S) \) and the detuning of the driving laser field \( (\Delta_L) \).

Here the density matrix equations can be derived from the master equation without any restriction over the direction of field polarizations. These density matrix equations for closed three level \( \Lambda \) system with probe field, coherent field and the bidirectional incoherent pumping (which acts on \( A^1\Sigma^+(v = 0, j = 2)(|f\rangle) \rightarrow |\rangle \) transition) have been solved exactly for the coherences and populations in the steady state limit keeping all the higher order terms for the system parameters and without neglecting any term or imposing any restrictions over the values of system parameters [8, 9]. This will facilitate the realization of such scheme in realistic (atomic/molecular) systems. The exact analytical expression for the probe field response at \( \Delta_p = \Delta_c = 0 \) has been shown in our previous work to show how EIT can occur due to the interplay between two types of coherences [10, 11]. Hence the exact analytical expressions for the susceptibility \( (\chi = \chi' + i\chi'') \), group velocity \( (v_g) \) and group index \( (n_g = c/v_g) \) can be obtained by using the exact analytical derivatives of coherences (see equations 14-24 in ref. [10]).

2. Results and Discussions

Fig.2 shows the variation of FWHM (full width at half Maximum) of the EIT window and \( (n_g - 1) \) as a function of incoherent pump rate in LiH molecule. The solid line indicates the variation of FWHM in the absence of homogeneous/inhomogeneous decay for \( \Omega = 10^{-13} \) a.u and \( G= 1.7323 \times 10^{-13} \). FWHM increases linearly with the increase in the incoherent pumping rate in absence of homogeneous/inhomogeneous decay indicating the lossless and distortionless transmission of probe light. It is well known that the condition for the distortionless pulse propagation is that the spectral width of the probe pulse should be contained within the transparency window of the medium [16]. If the pulse is short i.e. its spectrum is broad relative to the transparency window of the medium, absorption and also the higher order dispersion need to be taken into account. But if the transparency window is broad, short pulses with large bandwidth can be propagated without dispersion and absorption. For further increase in \( \gamma_0 \) (see dotted, dashed and dashed-dot curves), \( G \) should be increased accordingly to get EIT, e.g. for \( \gamma_0 = 10^{-8} \) a.u, \( \Omega = 10^{-13} \) a.u and \( G= 6.6797 \times 10^{-9} \). For a fixed value of the incoherent pumping rate, FWHM increases with \( \gamma_0 \). It has been found that the
EIT window is wider in presence of the homogeneous/inhomogeneous decay than that in the absence of it. This indicates that the presence of the inhomogeneous/homogeneous broadening facilitates the widening of the EIT window. A closer inspection reveals that initially the FWHM curves are almost flat in presence of the homogeneous/inhomogeneous decay. However with further increase in incoherent pumping rate, all the curves merge together with that obtained in absence of the homogeneous/inhomogeneous broadening and increase with the incoherent pumping rate together. It happens due to the fact that the incoherent pumping dominates over the homogeneous/inhomogeneous decay which leads to the suppression of the effects of these decays. The solid lines with circle and square show the variation of $(n_g - 1)$ (where $n_g$ is the group index) at the resonance as a function of the incoherent pump rate for two different value of the number density of molecules. These curves indicate that with the increase in the incoherent pump rate, the subluminal group velocity of probe light increases and approaches to the velocity of light, but does not exceed it. However by controlling the number density of the molecules, the superluminosity of the probe light can be increased for a fixed value of the incoherent pumping rate. As the homogeneous/inhomogeneous decay width is much larger than the collisional decay width, the inclusion of collisional broadening has no effect on the results in these cases.

3. Conclusion

It has been shown that the SGC in heteronuclear molecule (LiH) can be invoked by an external field and this scheme can be applied to achieve broadening of the EIT window by controlling the incoherent pumping rate. This broadening is further enhanced in presence of the homogeneous/inhomogeneous decay for the moderate values of the incoherent pumping rate. Moreover it has been shown that by increasing the number density of molecules, the subluminosity of the probe light can be increased for a particular value of the width of the EIT window, thus allowing a lossless transmission of the probe light, slower than the velocity of light.

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