Study of electromagnetically induced transparency (EIT) in strong blockade regime using four-photon excitation process in thermal rubidium vapor

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Motivation:

Line-width of two-photon excitation in thermal vapor $\approx 400$ MHz.

In cold atomic system, line-width $\approx 20$ KHz which greatly enhances the non-linearity.

Four-photon excitation in a Five-level system:

- Line-width can be reduced to zero limited by the transit time dephasing, i.e. $\Delta k v_{avg} \approx 0$. 

Fig: Schematic of two-photon excitation in a three level system

Fig: (a) Schematic of four-photon excitation in a five-level system and (b) laser geometry through atomic vapor
Five-level system:

The optical bloch equation: $\dot{\rho} = \frac{i}{\hbar} [\rho, H] + L_D(\rho)$

The total Hamiltonian of the five-level system:

$$H = -\frac{\hbar}{2} \begin{pmatrix}
0 & \Omega_1 & 0 & 0 & 0 \\
\Omega_1' & (\Delta_1-k_1v) & \Omega_2 & 0 & 0 \\
0 & \Omega_2' & 2\delta_2 + k_pv & \Omega_3 & 0 \\
0 & 0 & \Omega_3' & 2\delta_2 + 2\Delta_3 + k_pv - k_3v & \Omega_4 \\
0 & 0 & 0 & \Omega_4' & 2\delta_4 + k_pv + k_cv
\end{pmatrix}$$

$\delta_2 = (\Delta_1 + \Delta_2), \delta_4 = (\Delta_1 + \Delta_2 + \Delta_3 + \Delta_4)$

$\Delta K = k_c - k_p$ where $k_p = k_2 - k_1$, $k_c = k_4 - k_3$

$k_2 > k_1$ and $k_4 > k_3$

Susceptibility and transmission of the probe beam as:

$$\chi(\omega_1) = \frac{2N|\mu_{ge}|^2}{\hbar\epsilon_0\Omega_1} \frac{1}{\sqrt{2\pi}v_p} \int_{-\infty}^{+\infty} \rho_{eg} e^{-\frac{v^2}{2v_p^2}} dv$$

$$T = \frac{I}{I_0} = e^{-Im(\chi)k_1l}$$

Fig: Probe transmission in absence of coupling beam while scanning $\Delta_2$ (red circles) and in presence of coupling beam with $\Delta K = 0$ (black line) and with $k_c = 0.023 \times 10^6 m^{-1}$ (green squares). $k_p = 0.007 \times 10^6 m^{-1}$.

Fig: Probe transmission peak height as a function of $k_c$. 

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Adiabatic elimination of five level system to an effective three-level system:

\[ \Delta_1 \gg \Omega_1, \Gamma_{eg}, \text{and } \Delta_3 \gg \Omega_3, \Gamma_{eff} \]

\[ \frac{\partial}{\partial t} C_2(t) = \frac{\partial}{\partial t} C_4(t) = 0 \]

\[ \Delta_{eff1} = (\Delta_1 + \Delta_2) - \frac{|\Omega_2|^2}{4\Delta_1} + \frac{|\Omega_1|^2}{4\Delta_1} - \frac{|\Omega_3|^2}{4\Delta_3} \]

\[ \Delta_{eff2} = (\Delta_3 + \Delta_4) - \frac{|\Omega_2|^2}{4\Delta_1} + \frac{|\Omega_4|^2}{4\Delta_3} + \frac{|\Omega_3|^2}{4\Delta_3} \]

Interacting two-atom system:

\[ \chi(\omega_1) = \frac{2N|\mu_{ge}|^2}{\hbar \epsilon_0 \Omega_1} \frac{1}{\pi v_p^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \rho_{eg} e^{-\left(\frac{v_1^2 + v_2^2}{2v_p^2}\right)} \, dv_1 \, dv_2 \]
Experimental proposal in thermal rubidium vapor:

Fig: (a) Schematic of four-photon excitation in thermal rubidium vapor and (b) suitable laser geometry.

- $\omega_1 \rightarrow 780 \text{ nm}$
- $\omega_2 \rightarrow 776 \text{ nm}$ Line-width, $\Delta k\nu_{avg} \approx 0$
- $\omega_3 \rightarrow 2.41 \mu m$
- $\omega_4 \rightarrow 2.6 \mu m$

Fig: (a) Comparison of the probe transmission for a single-atom system (black line), non-interacting two-atom system (red circles) and interacting two-atom system with $V_{int} = 100$ MHz (black circles). The residual wave vector is $\Delta K = 0$. (b) Comparison of noninteracting two-atom system (red circles) and interacting two-atom system with $V_{int} = 100$ MHz (black circles). The residual wave vector is $\Delta K = 0.013 \times 10^6 m^{-1}$. (c) Normalized blockaded transmission as a function of $k_c$ and (d) $\Gamma_s$ for $V_{int} = 100$ MHz.
Thank you