The breaking point between fast- and slow-light in a degenerate two-level atomic system*

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This paper investigates the breaking point between fast- and slow-light in a degenerate two-level atomic system, where fast-light can be converted to slow-light arbitrarily on a single transition line by adjusting the strength of the pumping field. An equivalent incoherent pumping rate is introduced in this simplified theoretical model which exploits the dependence of this feature. The experimental observation is presented as evidence of the breaking point where the injected power is about 0.08 mW.

Keywords: degenerate two-level atomic system, breaking point, group velocity

PACC: 4250, 3280

1. Introduction

Compact and controllable optical buffers are key components for all optical networks and quantum information processing systems. The key point for such optical buffers is an adjustable delay time (i.e., group index) for input signal pulses. On the one hand, large pulse delay ("slow-light") is achievable in many media including hot and cold atom vapours,[1−6] doped crystals,[7,8] optical fibre,[9−12] photonic crystals,[13] and semiconductor quantum wells.[14] On the other hand, a considerable pulse advancement ("fast-light") is also achievable in atom vapours,[15,16] optical fibres,[11,17] etc. In addition, some researchers investigated the switching from fast-light to slow-light.[16,18−21] The steep dispersion generated by electromagnetically induced transparency (EIT) and by electromagnetically induced absorption (EIA) acts as the heart of the phenomena. Some are achieved at two different transition lines of atoms in these systems[16,22] where different transition lines are accompanied by EIT and EIA, respectively. In addition, an additional method,[21−23] such as buffer gas,[21] a microwave field,[23] can be used to affect the dispersion. But a more complex setup and control are needed. However, the switch based on a single atomic transition line is observed in a few theories[19] and experiments.[18] Furthermore, there is no detailed discussion which presents the nature of the switch point and explains how and when the jump occurs in a single two-level system.

In this paper, we studied the coherence effect in a degenerate two-level atomic system based on a novel equivalent theoretical model, where we can achieve both EIA and EIT on a single atomic transition line. Our theoretical model is appropriated with the real experimental atomic system where an incoherent pumping rate is introduced. Furthermore, a breaking point between fast-light and slow-light is studied in both theory and experiment, a detailed discussion about how the occurence of jump is presented. It is important that an integrated, controllable method to build all-optical buffer is provided.

2. Theoretical model

In this paper, we consider a degenerate two-level atomic system (see Fig. 1(a)), where two levels ($F = 1$, $F' = 2$) are split into a series of Zeeman sublevels (see Fig. 1(b)) in a magnetic field. The pumping effect of the coupling field (Ω) can be denoted by three equiva-

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lent pumping fields (with Rabi frequencies Ω_1, Ω_3 and Ω_4), $\Omega_n = \mu_{ij}E/\hbar$, where μ_{ij} is the dipole moment element from level $|i\rangle$ to level $|j\rangle$. They couple transition line from $m_F = -1$ to $m_{F'} = 0$, from $m_F = 0$ to $m_{F'} = 1$ and from $m_F = 1$ to $m_{F'} = 2$, respectively. Likewise, three equivalent weak probing fields ($\Omega_{\rm p} \ll \Omega$) are from the same field ($\Omega_{\rm p}$). They couple transition lines from $m_F = n$ to $m_{F'} = n - 1$, where $n = 1,\ 0,\ -1$. Their Rabi frequencies are Ω_2, Ω_2', Ω_2'', respectively. Every excited sublevel decays to the ground sublevels with the same spontaneous emission rate γ, respectively. The total spontaneous emission rate from the excited state is $\Gamma = 3\gamma$. As a closed system, there is no excited atom to decay to levels other than $F = 1$. The transition from $m_F = 0$ to $m_{F'} = 1$ is related to other transitions only by spontaneous decay. Because the pumping (Ω_4) ultimately changes the population distribution on lower sublevels, we exploit the nature of the transition line from $m_F = 0$ to $m_{F'} = 1$ by modeling the pumping field as the incoherent pumping. According to the optical pumping theory in the two-levels model and the mechanism of the atomic-decay processes, the strength can be represented by the equivalent incoherent-pumping rate γ_5,

$$\gamma_5 = \frac{\gamma\Omega_4^2}{\gamma^2 + \Delta_4^2 + \Omega_4^2}, \tag{1}$$

where Δ_4 is the detuning of the pumping field (Ω_4). In other words, this system is physically equivalent to the modified five-level system shown in Fig. 1(c). In this five-level system, we simplify the effect of Ω_4 as two incoherent pumpings. One is from level $|5\rangle$ to level $|1\rangle$, and the other is from level $|5\rangle$ to level $|3\rangle$. The Δ_1, Δ_2 and Δ_3 are the detunings for three transition channels, where $\Delta_1 = \nu_1 - \omega_{21}$, $\Delta_2 = \nu_2 - \omega_{23}$, $\Delta_3 = \nu_3 - \omega_{43}$. ω_{ij} is the resonant frequency between level $|i\rangle$ and $|j\rangle$. ν_1, ν_3 are the frequencies of the pumping field Ω_1 and the pumping field Ω_3, respectively, ν_2 is the frequency of the probing field Ω_2.

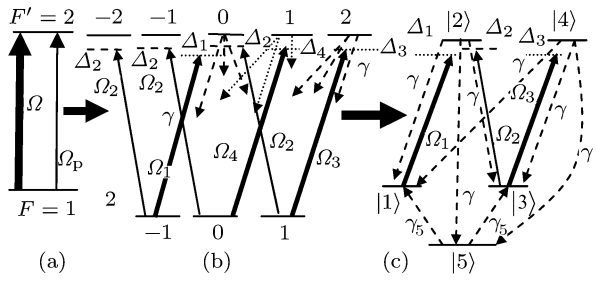


Fig. 1. (a) Two-level model, where Ω and $\Omega_{\rm p}$ are the Rabi frequencies of the coupling field and the probing field, respectively. (b) Configuration of Zeeman sublevels atomic system. (c) Equivalent five-levels system.

Thus, the Hamiltonian of the system in the rotating frame is

$$\begin{aligned} H =\ & \hbar\Delta_2|2\rangle\langle 2| + \hbar\Delta_3|4\rangle\langle 4| + \hbar(\Delta_2 - \Delta_1)|1\rangle\langle 1| \\ & - \hbar(\Omega_1|2\rangle\langle 1| + \Omega_2|2\rangle\langle 3| + \Omega_3|4\rangle\langle 3| + \text{h.c.}). \end{aligned} \tag{2}$$

Furthermore, we give the Liouvillian relaxation term (ζ) and the term (ξ) from spontaneous transfer of optical coherence,

$$\begin{aligned} \zeta(\hat{\rho}) =\ & (\gamma\rho_{44} + \gamma\rho_{22} + \gamma_5\rho_{55})|1\rangle\langle 1| \\ & - \frac{1}{2}(3\gamma)(|2\rangle\langle 2|\hat{\rho} + \hat{\rho}|2\rangle\langle 2|) \\ & + (\gamma\rho_{22} + \gamma\rho_{44} + \gamma_5\rho_{55})|3\rangle\langle 3| \\ & - \frac{1}{2}(3\gamma)(|4\rangle\langle 4|\hat{\rho} + \hat{\rho}|4\rangle\langle 4|) \\ & + (\gamma\rho_{22} + \gamma\rho_{44})|5\rangle\langle 5| \\ & - \gamma_5(|5\rangle\langle 5|\hat{\rho} + \hat{\rho}|5\rangle\langle 5|), \end{aligned} \tag{3}$$

$$\xi(\hat{\rho}) = \alpha\Gamma(|1\rangle\langle 3|\rho_{24} + |3\rangle\langle 1|\rho_{42}), \tag{4}$$

where ξ corresponds to the transfer of low frequency coherence from the excited level to the ground level, α denotes the relative transition amplitude. We can find the susceptibility of the system for the probing laser by solving the first order ρ_{23} in steady state,

$$\rho_{23}^{(1)} = \frac{\mathrm{i}\,\Omega_2\rho_{33}^{(0)} + \mathrm{i}\,\Omega_1\rho_{13}^{(1)} - \mathrm{i}\,\Omega_3\rho_{24}^{(1)}}{3\gamma/2 - \mathrm{i}\,\Delta_2}, \tag{5}$$

where $\rho_{33}^{(0)}$ is the populations in the absence of the probing field, $\rho_{ij}^{(1)}$ corresponds to the first order of perturbation theory on Ω_2. Furthermore, we can obtain the electric susceptibility $\chi = \chi' + \mathrm{i}\,\chi''$, where χ' is related to the refractive index of the medium, while χ'' is related to the absorption of the electric field in the medium, i.e.,

$$\begin{aligned} \chi' &= \frac{N\mu_{23}^2 \mathrm{Re}\left[\rho_{23}^{(1)}\right]}{2\hbar\epsilon_0\Omega_2}, \\ \chi'' &= \frac{N\mu_{23}^2 \mathrm{Im}\left[\rho_{23}^{(1)}\right]}{2\hbar\epsilon_0\Omega_2}, \end{aligned} \tag{6}$$

where N is the density of the atom gas, μ_{23} is the dipole moment element from level $|2\rangle$ to level $|3\rangle$, ϵ_0 is the permittivity in vacuum.

It should be mentioned that we assume a fixed relation between the Rabi frequency of the pumping fields in our numerical simulation. In fact, we adopt a single pump to interact with both pumped transitions, the strength (E) of the laser is the same for all transition lines. Therefore the Rabi frequency ($\Omega_n = \mu_{ij}E/\hbar$) only depends on μ_{ij}. Thus in a degenerate system, the relative strength of pumping fields

are $\Omega_1 = A\Omega_3$ and $\Omega_4 = B\Omega_3$, where A and B are constants in our model. In Fig. 2, we give the numerical simulation of dispersion and absorption curves according to Eq. (6). It illustrates the presence of the breaking point in Fig. 2. With increasing Ω_3, the strong absorption peak becomes flatter and flatter, and then a transmission peak becomes obvious. Then we can observe the switch from EIA to EIT. There is a breaking point where the hopping takes place, the value of Ω_3 is about 2.64 MHz. In addition, the dispersion changes from negative to positive. According to the expression of group velocity,

$$v_{\rm g} = \frac{c}{n + \nu {\rm d}n/{\rm d}\nu}, \tag{7}$$

the changing trend of the dispersion can be revealed by observing the pulse propagation. By adjusting the Rabi frequency of the pumping field, the sign of the dispersion turns hopping, and the transform from fast-light to slow-light will be realized in a degenerate two-level atomic system.

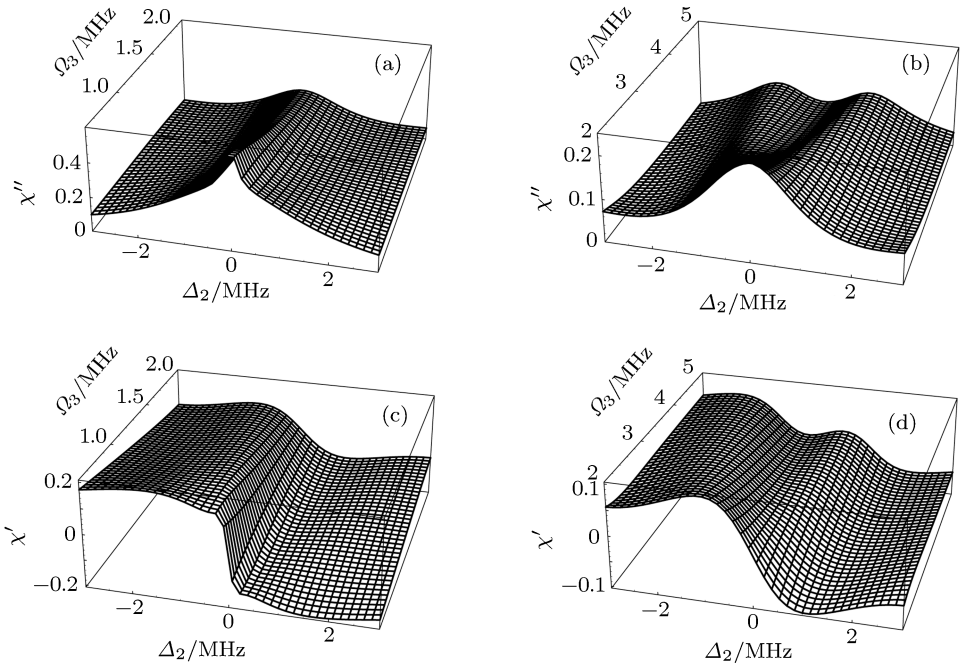


Fig. 2. Figures (a) and (c) illustrate the absorption change for different power of the pumping field. With increasing of the power, the strong absorption peak becomes flatter and flatter, and then a transmission peak becomes obvious. Figures (b) and (d) illustrate the dispersion change for different power of the pumping field. It happens that a hopping is from negative dispersion to positive dispersion. The power at the breaking point is about 2.64 MHz, $\gamma = 1$ MHz, $\Omega_1 = 0.79\Omega_3$, $\Omega_4 = 0.89\Omega_3$, $\alpha = 1/\sqrt{3}$, $\Delta_1 = \Delta_3 = \Delta_4 = 0$.

3. Experiment

It is shown in Fig. 3 that we employ the cycling transition of Cs ($|6S_{1/2},\ F = 4\rangle \rightarrow |6P_{3/2},\ F = 5\rangle$). The excited state is coupled to the ground state by the pumping field ($\Omega_{\rm p}$) and the probing field (Ω_2) at the same time. In addition, they are denoted as the circularly polarized light, i.e., σ_+ and σ_-, respectively. Our experimental setup is similar to that shown in Ref. [4]. We perform the experiment in a cesium (Cs) atom vapour cell without buffer gas at room temperature. An extended-cavity diode laser with narrow linewidth is used. The Pockels cell can slightly rotate the polarization of the input light to create a weak pulse, i.e., the probing field. The polarization of the signal field is perpendicular to that of the remaining light, which works as the pumping field. Our Cs cell is 5-cm long, 3 cm in diameter. In order to eliminate the influence of the magnetic field, there are three layers magnetic shields around the cell to shield the earth's magnetic field to within 4 mG.

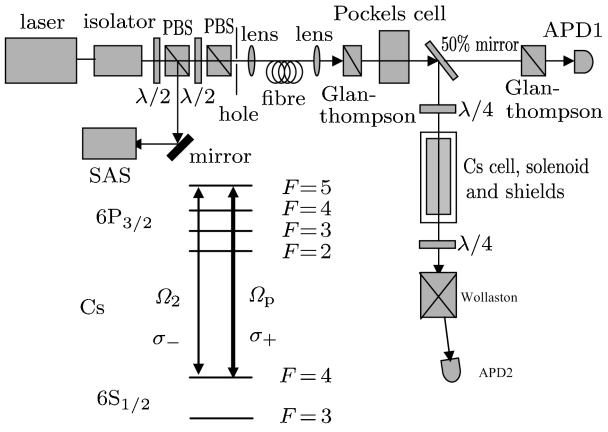


Fig. 3. Schematic diagram of the experimental setup. The closed transition line from level $|6P_{1/2},\ F = 4\rangle$ to level $|6P_{3/2},\ F = 5\rangle$ at D2 line of Cs is adopted. The APDs are avalanche photodiodes.

By adjusting the power of the pumping field, we want to reveal the breaking point where the switching from EIA to EIT happens. We give four transmission curves at four different injected laser powers in Fig. 4. At a low power of 0.06 mW, the spectrum presents a pure absorption curve near the resonant line. With the increasing of the power of the injected laser, the peak of the absorption curve becomes flatter and flatter, then a transmission peak appears in the absorption curve. We can find that an obvious transmission peak appears at the centre of EIA absorption signal at the power of 0.106 mW. As predicted in our theory, the absorption of the atomic system suffers a hopping. In our experiment, the power at breaking point is about 0.08 mW.

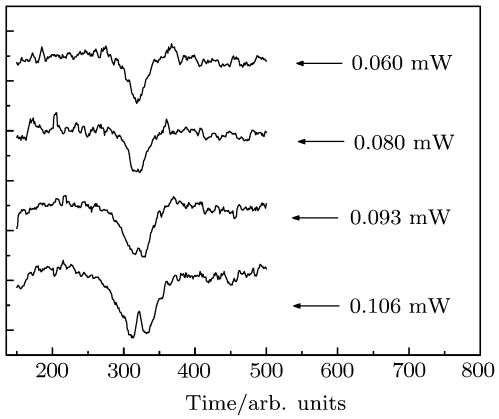


Fig. 4. The absorption curves versus different injected laser power. A transmission peak appears at the centre of EIA absorption signal with increasing injected laser power.

In order to verify the presence of the dispersion breaking point, we observe the pulse propagation in the media. At low power of the laser, the fast-light is observed in Fig. 5(a). The dashed line is the reference signal whilst the solid line is the fast-light signal. We find that the pulse goes faster after it passes through the sample cell. The Cs Faraday resonance is observed in the inset of Fig. 5(a) where the transmission amplitude is shown as a function of magnetic field. We can find the EIA absorption peak when the detuning of the Zeeman sublevels from the two-photon resonance condition is close to zero. By increasing the power of the injected laser, we can find that the pulse goes slower after it passes through the sample cell in Fig. 5(b). At the same time, the EIT transmission peak is shown as a function of magnetic field in the inset of Fig. 5(b). Therefore, without changing any other parameters, just changing the power of the injected laser, we obtain the switch between fast-light and slow-light based on a single transition line.

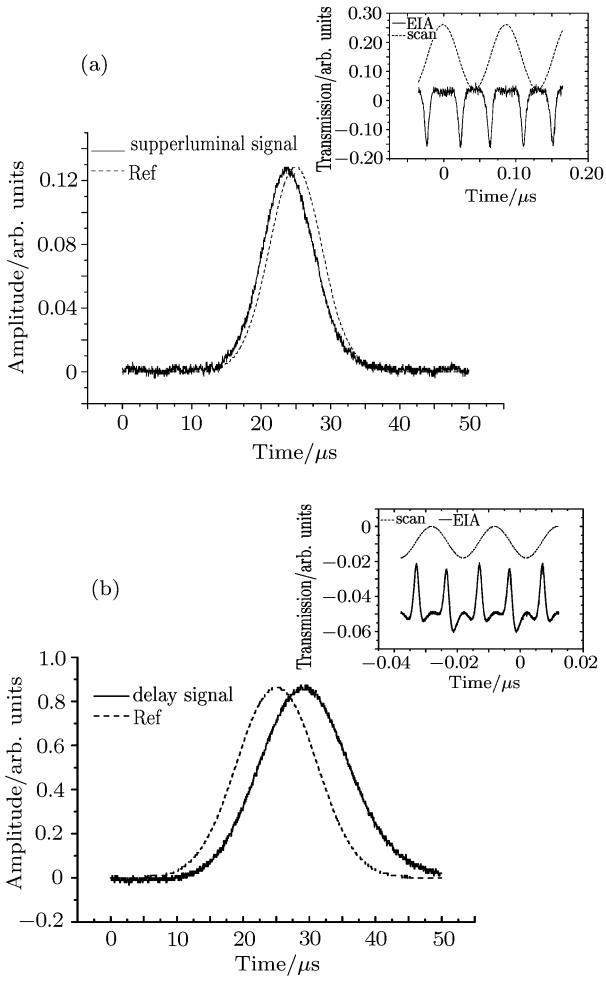


Fig. 5. (a) The fast-light signal at low power (about 0.06 mW) of the injected laser. The inset is the EIA absorption peak shown as the function of magnetic field. (b) The slow-light signal at high power (about 0.6 mW) of the injected laser. The inset is the EIT transmission peak shown as the function of magnetic field.

4. Conclusion

In this paper, we gave a new theoretical model to study the breaking point in a degenerate two-level system where EIT and EIA can be observed in a single transition line. The theoretical model is objective to image the real experimental condition. We analysed the condition from which arises EIA and EIT, respectively. In fact, the fruitful combination of Zeeman sublevels is responsible for the phenomenon in a degenerate two-level system. When the Rabi frequency of the pumping field is smaller than the spontaneous emission rate, the effect of spontaneous transfer of optical coherence is significant. Thus, the absorption of the probing field is enhanced. However, with increasing of the Rabi frequency of the pumping field, a majority of atoms is populated on the ground level, an equivalent V-type EIT system is presented. Therefore, only changing the Rabi frequency of the pumping field, we can get the switch between EIA and EIT. In addition, the changing trend of the susceptibility depended on Rabi frequency of pumping field is presented and the theoretical value of the breaking point is denoted. We investigated the phenomenon based on a closed transition line of Cs atom in experiment. With the changing of the power of the injected laser, the spectroscopy of the atomic system is transferred from EIA to EIT. The power of the breaking point is about 0.08 mW. On the other hand, by observing the fast-light and slow-light, we verify the development trend of dispersion depending on the power of the pumping field. The realization of the switch between EIA and EIT gives us a new method to build an integrated and compact all-optical buffer.

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