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Experimental investigation of slow light propagation in degenerate two-level system*

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Slowing a light pulse in a degenerate two-level system is observed with a double-frequency sweeping technique. The effects of coupling beam intensity, cell temperature and frequency detunings of the coupling and probe beams in resonance, on the slowing of light propagation in such a system are investigated. It is found that group velocities depend strongly on polarization combinations. A group velocity v_g=6760m/s of light pulses in caesium vapour is obtained under the optimal parameters.

Keywords: electromagnetically induced transparency, time delay, group velocity
PACC: 4250, 4225J, 3280

1. Introduction

Electromagnetically induced transparency (EIT)[1−3] is a quantum interference phenomenon that occurs when a weak probe beam that is in resonance with an atomic transition of its propagation through a medium shows a reduction in absorption due to the effect of a strong coupling beam on an associated transition. Many interesting phenomena, such as coherent population trapping,[4] lasing without inversion,[5] slowing of light propagation,[6−9] storage of light[10−12] have received considerable attention in recent years. Harris *et al* studied theoretically the dispersive property of EIT,[13] and indicated that there existed a highly normal dispersion in the centre of the transparency window in which the group velocity of light pulse could be very slow. Xiao and his co-workers obtained a group velocity $v_g=c/13.2$ in 1995.[14] Schmidt obtained a group velocity $v_g=c/3000$ in 1996.[15] In 1999, v_g=17ms^{-1} was obtained in magnetically trapped Na vapour by Hau *et al*.[7] However, to the best of our knowledge, no experiment has been reported to clarify the dependence of optimal slowing of light propagation on its associated conditions, such as temperature, intensity, the detuning of coupling and probe beams and their polarization combinations. The solution to this problem would be not only helpful for the understanding of the physical mechanism for the slowing of light propagation, but also of great importance in its applications. In this paper, we report electromagnetically induced transparency in degenerate two-level system. Optimal condition for the slowing of light propagation is obtained. A group velocity is measured under the optimal condition. A qualitative explanation of the result is also given.

2. Experimental set-up and results

The basic experimental set-up is depicted in Fig.1. An extended cavity diode laser (Sacher TEC100) is used as a resonant light source for the caesium D_2 line. The free-running linewidth is less than 1MHz. Two acoustooptic modulators (AOM) are used to produce mutually cohered coupling and probe beams with a finely tunable frequency offset. Two beams are so arranged that they propagate in the same direction through a 4.8-cm-long Cs-vapour cell with no buffer

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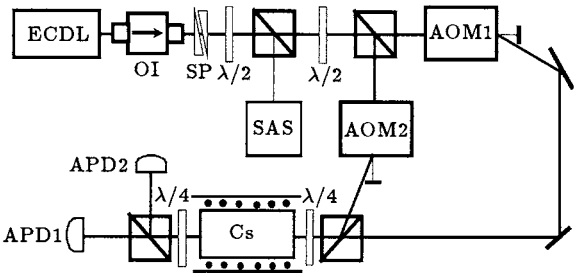


Fig.1. Experimental set-up. ECDL stands for external cavity diode laser; OI for optical isolator; SP for shaping prism; SAS for saturated absorption spectrum; AOM for acoustooptic modulator; APD for avalanche photodiode.

gas. The diameter of the probe beam is about 10mm, which is smaller than that of the coupling beam (15mm) to ensure a good overlapping. The power of the probe beam is 100μW before entering the Cs cell. The Cs cell is wrapped with four μ-metal sheets to minimize the terrestrial magnetic field inside. A controllable longitudinal magnetic field is generated by a solenoid mounted inside the magnetic shield to set off the residual magnetism. So all magnetic sublevels in the hyperfine structures are ideally degenerate. The probe and the coupling beams pass directly through the Cs cell to examine the light propagation. A quarter-wave plate controls the polarizations of both the coupling and probe beams. The saturated absorption spectrum is used as the frequency reference. After passing through the cell the probe and coupling beams are separated by a polarization prism. The signals of the probe and coupling are detected separately by avalanche photodiodes (Hamamatsu Si APD, S3884).

The relevant energy levels are shown in Fig.2. The coupling beam and the probe beam are coupled in the same transition $6S_{1/2}$, F=3→$6P_{3/2}$, F'=2, and the Zeeman sublevels of both ground states and excited states are well degenerate separately since the Cs vapour cell is μ-metal shielded from terrestrial magnetism. Figure 2(a) shows the level scheme in which the coupling and the probe beams are both polarized circularly but oppositely; this level scheme is denoted by COC. Figure 2(b) exhibits the level scheme in which the coupling beam and probe beam are both polarized linearly but perpendicularly; this level scheme is labelled by LPL.

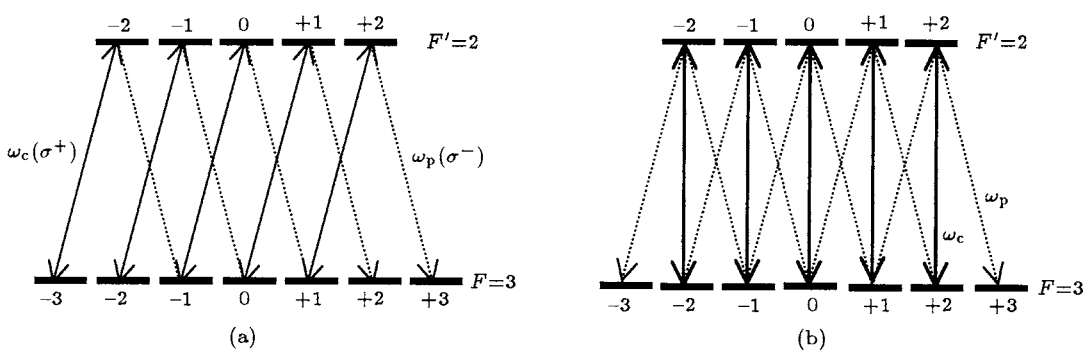


Fig.2. Different level configurations corresponding to the transitions $6S_{1/2}$, F=3→ $6P_{3/2}$, F'=2 for different choices of the coupling and probe polarizations: (a) for COC scheme; (b) for LPL scheme. Solid and dashed arrows correspond to the coupling and probe respectively.

A pulse of light propagates in a highly dispersive medium at a group velocity of

$$v_g = 2\pi(d\nu/dk) = c/[n + \nu(dn/d\nu)], \qquad (1)$$

where c is the speed of light in vacuum. Thus, the refractive index $n(\nu)$ and its derivative $dn/d\nu$ determine the value of the group velocity. A steep normal dispersion leads to a very small value of v_g. The value of v_g is measured by "time delay". The probe light is first transferred into a series of Gaussian pulses with an FWHM of 18μs. The light pulse series is further split into two pulse series by a beam-splitter (not shown in Fig.2) before entering the Cs cell: one serves as the probe light and the other is used as the reference light. Time delay is obtained by comparing the probe pulse with the reference pulse, and expressed as

$$\Delta T = L/v_g - L/c \cong L/v_g. \qquad (2)$$

In the experiment the double-frequency sweeping technique[16] is used. Two acoustooptic modulators are used to produce mutually cohered coupling and probe beams with a finely tunable frequency offset $\delta\upsilon$, and the two beams are in the COC scheme, the coupling power is 6mW and probe power is 100μW. The

laser frequency is slowly scanned across the Doppler profile while the frequency offset $\delta\upsilon$ is made to sweep tens of times faster but keeps its extent of variation less than the natural width of the optical transition (5.3MHz). When both the coupling and probe beams are in resonance with the $6S_{1/2}$, F=3→$6P_{3/2}$, F'=2 transition, a ground-state Zeeman coherence is achieved. The absorption profile is recorded at room temperature. Figure 3 is the EIT signal for the transition from $6S_{1/2}$, F=3→$6P_{3/2}$ levels.

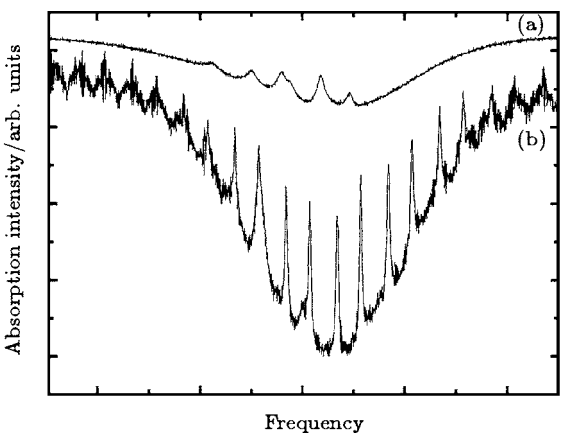


Fig.3. EIT signal observed in Cs cell at room temperature. The power of coupling is 6.0mW and the power of probe is 100μW. (a) Saturated absorption spectrum used as the frequency reference. (b) EIT signal versus the optical frequency for $6S_{1/2}$, F=3→$6P_{3/2}$ transition.

In order to obtain the optimal parameters for time delay in degenerate two-level systems, the effects of coupling beams intensity, cell temperature, frequency detunings of the coupling and probe beams and their polarization combinations, on the slowing of light propagation in such systems must be examined. Figure 4 shows the dependences of the time delay and the group velocity on the coupling beam intensity in the COC scheme. It can be seen that the time delay and group velocity vary nonlinearly with the coupling intensity. The occurrence of this nonlinearity can be attributed to the nonlinear dependence of EIT on coupling beam intensity. As the coupling beam intensity increases by a small value, both the EIT intensity and EIT linewidth can increase more rapidly. Correspondingly the time delay becomes ever larger until the coupling beam intensity reaches 6.8mW whereupon the time delay reaches the maximum. When the coupling beam intensity further increases, the EIT linewidth increases more rapidly than EIT intensity, thus leading to an ever more diminutive time delay of the probe light. The influence of the coupling beam intensity on the width and contrast of the absorption resonance generated by long-lived Zeeman coherence has been considered.

Agarwal and Dey studied the slowing of light propagation in a Doppler broadening two-level system using a theoretical calculation method.[17] For a two-level system interacting with a pumping light beam ω_c and a probing light beam ω, the effective susceptibility χ is given by[18]

$$\chi = -\frac{N|d|^2}{\hbar}\frac{1+\Delta^2T_2^2}{(1+\Delta^2T_2^2+4|G|^2T_1T_2)(\Delta+\delta+\mathrm{i}/T_2)} \times\left[1-\frac{2|G|^2(\Delta-\mathrm{i}/T_2)^{-1}(\delta+2\mathrm{i}/T_2)(\delta-\Delta+\mathrm{i}/T_2)}{(\delta+\mathrm{i}/T_1)(\delta+\Delta+\mathrm{i}/T_2)(\delta-\Delta+\mathrm{i}/T_2)-4|G|^2(\delta+\mathrm{i}/T_2)}\right], \quad (3)$$

where $\Delta=\omega_c-\omega_0$ and $\delta=\omega-\omega_c$ are the detunings of the pump and probe fields respectively. G is the Rabi frequency of the pump field. T_1 and T_2 are the longitudinal and transverse relaxation times, respectively. N is the density of atoms. For a Doppler broadening two-level system, the susceptibility χ should be averaged over the Doppler distribution of velocities to give a susceptibility $S(\omega)$ of the whole system. The group velocity v_g is related to the real part of $S(\omega)$ and given by

$$v_g=\frac{c}{n_g}=\frac{c}{(1+2\pi\mathrm{Re}[S(\omega)])+2\pi\omega\dfrac{\partial\mathrm{Re}[S]}{\partial\omega}}, \quad (4)$$

and the imaginary part of $S(\omega)$ gives the attenuation of the pulse.

It is pointed out that, under the condition of oppositely propagating pump and probe beams, a hole of the order of the homogeneous width is produced in the center of the Doppler broadening line. Numerical calculation gives the following results: assuming that the pump light is in resonance with the atomic transition, the imaginary part of $S(\omega)$ shows a typical Lamb lip while the real part of $S(\omega)$ exhibits a normal dispersion, which, in fact, is very pronounced. It is this sharp dispersion that produces the slowing of light propagation. A comparison shows that the present experimental results are in satisfactory accordance with the numerical calculations in Ref.[17].

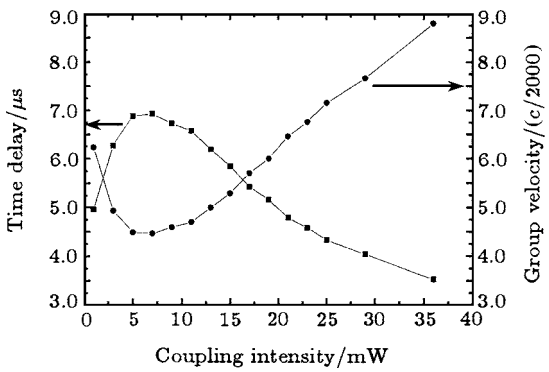


Fig.4. Time delay of the probe pulse (■) and Group velocity of the probe pulse (●), separately, as a function of coupling beam power.

It is found that the group velocity of probe light in dependent on polarization combination as shown in Fig.5, where symbols ▲ and ■ denote the COC scheme and the LPL scheme respectively.

Figure 5(a) shows the influence of Cs-cell temperature on the delay time. The temperature ranges from 22°C to 43°C and the curve is an exponential fit to the experimental data. It has been shown in Ref.[19] that

$$\rho_{21} \approx \frac{\mathrm{i}\Omega_1/2}{\gamma - \mathrm{i}\Delta_1 + \dfrac{\Omega_2^2/4}{\Gamma_3 - \mathrm{i}(\Delta_1 - \Delta_2)}}, \tag{5}$$

$$\chi = \frac{N\mu_{21}^*\rho_{21}}{E_1/2} = -\frac{2N\mu_{21}^2}{\hbar\Omega_1}\rho_{21}. \tag{6}$$

The magnitude of the EIT signal is proportional to the total number of atoms interacting with both coupling and probe fields while its spectral linewidth does not depend on the number of atoms. The atom density varies with temperature in an exponential way,[20]

$$\rho = 10^{(11.05-1.35\lg T-4041/T)}/(KT) \times 133.3. \tag{7}$$

The delay time is larger for higher Cs densities because $\mathrm{d}n/\mathrm{d}\nu \sim$N.[16] But when the temperature is raised above 43°C, the curve is falling instead of rising. The reason is presumably that the probe light is absorbed to a large extent. It can be concluded from Fig.5 that the slowing of light propagation is much slower in the COC scheme than in the LPL scheme. In other words, the EIT in the COC scheme is more efficient than in the LPL scheme, which is in accordance with the theoretical result.[21]

The time delays of probe pulse for various detunings until a fixed Cs-cell temperature 40°C are measured and shown in Fig.5(b), where the coupling and the probe beam frequencies are equal and both detuned from resonance by the same amount. The maximum delay time occurs when the two beams are in resonance. The reason for that is as follows. The Doppler broadening of Cs atoms is far larger than the natural linewidth of $6S_{1/2}$, F=3→$6P_{3/2}$, F'=2 transition. Therefore, the detuned beams interact only with those atoms for which the beam detuning is balanced by the Doppler frequency shift, namely, the velocity V and the beam detuning $\Delta\nu$ meet the condition $V = \lambda_0 \cdot \Delta\nu$, where λ_0 is the wavelength of the beam. Since the velocities of atoms obey a Gaussian distribution, the time delay is proportional to the number of interacting atoms. The dependence of time delay on detuning also has a Gaussian profile. In the present experiment, the combination of the COC scheme is more efficient than that of LPL scheme in the slowing of light propagation. This is because through the interaction magnetic sublevels are also divided into two subsystems connected by the spontaneous transition, and each subsystem contains a coherence population trapping (CPT) state.[22] Because the atom is transferred to the CPT state by a spontaneous process, the EIT is more efficient in the COC scheme than in the LPL scheme.

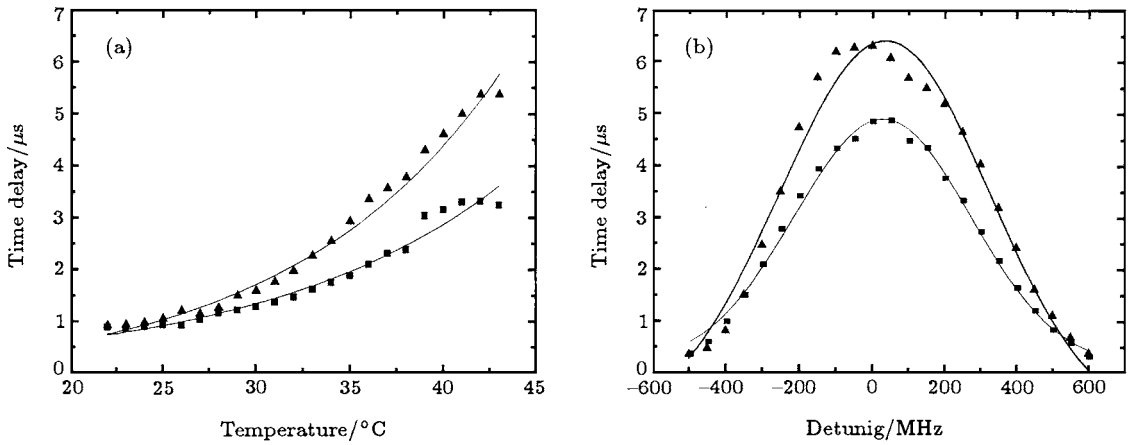


Fig.5. Time delay versus the temperature of Cs cell and detuning of coupling beam separately, the former is an exponential fit; the latter is a Gaussian fit. The symbol ▲ denotes the coupling beam and probe beam being circularly and oppositely polarized (COC scheme). The symbol ■ denotes the coupling beam and probe beam being linearly and perpendicularly polarized (LPL scheme).

A maximal time delay is observed under the optimal parameters, namely, the coupling beam being 6.8 mW in power and in resonance with $6S_{1/2}$, F=3→$6P_{3/2}$, F'=2 transition, the temperature of caesium cell being 40°C, coupling and probe polarizations being in the COC scheme. We have found that delayed pulses are slightly narrower in duration than the reference pulse. The reshaping happens mainly on the falling side. The delay times are measured by comparing the peak positions of the probe and reference pulses. Most of the error in the measurements is due to asymmetric pulse reshaping. In order to see the delay clearly, normalized heights of pulses are shown in Fig.6. The delay time is 7.1μs and the calculated group velocity is about 6760m/s.

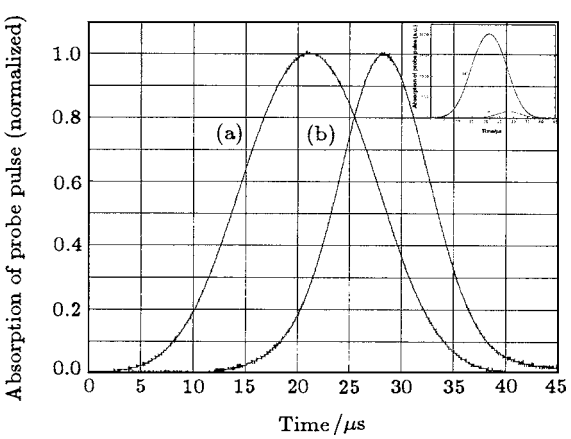


Fig.6. Normalized pulse delay for light pulses travelling through the caesium vapour in the EIT. (a) The reference pulse, (b) The probe pulse (in the COC scheme).

3. Conclusions

Long-lived Zeeman coherence causes a steep dispersion in atomic media. And the study of light propagation in such systems is still an interesting subject because of its significance in basic research and promising applications, including quantum information processing. The progress in the study of light propagation in degenerate systems is connected with storage of light.

The slowing of a light pulse in a degenerate two-level system is observed with a double-frequency sweeping technique. The effects of coupling beam intensity, cell temperature and frequency detunings of the coupling and probe beams in resonance, on the slowing of light propagation in such a system are investigated. It is found that the group velocity depends largely on polarization combination. A group velocity v_g=6760m/s of light pulses in caesium vapour is obtained under the optimal parameters.

As the next step, a Cs cell with buffer gas will be used to carry on the same experiment. In this way the long-lived Zeeman coherence will further be examined and a longer delay will be expected.

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