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The manipulation of light pulse from subluminal to superluminal propagation in a degenerate two-level Cs atomic system

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We experimentally demonstrate the propagation of light pulse from subluminal to superluminal light based on quantum coherence in a degenerate two-level atomic system in a Cs vapor cell. It is shown that the group velocity of light pulse can be switched from subluminal to superluminal propagation via changing the coupling field from a traveling wave to a standing wave, while can also be continuously manipulated by varying the intensity of two waves superposed to form a standing wave. The observed maximum delay and advance times are about 0.45 and 0.54 μs, corresponding to the group velocity of v_g = 168 km/s and v_g =−138 km/s, respectively. This investigation may have the practical applications of devices for optical tunable delay lines, optical switching and optical buffering.

group velocity, subluminal, superluminal, quantum coherence, standing wave

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1 Introduction

Quantum coherence of electromagnetically induced transparency (EIT) can make an optic opaque medium transparent due to the quantum interference between two dressed states [1], and the corresponding steep normal dispersion within the transparency window can leads to a large reduction in the group velocity of light [2]. These effects have attracted much interest owing to its applications in photon controlling and information storage [3–5] and quantum communications [6]. The quantum coherence created in the atom-light system can also leads to the electromagnetically induced absorption (EIA) [7] characterized by narrow absorption gain and abnormal dispersion, contrary to the effect of EIT. The mutual transform between EIT and EIA may be controlled, for instance, by properly chosen arrangements of levels, polarizations, and laser detunings [7,8], by applying of an external magnetic field [9] and a resonant microwave field [10], or by changing the coupling field from traveling wave (TW) to bichromatic fields [11–14] and standing wave (SW) [15,16].

EIT is the phenomenon of normal dispersion with the reduction of the probe's group velocity. On the other hand, EIA is the phenomenon of anomalous dispersion which makes the group velocity faster than the speed of light. However, this raised difficulties with the theory of relativity which states that no velocity can be higher than the velocity of light in a vacuum (c=3×10^8 m/s). In order to reconcile the superluminal group velocity in an anomalous dispersion medium with the implied limitation from relativity, Brillouin [17] pointed out that causality only requires the speed

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of a signal carried by light be limited by c, rather than the light pulse itself which travels at the group velocity.

The subluminal and superluminal light propagations have been well studied in a variety of situations. The first experimental demonstration of group velocity reduction to $v_g \sim c/165$ has been achieved in an atomic vapor via EIT [18]. The ultraslow group velocity has also been investigated in ultracold atoms [2,4], heated atomic vapor [5] and solid media [19–22]. And on the other hand, the superluminal light propagation has also been demonstrated experimentally in a lossless anomalous dispersive medium of Cs vapor cell [23] and in other material [24]. The mutual transformation between subluminal and superluminal light has also been observed in two- and four-level atomic system by changing the power of pump power with the corresponding group velocities $v_g \sim 0.0003c$, $-0.00007c$ and $v_g \sim 0.0003c$, $-0.0004c$ [25,26]. And also it can be accomplished in three-level system by changing the single-photon detuning [27]. Very recently, the continuous manipulation of the light group velocity from subluminal to superluminal propagation has been presented in a Λ-type system of ^{87}Rb vapor cell via an SW coupling field, the group velocity of the probe pulse was manipulated from $v_g \sim 0.004c$ to $v_g \sim -0.002c$ [28]. Under the SW coupling of Λ-type three-level atomic system, the dispersion of atoms was switched from normal to abnormal due to the absorption changing from EIT to EIA [16], leading to the change of group velocity from Subluminal to superluminal light. Actually, when the SW is coupled to the atoms, its periodic spatial intensity distribution makes the refractive index of the atomic medium be periodic spatial modulation, which behaves like a photonic crystal. We found that the similar effects of reflection band-gap, and optical diode were caused in ^{133}Cs atoms [29,30]. And by comparing the reflection spectra in the three- and degenerate two-level system, we showed that the reflection efficiency can be improved in degenerate two-level system due to enhanced quantum coherence via ground state population trapping. Based on these results, we then investigate, in this paper, the transformation of the light group velocity from subluminal to superluminal propagation in the degenerate two-level atom system of Cs vapor cell by controlling the coupling beam from TW to SW. The manipulation of group velocity (from subluminal to superluminal, again to subluminal propgation) is largely obtained by varying the amplitudes of the SW coupling field, and compared to the results in three-level system in Rb vapor [28], and one order of magnitude of group velocity is improved in the degenerate two-level system in Cs vapor, which are v_g = 0.00056c and $v_g = -0.00046c$, corresponding to the group velocity of $v_g = 168$ km/s and $v_g = -138$ km/s, respectively. In Table 1, we list the related results for the subluminal and superluminal propagation of light in atomic system.

2 Experimental setup

We investigate the propagation of light pulse in a coherently prepared two-level degenerate system of the transition $F=4 \leftrightarrow F'=3$ in the ^{133}Cs D1 line of a vapor cell driven by a SW coupling field and a TW probe field [23]. The experimental setup is shown in Figure 1. A Ti:sapphire laser (Coherent MBR110) with the linewidth of ~75 kHz serves as coupling and probe lights. When a linearly polarized laser beam is transmitted through an intensity electro-optic modulator (EOM) driven with an electrical Gaussian impulse, the polarization is slightly rotated to create a weak pulse light, and the beam is next split into two orthogonal linear components by a polarizing beam splitter (PBS), The weaker component causing a pulse is used as a probe pulse, whereas the strong continues-wave (CW) component is applied as a coupling light, which is further split into two beams of forward and backward coupling fields with a beam splitter (BS) to form the SW field. The solid black and grey lines represent the coupling and probe beams respectively, as shown in Figure 1. Both the coupling and the probe field pass through a 0.6-mm-diameter aperture before entering a 7.5 cm vapor cell with AR coated end windows (the loss of the far-off resonant light through the cell is measured to be 4%), and they were polarized linearly and perpendicular to each other. The vapor cell without buffer gas at 55°C is shielded against external magnetic fields by three layers of μ-metal.

3 Absorption and group velocity measurement

We first measure the absorption properties of the probe light under the SW coupling. In this case, the modulation of the

Table 1 Summary of subluminal and superluminal propagation

Year	Atom	System	Subluminal (km/s)	Superluminal (km/s)	Mechanism
2003(PRA)	Cs vapor	two-level	100	−20	via power and polarization of pump
2004(PRA)	Rb vapor	three-level	8.9	−80	via single-photon detuning
2004(PRA)	Rb trap	four-level	90	−120	via signal light
2011(PRA)	Rb vapor	three-level	1200	−600	via SW power, tunable
This work	Cs vapor	three-level	168	−138	via SW power, tunable

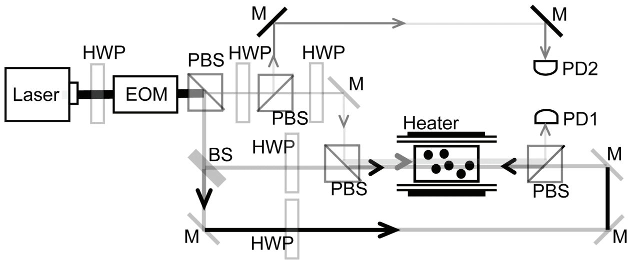

Figure 1 Schematic of the experimental setup. HWP: half-wave plate; EOM: electro-optic modulator; PBS: polarization beam splitter; BS: beam splitter; M: reflecting mirror; PD1, 2: photon detectors.

EOM is switched off, the light after EOM is only used as a strong TW coupling beam, and a grating-feedback external-cavity diode laser (Toptica DL100) with the linewidth of ~1 MHz is used as the CW probe light. The coupling laser frequency is locked to transition $F=4\leftrightarrow F'=3$ of cesium D1 line and the probe laser frequency was scanned across this transition. The powers of forward coupling and the probe fields are 4 mW and 100 μW respectively. The transmitted probe beam is detected by a PD1 and recorded by a digital oscilloscope. Figure 2(a) shows the probe absorption coefficient α vs. the probe detuning when the power of backward coupling field is varied from 0 to 4 mW. A typical EIT signal can be observed around the two-photon resonance condition, see curve (i) in Figure 2(a) with 0 mW backward coupling, i.e., only forward TW coupling. And the interesting aspect of this EIT situation is its controllability by appropriately changing the power of backward coupling field, as shown in curves (ii)–(vi). As the power is increased gradually, the EIT dip is changing gradually into a narrow absorption peak with small dips at the middle of spectrum. This implies that controlling power of the backward coupling fields can lead to controlling of absorption width, shape, and even its sign very effectively. The variation in absorption of medium from EIT to high absorption will be accompanied by variation in the dispersion of the medium from normal to anomalous [16], and correspondingly, the group velocity $v_g=c/(1+\omega\mathrm{d}n/\mathrm{d}\omega)$ of probe pulse with the frequency of ω will be manipulate from subluminal (for normal dispersion $\mathrm{d}n/\mathrm{d}\omega>0$) to superluminal (for abnormal dispersion $\mathrm{d}n/\mathrm{d}\omega<0$) propagation by controlling the power of backward coupling in this system.

The controllability of group velocity of light pulse by manipulating the backward coupling power is expected in the degenerate two-level system of $F=4\leftrightarrow F'=3$ of Cs D1 line because of the significant variation in the absorption induced by the efficient ground state population trapping [23]. We use only one laser of Ti:sapphire in order to ensure better coherence, and the frequency of laser is locked to the transition $F=4\leftrightarrow F'=3$. In order to measure the delay or advance time $\Delta T=L(1/v_g-1/c)$ ($\Delta T>0$ for subluminal light, $\Delta T<0$ for superluminal light) of the probe beam, we switch on the modulation of EOM to generate a pulse probe light with 8 μs width. A small part of pulse is extracted by a BS to be the reference pulse, which is detected by the detector PD2, as shown in curve (i) in Figure 2(b), and the other curves in Figure 2(b) are the normalized intensity of the output pulse throughout the vapor cell, when the power of forward coupling field is set to be 4 mW, while the power of backward coupling field is 0 mW (curve (i)), 1 mW (curve (ii)), 3 mW (curve (iii)), 3.4 mW (curve (iv)), 3.8 mW (curve (v)) and 4 mW (curve (vi)). The

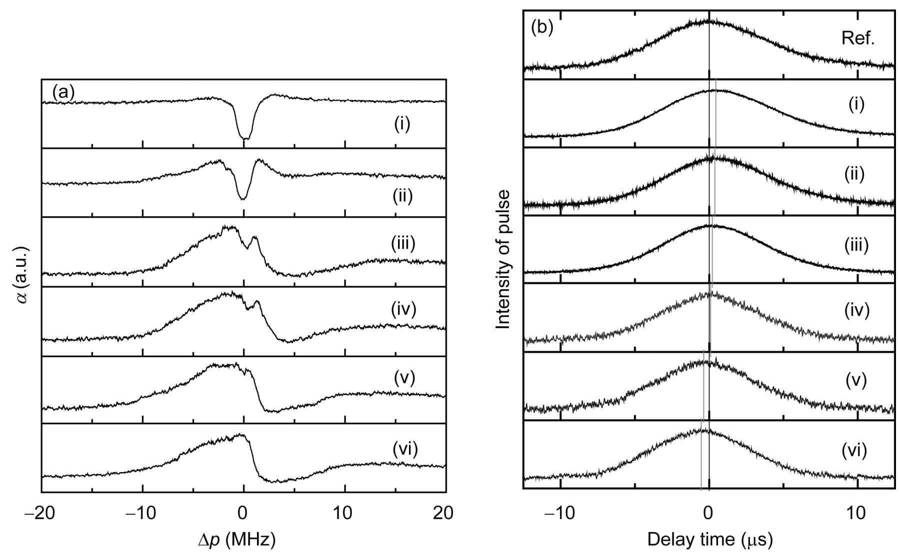

Figure 2 (a) The absorption spectrum of probe light vs. probe detuning for different power of backward coupling field of (i) 0 mW, (ii) 1 mW, (iii) 3 mW, (iv) 3.4 mW, (v) 3.8 mW, (vi) 4 mW, the power of forward coupling field is 4 mW, the temperature of vapor is set at 55°C. (b) The intensity of output pulse of probe light vs. time, the other parameters are the same as that in (a).

maximum delay time ΔT is 0.45 μs when the backward coupling field is 0 mW, and the corresponding subluminal group velocity of probe light is $v_g = 0.00056c$. With the increase of power of backward coupling field, the delay time decreases from 0.45 μs to zero (curves (ii)–(iv)) firstly, and then becomes negative (curves (v) and (vi)), which means that the group velocity of the weak pulse propagation can be changed from subluminal group velocity to superluminal group velocity by varying the power of backward coupling field. The power-dependent behaviors of both subluminal and superluminal propagation are shown in Figure 3. The group velocity for subluminal propagation occurs at the backward coupling light power of 0–3.4 mW. And the superluminal propagation happens with the power in the range of 3.4–5 mW. The maximum delay time $\Delta T = -0.54$ μs with the group velocity $v_g = -0.00046c$ is obtained under the condition that the backward coupling light power equals to the forward light power, i.e., complete SW coupling. A further increase of the power of backward coupling light (larger than 5 mW) will not lead to any changes in group velocity, and it may induce the deformation of output light pulse. It is also noted from Figure 3 that the subluminal group velocity changes slowly with the power of backward coupling light, and the superluminal behavior is more sensitive to the power of backward coupling light.

4 Conclusion

In conclusion, we have demonstrated manipulation of absorption properties of the probe light of the degenerate two-level system interacting with a weak travelling probe and a strong SW coupling lights. The absorption varied from EIT, EIT within absorption window, and only one steep absorption window with increase of backward coupling field, which provided various group velocity dispersion in the two-level system medium, and thus lead to the corresponding changes of the group velocity from subluminal to superluminal propagation.

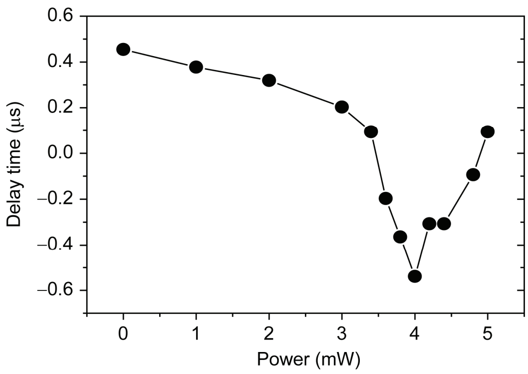

Figure 3 The delay time of the output light pulse vs. the power of the backward coupling field. The other parameters are the same as that in Figure 2.

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