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Superluminal reflection and transmission of light pulses via resonant four-wave mixing in cesium vapor

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Abstract: We report the experimental manipulation of the group velocities of reflected and transmitted light pulses in a degenerate two-level atomic system driven by a standing wave, which is created by two counter-propagating light beams of equal frequencies but variable amplitudes. It is shown that the light pulse is reflected with superluminal group velocity while the transmitted pulse propagates from subluminal to superluminal velocities via changing the power of the backward coupling field. We find that the simultaneous superluminal light reflection and transmission can be reached when the power of the backward field becomes closer or equal to the forward power, in this case the periodical absorption modulation for photonic structure is established in atoms. The theoretical discussion shows that the anomalous dispersion associated with a resonant absorption dip within the gain peak due to four-wave mixing leads to the superluminal reflection, while the varying dispersion from normal to anomalous at transparency, transparency within absorption, and electromagnetically induced absorption windows leads to the subluminal to superluminal transmission.

OCIS codes: (270.1670) Coherent optical effects; (270.5530) Pulse propagation and temporal solitons; (020.1670) Coherent optical effects.

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1. Introduction

The speed of light is one of the basic concepts of physics. An actual light pulse with a finite extent travels at a different speed, the velocity at which a peak of optical pulse travels is known as the group velocity v_g. The control of group velocity of light has attracted much

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interest due to their potential applications in nonlinear optics [1,2], photon controlling and storage [3,4], high-speed optical switching [5], quantum communication [6], and precision sensing [7,8].

The group velocity of a light pulse can be slowed down (i.e. subluminal propagation speed) when the dispersion has a steep positive slope in electromagnetically induced transparency (EIT) media of atoms [2–6,9,10], solids and fibers [11,12]. On the other hand, the group velocity can be faster than the speed of light in vacuum *c* (i.e. superluminal propagation speed), or even negative in anomalous dispersive atomic systems [13,14] and solid materials [15,16]. The manipulation of the group velocity from a subluminal to a superluminal propagation speed has also been demonstrated in atomic systems by changing one-photon detuning [17], amplitude [18] and single-into standing-wave [19] of the coupling field, and in optical fibers by changing the cross-gain modulation phase [20].

In order to investigate multichannel signal processing, the simultaneous control of the propagation of one more pulse should be necessary. Recently, the subluminal propagation of probe light and superluminal propagation of other interacting signal or pump light has been demonstrated in nonlinear EIT atomic systems [21,22]. Furthermore, the slow-slow or slow-fast pulse pair (note that one is the transmitted injected probe pulse and the other is the generated signal pulse) has also been investigated in four-wave mixing (FWM) atomic systems [23–25]. Very recently, the fast-fast pulse pair for injected and generated conjugate pulses could also be realized via stimulated Raman FWM in atomic vapor [26]. These results revealed that the nonlinear effects play a crucial role in the development of light propagation control [26,27].

Most of the discussions on the control of pulse propagations have been considered for one or two pulses, which are transmitted through the medium. It has been demonstrated in theory that, the pulse can be reflected with a superluminal propagation in phase conjugate and photonic devices [28–30], it means that the peak of reflected pulse exits the medium before the peak of incident pulse enters the medium. Thereafter, the experimental verification of such effect has been performed in solid mediums of photonic barriers and fibers [31–33]. It also has been predicted that both of the reflected and transmitted pulses can propagate superluminally [28], and can be used to discuss the Kramers–Kronig relation in a slab with a multiple interference effect [34]. The simultaneous superluminal propagation of two pulses could also have key applications in optical communication [27].

In our experiment, we first demonstrate the superluminal pulse reflection and transmission in an atomic system driven by a standing wave with two forward and backward propagating fields. When an incident probe pulse travels through the system, the group velocity varies from subluminal to superluminal via changing the power of backward field. Meanwhile, the probe pulse is also reflected with a superluminal group velocity. Changing the power of backward field while keeping the forward field constant makes the spatial intensity distribution of the coupling field vary from an imperfect standing wave to a perfect standing wave, which may result in the periodical absorption modulation in atoms, therefore the optical property of photonic structures with multiple interference could be established [35]. Consequently, the enhanced FWM and periodical absorption modulation in atoms leads to the effect that the group velocity of the transmitted and reflected pulses is controlled.

2. Experimental setup

Our experiments are performed with cesium atoms in a vapor cell with a length of 75mm (the loss of the far-off resonant light through the cell is 4%). Figure 1(a) shows the simplified three-level structure formed by a degenerate two-level system including a ground state ($F=4,6^2S_{1/2}$) and an excited state ($F'=3,6^2P_{1/2}$) of the D_1 line of the ^{133}Cs atom. Two identically polarized counter-propagating coupling light beams [red lines in Fig. 1(b)] with frequency ω_F, ω_B drive the transition $F=4\rightarrow F'=3$, while a probe light beam [blue line in Fig. 1(b)] of ω_p with a polarization perpendicular to the coupling light is interacting on this transition. In this atom-light coupling scheme, an efficient resonant FWM effect can be obtained, based on quantum coherence {see the results in ref [36] for continuous waves}. A FWM signal with frequency $\omega_r = \omega_F + \omega_B - \omega_p$ in the reflection direction of the probe light [dashed line in Figs. 1(a) and 1(b)] is generated due to phase-matching condition. The forward coupling light beam with power of 4 mW and the backward coupling light beam whose power is changing from 0 mW to 5 mW are superposed to form a partial standing wave (the powers of the two counter-propagating coupling light beams are different) or a perfect standing wave (the power of the two counter-propagating coupling light beams are equal to 4 mW). The probe field with a power of 100 μW is modulated by an electro-optic intensity modulator (EOM), such that a pulsed light beam is formed. The pulse is induced by driving the EOM with an 8 μs Full Width at Half Maximum (FWHM) electric Gaussian function. The vapor cell without buffer gas at $55\ ^{\circ}\mathrm{C}$ is shielded against external magnetic fields by three layers of μ-metal. A part of the light pulse split from the probe pulse by the PBS is used as a reference pulse to measure the propagation delay time of probe and reflected pulse. The transmitted probe, reference, and reflected FWM signal pulses are detected by photodetectors (PD) 1, 2, and 3, respectively.

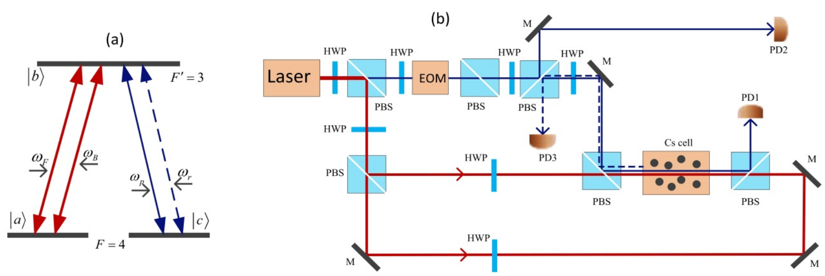

Fig. 1. (a) A simplified energy level scheme. (b) The schematic of the experimental setup. HWP: half-wave plate; EOM: electro-optic modulator; PBS: polarization beam splitter cube; M: reflecting mirror; PD1, 2, 3: photo detectors.

3. Experimental results

Figure 2 shows the detected delay time of the propagations of the probe and reflected signal pulses with the power of the backward coupling light, which increases from 0 mW to 5 mW, while the forward coupling light is fixed at a power of 4 mW. Hence, the strong coupling light is changed from a travelling wave, to an imperfect standing wave, to a perfect standing wave and then back to an imperfect standing wave again. Figures 2(a) and 2(b) are the delay times for the probe pulse transmitted through the vapor cell and for the reflected pulse passed through the vapor cell in backward direction, respectively. The delay time for the probe pulse is measured by comparing the peaks of the pulse on the detector PD2 [black line in Fig. 2(a)] with the peaks on PD1 [color lines in Fig. 2(a)], while the delay time for the reflected pulse is determined by the comparison of the pulses on PD2 [black line in Fig. 2(b)] and with the pulses on PD3 [color lines in Fig. 2(a)]. One can see that the delay time of the probe pulse varies from 0.45 μs to 0 μs and then to a negative value (i.e. advance time). The positive and negative values of the delay times Δt are corresponding to subluminal and superluminal propagation, according to the evaluation by $\upsilon_g = L/\Delta t$, where L is the length of the Cs cell. The maximum delay Δt of the probe pulse is 0.45 μs, which is obtained on the conditions of travelling-wave coupling light, corresponding to the group velocity $0.00055c$ (168 Km/s). The maximum advance time of the probe light is −0.54 μs, obtained with a perfect standing-wave coupling field. The corresponding group velocity is $-0.00046c$ (−138 Km/s). At the same time, the reflected signal pulse always exhibits superluminal propagation speed with an advance in time. The maximum advance in time for the reflected pulse is −0.87 μs, corresponding to a group velocity of −0.00029*c* (−87 km/s). These effects can be explained by atomic dispersion induced by quantum coherence. In this atom-light quantum coherence scheme, when the coupling light is changed from a single forward travelling light, partial standing wave, to a perfect standing wave, the absorption of the probe light is gradually transformed from an EIT dip, EIT within absorption, to a narrow absorption peak, correspondingly, the dispersion is gradually changed from a normal to a steep anomalous dispersion [37]. As a result, the velocity of probe pulse can be tuned from subluminal to superluminal by varying the intensity of coupling field. For the reflected light, a gain peak with an absorption dip in the center of resonant frequency is obtained due to resonant FWM, leading to an anomalous dispersion, which results in the superluminal propagation of the reflected light.

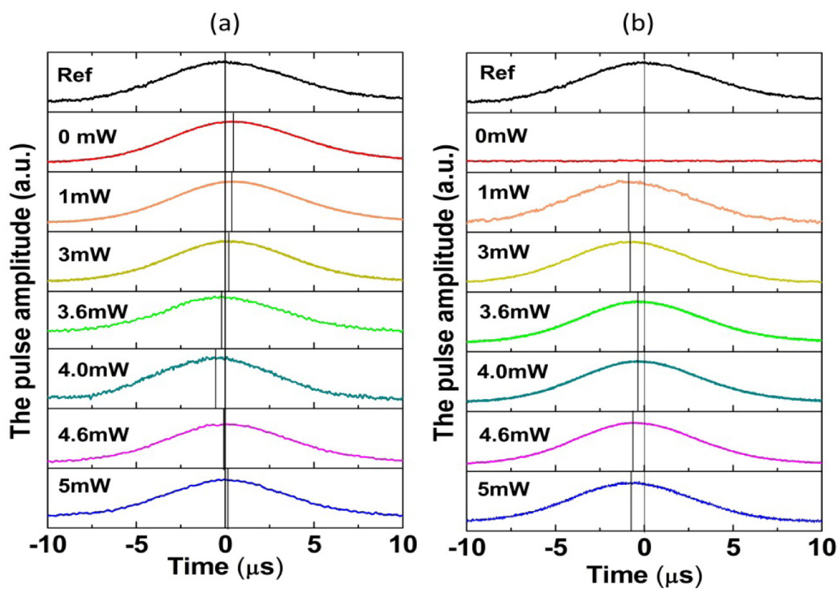

Fig. 2. The delay time for (a) probe and (b) reflected pulses.

Figure 3 shows the simultaneous manipulation of the group velocity of the probe pulse (red dots with error bar) and reflected pulse (blue triangles with error bar). In most cases, when the power of the backward coupled light is clearly not equal to the power of the forward coupled light, the propagation of the probe is subluminal while the reflected pulse is superluminal. However, when the power of the backward coupled light is nearly the same as the power of the forward coupled light, i.e. the light is forming a perfect standing wave, both, the probe pulse and the reflected pulse can propagate superluminally, in which case, the strong periodical intensity distribution of perfect standing wave leads to the periodical absorption modulation for probe. This may related to multiple interference effect due to the photonic property in atomic system [35]. The fast-slow to fast-fast pulse pair can be created via changing the power of the backward coupled light pulse. The solid lines in Fig. 3 are the theoretical fits with an incident Gaussian pulse expressed as:

$$E_p(0,t) = \frac{1}{\sqrt{2\pi}} Exp\left[\frac{-t^2}{2\tau^2}\right] \times Exp[-i\omega_0 t], \tag{1}$$

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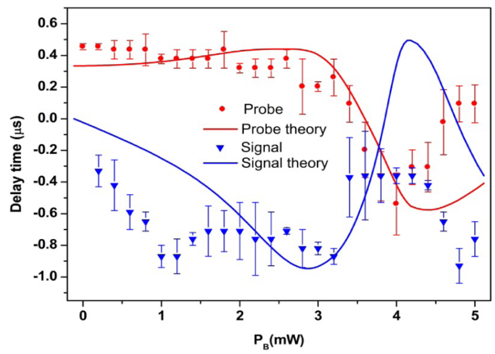

Fig. 3. The simultaneous manipulation of the delay for the probe and reflected pulses. The other experimental parameters are the same as those in Fig. 2.

Here $E_p(0,t)$ is the envelop of Gaussian pulse with the electro field of Gaussian pulse $\vec{E}_p = \vec{E}_0 E_p(0,t)$, $\vec{E}_0$ is a constant parameter [38,39]. The Fourier spectrum is

$$E_p(0,\omega_p) = \frac{\tau}{\sqrt{2\pi}} Exp\left[\frac{-\tau^2(\omega_p-\omega_0)^2}{2}\right], \tag{2}$$

where τ is the temporal width of the Gaussian pulse, and ω_0 is the center frequency. In the following numerical calculations, we take $\omega_0 = 2\pi\times 3.35\times 10^{14}\,\text{Hz}$ and $\tau=8\,\mu\text{s}$. The electric field of the pulse throughout the vapor cell L can be written as [38,39]

$$E_p(L,t) = \int_{-\infty}^{\infty} d\omega_p \times E(0,\omega_p)\times Exp\left[-i\omega_p\left(t-\frac{Ln(\omega_p)}{c}\right)\right], \tag{3}$$

The refractive index of atoms driving by two counter-propagating fields is [40]

$$n(\omega_p) = n_1 + n_2 E_F^* E_B = \tilde{n}_1 + \tilde{n}_2, \tag{4}$$

E_F, E_B are the amplitudes of the forward and backward coupling fields, respectively. The linear and nonlinear refractive indexes are

$$\tilde{n}_1 = 1+\frac{1}{2}\chi^{(1)},\ \tilde{n}_2 = \frac{3}{8}\chi^{(3)}E_F^* E_B, \tag{5}$$

The first- and third-order susceptibilities of the Doppler-broadened atoms in vapor cell are given by

$$\chi^{(1)} = \frac{N|\mu_{bc}|^2}{\varepsilon_0\hbar\Omega_p}\frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty}\tilde{\rho}_{bc}^{[0]}(\Delta_p,\Delta_d)\times\exp\left[-\Delta_d^2/(2\sigma^2)\right]d\Delta_d, \tag{6a}$$

$$\chi^{(3)} = \frac{N|\mu_{bc}|^2|\mu_{ba}|^2}{6\varepsilon_0\hbar^3\Omega_B\Omega_F^*\Omega_p}\frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty}\tilde{\rho}_{bc}^{[1]}(\Delta_p,\Delta_d)\times\exp\left[-\Delta_d^2/(2\sigma^2)\right]d\Delta_d, \tag{6b}$$

where N is the atomic number density, μ_{ab} and μ_{bc} are the dipole moments of transition, σ is the Doppler width. $\Omega_{F,B} = \mu_{ab}E_{F,B}/(2\hbar)$ and $\Omega_P = \mu_{bc}E_P/(2\hbar)$ are the Rabi

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frequencies of the forward (or backward) and probe fields, respectively. Δ_p is the detuning of probe field, Δ_d is the Doppler shift resulted from the moving atoms with finite velocity. $\tilde{\rho}_{bc}^{[0]}(\Delta_p,\Delta_d)$ and $\tilde{\rho}_{bc}^{[1]}(\Delta_p,\Delta_d)$ are the harmonic expansion coefficients of density matrix elements of atoms $\tilde{\rho}_{bc}=\sum_n \tilde{\rho}_{bc}^{[n]}(\Delta_p,\Delta_d)e^{-i2n\Delta_d t}$ given by

$$\frac{d\tilde{\rho}_{bc}}{dt}=\left(-i\Delta_p+i\Delta_d-\gamma_{bc}\right)\tilde{\rho}_{bc}+i\left(\Omega_F+\Omega_B e^{-i2\Delta_d t}\right)\tilde{\rho}_{ac}+i\Omega_p, \tag{7a}$$

$$\frac{d\tilde{\rho}_{ac}}{dt}=\left(-i\Delta_p-\gamma_{ac}\right)\tilde{\rho}_{ac}+i\left(\Omega_F^*+\Omega_B^* e^{i2\Delta_d t}\right)\tilde{\rho}_{bc}, \tag{7b}$$

γ_{bc} is the decay rate from the excited state $|b\rangle$ to the ground state $|c\rangle$. γ_{ac} is the decoherence rate between two ground states of $|a\rangle$ and $|c\rangle$. We assume that $\tilde{\rho}_{ac}=\sum_n \tilde{\rho}_{ac}^{[n]}(\Delta_p,\Delta_d)e^{-i2n\Delta_d t}$, so that we can obtain a time-invariant solution for $\tilde{\rho}_{bc}^{[0]}(\Delta_p,\Delta_d)$ and $\tilde{\rho}_{bc}^{[1]}(\Delta_p,\Delta_d)$ by taking $d\tilde{\rho}_{bc}^{[n]}/dt=0$ and $d\tilde{\rho}_{ac}^{[n]}/dt=0$.

In experiment, $\Omega_{F,B}$ is dependent on the forward (or backward) field intensity $I_{F,B}$, and determined by $\Omega_{F,B}=\gamma_{bc}\sqrt{I_{F,B}/2I_s}$. I_s is the saturation intensity. Therefore in Eqs. (4) and (5) we take the normalized forward Rabi frequency $\Omega_F=10$ (normalized by γ_{bc}), corresponding to the forward power of $P_F=4\,\text{mW}$ with the beam radius r = 0.5 mm. Correspondingly, Ω_B changes with the changes of backward power.

The imaginary (real) part of $\chi^{(1)}$ and $\chi^{(3)}$ correspond to the absorption (dispersion) of the transmitted probe and reflected signal fields, respectively. Figure 4 shows the absorption and dispersion properties of the transmitted probe pulse for different ratios of the Rabi frequency. We find that the absorption (dispersion) of the probe field experiences the transformation from EIT dip (normal dispersion), EIT dip within high absorption peak (normal dispersion) to absorption peak (anomalous dispersion) when the backward coupling light increases from Ω_B=0 ($R=0$) to $\Omega_B=10$ ($R=1$).

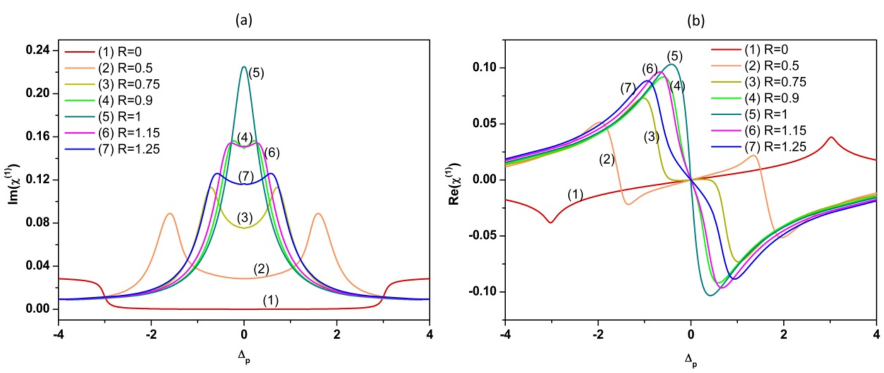

Fig. 4. The absorption (a) and dispersion (b) properties of the transmitted probe light. The related parameters are $\gamma_{ac}=0$, γ_{bc}=1, Ω_F=10, Ω_p=1.5.

While the absorption and dispersion properties of the reflected signal light pulse are simulated, as shown in Fig. 5. We find that the spectrum of the reflected field shows a resonant absorption dip within gain peak with anomalous dispersion.

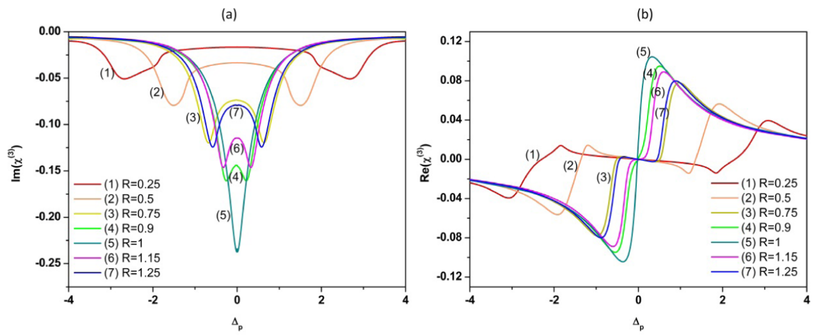

Fig. 5. The absorption (a) and dispersion (b) properties of the reflected signal light pulse.

The delay time of transmitted and reflected probe pulse is dependent on their absorptions and dispersions, represented by the following formula

$$\Delta t = \frac{L\omega_p}{2c}\frac{d\chi}{d\omega_p}, \tag{8}$$

It give rise to the effect that the group velocity of transmitted pulse changes from subluminal to superluminal due to the dispersion changes from normal to abnormal, while the group velocity of reflected field shows superluminal with always anomalous dispersion.

Seeing the obvious delay time of pulses, we substitute $\tilde{n}_1$ of Eq. (5) into Eq. (3), and obtain the intensity profiles of the transmitted pulses, showing the delay of the transmitted pulse. While substituting $\tilde{n}_2$ of Eq. (5) into Eq. (3), we can simultaneous obtain the intensity profiles of the reflected pulses, as shown in Figs. 6(a) and 6(b), see also inset for expanded view.

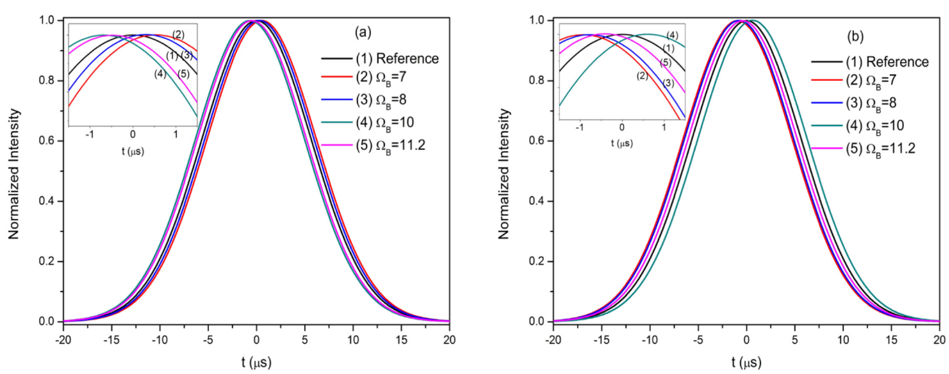

Fig. 6. The normalized intensity profiles of the transmitted pulses (a) and reflected pulses (b) at the different backward Rabi frequencies.

The delay time is obtained by comparing the peak of the transmitted and reflected pulses with the peak of Gaussian shaped reference pulse travelling through the vacuum (n = 1). It can be seen from Fig. 4(a) that when the Rabi frequency of backward Ω_B is lower than the Rabi frequency of forward $\Omega_F = 10$, the peak of transmitted pulse shows the delay time after the reference pulse peak. However, once $\Omega_B \geq \Omega_F = 10$, the peak of transmitted pulse shows the advance time before the reference pulse peak. Correspondingly, the pulse transmits from

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subluminal to superluminal when Ω_B varies. On the other hand, as shown in Fig. 4(b), the peak of reflected pulse shows the advance time with any value of backward Rabi frequency, except for the case of $\Omega_B = \Omega_F$ i.e the perfect standing-wave field formed by forward and backward fields, showing that the superluminal propagation of reflected pulse. It should be note that in the case of $\Omega_B = \Omega_F$, the reflected pulse shows its peak with delay time. But the experimental data shows that the reflected pulse propagates superluminally at any backward power. This deviation can be understood that when the reflected pulse is generated and transmitted throughout the atoms in the reflection direction, it has probe-like property for atoms under coupling with standing-wave field probe pulse, and therefore be re-absorbed by the atoms, this re-absorption supports superluminal propagation. See also Fig. 3, in which the solid curves are the fitted values to the experiment data using these theoretical results. The red theoretical curve for probe pulse is in good agreement with the experimental results (red dots). For the reflected signal pulse, the numerical simulations support the experimental results of superluminal propagation qualitatively.

4. Conclusion

In this paper, we have studied the simultaneous manipulation of the group velocity of a transmitted probe pulse and the reflected FWM signal pulse in a degenerate two-level atomic system. We realize the transformation from fast-slow light pair to fast-fast light pair and then to fast-slow light pair by solely changing the power of the backward coupling field. Moreover, we give a theoretical analysis of the experimental results. The results might be useful for controllable multichannel information processing, and development of active atomic devices be connected with compact photonic devices.

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