Observation of arbitrary group velocities of light from superluminal to subluminal on a single atomic transition line

Kyoungdae Kim, Han Seb Moon,* Chunghee Lee, Soo Kyoung Kim, and Jung Bog Kim†
Department of Physics Education, Korea National University of Education, Chung-buk, 363-791, Korea
(Received 27 September 2002; published 11 July 2003)

We were able to arbitrarily control the speed of a light pulse from subluminal to superluminal velocity by changing only the power of the laser for coupling coherently the single transition between $6\,^2S_{1/2}F=4$ and $6\,^2P_{3/2}F'=5$ in the D_2 line of a Cs atomic vapor system. With weak coupling power, a Gaussian light pulse was propagated superluminally with a negative group velocity $v_g=-c/14\,400$, which is caused by a highly anomalous dispersion related to an electromagnetically induced absorption. By increasing the coupling power at the same laser frequency, the pulses were propagated with a vacuum speed at the middle power and a subluminal group velocity $v_g=c/3000$ at high power, which is caused by a normal dispersion related to an electromagnetically induced transparency. It was also found that group velocities depend largely on polarization combinations.

DOI: 10.1103/PhysRevA.68.013810 PACS number(s): 42.50.Gy, 32.80.Qk

There are many interesting reports on the pulse propagations such as superluminal, subluminal, or even halting lights [1–3]. Since a light pulse has been stored in a solid sample [4], methods for slowing or stopping a light pulse have been investigated for many potential uses, not only as a tool for studying a very peculiar state of matter but also for developing quantum computers, high-speed optical switches, optical delay lines, and communication systems. As for superluminal light, many scientists agree that no information can be sent faster than the light speed c in vacuum as explained by Chiao [5]. It means that a signal velocity defined by Sommerfeld and Brillouin [6] cannot exceed c, but a group velocity can exceed c. From this point of view, a group velocity faster than c does not violate Einstein's principle of special relativity. Despite skeptic discussions about real applications by using speed controlled lights [7,8], it must be useful to have a system whose group velocity can be controlled freely on the single atomic transition line [9].

There have been a few attempts to realize both superluminal and subluminal lights in a single system. Talukder *et al.* have shown femtosecond laser pulses propagating from superluminal to subluminal velocities in an absorbing dye by changing dye concentrations [10]. Shimizu *et al.* were also able to control a light pulse speed, with only a few cold atoms in a high-finesse microcavity by detuning the laser frequency from a cavity resonant frequency locked to the atomic transition [11]. Speed controls in atomic systems have been done by changing mostly the laser frequency. Recently, Agarwal proposed the idea of obtaining light propagation from superluminal to subluminal velocity by simply changing the laser power in a little complicated atomic system [12], which adds another laser controlling atomic coherence between ground states in a conventional three-level electromagnetically induced transparency (EIT) scheme. In this communication, we report on a simple two-level atomic system, which can be changed from superluminal to subluminal group velocities of a Gaussian light pulse on a single atomic transition.

For controlling a group velocity, mostly alkaline atomic vapors have been prepared coherently as a propagating medium. Since EIT [13] and electromagnetically induced absorption (EIA) [14] effects in coherently degenerate two-level systems can produce a significant variation in the absorption with a subnatural linewidth, atoms become a very highly dispersive medium where various propagations can be realized. In order to realize all kinds of propagating velocities, we have to control atomic coherence for EIT and EIA between magnetic sublevels belonging to the same ground or excited level.

Figure 1 shows the schematic diagram of the experimental setup. The cw coupling laser generated from a tunable distributed Bragg reflector diode laser with an external cavity is sent into the 5-cm-long Cs vapor cell, which has no buffer gases [15] at the room temperature. A Gaussian probe pulse is generated by rotating slightly the polarization angle of the linearly polarized coupling laser by a Pockels cell, which is controlled by a high-voltage converter amplifying the elec-

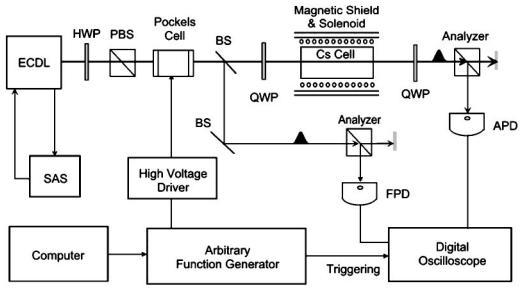

FIG. 1. Experimental setup for fast and slow pulse propagations by EIA and EIT. Pulses are detected by APD and FPD, respectively. Quarter-wave plates (QWP) are used for circular polarization experiments. The frequency of the tunable diode laser (ECDL) is monitored by the saturated absorption spectrometer (SAS).

*Also at Center for Information and Telecommunication Standards, Research Institute of Standard and Science, Daejon, 305-600, Korea.
†Email address: jbkim@cc.knue.ac.kr

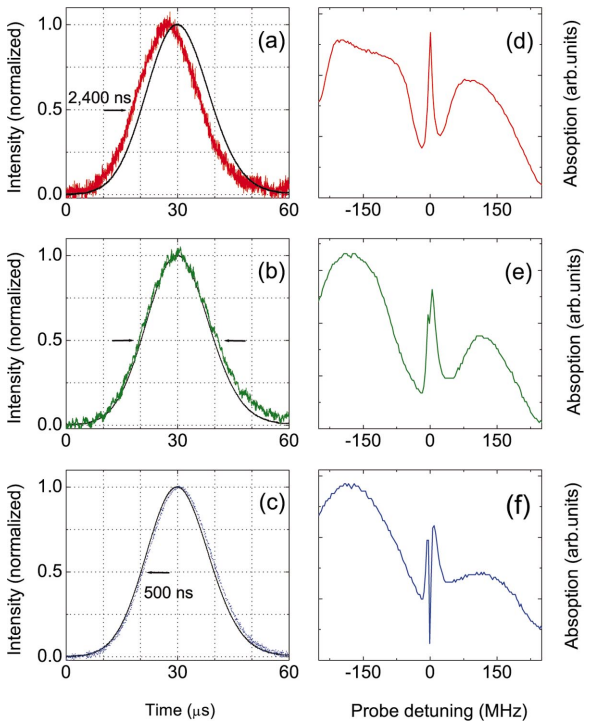

FIG. 2. (Color) (a)–(c) Various propagations with the reference pulses and (d)–(f) the corresponding absorption spectra. All pulses are the average of 512 pulses. The black solid line indicates the reference pulse transmitted at the far-off resonant frequency. (a) shows a pulse propagating superluminally through the EIA medium with the weak coupling power of 110 μW. For normalization, the superluminal pulse was multiplied by 69.1. (b) shows a pulse with near vacuum speed with the coupling power of 0.5 mW with multiplication factor of 2.6 and (c) shows a subluminal pulse with the strong coupling power of 1.5 mW with multiplication factor of 1.1, where the laser beam diameter is 5 mm. The polarizations of the coupling field and the probe pulse are linearly perpendicular to each other (LPL).

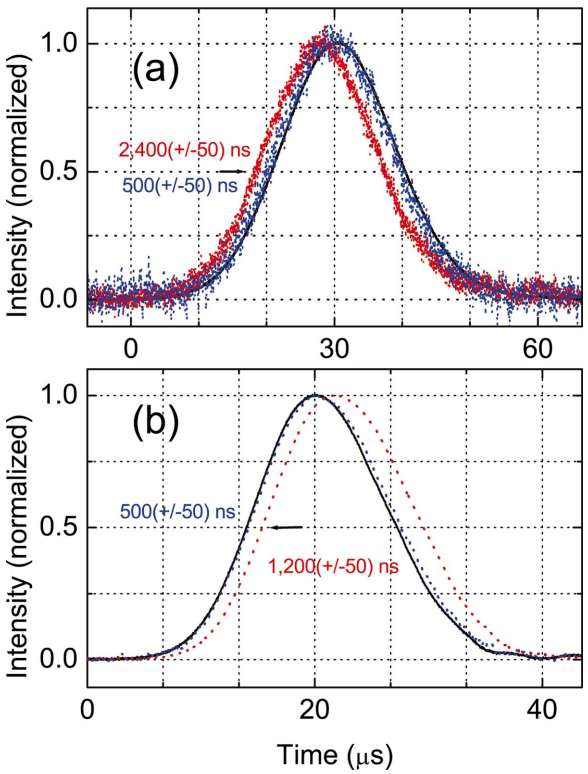

FIG. 3. (Color) (a) shows the polarization dependence of the superluminal signals with the coupling power of 110 μW. The red dotted line with the LPL combination indicates time advancement, 2400 ns corresponding to the group velocity, $-c/14\,400$. The blue dotted line with the CCP combination indicates time advancement, 500 ns. (b) shows the polarization dependence of the subluminal signals with the coupling power of 110 μW. The red dotted line with the CCP combination indicates time delay, 1200 ns corresponding to the group velocity $c/7200$. The blue dotted line with the LPL combination indicates time delay, 500 ns.

trical signal of the Gaussian shape generated by an arbitrary function generator. Because the rotated polarization component perpendicular to the polarization of the coupling field becomes the probe field, the temporal shape of the probe pulse is decided by the time-dependent voltage applied to the Pockels cell. After two laser fields have passed through the cesium vapor cell, only the probe pulse is separated by a polarizing beam splitter from the coupling laser beam. It is detected by an avalanche photodiode. The digital oscilloscope triggered by the arbitrary function generator displays the probe pulse transmitting through the coherent medium.

The μ-metal sheet protecting the earth magnetic field wraps the cell. A very weak magnetic field generated by Helmholtz coils can be applied to identify polarizations of laser fields to interacting atoms. The probe pulse generated at the far-off resonant frequency becomes the reference pulse to be compared with the resonant probe pulses. It is supposed to be the pulse traveling the same distance in vacuum as the length of the cell. The pulse split at the front of the cell is used for checking whether all triggers are executed always on the same time or not.

We adopt the transition $6\,^2S_{1/2}F=4$ to $6\,^2P_{3/2}F'=5$ in the cesium D_2 line, which is a closed and degenerate two-level system. By changing only the coupling power at the same laser frequency, we are able to control arbitrarily pulse speeds from superluminal, through the vacuum speed, to subluminal velocities as shown in Figs. 2(a)–2(c). The heights of the advanced pulses are significantly reduced after passing through the medium. The intensity of the transmitted pulse has been normalized to the height of the reference pulse to compare the reference pulse and advanced pulses. Shapes of all pulses are in good agreement with the input pulse without any significant distortions, even though superluminal pulses have some more noises because of absorption. Figures 2(d)–2(f) show the absorption spectra [16] corresponding to each group velocity, which were obtained by two independent laser sources. This absorption data would explain how various group velocities are transmitted.

The maximum pulse advancement in Fig. 2(a) compared to the reference is about 2400 ns, instead of the 0.1 ns time propagating the 5-cm-long cell with light speed in vacuum. The group velocity of the Gaussian probe pulse, which is defined by $v_g=d\omega/dk=c/[n(\omega)+\omega dn(\omega)/d\omega]$, can be calculated to be the negative group velocity v_g

$=-c/14\,400$, which is the fastest optical pulse, to our knowledge. The negative velocity means that the peak of the pulse emerges from the medium before its peak enters into the medium.

The superluminal propagation is based on the anomalous dispersion related to EIA as shown in Fig. 2(d). It is well known that EIA occurs because atomic coherences between excited states are spontaneously transferred to atomic coherences between ground states. These atomic coherences between ground magnetic sublevels also cause a Hanle effect [17]. This EIA material is highly negative dispersive because the linewidth of the absorption spectrum is much narrower than the natural linewidth of 6 MHz. By using one laser [18] we were able to observe the EIA spectrum of the linewidth up to about 280 kHz. The present group velocity is comparable to the expected value, $v_g=-c/23\,000$ in Rb atoms [19]. Also, our observation differs from previous studies that used linear [20], nonlinear gain lines [21], and tunneling barriers experiencing severe reshaping [22].

At the middle coupling power, as shown in Fig. 2(b), the pulse is propagated with about c. The EIA spectral bandwidth in Fig. 2(e) becomes much broader and starts to show a tiny EIT dip. This means that $dn(\omega)/d\omega$ is small, and the medium acts like a normal linear dispersive material. We can see a slight pulse broadening because of dispersion.

Figure 2(c) shows the subluminal propagation. The maximum subluminal delay of 500 ns is relatively small compared to the superluminal advancement of 2.4 μs, which will be discussed later. The subluminal propagation could be expected from the absorption spectra as shown in Fig. 2(f) because the EIA material with the weak-coupling power is converted into the EIT material with the strong-coupling intensity.

We have found a large dependence of the group velocity on the polarization combinations as shown in Fig. 3. In order to make the laser beams circularly polarized, two quarter-wave plates are installed on both sides of the cell. The first quarter-wave plate makes two linearly perpendicular polarized fields to be circularly polarized, which are counter-rotating. The second wave plate gets transmitted beams back into linearly polarized fields to be separated by the polarizing beam splitter.

Figure 3(a) shows the superluminal signals with a linear polarized (LPL) and circular polarized (CCP) combination, respectively. Superluminal velocity with the LPL is much faster than the CCP. In order to investigate the polarization effects on the subluminal propagation, we tried another transition line between $6\,^2S_{1/2}F=3$ and $6\,^2P_{3/2}F'=2$. The maximum pulse delay by the CCP was obtained by about 1200 ns, which corresponds to the group velocity of $v_g=c/7200$ as shown in Fig. 3(b). This time, we can see that EIT by the CCP is more efficient than the LPL as is pointed out in Refs. [23,24].

We were able to understand our experimental observations by applying density-matrix equations [15,16] considering spontaneous transfer of atomic coherence between excited magnetic sublevels to the simple system. This model system consists of two degenerate levels of $F=1$ for the ground level and $F=2$ for the excited level as shown in Fig. 4. Even though our model system is different from the real system, we believe that we can see all the physics from theoretical results. From Figs. 4(b) and 4(c), we are able to observe the conversion from EIA to EIT material by increasing only the coupling Rabi frequency. In order to get the theoretical absorption curves, we have to consider responses of all velocity components in the Doppler broadened vapor cell for fixed frequency of the coupling laser. This conversion occurs because of various effects such as Rabi splitting by the strong coupling, Doppler-free setup for effective two photon process, and ac Stark shift for the frequency detuning in moving atomic frame.

We can clearly see the EIA spectrum depending on the polarization combinations by comparing Figs. 4(b) and 4(d). The EIA spectrum by the LPL has a much narrower linewidth and larger signal than the CCP because the degenerate system coupled by the CCP is decomposed into two independent subsystems by the selection rules, which are both

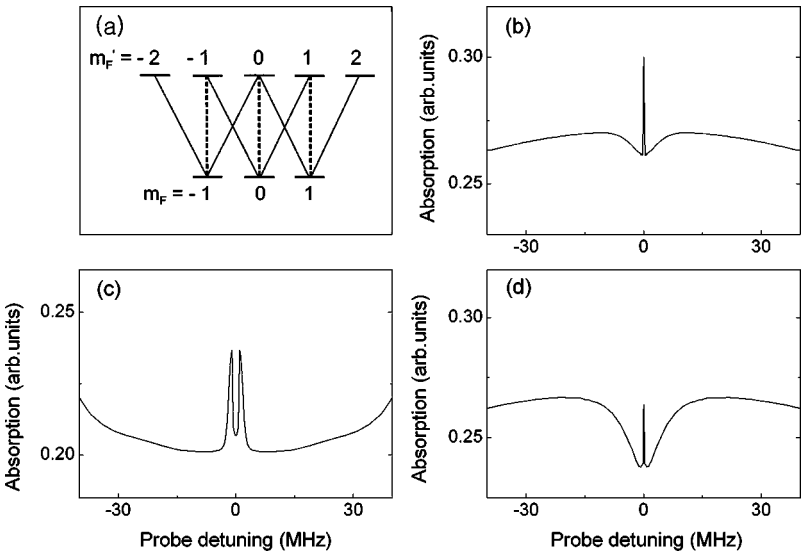

FIG. 4. (a) The theoretical model system for density-matrix equations. The prime for magnetic sublevels indicates the excited level. Selection rules are $\Delta m_F=0$ for the linear polarization and $\Delta m_F=\pm 1$ for the circular polarization, respectively. (b) The absorption spectrum in the LPL case of weak coupling; $\Omega_C=3$ MHz. (c) The absorption spectrum in the LPL case of strong coupling; $\Omega_C=50$ MHz. (d) The absorption spectrum in the CCP case of weak coupling; $\Omega_C=3$ MHz.

$-1' \leftrightarrow 0 \leftrightarrow 1'$ and $-2' \leftrightarrow -1 \leftrightarrow 0' \leftrightarrow +1 \leftrightarrow +2'$. Since these two subsystems are connected only by the spontaneous transition, the atomic coherence between ground sublevels has to be quite different from the LPL case. In the case of the LPL, all sublevels among the ground and excited levels are coupled coherently, and they give both the narrow linewidth and the large absorption signal.

As for the subluminal propagation shown in Fig. 3(b), however, the CCP is more efficient than the LPL. This is why, even though interacting magnetic sublevels are also divided into two subsystems connected by the spontaneous transition, each subsystem contains a CPT (coherent population trapping) state [25]. Because the atom is transferred to the CPT state by a spontaneous process, EIT is more efficient in the CCP than the LPL. In order to get theoretical pulse propagations for each case, we need to include other hyperfine structures also in the theoretical model.

In conclusion, we are able to get various speeds for the light pulse propagation by controlling only the coupling power on the single atomic transition line. The advantageous feature of our demonstration is that it does not require the two independent experimental setups to realize either superluminal or subluminal propagations and that the switching between them can be achieved easily, which should promise good applicability in such areas as high-speed optical modulation [26], quantum switching [27,28], and quantum computers with quantum memory [29]. It may be possible to develop a system in which we can accelerate or decelerate the optical pulse by using the spatially or temporally varying powers for the coupling laser, whose propagating direction should be sent perpendicular to the probe pulse.

The authors acknowledge the support from the Korea Research Foundation (Grant No. KRF 2001-015-DP0107).

[1] D.F. Phillips, A. Fleischhauer, A. Mair, R.L. Walsworth, and M.D. Lukin, Phys. Rev. Lett. **86**, 783 (2001).
[2] C. Liu, Z. Dutton, C.H. Behroozi, and L.V. Hau, Nature (London) **409**, 490 (2001).
[3] L.J. Wang, A. Kuzmich, and A. Dogariu, Nature (London) **406**, 277 (2000).
[4] A.V. Turukhin, V.S. Sudarshanam, M.S. Shahriar, J.A. Musser, B.S. Ham, and P.R. Hemmer, Phys. Rev. Lett. **88**, 023602 (2002).
[5] R.Y. Chiao, A.M. Steinberg, *Progress in Optics* (Elsevier, Amsterdam, 1997), Vol. XXXVII, p. 345.
[6] L.D. Brillouin, *Wave Propagation and Group Velocity* (Academic, New York, 1960).
[7] A. Kuzmich, A. Dogariu, L.J. Wang, P.W. Milonni, and R.Y. Chiao, Phys. Rev. Lett. **86**, 3925 (2001).
[8] R.Y. Chiao, J.M. Hickmann, and D. Solli, Proc. SPIE **4283**, 16 (2001).
[9] R.Y. Chiao, P.W. Milonni, Opt. Photonics News **13**, 27 (2002).
[10] Md. Aminul Islam Talukder, Y. Amagishi, and M. Tomita, Phys. Rev. Lett. **86**, 3546 (2001).
[11] Y. Shimizu, N. Shiokawa, N. Yamamoto, M. Kozuma, T. Kuga, L. Deng, and E.W. Hagely, Phys. Rev. Lett. **89**, 233001 (2002).
[12] G.S. Agarwal, T.N. Dey, and S. Menon, Phys. Rev. A **64**, 053809 (2001).
[13] S.E. Harris, Phys. Today **50**, 36 (1997).
[14] A.M. Akulshin, S. Barreiro, and A. Lezama, Phys. Rev. A **57**, 2996 (1998).
[15] M. Kwon, K. Kim, H.S. Moon, H.D. Park, and J.B. Kim, J. Phys. B **34**, 2951 (2001).
[16] K. Kim, M. Kwon, H.D. Park, H.S. Moon, H.S. Rawat, K. An, and J.B. Kim, J. Phys. B **34**, 4801 (2001).
[17] F. Renzoni, C. Zimmermann, P. Verkerk, and E. Arimondo, J. Opt. B: Quantum Semiclassical Opt. **3**, S7 (2001).
[18] M. Kwon, K. Kim, H.D. Park, J.B. Kim, and H.S. Moon, J. Korean Phys. Soc. **40**, 452 (2002).
[19] A.M. Akulshin, S. Barreiro, and A. Lezama, Phys. Rev. Lett. **83**, 4277 (1999).
[20] D.L. Fisher and T. Tajima, Phys. Rev. Lett. **71**, 4338 (1993).
[21] N.G. Basov, R.V. Ambartsumyan, V.S. Zuev, P.G. Kryukov, and V.S. Letokhov, Sov. Phys. JETP **23**, 16 (1966).
[22] A.M. Steinberg, P.G. Kwiat, and R.Y. Chiao, Phys. Rev. Lett. **71**, 708 (1993).
[23] D. McGloin, M.H. Dunn, and D.J. Fulton, Phys. Rev. A **62**, 053802 (2000).
[24] H.Y. Ling, Y.-Q. Li, and M. Xiao, Phys. Rev. A **53**, 1014 (1996).
[25] E. Arimondo, *Progress in Optics* (Elsevier, Amsterdam, 1996), Vol. XXXV, p. 257.
[26] P. Valente, H. Failache, and A. Lezama, Phys. Rev. A **65**, 023814 (2002).
[27] S.E. Harris and Y. Yamamoto, Phys. Rev. Lett. **81**, 3611 (1998).
[28] B.S. Ham and P.R. Hemmer, Phys. Rev. Lett. **84**, 4080 (2000).
[29] M.D. Lukin and A. Imamoglu, Nature (London) **413**, 273 (2001).