Continuous control of light group velocity from subluminal to superluminal propagation with a standing-wave coupling field in a Rb vapor cell

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We present the continuous control of the light group velocity from subluminal to superluminal propagation with an on-resonant standing-wave coupling field in the $5S_{1/2}$–$5P_{1/2}$ transition of the Λ-type system of ^{87}Rb atoms. When a coupling field was changed from a traveling-wave to a standing-wave field by adjusting the power of a counterpropagating coupling field, the probe pulse propagation continuously transformed from subluminal propagation, due to electromagnetically induced transparency with the traveling-wave coupling field, to superluminal propagation, due to narrow enhanced absorption with the standing-wave coupling field. The group velocity of the probe pulse was measured to be approximately $0.004c$ to $-0.002c$ as a function of the disparity between the powers of the copropagating and the counterpropagating coupling fields.

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I. INTRODUCTION

Control of the light group velocity by exploiting the dispersive property of an optical medium has been reported for the various optical media such as atoms, optical fiber, and quantum dots [1–17]. Ever since the experimental demonstration of the reduction of the light group velocity to 17 m/s in ultracold sodium atoms [2], the subluminal light propagation has been attracting a lot of interest because of its possible applications in optical delay, light storage, and quantum memory [2–9]. Many researchers have been interested in superluminal light propagation in which the velocity exceeded the vacuum light speed c, even though they accepted Einstein's principle of special relativity and the causality principle [3,10–12]. Even though the apparent phenomenology of superluminal light propagation is counterintuitive, the physics of superluminal light propagation is understood in terms of the reshaping of the light pulse caused by dispersion effects similar to those of subluminal light propagation.

In the atomic medium, electromagnetically induced transparency (EIT) and electromagnetically induced absorption (EIA) are useful phenomena of normal and anomalous dispersive media, respectively [2,9]. Generally, EIT and EIA appear independently in different atomic systems and transitions. However, the control of the light group velocity in a single system is very useful for practical applications based on subluminal and superluminal light propagations [17,18]. There have been attempts to experimentally demonstrate both subluminal and superluminal light propagations in a single system [17–21]. Kim *et al.* were able to control the arbitrary group velocities of light in a single system from superluminal to subluminal propagation on a single atomic transition line by changing only the intensity of the coupling laser [19]. Bigelow *et al.* observed subluminal and superluminal light propagations in an alexandrite crystal at room temperature [20]. Kang *et al.* tuned the light group velocity in cold Rb atoms by inducing large optical nonlinearities [21]. An additional pumping laser, incoherent pumping, and a squeezed field have been used to control the light group velocity [22,23].

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Recently, a three-level atomic vapor interacting with a standing-wave coupling field showed enhanced absorption in the transmittance spectrum of the probe field [13–17]. For a given atomic system and a single atomic transition, it is possible to generate not only the normal dispersive medium via EIT with a traveling-wave coupling field but also the anomalous dispersive medium via absorption phenomenon with a standing-wave coupling field. Although subluminal and superluminal light propagations have been well studied in a variety of situations, there are no reports of the arbitrary control of the light group velocity from subluminal to superluminal propagation with a standing-wave coupling field.

In this paper, we investigate the transformation of the light group velocity from subluminal to superluminal light propagation with an on-resonant standing-wave coupling field within a single system and a single atomic transition line. When the coupling field was changed from a traveling-wave to a standing-wave field in the $5S_{1/2}$–$5P_{1/2}$ transition of the Λ-type system of ^{87}Rb atoms, the group velocity of the Gaussian probe pulse changed from subluminal to superluminal propagation because of the normal and anomalous dispersions resulting from EIT and the enhanced absorption, respectively. The light group velocity of the probe pulse was analyzed by examining the transmittance and fluorescence spectra with respect to the power ratio between the copropagating and counterpropagating coupling fields.

II. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup for control of the light group velocity with the on-resonant standing-wave coupling field. The laser system used an injection locking scheme to produce two coherent lasers separated by a frequency equal to the hyperfine frequency between ground states [24]. The coupling (L_C) field, used as the master laser, was a grating-feedback external cavity diode laser (ECDL) and the probe (L_P) field, used as the slave laser, was a Fabry-Perot laser diode. The frequencies of the two lasers were adjusted and monitored by the saturated absorption spectra of two lasers, respectively. The frequency of the L_C was fixed on the $5S_{1/2}(F=2)$–$5P_{1/2}(F'=2)$ transition and the frequency

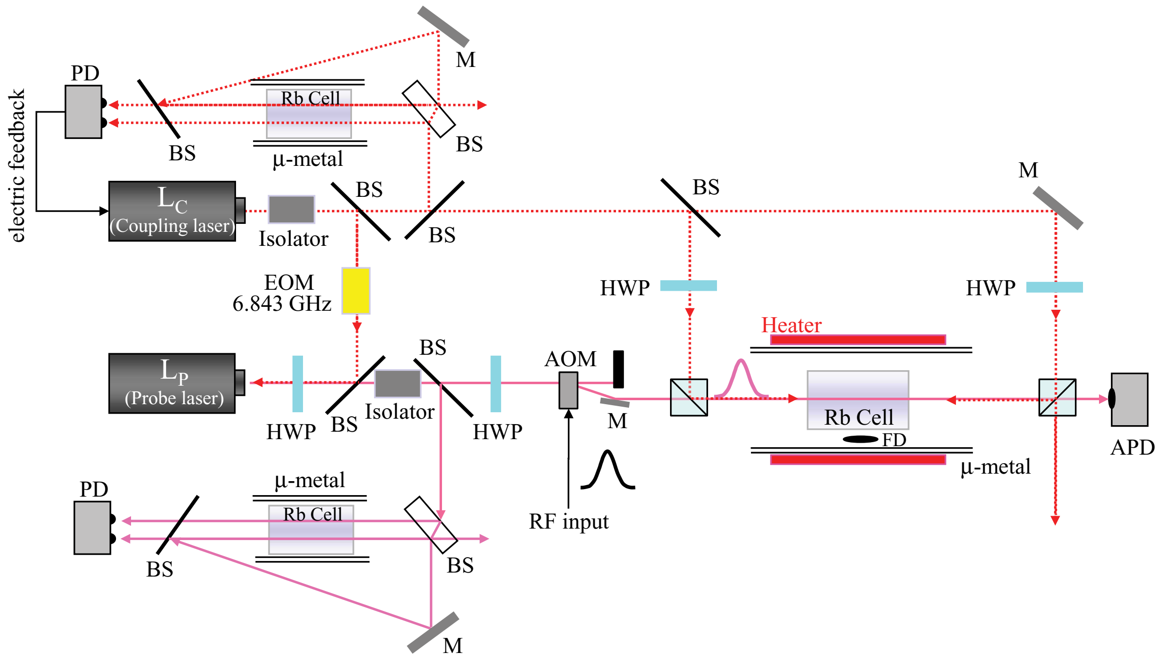

FIG. 1. (Color online) Schematic experimental setup for control of subluminal and superluminal propagations due to the EIT and the enhanced absorption with the standing-wave L_C field (BS: beam splitter, APD: avalanche photodiode, PD: photodiode, HWP: half-wave plate, and FD: fluorescence detector).

of the L_P was operated with free-running mode near the $5S_{1/2}(F=1)$–$5P_{1/2}(F'=2)$ transition. When the L_C passed through the electro-optic modulator (EOM) with 6.8 GHz the sidebands of the L_C were generated. The intensity of the sidebands was measured to be about 25% of the carrier by using a Fabry-Perot cavity with a free spectral range of 1 GHz. The L_C that passed through the EOM was injected into the L_P and the injected power of the L_C was optimized by a half-wave plate and a polarizing beam splitter. The locking bandwidth of the L_P was approximately 40 MHz.

To generate the standing-wave L_C field the L_C was split by a 50:50 beam splitter (BS) and the copropagating and the counterpropagating L_C fields overlapped (as shown in Fig. 1). A Gaussian L_P pulse was generated by an acousto-optic modulator (AOM) which was controlled by the output power of an 80 MHz rf driver. Both the L_C and the L_P were passed through a 2-mm-diameter aperture and were polarized linearly and perpendicular to each other. To control the group velocity of the L_P, the power of the counterpropagating L_C was altered using a polarized beam splitter (PBS) and a half-wave plate (HWP). The forward transmission and the fluorescence signal of the L_P were detected simultaneously by an avalanche photodiode (APD) and a fluorescence detector (FD), respectively. The Earth's magnetic field effects were reduced using a 2.5-cm-diameter, 5-cm-long Rb vapor cell wrapped in three layers of a μ-metal sheet. The used vapor cell contains a natural abundance such as ^{85}Rb and ^{87}Rb at 72% and 28%, respectively. The cell was maintained at 90 °C.

III. EXPERIMENTAL RESULTS

To control the group velocity of the L_P pulse, the normal and the anomalous dispersive mediums were induced by EIT and enhanced absorption, respectively [16]. The EIT medium was generated with a copropagating traveling-wave L_C field and the narrow enhanced absorption medium was generated with a standing-wave L_C field in a three-level Λ-type atomic system.

Figure 2(a) shows the normalized transmission of the L_P pulse as function of the superluminal propagation (gray solid line), reference pulse propagation (black solid line), and subluminal propagation (gray dashed line). The attenuations of the superluminal and the subluminal light pulses of Fig. 2 correspond to 82% and 42% of the reference light pulse, respectively. The power of the L_P laser was 10 μW and the cell temperature was 90 °C. The power of the copropagating L_C laser was fixed at 3 mW and that of the counterpropagating L_C lasers was changed from 0 mW (EIT) to 3 mW (enhanced absorption). When the power of the counterpropagating L_C laser increased, the group velocity of the transmitted L_P pulse changed from subluminal to superluminal velocity, at which time the time duration of the Gaussian-shaped L_P pulse was 0.45 μs. The maximum advancement and delay are approximated to be 72 and 43 ns, respectively. Although the intensity of the transmitted L_P pulse was significantly decreased by absorption in the Rb atoms, the pulse shapes of the normalized L_P pulse shown in Fig. 2(a) maintained a Gaussian shape without significant distortion.

When the atomic system interacts with a partially standing-wave L_C field by adjusting the power of the counterpropagating L_C field, the effects of the EIT and the enhanced absorption should be considered simultaneously because the intensity of the L_C field in the node is not zero. Here the partially standing-wave L_C field represents the contrast of the standing-wave L_C field. The group velocity of the L_P pulse could be controlled by changing the contrast of the standing-wave L_C

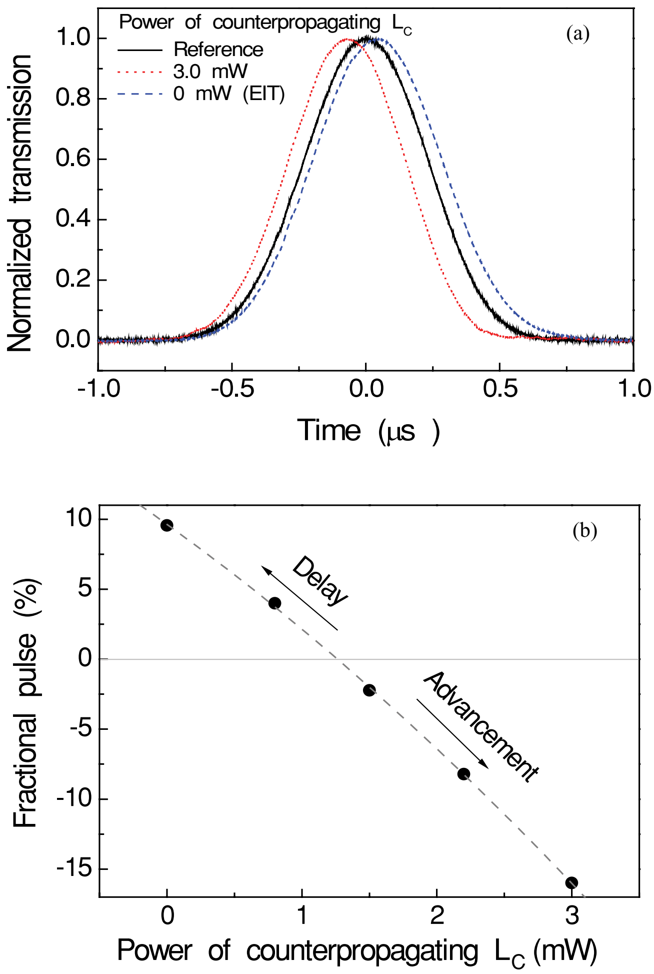

FIG. 2. (Color online) Transformation of the transmitted L_P pulse from subluminal to superluminal propagation according to the power of the counterpropagating L_C laser: (a) normalized L_P pulse and (b) the fractional pulse advancement and delay to the input pulse length according to the power of the counterpropagating L_C.

field. Since the contrast of the standing-wave L_C field is related to the power disparity between the copropagating and the counterpropagating L_C lasers, the contrast was continuously controlled by adjusting the power of the counterpropagating L_C. By adjusting the power of the counterpropagating L_C, dispersive property of the media was changed from the normal to the anomalous dispersion.

The results of Fig. 2(a) were fitted to a Gaussian pulse to measure the delay and advancement of subluminal and superluminal propagations as a function of the power of the counterpropagating L_C field. Figure 2(b) shows the fractional pulse advancement and delay to the input pulse length according to the power of the counterpropagating L_C. The maximum fractional pulse advancement and delay for a short pulse length of 0.45 μs were approximated to be 16% and 10% of the pulse length, respectively. As shown in Fig. 2(b) continuous control of the transmitted L_P pulse speed from subluminal to superluminal propagation is possible by adjusting only the power of the counterpropagating L_C. The group velocity of the Gaussian L_P pulse (v_g) is defined by $v_g = d\omega/dk = c/[n(\omega) + \omega dn(\omega)/d\omega]$ and simply derived by $v_g = d/(\Delta t - d/c)$, where d is the length of the Rb vapor cell and Δt is the time difference between the reference pulse and the transmitted L_P pulse [19]. From the results of Fig. 2(b), subluminal and superluminal group velocities can be calculated as $0.004c$ and $-0.002c$, respectively.

As shown in Fig. 2, the absolute advancement and delay are shorter than those mentioned in other reports [19–21]. However, the maximum fractional pulse advancement and delay to the input pulse of the reported results are as follows: $W = 20$ μs, $A = 12\%$, $D = 6\%$ (5-cm-long vapor atoms) [19]; $W = 2$ ms, $A = 25\%$, $D = 25\%$ (4-cm-long alexandrite crystal) [20,25]; and $W = 0.5$ μs, $A = 4\%$, $D = 5\%$ (2-mm-diameter cold atoms) [21], where the input pulse width is W, the maximum fractional pulse advancement is A, and the maximum fractional pulse delay is D. This is important to the maximum fractional advancement and delay to the input pulse because the EIT spectral window is related to the pulse bandwidth [26]. Although our method is not very effective, our new technique is an alternative method to the arbitrary control of the light group velocity from subluminal to superluminal propagation in the same atomic system and a single atomic transition.

When the group velocity of the L_P pulse changed from subluminal to superluminal propagation for the $5S_{1/2}$–$5P_{1/2}$ transition of ^{87}Rb atoms, the transmission and the fluorescence spectra of the L_P were observed simultaneously (as shown in Fig. 3). To observe the spectra of the L_P, the frequency of L_P after the AOM was scanned over the range of the $5S_{1/2}(F = 1)$–$5P_{1/2}(F' = 2)$ transitions by changing the frequency of the EOM driver in the region near the resonance between two ground states. Figures 3(a) and 3(b) show the transmission and the fluorescence spectra corresponding to each group velocity under the same conditions as Fig. 2(b). Because the transmittance spectrum of the L_P with the standing-wave L_C field is included by both the enhanced absorption and

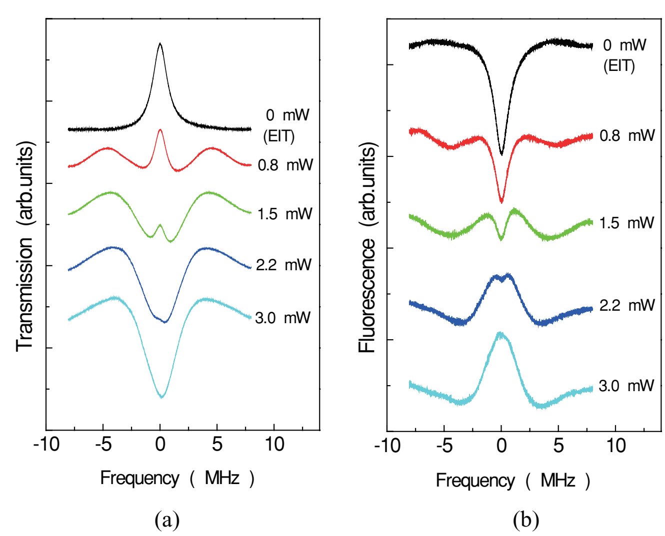

FIG. 3. (Color online) The simultaneously measured (a) transmission and (b) fluorescence spectra according to the power of the counterpropagating L_C in the Λ-type system of the $5S_{1/2}$–$5P_{1/2}$ transition of ^{87}Rb atoms, where the power of the copropagating L_C is 3 mW.

the Bragg reflection by periodic modulation of the atomic absorption [16], we simultaneously measured the transmission and the fluorescence of the L_P to analyze the effects of the enhanced absorption and the Bragg reflection [as shown in Fig. 3(b)]. However, the enhanced absorption affects the anomalous dispersion of the atomic medium, not Bragg reflection.

As noted above, the group velocity of the Gaussian L_P pulse changed from subluminal to superluminal propagation because of normal dispersion resulting from EIT and anomalous dispersion resulting from the enhanced absorption. When the power of the counterpropagating L_C was zero, a typical EIT spectrum was observed with the traveling-wave L_C field (as shown in Fig. 3). The spectral width of the EIT was measured to be 1.5 MHz. The subluminal propagation in Fig. 2 was observed under the condition of the EIT. With increasing power of the counterpropagating L_C, the magnitude of the EIT decreased and that of the enhanced absorption increased. When the dispersion of the atomic medium changed from normal due to the EIT to anomalous due to the enhanced absorption, the detection time of the transmitted L_P pulse through the atomic medium changed from positive, through zero, to negative [as shown in Fig. 2(b)]. However, when the power of the counterpropagating L_C was 1.5 mW, the EIT and the enhanced absorption coexisted in the transmission and the fluorescence spectra. Because the L_P pulse passed through the atomic medium with both normal and anomalous dispersions, its group velocity approached c [as shown in Fig. 2(b)]. Finally, when the standing-wave L_C field was generated by the counterpropagating L_C, the enhanced absorption spectrum was observed. The spectral width of enhanced absorption was measured to be a subnatural spectral width of 3 MHz. However, the spectral broadening of the enhanced absorption is why the enhanced absorption spectrum is saturated due to the highly dense atomic vapor. When the temperature of the atomic vapor cell is less than 60 °C, spectral widths of the EIT and the enhanced absorption are approximately equal and the magnitude of the enhanced absorption increases with temperature. When it is more than 60 °C, the enhanced absorption's spectral width is broader and its magnitude is maintained because of the saturation effect of the absorption. The maximum superluminal propagation advancement of 72 ns is relatively large compared with the maximum subluminal propagation delay of 43 ns, because the time duration 0.45 μs of the L_P pulse is optimized for enhanced absorption with a spectral width of 3 MHz.

The transmission spectrum of the L_P was calculated according to the counterpropagating L_C Rabi frequency to compare experimentally and demonstrate theoretically the transformation of subluminal propagation due to the EIT to superluminal propagation due to enhanced absorption (as shown in Fig. 4). The experimentally measured spectra in Fig. 4(a) are the same data in Fig. 3(a), but we showed the data again to easily compare with theoretically calculated results in Fig. 4(b). The density-matrix equations with a standing-wave based on the three-level Λ-type atomic system are solved and the continued-fraction expansion is calculated and integrated numerically with the Maxwell distribution [13]. In this calculation, we considered the power disparity between the copropagating and the counterpropagating L_C lasers.

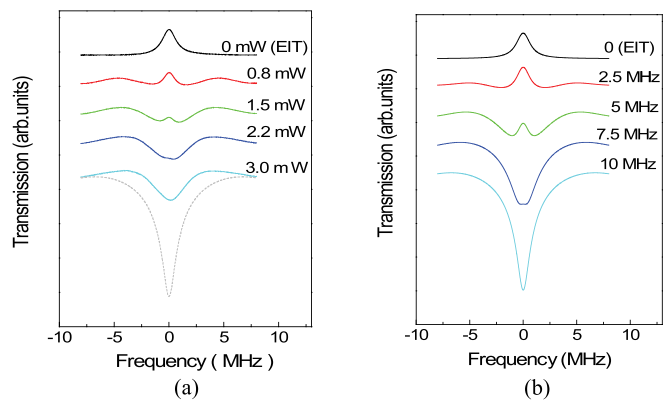

FIG. 4. (Color online) The (a) measured and (b) calculated spectra according to the counterpropagating L_C power and Rabi frequency in the three-level Λ-type atomic system, respectively.

The parameters for the calculation were the decay rate of 0.5 MHz between the ground states, the L_C Rabi frequency (Ω_C) of 10 MHz, and the L_P Rabi frequency (Ω_P) of 0.1 MHz. The most probable velocity in a Maxwell distribution was 270 m/s.

When the power of the copropagating L_C Rabi frequency (Ω_C) was fixed to 10 MHz and that of the counterpropagating L_C Rabi frequency was changed from 0 to 10 MHz, EIT was transformed into narrow enhanced absorption according to the counterpropagating L_C Rabi frequencies [as shown in Fig. 4(b)]. However, the discrepancies between the experimental and the calculated results arise because the theoretical three-level Λ-type atomic system is different from the real atomic system. For example, the gray dashed trace of Fig. 4(a) is exactly the same as the bottom trace of Fig. 4(b) which is considerably different with experiment data of Fig. 4(a) when the counterpropagating L_C is 3 mW. The calculated result in the simple three-level Λ-type atomic system does not take into account the saturation effect due to the dense atomic medium. Also, the calculated results should consider the effects of optical pumping, atom-laser interaction time, and Zeeman sublevels.

IV. CONCLUSIONS

In a single atomic system and a single atomic transition line the continuous control of the light group velocity from subluminal to superluminal propagation was examined using an on-resonant standing-wave L_C field in the $5S_{1/2}$–$5P_{1/2}$ transition of the Λ-type system of ^{87}Rb atoms. When the L_C field was changed from a traveling wave to a standing wave by controlling only the counterpropagating L_C laser power, the group velocity of the Gaussian L_P pulse changed from subluminal to superluminal propagation. Under the conditions for the maximum fractional pulse advancement for a short pulse length of 0.45 μs, the maximum fractional pulse advancement was measured to be 16%, which correspond to the superluminal group velocity of $v_g = -0.002c$, and the maximum fractional pulse delay was measured to be 10%, which correspond to the subluminal group velocity of $v_g = 0.004c$. The transformation of the light group velocity from subluminal to superluminal light propagation could be explained by analyzing the transmission and the fluorescence spectra of the L_P. When the EIT with the traveling-wave L_C field was observed, the L_P pulse propagated subluminally in a normal dispersive atomic medium because of the EIT. When the enhanced absorption with the standing-wave L_C field was observed, the L_P pulse propagated superluminally in an anomalous dispersive atomic medium because of the enhanced absorption. The group velocity of the pulse could be easily and continuously controlled from subluminal to superluminal propagation. It is hoped that such continuous control of light speed contributes to potential applications of optical delay, quantum memory, and optical computing.

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