Direct Observation of a Pulse Peak Using a Peak-Removed Gaussian Optical Pulse in a Superluminal Medium

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A series of experiments is performed to examine the arrival of a pulse peak, using a Gaussian-shaped temporal wave packet as the input pulse and truncating it at various positions on or before the peak of the packet. When the truncating point is within the negative group delay limit of the fast light medium, a smooth Gaussian peak is observed at the exit port, despite the absence of an input pulse peak. The experimental results explicitly demonstrate that the superluminal propagation of a smooth Gaussian-shaped pulse peak is an analytic continuation over time of the earlier portion of the input pulse envelope. To investigate the physical meaning of the pulse peak further, we also examine the propagation of triangular-shaped pulses, for which the pulse peak can be recognized as a nonanalytical point.

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Optical pulse propagation through highly dispersive media has fascinated physicists, especially in connection with the significance of the peak of a wave packet [1–7]. Historically, Sommerfeld and Brillouin [1] pointed out that the group velocity can be infinite or even negative in the anomalous dispersion region, and that the pulse peak can propagate at a speed faster than the speed of light in vacuum, c. This behavior was directly verified by Chu et al. [4] through experiments on excitonic absorption in semiconductors; the amplitude of the outgoing pulse was significantly attenuated, due to intrinsic absorption, but this attenuation was not essential. A lossless-linear anomalous dispersion in the double gain lines has been suggested, and distortionless superluminal pulse propagation was observed by Wang et al. [5] in Cs gas; they demonstrated that the peak of a Gaussian pulse can appear at the far side of a sample before entry of the peak at the near side of the sample [5,6]. These experiments suggest that the conventional group velocity v_g does not lose physical meaning, even in a superluminal medium. The pulse peak appears exactly at the time predicted by v_g, as long as the propagation distance is sufficiently short [7].

The natural consequence of the above discussions is that it is possible to observe the pulse peak at the output, even when one truncates the pulse before its peak has entered the medium. A similar case has been investigated theoretically [8–11], and emulated in electric circuits through signal transmission in operational-amplifier bandpass filters [12–14]. However, to date, experiments of this kind in the optical regime have yet to be reported, due to experimental difficulties. While the superluminality phenomenon has sparked significant interest in various fields, such as the faster-than-light neutrino at CREN [15] and left-handed materials [16], the fundamental interest of this effect lies in the context of light speed or causality in special relativity, the cornerstone of modern physics. The exact meaning of superluminal propagation of the pulse peak and the interpretation of the information velocity in the optical regime remains an open problem, which relies on the detailed experimental investigation of the pulse propagation in the fast light medium.

In this study, we prepared a Gaussian optical pulse and performed a series of experiments by truncating the input pulse at different positions on or before the Gaussian peak. We confirmed that a smooth Gaussian-shaped pulse peak exited from the far side of a negative group-velocity medium, despite the input optical pulse not having a Gaussian peak. The experimental results explicitly demonstrated that the superluminal propagation of the peak of Gaussian-shaped pulses is an analytic continuation over time of the earlier portion of the input pulse envelope, and that the output pulse peak is not information. For further investigation of the physical meaning of the pulse peak, we also examined the propagation of a triangular-shaped optical pulse. In this case, we did not observe the inputlike pulse peak when the incident pulse was truncated on or before the peak.

Figure 1 shows the experimental setup. We used a fiber ring resonator, which offers highly controllable dispersion via the cavity loss and coupling strength between the fiber and the ring resonator. The stationary input-output characteristics of the resonator can be analyzed based on directional coupling theory [17,18]. The transmitted light intensity $T(\omega)$, as a function of ω, shows a periodic dip structure due to resonance. The dispersion relationship depends on the loss and coupling strength. For the undercoupling condition, the transmission phase $\theta(\omega)$ as a function of frequency shows an anomalous dispersion at the center of the resonance, and the group delay is expected to be negative, $\tau_g = \partial\theta/\partial\omega < 0$, corresponding to superluminal pulse propagation, namely, fast light [17,18]. In contrast, when the coupling is strong, the transmission

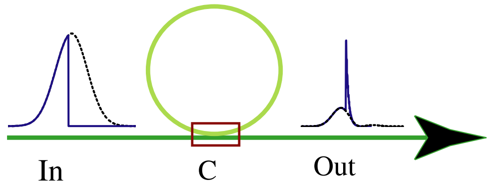

FIG. 1 (color online). Schematic diagram of the experimental setup. C is the fiber coupler. In and Out show the schematic input and output pulses, respectively, where the dashed-black lines correspond to the original Gaussian pulse and the blue solid lines represent the sharply truncated pulses.

phase shows normal dispersion, and one would expect to observe slow light.

In the current study, a 90:10 coupler was used to achieve the undercoupling condition. We inserted an additional loss element within the ring resonator to control the loss parameter. The physical length of the ring was $L_R = 200$ cm. An Er-fiber laser was used as the incident light source. The spectral width was 1 kHz, and the laser frequency was tuned by piezoelectric control of the cavity length. Gaussian-shaped temporal pulses were generated using a LiNbO3 (LN) modulator; a temporal pulse duration t_p of 200 ns (FWHM), repetition rate of 100 kHz, and incident power of 0.1 mW. The truncating points were encoded on or before the peak of the Gaussian-shaped pulses. The transmission intensity through the system was observed using an InGaAs photodetector and was reordered using a 600-MHz digital oscilloscope. Figure 2(a) shows the transmission spectrum as a function of the detuning frequency observed in continuous-wave mode, where the LN modulator was operated in open mode. The FWHM of the resonance dip was $\delta\nu = 6.4$ MHz. Figure 2(b) shows the experimentally observed output pulse after being injected with the Gaussian-shaped input pulse. The peak of the on-resonance pulse had a negative delay of -160 ns, which was in good agreement with the calculated value, $\tau_g = -160$ ns, demonstrating fast light in the ring resonator.

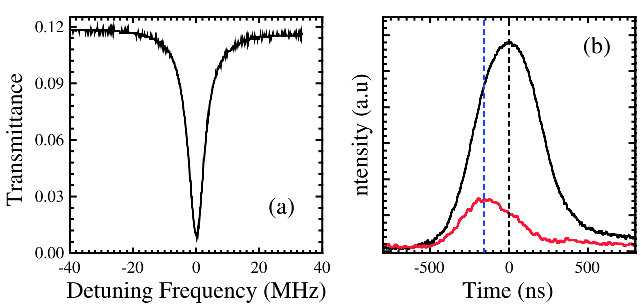

FIG. 2 (color online). (a) Resonance spectrum of the ring resonator with a spectral width of 6.4 MHz. (b) Experimentally observed negative delay of the output (solid red curve) peak when a Gaussian input (solid black curve) is injected into the resonator. Intensity is normalized to the peak of the input Gaussian pulse, whereas the output intensity is magnified (2×) in the graph. The green dashed vertical line corresponds to the peak of the input pulse. The blue-dashed vertical line corresponds to that of output pulse, showing a negative delay of $\tau_p \cong \tau_g = -160$ ns.

To investigate the significance of the peak for pulse propagation through a dispersive medium, we truncated the input pulse at different temporal positions t_R on or before its Gaussian peak (i.e., a portion of the front half of the Gaussian pulse propagating through the resonator was used). Therefore, the shape of the truncated input is Gaussian until time t_R, where it drops sharply to zero. Figure 3 shows the results of our experiments with the peak removed from the input pulses. The colored-solid curves in the left column show the input pulses truncated at different positions t_R from a temporal Gaussian pulse (dashed-black curve); the colored-solid and dashed-black curves in the right column show the corresponding output pulses after being injected with the truncated and original Gaussian

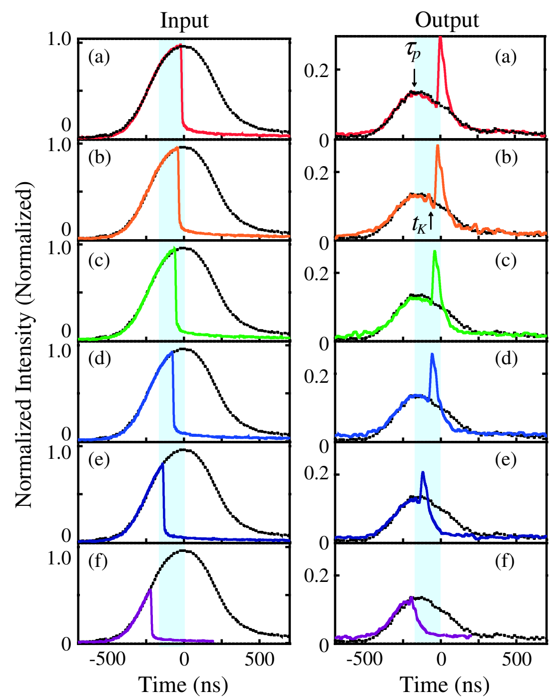

FIG. 3 (color online). Observed input (left) and output (right) pulses through the resonance shown in Fig. 2(a). All intensities are normalized to the maximum of the input Gaussian pulse. In the left column, colored-solid curves show the input pulses truncated at different positions: (a) $t_R = 0$ ns, (b) $t_R = -40$ ns, (c) $t_R = -60$ ns, (d) $t_R = -80$ ns, (e) $t_R = -150$ ns, and (f) $t_R = -210$ ns, before the peak of the original Gaussian pulse shown by dashed-black curves. The colored-solid curves in the right column show the output pulses that correspond to the truncated input in the left column. For comparison, the dashed-black curve in each graph represents the transmitted pulse when the original Gaussian pulse was injected. The hatched region indicates the τ_g range (-160 ns), i.e., the peak advancement of the on-resonance pulse peak, relative to the off-resonance Gaussian pulse peak.

pulses shown in the left column. When the input pulse contains its peak under the condition $(\tau_g <)0 < t_R$, the output pulse is transmitted through the resonator with superluminal peak velocity. Our special interest lies in the region where $\tau_g < t_R \leq 0$ for which the input pulses do not have Gaussian peaks. A smooth peak at the output emerges (colored-solid curves in the right column). The output peak for the truncated pulse has the same advancement τ_g ($\cong -160$ ns) as that for the original Gaussian pulse. Furthermore, the wing of the smooth Gaussian pulse extends from the output peak to the positive direction ($\tau_g < t \leq t_R$), as shown in Figs. 3(a)–3(d). This experimental result, therefore, demonstrates that the superluminal propagation of the peak of smooth Gaussian-shaped pulses is an analytic continuation over time of the earlier portion of the input Gaussian pulse. Figure 3(e) is for the condition $t_R \cong \tau_g$; the peak in the output pulse has just emerged in this case. For the condition $t_R < \tau_g < 0$ of the input pulse, the output pulse does not have a peak, as shown by Fig. 3(f).

Note that while the pulse peak appears for $\tau_g < t_R$ the truncating point of the pulse, at which the pulse amplitude drops sharply to zero, behaves as a nonanalytical point. The discontinuous point was neither advanced nor delayed, but appeared in the output instantly as it entered the system. A sharp nonanalytical point with an infinite frequency range cannot move faster than c, as this is the maximum limit of the traveling speed of the pulse front [19–23]. In our experiments, the fall time of the discontinuous point was 2.0 ns, i.e., 500 MHz. In contrast, the resonance width of the present ring resonator was $\delta\nu = 6.4$ MHz. Therefore, the temporal structures that have Fourier components higher than 6.4 MHz can be recognized as nonanalytical for the present ring resonator. True information cannot be included in the pulse peak; however, it has gradually been accepted that information is encoded in the nonanalytical points, t_{NA}, on the wave packets. The experimental results confirmed that the information velocity is equal to the velocity of light in vacuum or in the background medium, independent of the group velocity [19–23].

For comparison of our experimental results, we performed a numerical simulation [21] (Fig. 4). We produced a resonance line with $\tau_g \sim 160$ ns for a Gaussian-shaped input pulse. The calculated results also show that a smooth Gaussian peak appears in the output pulse for $\tau_g < t_R \leq 0$, despite the fact that the input pulse does not have a Gaussian peak (Fig. 4). This is in excellent agreement with the experimental results of Fig. 3. Figure 5 summarizes the arrival time of the peak τ_p and the large kick point t_K (nonanalytical point) observed in the transmitted pulse as a function of the peak removal time t_R in the input pulses. The main region of interest for this experiment, $\tau_g < t_R \leq 0$, is shown by the shaded portion in the graph. The arrival time of the peak is independent of t_R, but the kick point t_K is approximately equal to t_R ($t_K \sim t_R$).

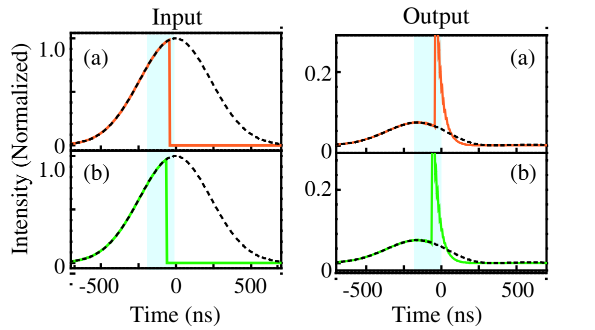

FIG. 4 (color online). Calculated input (left) and output (right) pulses through the resonator corresponding to the graphs in Figs. 3(b) and 3(c). All intensities are normalized with respect to the maximum of the input Gaussian pulse.

For pulse propagation in dispersive media, a convenient analytic form to represent the outgoing pulses within the group-velocity approximation is given by Ref. [8] as

$$E_{\text{out}}(t, z) = \frac{1}{2\pi} \exp\left[z\left(\frac{1}{c} - \frac{1}{v_g}\right)\frac{\partial}{\partial t}\right] E_{\text{in}}\left(t - \frac{z}{c}\right). \qquad (1)$$

Equation (1) mathematically represents that the propagation, over a distance z corresponds to an analytic continuation over time, $z/c - z/v_g$, of the vacuum-propagated pulse envelope $E_{\text{in}}(t - z/c)$. A superluminal group velocity does not imply a superluminal propagation of new information, because all of the information in $E_{\text{out}}(\tau_p, z) = E_{\text{in}}(\tau_p - z/v_g)$ is already contained in $E_{\text{in}}(\tau_p - z/c)$. From Eq. (1), it can be concluded that

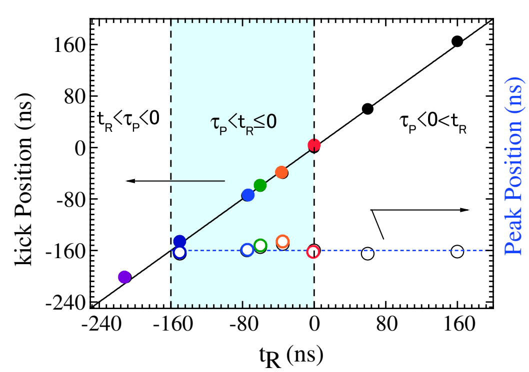

FIG. 5 (color online). Peak and kick positions observed in the transmitted pulse as a function of peak removal time in the input pulses. The open and solid circles represent the experimentally observed peak τ_p and kick positions t_K, respectively; the solid and dashed lines represent the corresponding simulations. The colors of the circles indicate different truncating position of input pulses shown in Fig. 3.

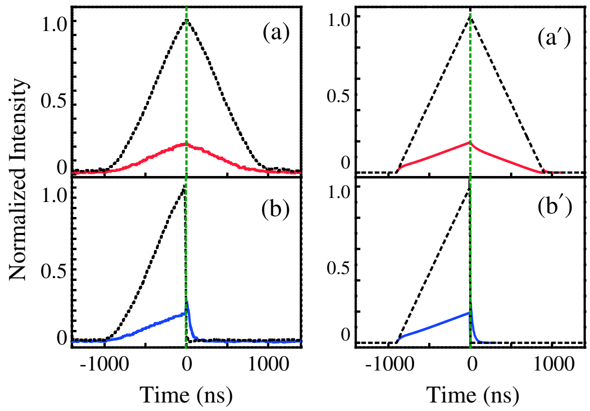

FIG. 6 (color online). Left column: experimental results for triangular-shaped pulse propagation through the same negative velocity medium shown in Fig. 2. Solid-red curve in (a) and solid-blue curve in (b) represent the transmitted output pulses after being injected with the original triangular [dashed-black curves in (a)] and the truncated triangular pulses [dashed-black curves in (b)] at $t_R \leq 0$ ns, respectively. Right column: plots (a′) and (b′) are the calculated results that correspond to plots (a) and (b) in the left column. All intensities are normalized with respect to the maximum of the original triangular pulse.

$$\lim_{\varepsilon\to 0} E_{\text{out}}(t_{NA} + c/z - \varepsilon, z) \neq \lim_{\varepsilon\to 0} E_{\text{out}}(t_{NA} + c/z + \varepsilon, z). \tag{2}$$

Hence, the nonanalytical points propagate at speed c, not v_g.

In Gaussian-shaped pulses, the pulse peak does not transfer any information. The pulse peak could, however, have more active meaning in some cases. Figure 6 shows the propagation of triangular-shaped pulses, instead of Gaussian-shaped pulses. Figure 6(a) shows the experimentally observed transmitted pulse (solid red line) after being injected with the triangular pulse (dashed-black line). Despite being injected in the same superluminal medium, the peak of the transmitted triangular pulse did not show any superluminal group velocity. We performed experiments using truncated triangular pulses. Figure 6(b) shows the experimentally observed pulse (solid blue line) after being injected with the input pulse truncated at $t_R \leq 0$ (dashed-black line). A large kick was observed at the truncating point, similar to that observed with Gaussian pulse propagation in Fig. 3(a). The triangular pulse peak, however, did not appear in the output in this case, because the arrival of the pulse peak of a triangular pulse cannot be predicted by the analytic continuation of the leading part of the pulse. The right column in Fig. 6 shows the simulation for the experimental observations.

In summary, we experimentally demonstrated that a smooth Gaussian-shaped peak exits from the far side of a negative group-velocity medium, even though the incident pulse was terminated before its Gaussian peak. The experimental results explicitly demonstrated that the superluminal propagation of the peak of Gaussian-shaped pulses is an analytic continuation over time of the earlier portion of the input pulse envelope, and that the output pulse peak is not information, in good accordance with the causal principle of information transfer in fast light systems.

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