Optical control of superluminal propagation of nanosecond laser pulses

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We present an all-optical incoherent control of superluminal propagation of a 3 ns laser pulse. The experimental results show an induced advance up to 400 ps, without significant distortion, continuously controlled by the characteristics of a control pulse. The measurements agree with numerical simulation.

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In recent years there has been substantial interest in modifying the characteristics and propagation of light pulses by means of optical control [1,2]. Some experiments have resulted in extremely slow light with very small group velocities [3–11], while others exhibited the ability to store and retrieve optical pulses [12–15]. It has been also demonstrated that several characteristics of the light pulses such as temporal shape [16], central frequency [17–19], and spectral distribution [20] can be optically controlled. It is also possible to generate a dispersion relation that results in group velocities larger than c ("superluminal" or "fast" light). The group velocity can be even negative, in such a case the exiting pulse's peak can appear to exit the medium before the peak of the input pulse enters. It is important to stress that this superluminal group velocity does not contradict special relativity and causality: it has been shown theoretically [21] and experimentally that the front of a step pulse travels always at c also for single photon propagation [22,23].

The simplest way, and the first performed [24], to achieve fast light was the propagation in a passive two-level system at the expense of a very strong absorption (10^{-3} transmission). Several approaches have been used to optically control fast-light propagation and reduce absorption or even obtain amplification: Raman gain in atomic gas [25,26], Brillouin scattering in optical fibers [27], coherent population oscillations in solid [28], and liquid-crystal light valve [29]. Recently a technique based on four-wave mixing has been used in Rb vapor [30]. Other kinds of control of fast light has been used such as electrical [31] or thermic control [32] in solid state materials. Experimental research on the statistical properties of slow and fast light has been also performed [33].

Many approaches allowed remarkable results in term of optical control of superluminal propagation by using relatively long pulses (hundreds of ns or longer for amplified pulses and 40 ns [27] with more than 90% absorption). It is then desirable, in order to gain better insight into the fundamental process and perspectives on a possible application of the optical control of superluminal propagation technique to information technology, to perform an experiment with shorter pulses and smaller absorption.

In this paper we present an experimental study of the generation of fast light in hot sodium vapor, using a simple all-optical control scheme, for 3 ns long pulses which is up to now the shortest value used in superluminal experiments. A similar all-optical control scheme has been very recently applied to slow light control [34]. The advance of the probe pulse, which is also slightly amplified, is optically controlled by varying the characteristics of a second optical pulse (control pulse): energy and probe-control pulse timing. The probe pulse advance is continuously controlled from 0 to up 400 ps without significant distortion by means of incoherent control based on two-photon population induced by the control laser pulse. The probe pulse advance is also dependent on the frequency of the probe pulse. The results are compared to a theoretical analysis.

Our scheme (see Fig. 1) is based on the optical preparation of the medium by a control pulse populating the doublet, $|2\rangle$, $|3\rangle$ ($D_{5/2}$, $D_{3/2}$ of sodium), by a two-photon transition from the ground state $|0\rangle$ ($S_{1/2}$). A subsequent pulse (probe pulse) connecting the state $|1\rangle$ ($P_{3/2}$) to the doublet would experience an inverted medium in the anomalous dispersion region resulting in amplification and superluminal propagation. This characteristics depends on the population of the doublet and then can be controlled by two field parameters: pulse energy and control-probe pulse temporal separation. A third important parameter is the frequency of the probe pulse. The broadband (30-GHz FWHM) 4 ns duration control laser, provided by a frequency-tunable dye laser pumped by a frequency-doubled Q-switched Nd:YAG laser at a repetition rate of 10 Hz, is sent into the cell containing the atomic sodium at the temperature T = 220 °C. Once the control pulse has excited the sodium in the doublet state and its interaction with the atomic medium is over, the probe pulse of central frequency λ_P, with a delay time Δt (measured from the two pulse peaks at the cell entrance), is sent into the medium in the same direction of the pump pulse. The probe pulse is obtained from a single-mode cw extended-cavity diode laser (ECDL), whose frequency ω_P can be tuned around the transitions $|1\rangle \longrightarrow |2\rangle$ and $|1\rangle \longrightarrow |3\rangle$.

The cw emission of the ECDL is coupled to a single-mode optical fiber and injected into an electro-optic modulator which produces pulses with a duration of 3.0 ns. The electro-optic modulator is driven by an electric pulse generator (Stanford DG535) that produces an electric pulse after a selectable delay from the trigger signal received from the control unity of Nd:YAG, in order to achieve a synchronization between pump and probe pulses. The two beams enter the cell collinearly and spatially overlapped and, at the exit, they are spatially separated using a dispersive prism. The probe pulse is collected

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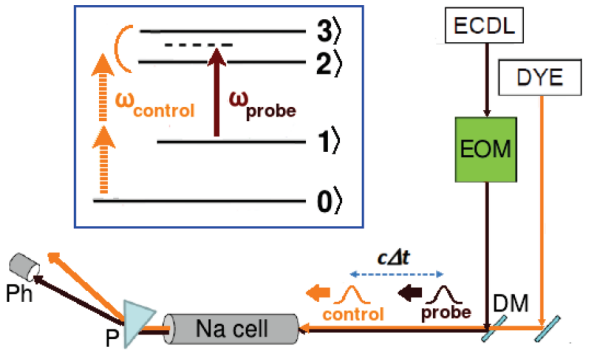

FIG. 1. (Color online) Schematic diagram of the level schemes and experimental setup.

by a fast 12-GHz-bandwidth photodiode and the signal is analyzed using a 7-GHz-bandwidth digital oscilloscope to measure pulse amplification and advance. A reflection of the probe pulse is sent to a wavelength meter with a resolution of 1 pm to monitor the probe field wavelength during the measurements. To reduce experimental errors, two electrically generated probe pulses are sent into the cell for each control pulse. The first probe pulse (not present in Fig. 1) is sent before the control pulse, and it propagates unaltered through the cell. The second probe pulse arrives after the control pulse, and its propagation is affected by the optical properties of the atomic medium. In this experimental configuration, gain and advance experienced by the probe pulse can be measured with respect to the reference at each laser shot, eliminating the error due to amplitude and time-jitter fluctuations of the optical pulses. The measurement system is automatic and controlled by a PC, which also stores traces acquired by the oscilloscope.

Figure 2 shows a typical temporal profile obtained for $\lambda_P = 819.710$ nm. The probe pulse presents an advance, as measured at half height on the front edge, of 410 ± 50 ps. The advance is correlated with the group velocity larger than c that is possible in the presence of an anomalous behavior of

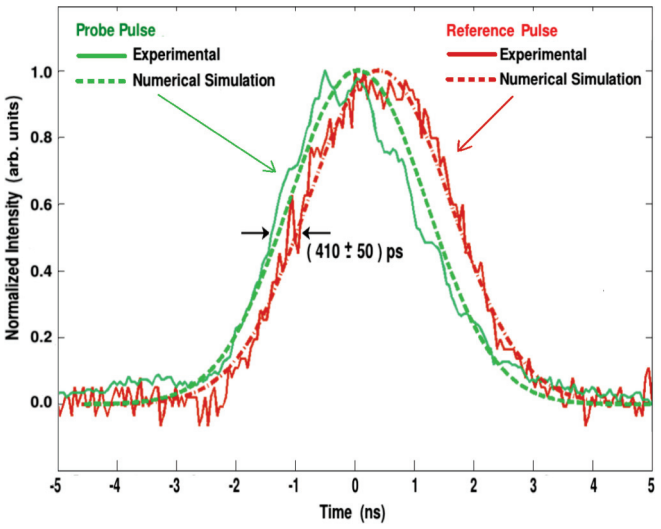

FIG. 2. (Color online) Typical temporal profiles of probe and reference pulses at cell exit in comparison with numerical simulations at $\lambda_P = 819.710$ nm. The probe pulse advance is 410 ps and its amplification is 5.4.

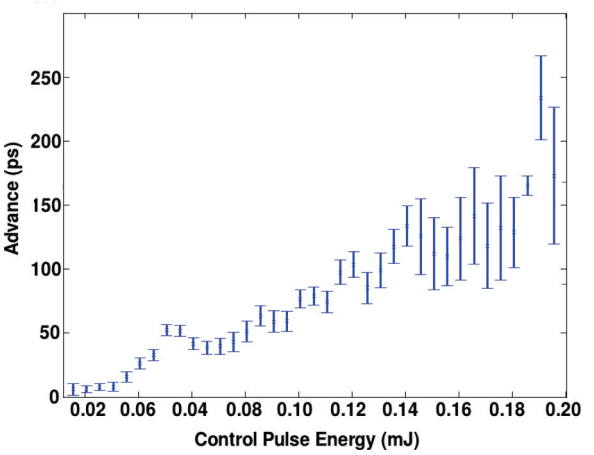

FIG. 3. (Color online) Probe pulse time advance vs control pulse energy for $\lambda_P = 819.706$ nm.

the dispersion curve. This is indeed the case in our study for that wavelength in the amplifying medium. The opposite case, slowing of the group velocity, is observed in the nonanomalous behavior of the dispersion curve and can be very effective as, for instance, in the electromagnetically induced transparency (EIT) modified media. The experimental profile is in good agreement with numerical simulation, which is described in a following part of the paper. The probe pulse, as compared to the reference pulse, shows small difference in the shape, presenting a moderate compression. The physical reason is in the composite effect of the dispersion and frequency-dependent amplification of the medium. The quantitative balance effect is computed in the numerical simulation, which takes into account the frequency dependence of the medium, confirming the experimental results in both the advance and the small compression.

Figures 3 and 4 show the advance obtained as a function of control pulse energy for two different wavelengths of the probe laser ($\lambda_P = 819.706$ and $\lambda_P = 819.710$ nm). The data presented are obtained analyzing a minimum of 20 shots for each energy value up to 2000 for low energy values. The results show that the advance of the probe pulse has been continuously controlled up to more than 400 ps by means of an optical parameter: the energy of the control pulse. The

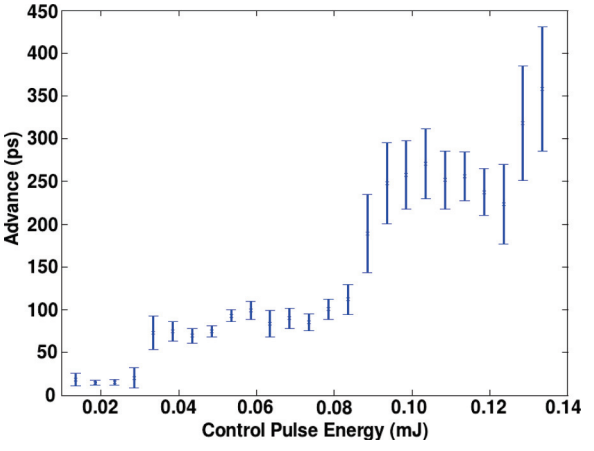

FIG. 4. (Color online) Same as Fig. 3, but for $\lambda_P = 819.710$ nm.

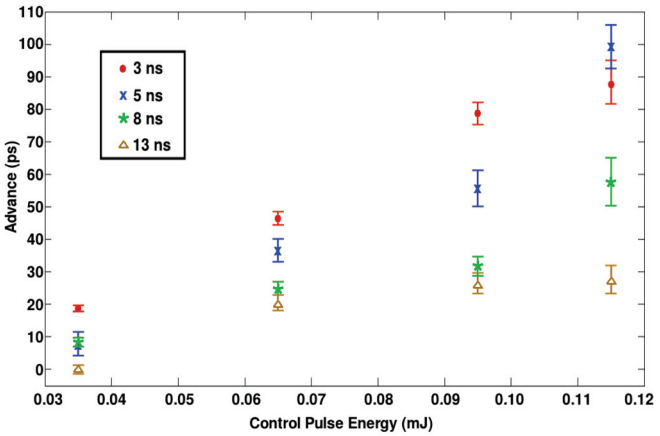

FIG. 5. (Color online) Probe pulse advance vs pump energy at $\lambda_P = 819.706$ nm for different separation time control-probe pulse temporal separation Δt.

basic physical mechanism for this optical control relies in the dependence of the two-photon population of the states 2 and 3 by the energy of the control pulse. The more the transitions $|1\rangle \longrightarrow |2\rangle$ and $|1\rangle \longrightarrow |3\rangle$ are inverted, the more the probe pulse is advanced with respect to the propagation at c. The advance is different for the two wavelengths used and it is larger for the $\lambda_P = 819.710$ nm case; the group velocity is indeed dependent on the wavelength because of the frequency dependence of the medium and, in particular, by the slope of the dispersion curve. In Fig. 6 is reported the behavior of the dispersion curve taking into account also the Doppler effect. In Fig. 5 the results for the advance are presented for four values of the control pulse energy and four values of the probe pulse delay. The results show a general decrease of the advance time with the control-probe pulse temporal separation Δt in agreement with the decay of the population of the states of the doublet in the time Δt. The results show that in our scheme the relative temporal timing is a second control parameter for the advance of the probe pulse.

To give a quantitative comparison of the theoretical predictions with our experimental results, we have numerically solved the propagation equation of a probe pulse in the inverted medium. The population inversion of the atomic medium after the propagation of the control pulse is given by $\rho_{11} = 0$ and

$$\rho_{ii} = \rho^0 e^{-\Gamma_i(\Delta t - z/c)} \quad i = 2,3. \tag{1}$$

Our model assumes the weak probe pulse approximation, i.e., the population is not affected by the interaction with the pulse itself, and equals the population of the doublet states (ρ^0). We neglect also the decay during propagation of the probe pulse. Considering the electric field at the cell input as

$$E(z = 0,t) = \epsilon(z = 0,t)e^{-i\omega_p t}, \tag{2}$$

we can solve, in our approximation, the propagation and obtain the electric field at the cell output:

$$E(z,t) = \exp\left\{-i\omega_p t \int_{-\infty}^{+\infty} \tilde{\epsilon}(0,\omega') \exp[i(kz - \omega' t)]\, d\omega'\right\}, \tag{3}$$

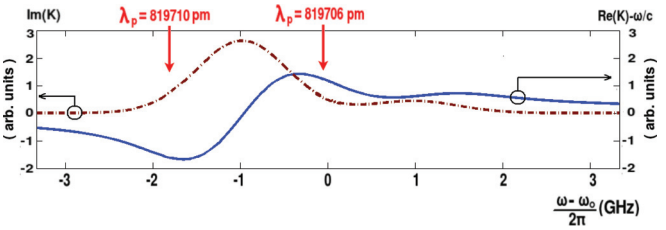

FIG. 6. (Color online) Absorption and dispersive profile evaluated from Eq. (4). The arrows indicate the two probe laser wavelengths used in the results of Figs. 3 and 4.

where $\tilde{\epsilon}(0,\omega')$ is the Fourier transform of the temporal dependent amplitude of the pulse at the cell input $\epsilon(z = 0,t)$. The wave vector for our atomic sample is given by

$$k(\omega = \omega_p + \omega') = \frac{\omega_p + \omega'}{c} + N\frac{\omega_a}{4\hbar\epsilon_0 c} l\left\langle \frac{\rho_{22} {d_{12}}^2}{i\gamma_2 - (\omega_p v/c + \omega' + \delta_2)} \right\rangle_v + N\frac{\omega_a}{4\hbar\epsilon_0 c}\left\langle \frac{\rho_{33} {d_{13}}^2}{i\gamma_2 - (\omega_p v/c + \omega' + \delta_3)} \right\rangle_v, \tag{4}$$

where γ_i and δ_i represent, respectively, all kinds of dephasing rates and detunings of the carrier wave frequency from the $i \rightarrow 1$ transition. The second and third terms are numerically averaged over the Doppler velocity distribution, using experimental parameters.

In Fig. 6 the dispersion and absorption profiles are reported after averaging on the Doppler distribution. Numerical solution of Eq. (3) is based on a discrete Fourier transform (DFT) technique, computed with a fast Fourier transform (FFT) algorithm. The pulse $\epsilon(z = 0,t)$ used in the numerical simulation is a Gaussian pulse fitted on the temporal shape of the actual probe pulse used in the experiment. The population ρ^0, which is needed in the numerical simulation, is not directly obtainable by the knowledge of the experimental control parameters. We choose to perform the comparison between theory and experiment looking at the advance as a function of amplification: the ρ^0 parameter is fixed by requiring that

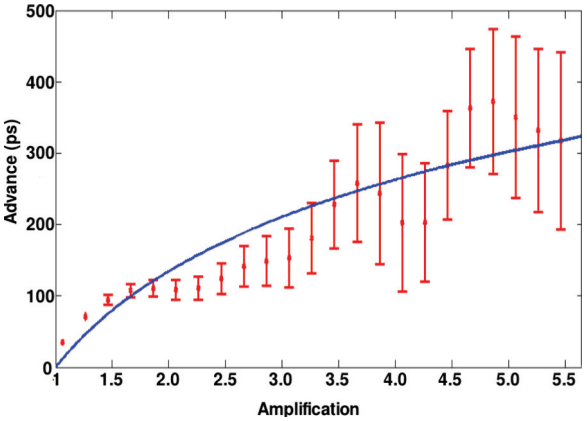

FIG. 7. (Color online) Comparison between experimental results and theory obtained by numerical calculation of the probe field propagation.

the amplification of the simulation be equal to the measured one. The simulation is obtained by numerical solution of expression (3) with all the quantities fixed by experimental and spectroscopic values. With this procedure, used for theoretical results reported in Figs. 2 and 7, no free parameters have been used in the comparison. In Fig. 7 is reported the advance versus amplification: the advance of the pulse is strictly connected to the amplification at $\lambda_P = 819.710$ nm. The two characteristics are both due to the effect of the population inversion in the transitions $|1\rangle \longrightarrow |2\rangle$ and $|1\rangle \longrightarrow |3\rangle$ that is determining the propagation of the probe pulse. The quantitative comparison shows that the experimental results are well reproduced by numerical calculations.

In conclusion we have presented an all-optical control of superluminal propagation in an atomic sample. The advance of a 3.0 ns pulse, slightly amplified, is continuously controlled from 0 up to 400 ps without significant distortion. The proposed and experimentally demonstrated technique, based on an incoherent optical control, allows control by means of the characteristics of an optical pulse: energy and probe-control pulse timing. The experimental results agree with numerical simulation.

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