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Slow and fast light effects induced by interference with a control light field

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Abstract: The group velocity of light is governed by the dispersive properties of the optical material. Controlling these properties has led to concepts such as fast and slow light. In a vacuum, the group velocity of light is equal to c , excluding *a priori* the possibility of controlling the propagation time of a light pulse. Here, we prove that to some extent, this limitation can be circumvented by exhibiting a specific class of periodic light pulses that can be advanced or delayed by simple linear interference with a monochromatic light field. We show that such pulses are easily generated in a recirculating frequency shifting loop, and we experimentally demonstrate the possibility of advancing or delaying these pulses by times exceeding the nanosecond.

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1. Introduction

It is well known that in a transparent medium, a light pulse propagates at a speed fixed by the refractive properties of the medium. More precisely, considering that the frequency-dependent refractive index of the medium $n(f)$ varies linearly in the vicinity of the pulse carrier frequency f_0 , the ratio between c , the speed of light in vacuum and v_g , the group velocity (*i.e.* the velocity of the pulse envelope) is equal to $n(f_0) + f_0 \frac{\partial n}{\partial f}(f_0)$, a quantity defined as the group index of the medium [1,2].

In a two-level system, the group index at the exact resonance can be less than unity, a property leading to supraluminal propagation or fast light [3]. In this case, the pulse undergoes simultaneously a strong absorption. This drawback can be overcome by taking advantage of the anomalous dispersion regime that appears between two Raman gain lines [4,5], or in the specific dynamics of saturable absorbers [6–8]. Furthermore, the possibility of inducing a negative group index leads to the paradoxical phenomenon that the pulse inside the medium propagates backward, and the peak of the pulse leaves the medium before that of the input pulse enters it [9]. The compatibility of these observations with relativistic causality has led to long-standing controversies [10], but it has been shown that despite the fact that the group velocity exceeds c in a fast light medium, the information velocity remains less than c [1,11]. In contrast to fast light, slow light propagation occurs when the group index is greater than one. In practice, the group index can be considerably increased by burning a transparency window inside a resonant absorption line using a coupling field [12–15]. It has also been shown that when the coupling field is turned off, the input pulse is stopped and stored in the medium as a dark state polariton [16], that can be converted back to a light pulse by reapplying the coupling field [17]. More recently, non-linear effects in silica such as stimulated Brillouin or Raman scattering, have been used to demonstrate slow and fast light effects in optical fibers [18]. Fast light and slow light illustrate the fascinating possibilities of controlling the speed of light in material media, while offering promising applications for classical and quantum data storage, data processing in fiber networks, ultrasensitive sensors, and radio-frequency photonics-assisted beamforming [19].

However, contrary to most physical media, in vacuum, the group velocity of light is equal to c , excluding *a priori* the possibility of controlling the speed of a light pulse. Still, independently of their counter-intuitive characteristics, let us recall that fast and slow light come essentially from the same effect: the interference between monochromatic frequency components undergoing different phase velocities, which move the constructive interference point (*i.e.* the peak of the pulse) to another point of the space-time [1]. In line with this idea, it has been recently demonstrated that dedicated shaping of the space-time spectrum of a light field generates so-called space-time wave packets, which can have arbitrary group velocity in free space [20]. Here, we propose a simpler approach, which does not make use of transverse propagation effects of the light. Indeed, we show that a specific class of light pulses can have its constructive interference point advanced or delayed by linear interference with a monochromatic control light field, while preserving its envelope. The concept is depicted in Fig. 1. In vacuum, a light pulse travels distance ct for time t (Fig. 1(a)). The class of light pulses we define in this letter can be delayed (Fig. 1(b)) or advanced (Fig. 1(c)) by recombination on a beamsplitter with a monochromatic light field, achieving in vacuum the characteristics of slow or fast light in strongly dispersive media.

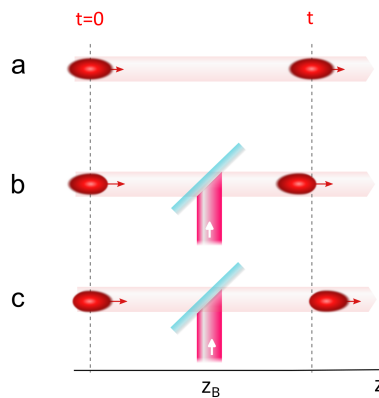


Fig. 1. Sketch of the proposal. As compared to regular propagation of a light pulse in vacuum (a), we exhibit here a specific class of light pulses that can be delayed (b) or advanced (c) by combination on a beamsplitter (located at z_B) with a monochromatic light field.

The paper is organized as follows. First, we derive the mathematical expression of the light field that satisfies the desired condition. We show that the corresponding pulses can easily be synthesized in a frequency shifting loop. Then, we provide an experimental demonstration of the phenomenon, by proving the capability of delaying or advancing the pulse train by simple coherent recombination on a beamsplitter with a monochromatic control light field. Notice that for the sake of simplicity and without loss of generality, our experiments are carried out not in vacuum, but in fiber components. Given the small spectral width of the pulses involved, we can consider dispersion to be completely negligible. To conclude, we establish the link between our results and the very process of generation of these pulses in the frequency shifting loop, and we discuss our results in the context of propagation speed of information.

2. Theoretical approach

The question one addresses here is: what is the electric field of a pulse that can be delayed or advanced by simple interference on a 50:50 beamsplitter with a monochromatic control field? Defining $E(t)$ as the slowly-varying envelope of the sought light field and E_0 the amplitude of the monochromatic control field, the electric field at an output port of the beamsplitter is

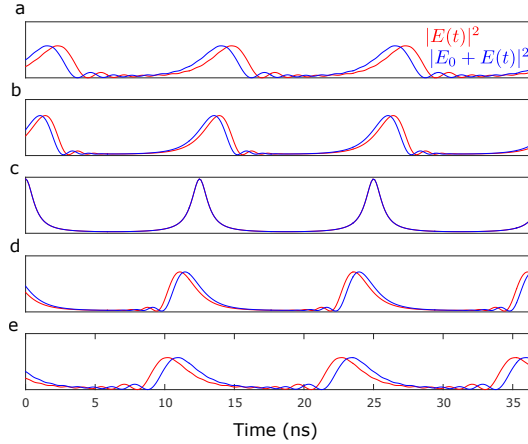


Fig. 2. Numerical simulations of the pulse train with respect to time. The red trace represents the square modulus of $E(t)$ (as defined in Eq. (3)) and the blue one that of $E(t) + E_0$. The traces have been normalized for clarity reasons. In all cases, $f_s = 80$ MHz ($1/f_s = 12.5$ ns). From a to e, the equivalent GDD D_2 takes the following values (in ns^2): -1.24 , -0.62 , 0 , $+0.62$, and $+1.24$. The light pulses are advanced (resp. delayed) when D_2 is negative (resp. positive).

$1/\sqrt{2}(E(t) + E_0)$. Introducing τ as the time lag induced by the recombination process, the aforementioned hypothesis writes:

$$|E(t + \tau)|^2 = \frac{1}{2}|E(t) + E_0|^2, \quad (1)$$

which simply rewrites: $E(t + \tau) = \frac{1}{\sqrt{2}}e^{i\phi(t)}(E(t) + E_0)$. Obviously, there is no solution for a single pulse whose field is strictly equal to zero outside a finite interval. However, solutions exist for periodic light fields. Assume that $E(t)$ has a repetition rate of f_s , and expands as the Fourier series: $E(t) = E_0 \sum_n c_n e^{i2\pi n f_s t}$, where c_n are the complex Fourier coefficients of $E(t)$. This implies that the complex exponential $e^{i\phi(t)}$ is also a $1/f_s$ -periodic function. We choose to restrict the range of solutions by considering the simplest case, corresponding to $\phi(t) = 2\pi f_s t$. Then, simple calculations lead to the following conditions for the c_n coefficients:

$$\begin{cases} c_1 e^{i2\pi f_s \tau} = \frac{1}{\sqrt{2}}(1 + c_0) \\ c_n e^{i2\pi n f_s \tau} = \frac{1}{\sqrt{2}}c_{n-1} \quad (\text{where } n \neq 1). \end{cases} \quad (2)$$

The only solution that avoids the divergence of coefficients c_n when $n \rightarrow -\infty$ involves $c_0 = 0$, which results in the following expression of the electric field:

$$E(t) = E_0 \sum_{n=1}^{\infty} \left(\frac{1}{\sqrt{2}}\right)^n e^{i2\pi n f_s t} e^{-i\pi n(n+1)f_s \tau}. \quad (3)$$

In the case where $f_s \tau \ll 1$, this class of functions describes a periodic train of pulses (period: $1/f_s$) with a quadratic spectral phase, or chirps. The spectral phase is conveniently described by the equivalent group delay dispersion (or GDD): $D_2 = \{f_s \tau\} / (2\pi f_s^2)$, where $\{x\}$ denotes the fractional part of x [21,22].

The ability of this specific class of pulses to be advanced or delayed by interference with a monochromatic field is depicted in Fig. 2 which plots, for different values of the GDD, the pulse

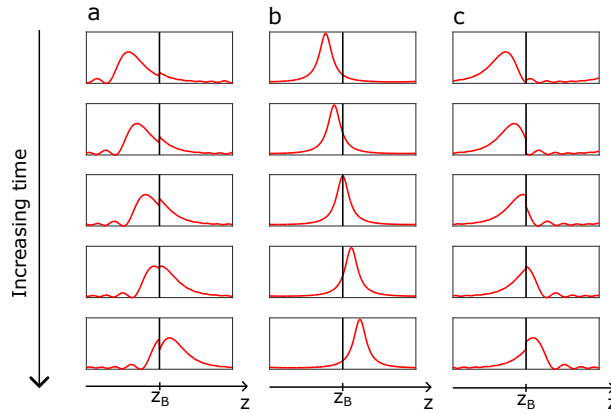


Fig. 3. Computed propagation of the light pulse on either side of the beamsplitter (z_B) where recombination with the control field occurs. The equivalent GDD is respectively equal to -1.24 (a), 0 (b), and $+1.24 \text{ ns}^2$ (c).

train before (in red) and after recombination (in blue) with the control field on the beamsplitter. The sign of the GDD sets the type of lag (advance or delay), while its value determines the lag time. The counterpart of this effect in space can be simulated by plotting the pulse envelope as a function of the propagation distance on either side of the beamsplitter (Fig. 3). When the GDD is negative (resp. positive), the coherent addition of the control field on the beamsplitter results in an advance (resp. delay) of the light pulse. On the contrary, the unchirped pulse ($D_2 = 0$) is unaffected by the recombination.

Experimentally, the pulse train described by Eq. (3) could be generated by spectral shaping of a mode-locked laser, where the amplitude of the comb lines should follow an exponential variation, and the spectral phase a quadratic dependence. However, a simpler approach consists in generating this pulse train directly in a frequency shifting loop (or FSL) seeded with a monochromatic laser. Recall that a FSL is a versatile tool for generating frequency combs [23] or pulse trains with high repetition rates [24], for applications in laser metrology [25] or microwave photonics [26], among others. Here, we consider a FSL in its simplest version: a fiber loop (travel time: τ_c) containing an injection, and an output coupler. An acousto-optic frequency shifter (AOFS) (frequency shift per round-trip: f_s) is placed between the two. When the loop is seeded with a monochromatic laser at frequency f_0 , the output electric field consists of a sum of frequency components shifted from f_0 by multiples of f_s . Introducing η as the single pass transmission coefficient of the loop, it can be shown that the output electric field envelope writes [22,24,27]:

$$\mathcal{E}(t) = E_0 \sum_{n=1}^{\infty} \eta^n e^{i2\pi n f_s t} e^{-i2\pi(n-1)f_0\tau_c} e^{-i\pi n(n-1)f_s\tau_c}. \quad (4)$$

Identifying η with $1/\sqrt{2}$ and noticing that the linear spectral phase terms in Eq. (3) and Eq. (4) can be dropped by a proper change of the origin of time leads to an equivalence of this electric field with that of Eq. (3). In practice, it is convenient to consider implementations where τ_c and $1/f_s$ are close to each other. Then, defining τ according to $f_s = 1/(\tau_c - \tau)$ (where $\tau \ll \tau_c$) leads to an expression of the slowly varying envelope of the pulse train similar to that in Eq. (3). The time shift that is expected when this field is recombined with the control field on a beamsplitter is simply $\tau = \tau_c - 1/f_s$.

3. Experimental results

To demonstrate the proposed concept, a fiber FSL is implemented with Panda polarization-maintaining fiber components soldered together (Fig. 4(a)). It contains two identical 90:10 couplers enabling respectively to inject the loop, and to extract a fraction of the light. An AOFS is placed between the two couplers. It can be driven at frequencies between 70 MHz and 90 MHz. The length of the fiber loop is carefully set, so that $1/\tau_c = 77.0$ MHz. The FSL is seeded by a narrow-linewidth single frequency laser at 1550.0 nm. The FSL output is split in two. One channel is sent to a fast photodiode (PhD₁). The other is recombined on a 50:50 beamsplitter with a fraction of the injection laser (*i.e.* the coupling field), and the recombined signal is detected by a second photodiode, PhD₂, identical to the first one. Prior to recombination on the 50:50 beamsplitter, the power of the coupling field is controlled by a variable optical attenuator (VOA).

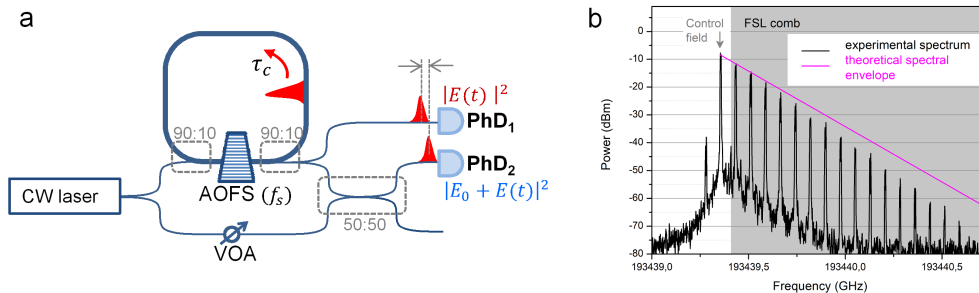


Fig. 4. a: Sketch of the experimental set-up. A CW laser seeds a FSL (travel time: τ_c). An acousto-optic frequency shifter (AOFS) imprints a frequency shift equal to f_s . The output light field is recombined on a 50:50 beamsplitter with the control light field (*i.e.* a fraction of the seed laser controlled by a variable optical attenuator - VOA). Two fast photodiodes record the pulses without (PhD₁) and after (PhD₂) recombination with the control field. b: Optical spectrum at PhD₂. The power of the AOFS driving signal and the VOA are adjusted, so that the power ratio between consecutive comb teeth is -3 dB (magenta line).

To produce the light field that satisfies Eq. (3), we set the system, so that $\eta = 1/\sqrt{2}$. To this end, we measure the comb spectrum at the FSL output by means of a high resolution optical spectrum analyzer placed at the second output port of the 50:50 beamsplitter. We adjust the power of the AOFS driving signal, so that the relative power between consecutive comb lines is -3 dB. Similarly, we adjust the VOA, so that the power of the control field is 3 dB above that of the first comb line (Fig. 4(b)). Notice that the total bandwidth of the generated frequency comb does not exceed 1 GHz. Therefore all dispersion effects can be neglected in the FSL itself, and in the subsequent fiber components.

To demonstrate the influence of the control field on the pulse train after recombination, we record the signals recorded by PhD₁ and by PhD₂ when f_s is varied from 72 to 82 MHz. Notice that the control light field needs to be phase-coherent with the pulse train. For simplicity, we did not implement any phase stabilization scheme and let the system drift under (slow) thermal fluctuations. However, the experimental data were recorded only when the phase of the control laser matched that of the output train, a condition that is met when the signals measured by the two photodiodes have similar shapes. We observe the following properties: when f_s is below (resp. above) 77 MHz, the pulse train is delayed (resp. advanced) by the control field (Fig. 5(a), 5(b) and 5(d), 5(e)). When f_s is set to 77 MHz, *i.e.* $1/\tau_c$, the timing of the pulse train is not modified by the control field (Fig. 5(c)). The relative delay between the two traces is measured as a function of f_s , and plotted in Fig. 5(f), in agreement with the expected values of $\tau = \tau_c - 1/f_s$.

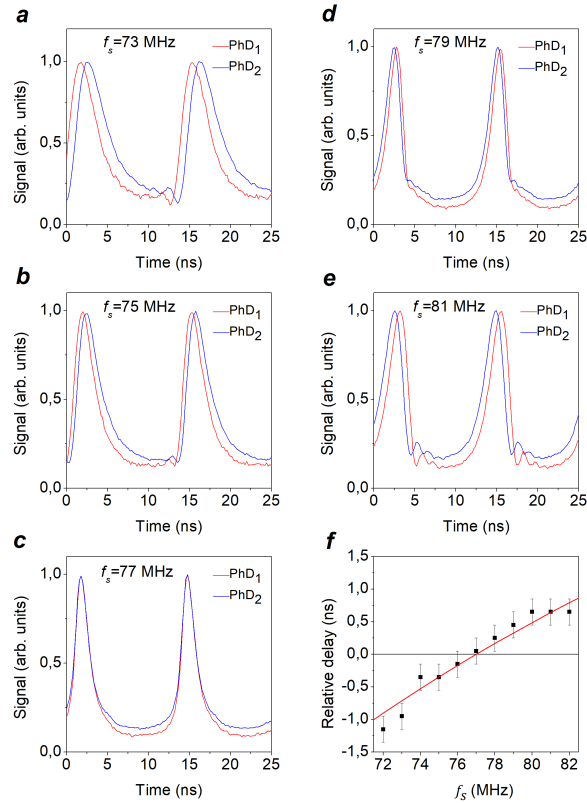


Fig. 5. a to e: Traces measured by the photodiodes PhD₁ and PhD₂ for different values of f_s . f: Variation of the relative delay between the traces measured by PhD₁ and PhD₂ as a function of f_s . The experimental data points are compared to the theoretical variation $\tau = \tau_c - 1/f_s$ (red curve).

4. Discussion and conclusion

We have exhibited a specific class of light fields that can be advanced or delayed by coherent recombination with a CW control light field on a beamsplitter. This effect can be seen as a generalization to non-dispersive media, of the fast and slow light effects, which have been reported to date in highly dispersive materials. We have shown that this light field is readily generated in a FSL, and have evidenced experimentally time lags as large as the ns, *i.e.* about 8% of the period of the pulse train.

First, these results bring an interesting insight into the operation of the FSL itself. In fact, the phenomenon of light advance or delay occurs continually in the FSL at the injection coupler. More precisely, τ_c , the travel time of the pulse in the FSL, is set by the fiber length. On the other hand, the spectrum of the light in the FSL is a frequency comb with a spacing of f_s , which implies that the repetition rate is equal to f_s . Therefore, when $f_s \neq 1/\tau_c$, the FSL imposes simultaneously two contradictory conditions of the period of the pulse. This apparent contradiction is overcome by the fact that, at the injection coupler, the pulse repeatedly shifts in time, bringing it back into line with its natural period of $1/f_s$.

In the present manuscript, we have deliberately limited the problem to special cases. First, we have considered the case of a 50:50 beamsplitter. This work could be extended to the case of a beamsplitter with arbitrary transmission/reflection coefficients. In this case, Eq. (1) would simply be rewritten as $|E(t + \tau)|^2 = |RE(t) + TE_0|^2$ where R and T are respectively the complex reflection

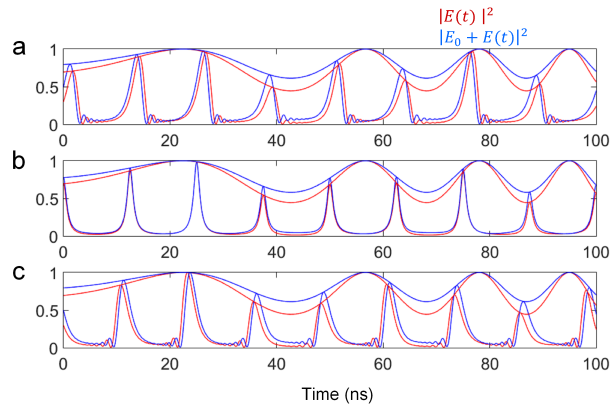


Fig. 6. Numerical simulations of the pulse trains with respect to time when the input pulse train $|E(t)|^2$ (in red) is modulated in intensity by an arbitrary signal. The pulse train after recombination with the control field $|E(t) + E_0|^2$ is in blue. The traces have been normalized for clarity reasons. In all cases, $f_s = 80$ MHz ($1/f_s = 12.5$ ns). From a to c, the equivalent GDD in equal to : -1.24 , 0 , and $+1.24$ (in ns^2).

and transmission coefficients in amplitude of the beamsplitter ($|R|^2 + |T|^2 = 1$). Additionally, we have restricted here to the simplest expression of $\phi(t)$, *i.e.* $\phi(t) = 2\pi f_s t$. In this case, considering a beamsplitter with arbitrary coupling coefficients would essentially lead to an expression of the electric field similar to Eq. (3), where $1/\sqrt{2}$ should be replaced by a real number $0 < \beta < 1$. As said, other solutions of $\phi(t)$ are foreseeable, and we anticipate that the light field generated in a fiber loop containing a phase modulator instead of a frequency shifter, could also be a solution of Eq. (1) and should show similar behaviors as the light field generated in the FSL [28].

Finally, beyond potential applications (signal synchronization, beam-forming, . . .), the capability of advancing/delaying a pulse train by simple linear interference with a control light field is a new insight into interference effects in the temporal domain. It also leads to the unavoidable question of whether the system can be used for faster-than-light communication. Indeed, one could imagine concatenating multiple sequences of couplers (which achieve input ports to the control beam) and frequency shifters. Then a pulse train at the input of the sequence would experience repeated time advances (or delays) and show a propagation speed in average potentially smaller (or larger) than c . However, it turns out that despite the fact that the pulse train can be advanced or delayed, the timing of the information carried by the pulse train is not modified by the process. To highlight this, we consider an input pulse train (*i.e.* before the beamsplitter) modulated in intensity by an arbitrary signal. Figure 6 shows that despite the pulses after the beamsplitter (in blue) are advanced or delayed with respect to the incident ones (in red), the envelope of the pulse train remains identical for both pulse trains. Therefore, the timing of the signal carried by the pulse train is not affected by the reported process, excluding *a priori* the capability of such a link for supraluminal transmission of information.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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