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Phase tunability of group velocity by modulated-pump-forced coherent population oscillations

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We propose a technique to obtain slow and fast light propagations based on coherent population oscillations forced by a modulated pump. This mechanism produces an enhancement of 1 order of magnitude of the delay or advancement of light signals. The relative phase between the pumps to the signal fields is used as a knob for changing light propagation from ultraslow group velocities to negative group velocities. The experimental realization of the phenomenon was carried out in an erbium-doped fiber amplifier at room temperature.

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The control of the group velocity of pulses or signals in a medium has evolved into a subject of intense research. One of the most significant works on slow light is due to Kasapi *et al.* [1], where electromagnetic induced transparency (EIT) [2] was used to obtain a group velocity of $v_g=c/165$ in a Pb vapor. It is a well-established fact that in a resonant medium group velocity of a light pulse can be much lower than c, or even faster, without violating causality principle due to the high dispersion at the resonance frequency and the narrow transparency window arising from quantum interference. However, the experimental realization is difficult since EIT phenomenon is strongly influenced by the coherence dephasing time, thus requiring extremely refined experimental setups at low temperatures. Group velocities as low as $v_g=17\ \mathrm{ms}^{-1}$ in a Bose-Einstein condensate [3] have been measured. Fast and negative group velocities were also observed, as, for example, in a Cs vapor where $v_g=-c/310$ were obtained [4].

Coherent population oscillations (CPOs) have been shown to be another physical mechanism which allow for the variation in group velocity. The periodic modulation of the ground-state population at the beat frequency between a control and a probe field sharing a common atomic transition produces scattered light from the control field to the probe field leading to a decrease in the absorption of the probe field. This produces a narrow hole in the absorption profile for the probe field leading to slow light propagation [5]. This process is governed by the population relaxation time and becomes nearly insensitive to temperature. Slow and fast light at room temperature originated by CPO has been experimentally observed in solid-state crystals [5–7], semiconductor structures [8,9], erbium-doped fibers (EDFs) [10–12], and biological thin films [13]. A change from subluminal to superluminal propagation has been observed by turning the operating regime from absorption into gain by means of an additional pump beam [10] or current injection [14]. The delay or advancement achieved saturates with both pump and control field intensities due to gain saturation [5,6,10].

In previous works by our group [11], we have studied the effect of high doping levels in slow and fast light propagations in erbium-doped fiber amplifiers (EDFAs). A change from subluminal to superluminal propagation solely upon increasing the beat frequency was observed due to the nonlinear propagation effects (strongly depleted regime) arising from the high value of the doping level. Here, in this work, we present a method to enhance 1 order of magnitude the delay or advancement of light signals by inducing a beat in the pump field at the same frequency as the beat between the control field and the probe field. The modulation of the pump imposes an extra oscillation of the population of the ground state that increases the amplitude of the population oscillations that produce the slow and fast light effects for the probe field. The possibility to modify at will the relative phase of the pump field to the probe field allows us to manage the magnitude of the delay or advancement experienced by the probe field. We show the feasibility of the method in EDFAs.

CPO in two-level atoms is a well-studied problem [15], which has received a renewed attention after the emergence of the experimental studies on slow light. The two levels $|1\rangle$ and $|2\rangle$ are connected by a field we call "signal" from now on (with Rabi frequency Ω_s), which is comprised of a strong control field Ω_{s0} at the resonant frequency ($\omega_{s0}=\omega_{21}$) and a weak probe field Ω_{s1} frequency shifted (see Fig. 1). This field can be written as $\Omega_s=\Omega_{s0}+\Omega_{s1}e^{-i\delta t}$, where δ is the beat frequency. As explained above, when the population oscillates at the beat frequency δ, the probe field experiences a delay. The addition of a pump field Ω_p with angular frequency far from that of the signal field and connecting the ground level to an auxiliary level $|3\rangle$ will allow us to turn

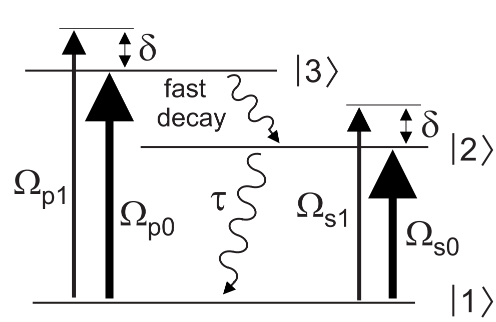

FIG. 1. Three-level atom with the control (Rabi frequency Ω_{s0}) and the probe (Rabi frequency Ω_{s1}) signal fields coupling $|1\rangle$ to the excited state $|2\rangle$. The strong (Rabi frequency Ω_{p0}) and weak (Rabi frequency Ω_{p1}) pump fields couple the ground state $|1\rangle$ to the fast decaying excited state $|3\rangle$. The Rabi frequencies are expressed in frequency units.

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delay into advancement for the probe field, depending on the pump power. Our goal is to force the population oscillations by modulating the pump field. Here, we consider that the pump field is also comprised of a strong field Ω_{p0} and a weak field Ω_{p1} frequency shifted at the same beat frequency δ (see Fig. 1). This pump field can be written as $\Omega_p = \Omega_{p0} + \Omega_{p1} e^{-i(\delta t - \varphi)}$ so that it could be out of phase with the probe field by a magnitude φ that can be externally changed. Let us assume that the third level $|3\rangle$ presents a fast decay into level $|2\rangle$ to reduce the system to an equivalent two-level atom whose dynamical evolution is given by

$$\frac{\partial \rho_{21}}{\partial t} = -\gamma_{21}\rho_{21} - i\Omega_s W, \tag{1}$$

$$\frac{\partial W}{\partial t} = -\frac{1+W}{\tau} + I_p \frac{1-W}{\tau} - 2i(\Omega_s^* \rho_{21} - \Omega_s \rho_{12}), \tag{2}$$

where ρ_{21} is the slowly varying coherence between levels $|1\rangle$ and $|2\rangle$ and $W \equiv \rho_{22} - \rho_{11}$ is the population inversion. γ_{21} is the coherence decay time, and τ is the relaxation decay time of level $|2\rangle$. $I_p = 2\tau|\Omega_p|^2/\gamma_{31}$ is the normalized pump intensity (pump intensity normalized to the pump saturation intensity), where γ_{31} is the coherence decay time from $|3\rangle$ to $|1\rangle$. A further simplification arises when the decay of the coherence takes place faster than the decay of the population inversion, i.e., by assuming that $\gamma_{21} \gg 1/\tau$. Then, the coherence ρ_{21} can be adiabatically eliminated, which reduces the problem to a modified rate equation of the form

$$\frac{\partial W}{\partial t} = -\frac{1+W}{\tau} + I_p \frac{1-W}{\tau} - I_s \frac{W}{\tau}, \tag{3}$$

where we have defined the normalized intensity for the signal beam as $I_s = 4\tau|\Omega_s|^2/\gamma_{21}$ (signal intensity normalized to the signal saturation intensity). Note that the phase delay φ leads to a phase shift between the modulation of the normalized signal intensity $I_s \simeq I_{s0} + 2\sqrt{I_{s0} I_{s1}}\cos(\delta t)$ to the modulation of the normalized pump intensity: $I_p \simeq I_{p0} + 2\sqrt{I_{p0} I_{p1}}\cos(\delta t - \varphi)$, where $I_{sj} = 4\tau|\Omega_{sj}|^2/\gamma_{21}$ and $I_{pj} = 2\tau|\Omega_{pj}|^2/\gamma_{31}$ with $j = 0, 1$. We are interested in the group velocity of the probe field, thus we resort to use the Floquet harmonic expansion by expressing W in terms oscillating at harmonics of the beat frequency δ, as $W = W^{(0)} + W^{(+)} e^{-i\delta t} + W^{(-)} e^{i\delta t}$. We insert this expansion in Eq. (3), and by equating coefficients oscillating at the same harmonic of δ we obtain the following coefficients:

$$W^{(0)} = \frac{I_{p0} - 1}{\omega_c}, \tag{4}$$

$$W^{(+)} = \frac{-\frac{4\tau}{\gamma_{21}}\Omega_{s0}\Omega_{s1}W^{(0)}}{\omega_c - i\delta\tau} + \frac{\frac{2\tau}{\gamma_{31}}\Omega_{p0}\Omega_{p1}(1 - W^{(0)})e^{i\varphi}}{\omega_c - i\delta\tau}, \tag{5}$$

where $\omega_c = 1 + I_{p0} + I_{s0}$ is the dimensionless optimum modulation frequency that roughly measures the width of the spectral hole in the absorption profile, that is, the maximum modulation bandwidth available [16]. To study the response of the system to the probe field, we calculate the susceptibility of the system as $\chi_{s1} = N_a \mu_{21}^2 \rho_{21}^{(+)}/(2\hbar\epsilon_0\Omega_{s1})$, where N_a is the number of atoms in the system, μ_{21} is the electric dipolar moment, and $\rho_{21}^{(+)} = -i/\gamma_{21}(W^{(0)}\Omega_{s1} + W^{(+)}\Omega_{s0})$ is the part of the coherence oscillating at the beat frequency. The real part of the susceptibility, which accounts for the delay or advancement, depends on the imaginary part of $W^{(+)}$, i.e., the amplitude of the population oscillations which oscillate 90° out of phase (in quadrature) with respect to the probe field. $W^{(+)}$ has two terms [see Eq. (5)]: the first one corresponds to the amplitude of the population oscillations when only the signal field is modulated observed up to date. The second term corresponds to the contribution of the pump modulation to the amplitude of the population oscillations. To visualize the effect of pump modulation in the slow and fast light phenomena we plot in Fig. 2 the imaginary part of $W^{(+)}$ as a function of $\delta\tau$ in the case without pump modulation (solid line) and in the case with pump modulation for different values of φ (dashed and dotted lines). We observe how the amplitude of the population oscillations gets amplified when modulating the pump, which in turn will enhance the delay or advancement experienced by the probe field. Furthermore, this increase in the amplitude of the population oscillations is more pronounced for the phases $\pi/2$ and $3\pi/2$.

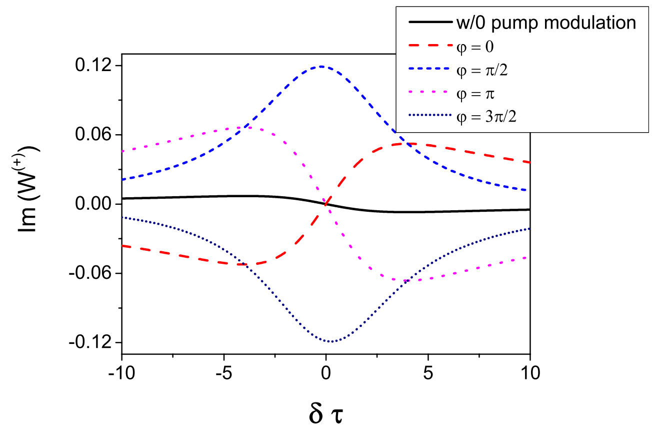

FIG. 2. (Color online) Imaginary part of $W^{(+)}$ as a function of $\delta\tau$ for $I_{s0} = 1$, $I_{p0} = 2$, $I_{s1}/I_{s0} = 0.05$, and $I_{p1}/I_{p0} = 0.1$ in the pump modulation cases for different values of φ.

From the real part of the susceptibility we arrive to the phase delay ϕ_{s1} experienced by the probe field after propagating through a medium of length L:

$$\phi_{s1} = \frac{\alpha_0 L}{2}\left[\frac{A_0\delta\tau - A_1(\omega_c \sin\varphi + \delta\tau\cos\varphi)}{\omega_c(\omega_c^2 + (\delta\tau)^2)}\right], \tag{6}$$

where $\alpha_0 = N_a \omega_{21}\mu_{21}^2/(2\hbar c\epsilon_0\gamma_{21})$ is the unsaturated absorption coefficient, $A_0 = I_{s0}(I_{p0} - 1)$, and $A_1 = \sqrt{I_{p0}I_{p1}/(I_{s0}I_{s1})}(I_{s0} + 2)$. We define the fractional advancement as $F = \phi_{s1}/(2\pi)$. A close inspection of Eq. (6) reveals the important role played by the weak part of the pump field in the slow and fast light phenomena. The new term that arises when modulating the pump is proportional to $\sqrt{I_{p1}}$ and can lead to delay or advancement depending on the value of φ. Note that if the pump field is not modulated, the strength of the probe field does not influence the fractional advancement, as shown in previous works on CPO without pump modulation [11]. It should be pointed out that Eq. (6) as-

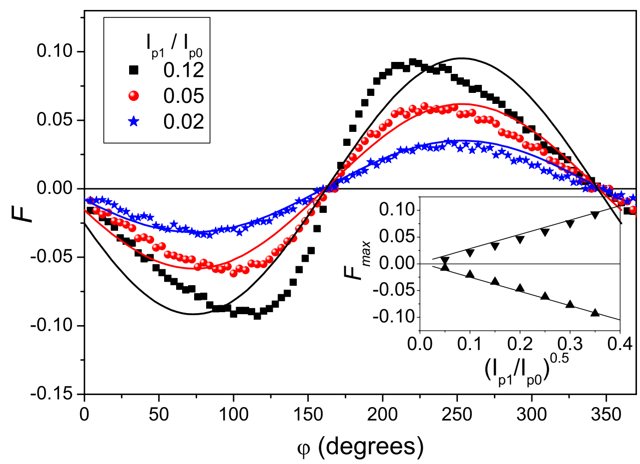

FIG. 3. (Color online) Experimental (symbols) and theoretical (lines) fractional delays or advancements as a function of phase φ for different weak normalized pump field intensities I_{p1}. (Inset) Experimental (symbols) and theoretical (lines) maximum fractional delays and advancements versus $\sqrt{I_{p1}/I_{p0}}$. The normalized signal intensity is set to $I_{s0}=0.3$, the normalized pump intensity to $I_{p0}=2.4$, and the weak normalized signal intensity to $I_{s1}=0.075\ I_{s0}$ for a fixed value of $f_m=20$ Hz.

sumes implicitly the absence of z dependence in the field intensities, i.e., we assume the so-called undepleted solution.

To experimentally show the feasibility of the proposed technique we used an EDFA in the forward-pumped configuration (see [11] for more details on the experimental setup). A laser field tuned to 1550 nm couples the transition between the erbium ground state $^4I_{15/2}$ (level $|1\rangle$) and the state $^4I_{13/2}$ (level $|2\rangle$) whose lifetime is around $\tau=9$ ms. Another laser field tuned to 980 nm couples the ground state to level $^4I_{11/2}$ (level $|3\rangle$). The relaxation time of coherence ρ_{21} is around 10^{-11} s, far from the time scale we are interested in ($\sim 10^{-2}$ s), thus the adiabatic following of coherence is satisfied. Both laser output powers are sinusoidally modulated at the same modulation frequency $f_m=\delta/(2\pi)$ by two synchronized function generators in order to control the relative phase φ between them. This relative phase is set to 0 by measuring the phase delay between pump and signal references. We use a 10-cm-long single mode Al_2SiO_5-glass-based fiber-doped with Er^{3+} ions (ion density $N_a=6.3\times 10^{25}$ m^{-3}). The linear absorption coefficient is $\alpha_0\simeq 0.24$ cm^{-1}. The signal and pump saturation powers are 0.42 and 1.5 mW, respectively. We use the insertion losses as fitting parameters to reproduce the experimental curves, obtaining 0.96 for the signal and 0.35 for the pump. We compute the time delay or advancement t_d from the correlation of the reference signal and the signal propagated through the EDF. Then, the fractional delay or advancement is expressed as $F=t_d f_m$.

We plot in Fig. 3 the fractional delay or advancement versus φ when we modulate the pump and the signal powers at a modulation frequency of $f_m=20$ Hz (signal power 0.14 mW and pump power 10 mW). Different curves correspond to different weak normalized pump field intensities. First of all, we observe subluminal or superluminal light propagation depending on the relative phase φ. This result demonstrates the viability to control the propagation regime by means of the relative phase φ. Furthermore, we see that the maximum values achieved for the delay and the advancement scale with $\sqrt{I_{p1}}$ (see inset in Fig. 3), in accordance with the theoretical prediction stated in Eq. (6). The value of φ that leads to the maximum fractional delay or advancement can be estimated from Eq. (6) and reads as $\tan\varphi=\omega_c/(\delta\tau)$. Then, at low frequencies ($\delta<\omega_c/\tau$) the maximums take place around $\pi/2$ and $3\pi/2$, in agreement with the experimental results shown in Fig. 3. The theoretical curves using Eq. (6) have also been plotted in Fig. 3 (lines). In spite of the simple theoretical model developed, the analytical predictions present good agreement with the experimental findings. The small discrepancies between the analytical results and the experiments could be fixed by solving numerically the propagation equations for the normalized pump and signal intensities and the phase delay. However, for the sake of simplicity, we only include in this work the analytical results. The behavior found and depicted in Fig. 3 is not restricted to the particular modulation frequency of $f_m=20$ Hz. We have checked that the effects of the relative phase φ on the magnitude F are also obtained at other modulation frequencies while maintaining f_m within the width of the spectral hole. It is worth mentioning that the value of the maximum fractional delay or advancement reported here for a 10-cm-long fiber corresponds to that obtained in fibers ten times longer (see [11]) using similar values of pump power (10 mW) which reveals the potentiality of the modulated-pump-forced CPO mechanism.

To study the magnitude of the enhancement of the delay or advancement obtained, we have carried out a series of experiments to determine the curves F versus f_m in the absence and in the presence of the modulation in the pump field while keeping constant the rest of experimental parameters. In the presence of modulation we also varied the values of φ. From each one of these curves $F(\varphi)$, we compute both the maximum values of the delay and the advancement achieved, F_{max}.

When the pump is not modulated, the maximum delay or advancement that can be achieved is given by $\mp\alpha_0 L/(32\pi)$, which for our experimental system is close to ∓ 0.02. The maximum delay is achieved without pump, at the optimum modulation frequency $\delta\tau\simeq\omega_c$, and $I_{s0}\simeq 1$ (signal saturation intensity); while the maximum advancement is achieved at high pump values. These two optimum cases have been measured when we modulate the signal with $I_{s1}/I_{s0}=0.02$. Optimum delay was obtained for a signal power of 0.53 mW, while optimum advancement was achieved increasing the signal power to 2 mW and applying a pump power of 23 mW. The results are shown in Fig. 4 (triangles), where F_{max} is plotted versus f_m. In order to analyze the effect of the periodic modulation of the pump, we used the same parameters than in the case for the optimum advancement, while we periodically modulate the pump intensity such that $I_{p1}/I_{p0}=0.16$. The results show a great increase in both delay and advancement [Fig. 4 (circles)]. We have also characterized the performance of the system for other values of the control field and strong pump field intensities obtaining in all cases a maximum fractional advancement and delay around 1 order of magnitude larger than the one obtained without

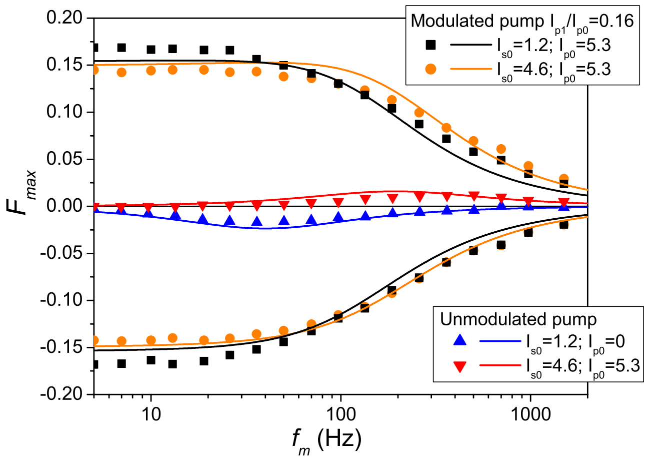

FIG. 4. (Color online) Experimental (symbols) and theoretical (lines) fractional delays or advancements as a function of f_m for different normalized signal and pump intensities. Unmodulated pump: optimum delay (up triangles) $I_{s0}=1.2$ and $I_{p0}=0$; optimum advancement (down triangles) $I_{s0}=4.6$ and $I_{p0}=5.3$. Modulated pump with $I_{p0}=5.3$ and $I_{p1}/I_{p0}=0.16$: (circles) $I_{s0}=4.6$ and (squares) $I_{s0}=1.2$. In all cases we used $I_{s1}/I_{s0}=0.02$.

pump modulation which revels the generality of these results. As an example, we plotted in Fig. 4 (squares) the results for the same pump power and a lower signal power of 0.53 mW. For measured fractional delay or advancement of ∓ 0.17 for 10 Hz [Fig. 4 (squares)], we get a time delay or advancement in the 0.1-m-long fiber of ∓ 0.017 s, which means we cover the range from ultraslow group velocities (≈ 6 m/s) to negative group velocities (≈ -6 m/s). The analytical curves have also been plotted in Fig. 4 (lines) showing the general behavior found in the experiments.

In conclusion, we observed an enhancement of the slow and fast light propagation effects when forcing the population oscillations with a modulated pump. The induced beat in the pump field has the same frequency as the corresponding to the probe field. This condition could make difficult the application of the proposed mechanism for unpredictable signals such as a data stream. The relative phase between the pump to the probe fields is used to switch between subluminal and superluminal propagation. The delay and advancement can be adjusted by means of this relative phase. This modulated-pump-forced CPO technique has been experimentally carried out in an EDFA at room temperature obtaining an enhancement of the fractional delay or advancement 1 order of magnitude larger than the one obtained without pump modulation. Similar results are expected to be obtained in other materials such as ruby or alexandrite, which share an equivalent theoretical description. This technique could be used with proper modifications in the field of semiconductors which are good candidates for telecommunication applications due to their fast characteristic relaxation time scale (GHz).

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