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Slow-light: Fascinating physics or potential applications?

# Light propagation in a solid doped with erbium ions: From ultraslow light to the superluminal regime

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**Abstract**

In this article we report on ultraslow or fast light propagation, exciting behavior that become achievable thanks to the Coherent Population Oscillations effect (CPO). We show that the group velocity, the speed at which light propagates, can be drastically modified and engineered using the CPO effect in a crystal doped with triply ionized erbium ions, namely: $Er^{3+}$:$Y_2SiO_5$. The steep dispersion of the index of refraction caused by the CPO effect is at the origin of group velocities as low as $v_g = 3$ m/s. By inverting the slope of the index dispersion, we can make, in the same crystal, light go faster than if it was propagating in vacuum. This particular regime is characterized by larger than $c$ or negative group velocities. In the 3-mm-long $Er^{3+}$:$Y_2SiO_5$ crystal, we have achieved a delay of $-0.2$ ms corresponding to a group velocity of $v_g = -15$ m/s. ***To cite this article: E. Baldit et al., C. R. Physique 10 (2009).***


**Résumé**

**Propagation de la lumière dans un solide dopé aux ions Erbium : de la lumière ultralente au régime superluminal.** Dans cet article, nous décrivons la propagation ultralente et superluminale de la lumière, deux comportements étranges qui sont rendus possible grace à l'Oscillation Cohérente de Population (OCP). Nous montrons que la vitesse de groupe, vitesse de propagation de la lumière, peut être radicalement altérée et manipulée à l'aide de l'OCP dans un cristal dopé aux ions Erbium triplement ionsés : $Er^{3+}$ :$Y_2SiO_5$. La forte dispersion de l'indice de refraction causée par l'effet OCP est à l'origine de vitesses de groupe aussi faibles que $v_g = 3$ m/s. En inversant le signe de la dispersion de l'indice de refraction, il est possible d'atteindre un régime où la lumière se propage plus vite que dans le vide. Celui-ci est caractérisé par des vitesses de groupes supérieures à $c$ ou par des vitesses de groupe negatives. Dans le cristal $Er^{3+}$ :$Y_2SiO_5$ long de 3 mm, nous avons obtenu des retards optiques de $-0.2$ ms correspondant à une vitesse de groupe $v_g = -15$ m/s. ***Pour citer cet article : E. Baldit et al., C. R. Physique 10 (2009).***


*Keywords:* Slow light; Rare-earth ion-doped crystal; Coherent population oscillation

*Mots-clés :* Lumière lente ; Cristal dopé aux ions terres rares ; Oscillation cohérente de population

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## 1. Introduction

The speed of light in vacuum, as we know it nowadays, is a universal constant, fixed since 1983 to $c = 299\,792\,458$ m/s. It is the consequence of the most precise and first laser-based speed-of-light measurement achieved in 1972 by K.M. Evenson et al. [1]. However, the first attempt on the surface of the Earth to measure the speed of light was made by Fizeau in 1848 and it consisted in measuring the time of flight of an optical pulse created by a chopper and traveling back and forth between two places separated by 8.6 km. In fact Fizeau did not measure the speed of light corresponding to what we know as the phase velocity but rather measured the group velocity, corresponding to the speed at which a pulse wavepacket propagates.

In general, the group velocity $v_g$ in a dispersive medium is given by

$$v_g = \frac{c}{n(\omega_0) + \omega_0 \frac{\partial n}{\partial \omega}|_{\omega_0}} \tag{1}$$

where $\omega_0/(2\pi)$ is the central oscillating frequency of the pulse and where $n$ is the medium wavelength-dependent index of refraction. As expressed by definition (1), the group velocity depends on the dispersion of the index $n$ in which propagation takes place. In vacuum, the index of refraction is unity and its dispersion is negligible, so the group velocity equals $c$. It is by modifying the dispersion that the group velocity can be altered. A very steep dispersion of the index of refraction is at the heart of the manipulation of the velocity at which light can propagate. Depending on the sign of the dispersion, the group velocity can be very low, larger than $c$, or even negative. According to the Kramers–Krönig relation, dispersion and transmission are closely connected in a medium. To a narrow transparent window in an absorptive profile is associated a steep positive dispersion of the index of refraction and thus a group velocity smaller than $c$ is reached. For very low group velocities, the approaches chosen are based on coherent or nonlinear optical processes, among which Coherent Population Oscillations (CPO) [2,3], Electromagnetically Induced Transparency (EIT) [4] or Stimulate Brillouin Scattering (SBS) [5].

The first direct demonstrations of Slow Light Propagation [4,6–9] were achieved via Electromagnetically Induced Transparency (EIT) [10]. EIT was originally implemented by applying a secondary control field to eliminate the linear absorption of a resonant probe field propagating through an otherwise absorbing medium. The standard scheme for EIT is a three-level $\Lambda$-like system, where the probe field drives the system from one of the ground states and the control field from the second ground state. The width of the spectral hole burned in the homogeneous absorption profile is proportional to the inverse of the dephasing time of the ground state, requiring thus stringent preparation of the system and its isolation from the perturbation induced by the environment. Another physical effect more recently implemented to reduce the speed of light to as low as few tens of meters per second is Coherent Population Oscillations (CPO) [11,12]. In contrast to EIT, the CPO effect is achieved in a two-level system excited by a strong pump field oscillating at $\omega$ and a weak probe field oscillating at $\omega + \delta$. In this configuration, the populations oscillate at the pump–probe beat frequency $\delta/(2\pi)$. Such oscillations are significant when $\delta$ is smaller than the natural linewidth $1/T_1$, where $T_1$ is the lifetime of the excited state. As a result, a narrow spectral hole, whose width is proportional to $1/T_1$, is induced in the homogeneous absorption profile of the probe field. M.S. Bigelow et al. [2] used this effect in a 7.25-cm-long ruby crystal at room temperature to achieve a spectral hole width of 36 Hz and reduce the group velocity of light down to 57 m/s. CPO effect was also implemented in GaAs/AlGaAs semiconductor quantum wells, where Ku et al. [13] showed a group velocity of 9600 m/s.

More recently we reported [3] on slow light propagation induced by the CPO effect in a crystal insulator doped with rare-earth ions. We have chosen erbium ions since they allow us to address the important wavelength range around 1.5 μm, fitting the transparent window of silica fibers and to use well mastered commercial lasers. Thanks to the long-lived excited state of the ions which is at the origin of the very narrow spectral hole and the steep dispersion of the refraction index, we successfully achieved ultraslow light propagation in this solid-state material. The corresponding group velocities are comparable to those achieved in slow light propagation via EIT in a Bose–Einstein condensate [4,6]. The optical intensities we use are as weak as the intensities concerned in Refs. [4,6] and are orders of magnitude weaker than those used in Refs. [2,13] for SLP via the CPO effect. We investigate the influence of the power and the absorption coefficient on the SLP. More importantly, we show that CPO-induced slow light propagation is robust in the presence of inhomogeneous broadening inherent to rare-earth ion-doped crystals. In fact, it constitutes an additional control parameter we are able to manipulate to tune both the group velocity and the transmission coefficient.

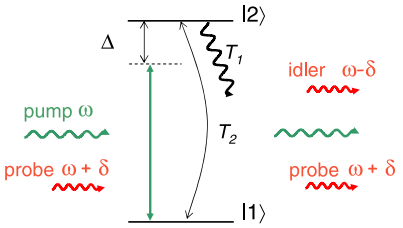


Fig. 1. Two-level atomic system considered for the CPO effect. It is excited by the pump and probe fields and radiates at the probe and idler frequencies. $T_1$ and $T_2$ are respectively the lifetime of the excited state and the decoherence time.

In this article we extend the results of [3] by addressing several important additional points. In the original letter, although the experimental demonstration clearly showed the importance and the usefulness of the inhomogeneous broadening, the homogeneous broadening theoretically considered was not sufficient to understand the full behavior. In particular, the power at which the group delay is maximum and the rate with which the group delay decreases as the power is further increased were not captured by the simplified model only based on homogeneously broadened two-level systems. In this article we extended the theory to take fully into account the inhomogeneous broadening. We also considered two additional experimental situations that allow us to further explore the propagation in the presence of CPO effect. We considered not only slow light propagation of a modulation encoded into a carrier frequency, but also the case where CPO is self induced during a pulse propagation. Finally, by inverting the population a steep negative dispersion is induced that allows 'negative' group velocities and acceleration of light both in the modulation and in the pulse configurations.

The article is organized as following. In Section 2, we introduce the theoretical background necessary to understand the CPO effect in the homogeneous and inhomogeneous cases. Although CPO is driven by population dynamics, a matrix density formalism is introduced in order to fully take into account the inhomogeneous broadening of the two-level systems. Section 3 is dedicated to the description of the experimental setup as well as the measurements we have conducted in the crystal doped with erbium ions, both in the modulated and pulsed configurations. We show that both slowing down the group velocity and accelerating the light beyond $c$ are possible. We analyze in detail the role of the inhomogeneous broadening that, rather than being a drawback, becomes a resource for group velocity control.

## 2. Theory

Coherent population oscillations (CPO) has been introduced for the first time by Schwarz and Tan in 1967 [14] to understand the instabilities observed in dye lasers and also to explain the presence of windows of transparency narrower than the homogeneous broadening and close to the natural linewidths. In the same paper, Schwarz and Tan propose to use the CPO effect as a spectroscopic tool in order to measure the lifetime $T_1$ of an atomic system when it is too short or when the atomic system is not fluorescent.

For the theoretical description of the CPO effect, we consider an ensemble of two-level atomic systems as depicted in Fig. 1, characterized by a lifetime $T_1$, a dephasing time $T_2$ and interacting with two electromagnetic fields: a pump oscillating at $\omega$ and a weak probe oscillating at $\omega + \delta$. We further suppose that both fields are close to resonance with the atoms, that is $\omega, \omega + \delta \simeq \omega_{12}$. Due to the temporal interference between the pump and the probe, the population of the atomic systems will oscillate at the beating frequency $\delta/(2\pi)$, in phase with the interference. The interaction of the pump with a susceptibility oscillating at $\pm\delta$ induces two radiations at $\omega - \delta$ and $\omega + \delta$. This second radiated field coincides with the probe and partially annihilates its absorption. As the beating frequency $\delta/(2\pi)$ gets larger than the natural linewidth $1/T_1$, the population oscillations decline and the radiated field at $\omega + \delta$ vanishes.

The CPO effect is a phenomenon driven by population dynamics. Though a simple model based on population rates is then sufficient to describe it, for the inhomogeneously broadened two-level atomic systems, the theoretical description requires the matrix density formalism. Let us consider that the atomic systems are interacting with a pump field $E_p(\omega)$, a probe field $E_s(\omega + \delta)$, and an idler field $E_i(\omega - \delta)$ and further that both probe and idler are weaker than the pump. This configuration corresponds to our experimental situation where the three fields are obtained by modulating sinusoidally at $\delta$ the intensity of a single laser beam. Indeed, in the Fourier space the modulated beam

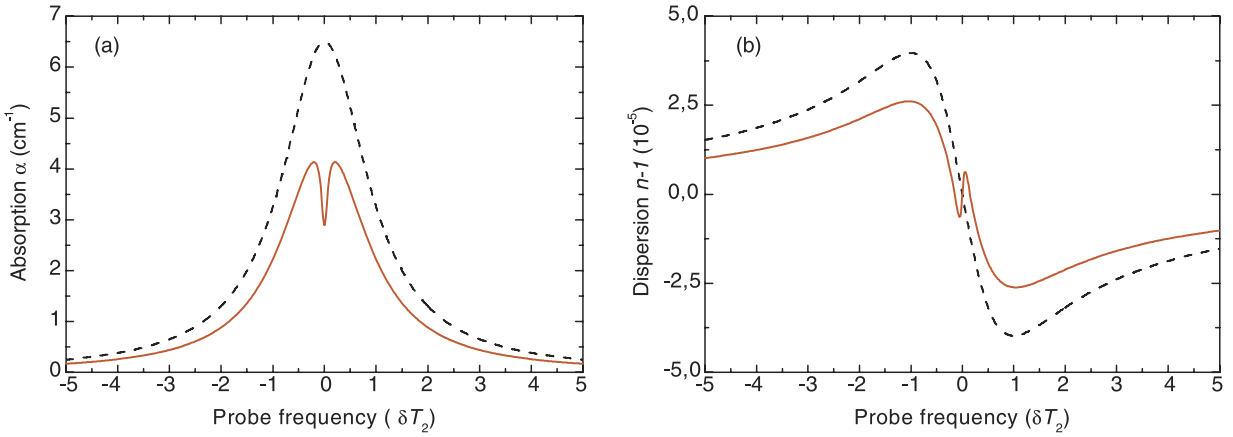


Fig. 2. Absorption (a) and index of refraction $n-1$ (b) of the probe field when the pump is present (continuous red line) and without the pump (dashed black line). The parameters are $\alpha_0 = 6.5\ \mathrm{cm}^{-1}$, $s = 0.5$, $T_1/T_2 = 20$, and a pump frequency $\Delta \times T_2 = 0$.

presents a spectral component at $\omega$ playing the role of the pump field, and two new side components at $\omega \pm \delta$ playing the role of probe and idler fields.

In the matrix density formalism, we are interested by the evolution of both the population difference $w = \sigma_{22} - \sigma_{11}$ and the microscopic polarization $p = \mu_{12}\sigma_{21}$. They are given by

$$\dot{p} = \left(i\Delta - \frac{1}{T_2}\right)p - \frac{\imath}{\hbar}|\mu_{ba}|^2 E w \tag{2}$$

$$\dot{w} = -\frac{w - w^{\mathrm{eq}}}{T_1} + \frac{4}{\hbar}\,\mathrm{Im}\left(pE^*\right) \tag{3}$$

where $E = E_p + E_s e^{-\imath\delta t} + E_i e^{+\imath\delta t}$ is the total field in the frame rotating at $\omega$, $\Delta = \omega - \omega_{12}$ is the pump detuning from the atomic resonance, and $w^{\mathrm{eq}} = -1$ is the population difference at equilibrium, where all atoms are supposed to be in the ground state. In order to solve Eqs. (2) and (3), we follow the formalism in [11] by considering solutions in the form of $K = K_p + K_s e^{-\imath\delta t} + K_i e^{+\imath\delta t}$, where $K = \{w, p\}$. By solving the equations in the stationary regime at all orders for the pump field and to the first order for the probe and the idler, and after some mathematical manipulations, we obtain the susceptibility at the probe frequency $\omega + \delta$

$$\begin{aligned}\chi_s^{(1)}(\delta,\Delta) &= \frac{Np_s}{\varepsilon_0 E_s} \\ &= -\left(\frac{\alpha_0 c}{\omega_{12}}\right)\frac{1}{T_2}\,\frac{1}{\Delta+\delta+\imath/T_2}\,\frac{1+\Delta^2T_2^2}{1+\Delta^2T_2^2+\Omega_p^2T_1T_2}\left[1-\frac{\Omega_p^2}{2D(\delta,\Delta)}\,\frac{(\delta+2\imath/T_2)(\Delta-\delta-\imath/T_2)}{\Delta-\imath/T_2}\right]\end{aligned} \tag{4}$$

where $D(\delta,\Delta) = (\delta+\imath/T_1)(\Delta+\delta+\imath/T_2)(\Delta-\delta-\imath/T_2) + \Omega_p^2(\delta+\imath/T_2)$, $\Omega_p = 2|\mu_{ba}||E_p|/\hbar$ is the pump Rabi frequency, $N$ the density of the atomic systems and $\alpha_0$ is the linear unsaturated absorption at resonance, whose expression is given by $\alpha_0 = -(N|\mu_{ba}|^2 w^{\mathrm{eq}}\omega_{12}T_2)/(c\hbar\varepsilon_0)$. We define the saturation parameter $s$ as the pump intensity normalized to the saturation intensity. It is also related to the pump Rabi frequency through the relation $s = \Omega_p^2 T_1 T_2$. Fig. 2 shows the index of refraction $n(\delta) - 1 = 1/2\,\mathrm{Re}(\chi_s^{(1)})$ and the absorption $\alpha(\delta) = (\omega+\delta)/c\,\mathrm{Im}(\chi_s^{(1)})$ for an absorption $\alpha_0 = 6.5\ \mathrm{cm}^{-1}$, a saturating parameter $s = 0.5$ and for $T_1/T_2 = 20$. The pump field is supposed to be in resonance with the atomic transition ($\Delta = 0$). As shown in Fig. 2, a narrow CPO hole appears in the homogeneous absorption line (Fig. 2(a)), to which a steep dispersion of the index of refraction is associated (Fig. 2(b)). The dashed curves are the absorption and the index of refraction in the same atomic systems when only excited by the probe.

For inhomogeneously broadened two-level atomic systems, the susceptibility at $\omega + \delta$ is given by integrating the susceptibility (4) over the hole inhomogeneous profile [15]

$$\chi_s^{\mathrm{inh}}(\delta,\Delta_0) = \int \chi_s^{(1)}(\delta,\Delta-\Delta_0)g(\Delta)\,d\Delta \tag{5}$$

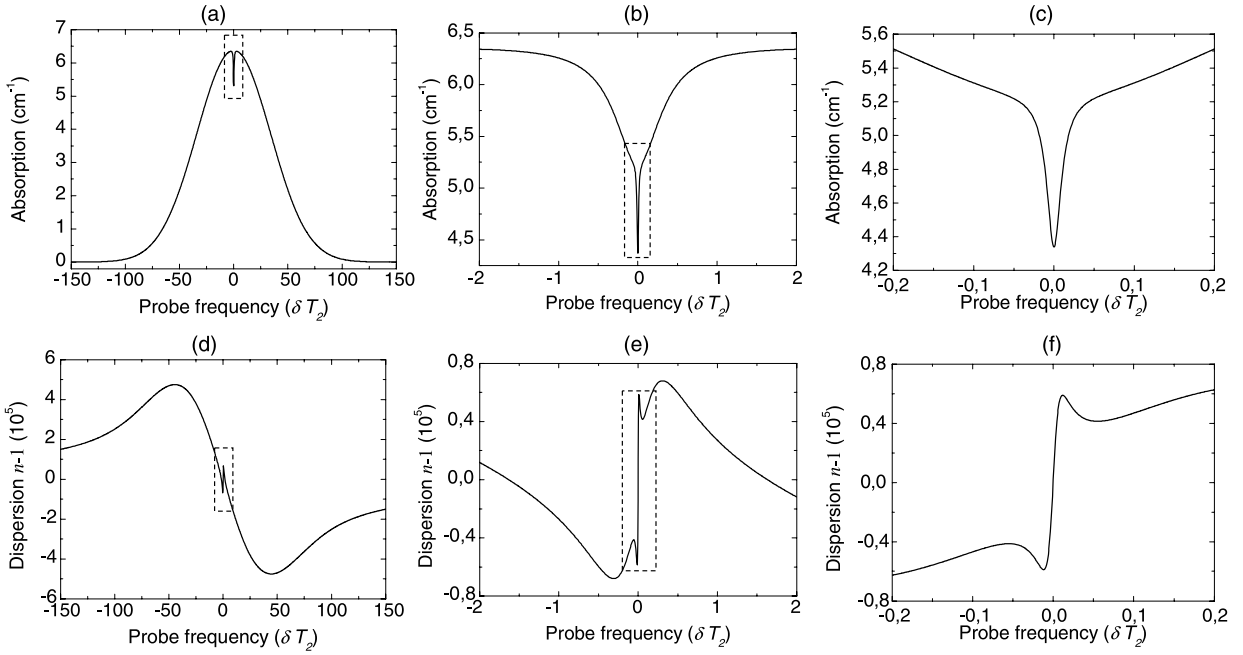


Fig. 3. Absorption coefficient and index of refraction $n-1$ of the probe field with respect of the probe frequency $\delta$ in units of $1/T_2$ in the case of inhomogeneously broadened two-level atomic systems. The FWHM inhomogeneous broadening is $\Gamma_{\text{inh}} \times T_2 = 80$, $s = 0.5$, $T_1/T_2 = 20$, and the pump frequency detuning from the central atomic resonance is $\Delta_0 \times T_2 = 0$. (a) and (d): Absorption and index or refraction over the whole inhomogeneous line. (b) and (e): Zoom of the dashed boxes in (a) and (d) around the homogeneous line absorption. (c) and (f): Zoom of the dashed boxes in (b) and (e) around the CPO hole.

where $\Delta_0$ is the detuning of the pump field from the central atomic resonance in the inhomogeneous line and $g(\Delta)$ is the inhomogeneous Gaussian-like distribution. Fig. 3 represents the absorption and dispersion in a theoretical case of an FWHM inhomogeneous broadening $\Gamma_{\text{inh}}$ 80 times larger than the homogeneous line. Figs. 3(a) and (d) show, respectively, the probe absorption and dispersion $n-1$ as its frequency is tuned over the whole inhomogeneous line. A deep hole appears in the absorption profile. It is due to the saturation effect induced by the pump field, the well known spectral hole-burning effect. The linewidth of this hole is the homogeneous linewidth given by $\Gamma_{\text{hom}} = 1/T_2$. Within this hole and due to the CPO effect, an additional even narrower hole appears. Its width, $\Gamma_{\text{CPO}}$, approaches the natural broadening $1/T_1$ of the atomic systems, as can be seen in the zoom presented in Fig. 3(c).

## 3. Experiment

### *3.1. The setup and the crystal*

The scheme of our experimental setup for slow light propagation in an erbium-doped crystal is depicted in Fig. 4. The light source is a 2-kHz linewidth, continuous-wave (cw) fiber laser (KOHERAS) emitting more than 150 mW at 1536.1 nm. The laser is both PZT and temperature tunable with an overall tunability of 1 nm which is sufficient for our measurements.

The crystal used in our experiments is an yttrium oxyorthosilicate ($Y_2SiO_5$) lattice doped with 0.005 at.% of $^{167}Er^{3+}$ ions supplied by Scientific Materials, Inc. (Bozeman, Montana). The energy levels of the ions in such host crystal are depicted in the box, Fig. 4. Due to the crystal field, the degeneracy of the total momentum $J$ is partially lifted, which gives rise to 8 Kramers doublets in the ground state $^4I_{15/2}$ and 7 in the excited state $^4I_{13/2}$. Isotope 167 is characterized by a nuclear spin $I = 7/5$ that interacts with the effective electronic spin $\tilde{S} = 1/2$ of the Kramers doublet of the ground state $^4I_{15/2}$, inducing a hyperfine structure not shown in Fig. 4 with 16 sub-levels in both ground and excited states [16]. The two-level system under investigation concerned by slow light propagation corresponds to the optical transition at 1536 nm which goes from the lowest Kramers doublet of the fundamental state $^4I_{15/2}$ to the lowest Kramers doublet of the excited state $^4I_{13/2}$ of the erbium ions.

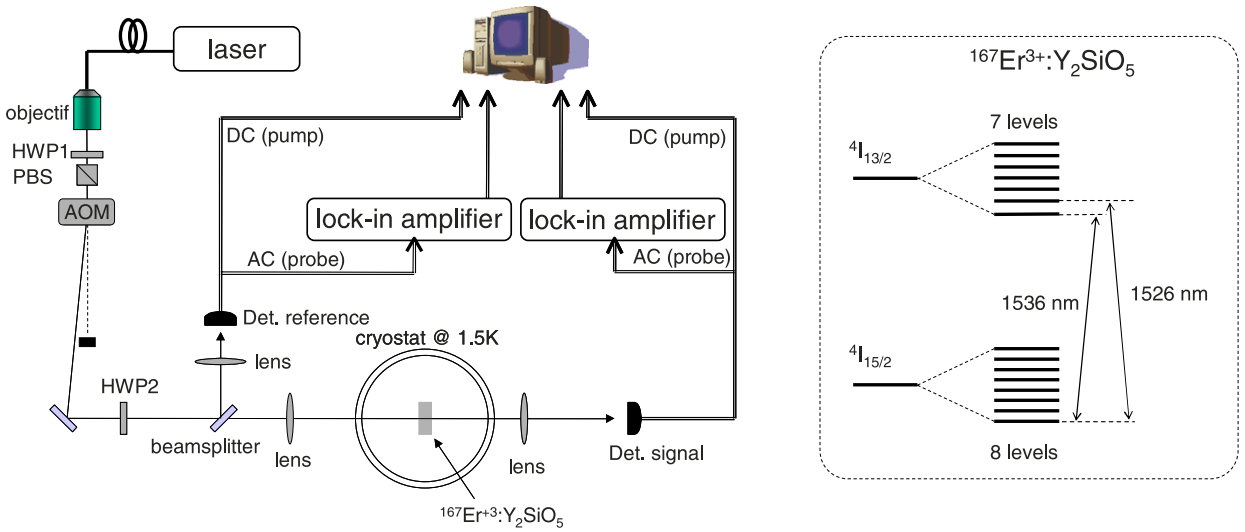


Fig. 4. Scheme of the experimental setup and energy diagram of erbium ions.

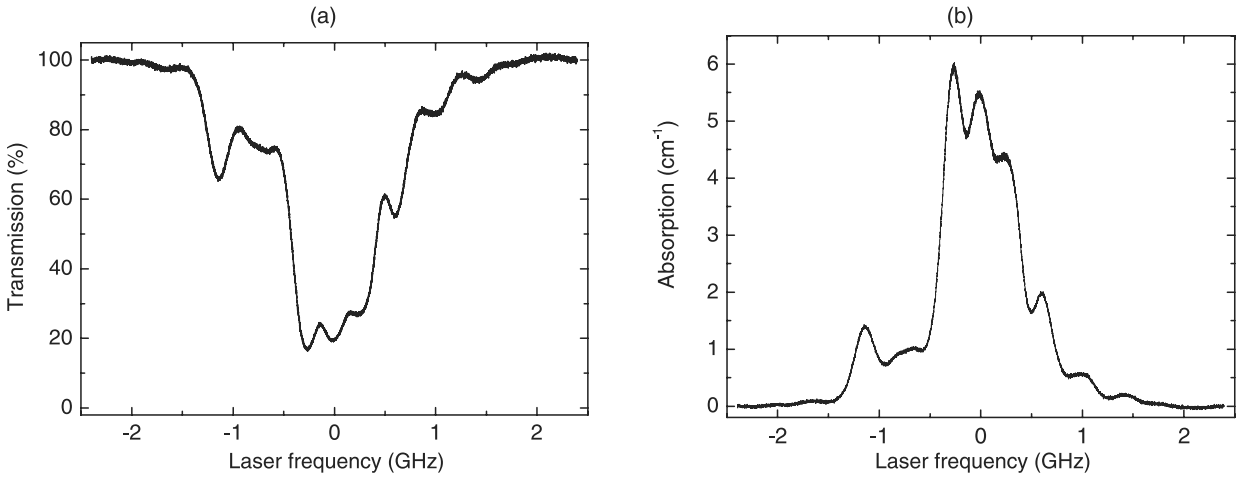


Fig. 5. Linear transmission (a) and the corresponding absorption coefficient (b) of a weak laser field in the 3-mm-long $^{167}Er^{3+}$:$Y_2SiO_5$ crystal kept at 1.5 K.

The crystal temperature is maintained at 1.5 K in a liquid helium cryostat in order to reduce the homogeneous linewidth to the sub-MHz level. However, due to the static electric field strength in the crystal an inhomogeneous broadening larger than 100 MHz is present and prevents from unambiguous direct measurement of the homogeneous spectral line. Fig. 5(a) shows a typical transmission spectrum of $^{167}Er^{3+}$:$Y_2SiO_5$ when excited by a weak probe field tuned by few GHz around 1536 nm. The corresponding absorption is presented in Fig. 5(b). A departure from a Lorentzien profile is clearly seen, with several peaks both in transmission and in absorption spectra. They result from the convolution of the hyperfine sub-level transitions of erbium 167 ions with the inhomogeneous broadening. Using the spectral hole burning method, we measure the lifetime $T_1$ of the excited state to be 10 ms. To this long lifetime, a CPO hole of about $\simeq 16$ Hz is expected in our measurements. To measure the dephasing time $T_2$, the photon echo technique is used. $T_2$ is found to be 3 μs at 1.5 K, a rather short value in comparison with $T_1$. These spectroscopic results will be discussed elsewhere.

In order to excite the extremely narrow CPO hole, the pump–probe relative frequency stability should be better than the hole linewidth. This is rather difficult to achieve using two different laser sources. We adopt an alternative approach, proposed by M.S. Bigelow et al. [2], which consists in using an intensity-modulated cw laser source,

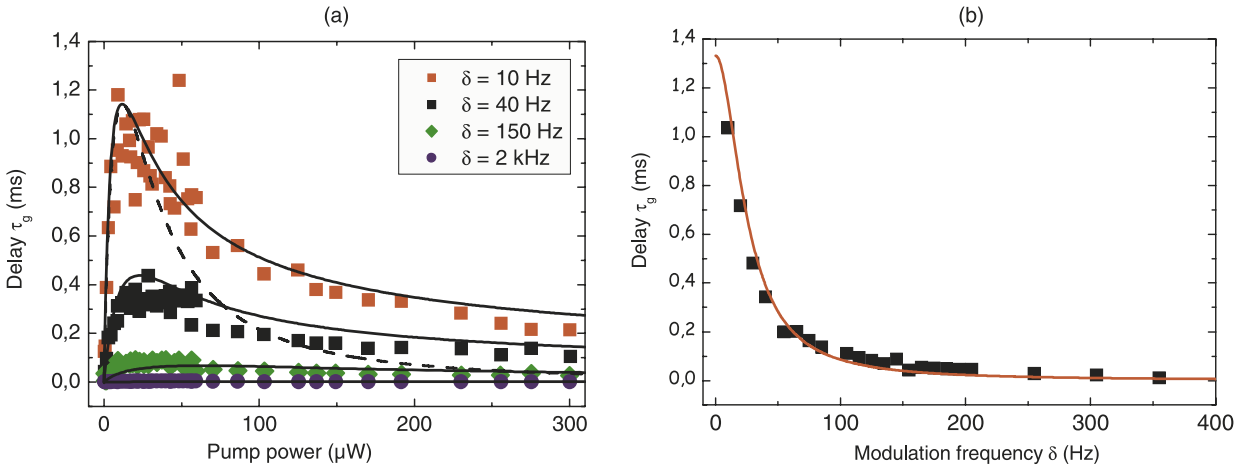


Fig. 6. (a) Delay $\tau_g$ for different modulation frequencies $\delta/(2\pi)$ as a function of the pump power (b) and when the pump intensity is fixed at 2.1 mW/cm$^2$ as a function of the modulation frequency.

producing in the Fourier space new spectral components playing the role of the probe field whereas the carrier plays the role of the pump. A key element of the experimental setup is thus an acousto-optic modulator (AOM). By driving the rf-power of the AOM with an $f(t) = 1 + m\sin(\delta t)$ wave function, where $m$ is the modulation depth, a sine wave intensity modulation is induced on the laser beam. This modulation corresponds, in the Fourier space, to the appearance of two spectral components at $\pm\delta$ around the carrier at $\omega$. This situation is similar to the theoretical description of the CPO discussed in Section 2, where the two-level systems are excited by a pump, a probe and an idler. By applying instead a pulse shaped modulation to the AOM, it is also possible to generate Gaussian-like optical pulses. Indeed, the CPO effect can be observed through self delayed pulses as long as the pulses are longer than the lifetime $T_1$ or equivalently as long as the pulses spectrum fits in the CPO hole.

After the AOM, the beam is split by an 80/20 beamsplitter BS, allowing the separation of two paths. The first path (20%) is taken as the reference beam, while the second (80%), called the signal, is sent through the crystal located in the cryostat. The signal beam is focused with a 250-mm lens located in front of the cryostat down to a waist of 540 μm in the 3-mm-long crystal. Its linear polarization is oriented with the half-wave plate HWP2 parallel to the $D_2$ axis of the crystal, for which we have achieved less than 20% transmission corresponding to an absorption of 6 cm$^{-1}$. The signal and the reference beams are then detected using InGaAs photodiodes (New Focus 1811). The AC components of the photocurrents, proportional to the amplitude of the modulation, are demodulated using lock-in amplifiers (SR830 DSP). The lock-in outputs and the DC component are sampled with an Analogic-to-Digital acquisition card and stored in a computer after being averaged over more than 10 000 samples.

### 3.2. *Slow propagation of a modulated light*

In this section, we consider slow light propagation induced by the CPO effect using the pump–probe scheme described theoretically in Section 2 in the modulation approach. Intensity modulation is achieved, as described in Section 3.1, for a sine wave with $m = 0.1$ corresponding to a modulation depth of 10%. The delay $\tau_g$ of the weak probe is deduced from the signal and reference beam phases, $\phi_m$ and $\phi_r$, extracted from the lock-in amplifiers. It is given by $\tau_g = (\phi_m - \phi_r)/\delta$. This delay is also related to the group velocity through $\tau_g = L/v_g$, where $L = 3$ mm is the crystal thickness. Fig. 6(a) shows the measured delay $\tau_g$ for different modulation frequencies $\delta/(2\pi)$ as a function of the pump power. The pump field wavelength is tuned to the maximum of the absorption in the inhomogeneous profile. The continuous line is the plot of the theoretical expression of the delay obtained using the group velocity (1). Since the signal field has three spectral components and $\delta \ll \omega$, the group velocity can be reduced to

$$v_g = \frac{c}{n(\omega) + \omega\frac{n(\omega+\delta)-n(\omega-\delta)}{2\delta}} \simeq \frac{2\delta c}{\omega(n(\omega+\delta) - n(\omega-\delta))} \tag{6}$$

and since the index of refraction is anti-symmetric we can write

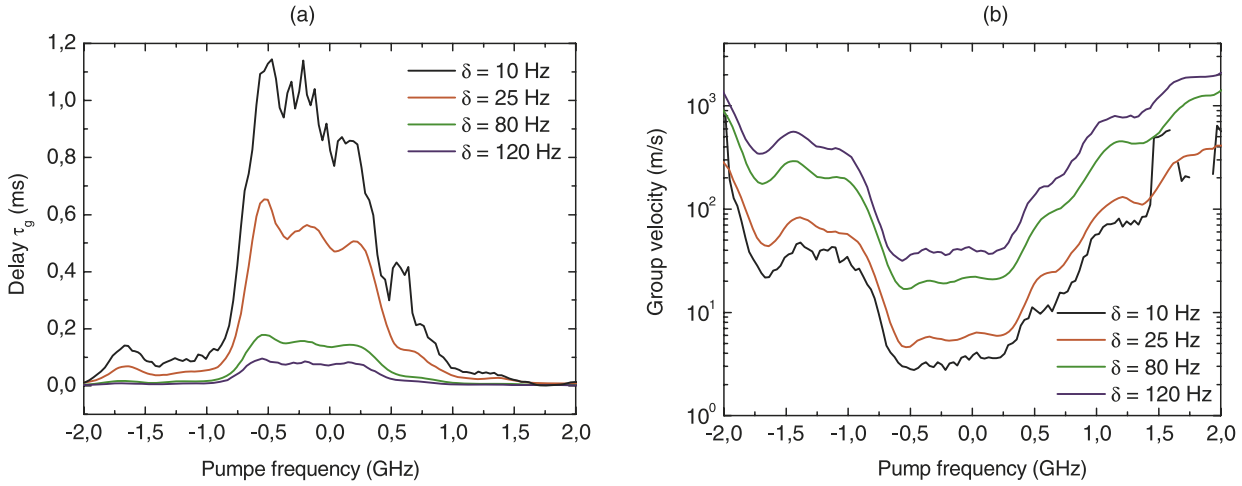


Fig. 7. (a) Delay $\tau_g$ for different modulation frequencies $\delta/(2\pi)$ as a function of the pump frequency in the homogeneous profile (b) and the corresponding group velocities.

$$\tau_g = \frac{2\delta L}{\omega c}\,\mathrm{Re}\big(\chi_s^{\mathrm{inh}}(\delta, \Delta_0)\big) \tag{7}$$

From Fig. 6(a) several interesting points are clearly seen. Firstly, the delay $\tau_g$ increases as the pump power is increased. This is due to the increased number of erbium ions contributing to the CPO process. Secondly, as the pump power is further increased, the delay reaches a maximum value and then declines. This is mainly due to two effects. When the saturation level is attained the number of erbium ions whose populations are oscillating in the CPO process reaches a stationary level. A further increase on the pump power induces a power broadening of the CPO hole. This, in turn, is associated with a smoothed dispersion profile which is at the origin of the weaker delays. For a pump power of 12 μW corresponding to an intensity of 2.1 mW/cm$^2$ a maximum delay $\tau_g^{\mathrm{exp}} = 1.1$ ms is achieved for a modulation frequency $\delta/(2\pi) = 10$ Hz, corresponding to a group velocity $v_g^{\mathrm{exp}} = 2.7$ m/s. Note that this value is eight orders of magnitude lower than the velocity of light in vacuum. As the frequency modulation gets higher, the maximum delay tends to zero since the modulation is faster than $1/T_1$. The continuous lines in Fig. 6(a) are the theoretical plots of Eq. (7) for the modulation frequencies $\delta/(2\pi) = 10$, 40, 150, 2000 Hz, with the parameters: $T_1 = 10$ ms, $T_2 = 3.5$ μs and $\alpha_0 = 6\ \mathrm{cm}^{-1}/(T_2\Gamma_{\mathrm{inh}})$. The maximum delay is obtained for a pump power such the saturation parameter is $s \simeq 1$.

The dashed lines in Fig. 6(a) represent the theoretical delay $\tau_g$ for $\delta/(2\pi) = 10$ Hz when only the homogeneous broadening description is considered. One has then to replace in Eq. (7) the inhomogeneous susceptibility by the susceptibility of Eq. (4) with the parameters: $T_1 = 10$ ms, $T_2 = 3.5$ μs and $\alpha_0 = 6\ \mathrm{cm}^{-1}$. In the case of the homogeneous broadening, however, the maximum delay is reached for a pump power $s \simeq 0.5$. Both theoretical plots show the same shape. However, for strong pump powers ($s \gg 1$) the delay $\tau_g$ goes rapidly to zero for the homogeneously broadened systems whereas for inhomogeneously broadened systems the delay does not vanish. This is explained by the fact that in the inhomogeneous case, though the atoms in resonance with the pump field are in the saturating regime, it always exists off resonance unsaturated atoms that still contribute to the CPO effect.

In Fig. 6(b) we show the delay $\tau_g$ for a pump intensity of 2.1 mW/cm$^2$ as a function of the modulation frequency $\delta/(2\pi)$ which is also the relative pump–probe frequency detuning. The continuous line is the theoretical plot of Eq. (7) with the same parameters of Fig. 6(a) and for a saturation parameter $s = 1$. As expected, the delay due to the CPO effect declines as $\delta$ is increased. The half width at half maximum of 26 Hz is consistent with the natural linewidth $\gamma_{\mathrm{nat}} = 1/\pi T_1 = 32$ Hz.

According to Eqs. (4) and (7), the CPO-based slow light propagation depends on the atomic system absorption. The $^{167}Er^{3+}$:$Y_2SiO_5$ crystal exhibits an inhomogeneous broadening which reflects the distribution of ions concentration for a given optical frequency $\omega$ and within a spectral bandwidth $d\omega$. The inhomogeneous broadening is thus associated with the distribution of the unsaturated absorption $\alpha_0$. By tuning the pump over this inhomogeneous profile we are able to address different erbium ion concentrations, that is different absorption coefficients. It becomes then possible to tune at will the ultraslow group velocities in this particular crystal and under the same experimental conditions. Fig. 7(a) shows the measured delays $\tau_g$ when the pump wavelength is tuned over the inhomogeneous broadened

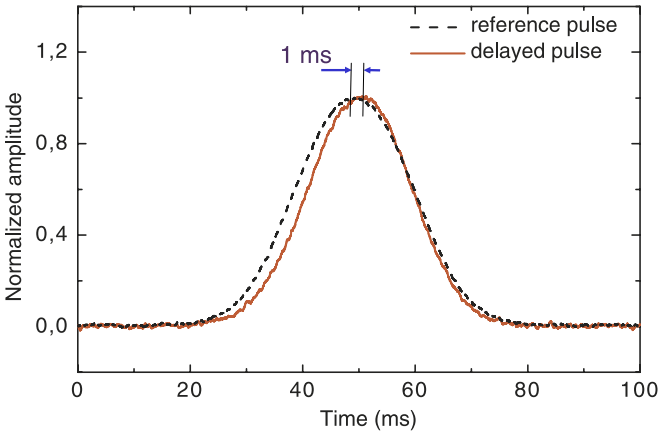


Fig. 8. In continuous red: normalized 20-ms duration optical pulse propagating in the crystal. In dashed black: the reference pulse.

transition of the erbium ions. The pump power is always set at 2.1 mW/cm$^2$ and the probe–pump frequency detuning is $\delta/(2\pi) = 10$, 25, 80 and 120 Hz. Fig. 7(b) represents the associated group velocities. The shapes of both delays $\tau_g$ and group velocity closely follow the absorption and transmission profiles of Fig. 5. We also see in Fig. 7(b) that we can tune the group velocity from the lowest value of 3 m/s to less than 1000 m/s by tuning the pump wavelength from the center to the wings of the inhomogeneous absorption line. Finally, note that group velocity remains very low while probe transmission is set at values larger than 80% as shown in Fig. 5.

### *3.3. Slow propagation of pulsed light*

Slow light propagation of optical pulses is also allowed by the CPO effect, provided the pulse spectrum is narrower than the width of the CPO hole. In this case the whole pulse feels the strong dispersion induced by the CPO phenomenon and each spectral component behaves as a probe while the optical carrier frequency of the pulse plays the role of the pump. Clearly, as long as the difference between the pump and any of the spectral component of the pulse is smaller than $1/T_1$, the CPO effect happens and induces the steep dispersion of the index of refraction at the origin of slow light propagation.

As a result, in order to observe self delayed optical propagation in the $^{167}Er^{3+}$:$Y_2SiO_5$ crystal, it is necessary to generate pulses having a duration longer than $T_1 = 10$ ms. This is achieved by applying a Gaussian-like amplitude modulation on the RF power driving the AOM. Fig. 8 shows a typical optical pulse having a duration of 20 ms delayed by the CPO process in the erbium-doped crystal. The dashed black curve is the reference pulse. For a peak pulse power of 0.5 μW a delay of 1 ms is measured. This delay corresponds to a group velocity $v_g = 3$ m/s, close to the value achieved in the case of modulated light configuration. We draw the attention on the fact that the definition of the group velocity given by Eq. (1) is only valid for undistorted Gaussian-like optical pulses. This is the case in our measurements, as can be seen in Fig. 8 and further confirmed by fitting the shape of the input and the output pulses.

Fig. 9 shows how the pulse delay varies when the peak power is increased from almost zero to 8 μW. The experimental data follows a similar shape of that in Fig. 6, rapidly growing towards a maximum value before smoothly relaxing towards zero. Here too, the behavior is well described by the theoretical model including the inhomogeneous broadening.

### *3.4. Acceleration of light or negative group velocities*

Slow light propagation is a consequence of the steep positive dispersion of the index of refraction, as can be inferred from definition (1) of the group velocity. It is obtained when a narrow transparency is created in an absorbing medium. In turn, when the medium presents an optical gain, the sign of the dispersion is reversed. In this case, we obtain negative or larger than $c$ group velocities which seems defying the physics laws and contradicting the fact that information cannot propagate faster than $c$. Following the theoretical work of Brillouin [17], the propagating speed of information is the velocity at which a sharp pulse front (change from '0' to '1') can propagate. Stenner et al. demonstrated that

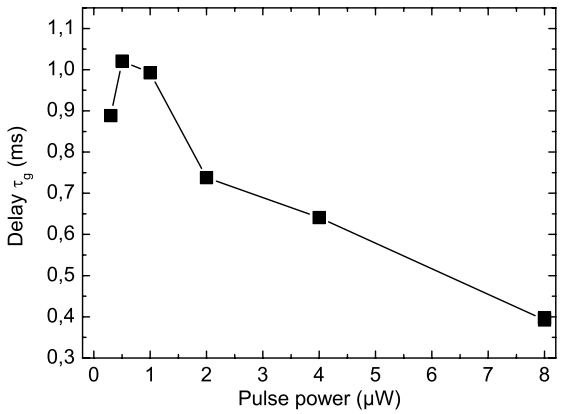


Fig. 9. Delay of a 20-ms pulse propagating in the crystal as the pulse peak power is varied.

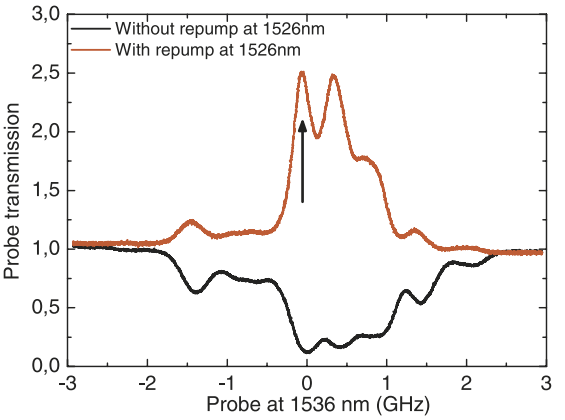


Fig. 10. Probe transmission in $Er^{3+}$:$Y_2SiO_5$ with and without the repumping.

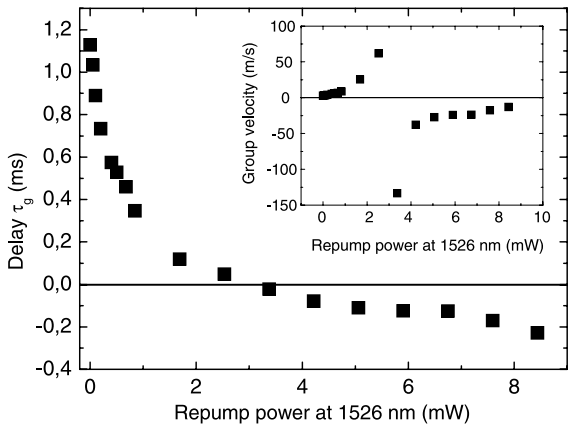


Fig. 11. Time delay and advance (negative delay) of a probe detuned by $\delta/(2\pi) = 6$ Hz from the pump as a function of the repump field power. Shown in the insert are the associated group velocities.

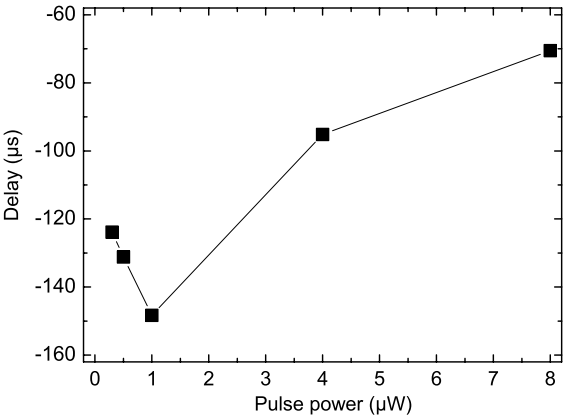


Fig. 12. Negative delays of a 20-ms pulse versus pulse power. The repumping power is 10 mW.

this front does not propagate at the group velocity neither in a slow light regime ($v_g \ll c$) [18] nor in a superluminal regime ($v_g > c$ or $v_g < 0$) [19], but at the maximum velocity $c$. So how can the group velocity be negative or larger than $c$? Optical pulses are the result of coherent constructive interference of monochromatic electromagnetic fields having infinite temporal and spatial extensions and moving forward at phase velocities. Although they look very localized in space and time with Gaussian-like shapes moving forward at the group velocity, optical pulses have infinite but still negligible amplitude extensions. By propagating in slow or supraliminal medium, the relative phases between the monochromatic electromagnetic fields are modified. This alters the structure of the interference, the pulse is then tailored with delayed or advanced position of its peak, corresponding to very small, negative or larger than $c$ group velocities. In fact, pulse shaping is the key point behind ultraslow or superluminal light propagation.

In order to reverse the slope of the dispersion in the $^{167}Er^{3+}$:$Y_2SiO_5$ crystal, a repumping field is applied to the transition going from the lowest Kramers doublet of the fundamental level $^4I_{15/2}$ to the Kramers doublet above the lowest one of the excited state $^4I_{13/2}$. As depicted in Fig. 4, the wavelength of this transition is 1526 nm, and it is experimentally excited by a secondary cw widely tunable laser source (Tunics).

When exciting the crystal with a 10-mW repumping field at 1526 nm, an optical amplification is observed. Fig. 10 shows the transmission of a 40-μW probe field tuned around the optical resonance at 1536 nm with and without the repumping field, reaching a maximum gain of 2.5. By tuning the pump field at 1536 nm to the frequency indicated by an arrow in Fig. 10, we were able to measure the delay or advance (negative delay) of the probe field detuned from the pump by $\delta/(2\pi) = 6$ Hz as a function of the repumping power as presented in Fig. 11. The insert shows the

respective group velocities. The pump field power is optimized when the repumping field is off in order to achieve the best performance in terms of delay $\tau_g$, that is $\simeq 1.1$ ms. For the same set of parameters we were able to achieve a negative delay $\tau_g \simeq -0.2$ ms, for the maximum repumping power (10 mW) available. The insert in Fig. 11 shows the corresponding group velocities which become negative for repump powers higher than 3 mW. In the same manner as for delayed pulses, it is also possible to make the pulse arrive before than if it was propagating in the vacuum. Fig. 12 shows the advance of a 20-ms Gaussian-like optical pulse as a function of the peak power of the pulse. The repumping power is 10 mW.

## 4. Conclusion

We investigated theoretically and experimentally the manipulation of the group velocity of cw and pulsed light via the CPO effect in an erbium-doped crystal. The inhomogeneous broadening associated with such solid state materials is demonstrated to be an interesting resource that allows the tuning of the group velocity. Both tunable ultraslow light and superluminal light are archived with very low optical powers.

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