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Slow light with photorefractive beam fanning

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The beam fanning naturally occurring in a photorefractive crystal is shown to slow down a single light pulse at room temperature. Slow light is demonstrated for both visible and infrared wavelength light pulses as short as the response time of the photorefractive crystal and with fractional delay- i.e ratio of delay to output pulse duration- up to 0.4.

Since the last decade, slow light has turned to be of interest for several applications. Reducing the group velocity v_g - i.e the propagation velocity of a pulse envelope- improves the performances in optical buffering and drives new technologies of optical delay lines [?]. Recent works have unveiled different mechanisms for slow light. v_g depends on the refractive index n of the medium and on the dispersion characteristic $\frac{dn}{d\omega}$, with ω being the oscillation frequency. Slow light can therefore be achieved using the strong dispersion in specific materials [?, 1–4]. Already more than a century ago, Hendrik Lorentz [5] demonstrated that the propagation velocity in an atomic vapor may be smaller than that of light in a vacuum. More recently, Hau *et al* [6] reported on a group velocity as short as 17 m/s using Electromagnetically Induced Transparency (EIT) in an ultracold atomic gas. Slow light at room temperature was later shown in an optical fiber using stimulated Brillouin [?, 1] or Raman scattering [?], and also in photonic crystal waveguides [?, ?, ?].

Photorefractive crystals (PR) are other well-known dispersive materials that can achieve low group velocities v_g . More specifically, the coupling of a probe signal with continuous wave modulates the refraction index and increases the dispersion of the photorefractive crystal, hence inducing deceleration of the output pulse [?, ?, ?, 7, 8]. Based on the nonlinear two wave mixing (TWM) process, a group velocity less than 1 cm/s is achieved at room temperature in several photorefractive crystals such as BaTiO₃ [?] and SPS [?]. However, the large dispersion of the photorefractive crystal induces the broadening of the transmitted pulse, therefore reducing the so-called fractional delay (FD) [?] which is defined as the ratio between the delay and the output pulse full width at half maximum. By optimizing the TWM and the nonlinearity strength of the photorefractive gain in the SPS photorefractive crystal, we achieved a maximum fractional delay of the order of 0.79 for a pulse duration of the order of 100 ms [?] and a group velocity of order of 0.9 cm/s. To the best of our knowledge, this remains one of the best trade-off so far on v_g , FD and pulse duration at room temperature.

In this paper, we report on an alternative much simpler proposal to slow down light pulse in a photorefractive crystal which uses the coupling of the single input pulse with the so-called beam fanning. Beam fanning is used for several optical applications including self-pumped phase conjugation [?]. Its strength depends on the input beam intensity and is characterized as the depletion variation of the input beam when it propagates through the crystal. It appears when a single incident beam propagates through a photorefractive crystal with a certain angle with respect to the c-axis and interferes with the radiation scattered by crystal imperfections [?, ?]. In 2014, A. Grabar *et al.* [?] have used the beam fanning to achieve fast light in Sb-doped SPS crystal for pulse durations in the range of 1 ms to 100 s. Here we show that beam fanning can also be exploited to achieve slow light at both visible and infrared wavelengths. State-of-the-art performances are achieved with reduction of v_g down to 25 cm/s and a fractional delay up to $FD = 0.4$. The performances are analyzed in detail as a function of the input pulse duration and for both visible and infrared wavelengths.

As shown in Fig. 1, the proposed experimental setup is much simpler than the one used in the two-wave mixing configuration and in particular avoids a careful alignment between the pump and signal beams. A continuous wave (cw) laser is controlled and modulated respectively by an attenuator A and an electro-optic modulator (EOM) driven by an electronic signal generator. The input pulse of Gaussian shape is transmitted through a 0.5 cm-long SPS doped Te photorefractive crystal in z direction. Finally, the input and output pulses are recorded by two photo-detectors D_1 and D_2 . The photorefractive response time τ is determined from the experimentally measured two-wave mixing gain Γ , considering that [9]:

$$\Gamma = \Gamma_0 \left(1 - e^{(-t/\tau)}\right) \quad (1)$$

where Γ_0 is the saturation photorefractive gain value. For an input intensity $I_0 = 3 \text{ W/cm}^2$, we find that the maximum two-wave mixing gain is achieved for an angle of 42°

between pump and signal beams (or correspondingly a period grating $\Lambda = 1.8 \mu\text{m}$) and the corresponding response time is therefore estimated to be of the order of 10 ms and 13 ms respectively at 638 nm and 1064 nm.

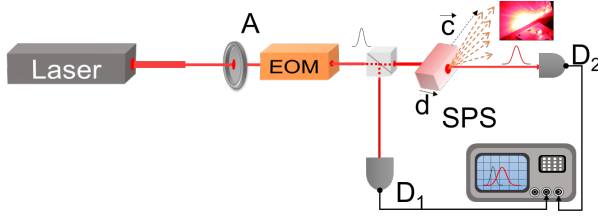


Figure 1: Experimental setup of slow light using beam fanning at two wavelengths 638 nm and 1064 nm. ; A is the attenuator, EOM is the electrooptic modulator, $D_{1,2}$ are the detectors and d is the photorefractive SPS crystal thickness.

If we turn the crystal so that the c-axis and the incident beam make an incidence angle $\theta = 45^\circ$, a maximum beam fanning effect appears in the direction of the transmitted pulse. By placing a screen behind the crystal, we can observe the beam fanning as a broad fan-shaped beam. In [?], the beam fanning strength is measured as the depletion variation of the input beam when it propagates through the crystal. It can be characterized by the depletion factor D [?] of the transmitted beam :

$$D = \frac{I_0 - I_{t\infty}}{I_0} \quad (2)$$

where I_0 and $I_{t\infty}$ are respectively the initial intensity at $t = 0$ and the transmitted intensity at $t = \infty$. In agreement with previous studies [?] and as shown in Fig. 2(a), the depletion factor increases with the input beam intensity.

The coupling of the input pulse and the beam fanning in the photorefractive crystal leads to the creation of a noisy index grating in the crystal. In addition, the modulation of the refractive index increases the dispersion in the material which allows the slow-down of the output pulse compared to the input one. Using Eq. 2, the Fourier transform of the beam intensity $I_\omega(d)$ at the crystal output with a crystal thickness d can be written as:

$$I_\omega(d) = I_\omega(0)(1 - D)^f \quad (3)$$

where $I_\omega(0)$ is the Fourier transform of the input intensity $I(0)$, ω is the frequency and $f = \frac{b + \omega^2 \tau^2 - i\omega\tau}{1 + \omega^2 \tau^2}$ is the SPS characteristic response function [10] with b a variable between 0 and 1 called the charge compensation degree. Finally, the intensity of the transmitted pulse $I(d, t)$ is given as following:

$$I(d, t) = \int_{-\infty}^{\infty} I_\omega(0)(1 - D)^f e^{-i\omega t} d\omega \quad (4)$$

Eq. 4 predicts how the output pulse is slowed down. The time delay $\Delta\tau$ (Fig. 2(b)) is calculated as the shift between the maximums of the input and output pulses as illustrated in Fig. 2(c). Numerical simulations for different input pulse

intensities and durations show that: (i) the delay value and the output pulse duration change with the depletion factor D and not with the input pulse duration, (ii) the attenuation of $I(d, t)$ increases as a function of D which is caused by the input beam depletion.

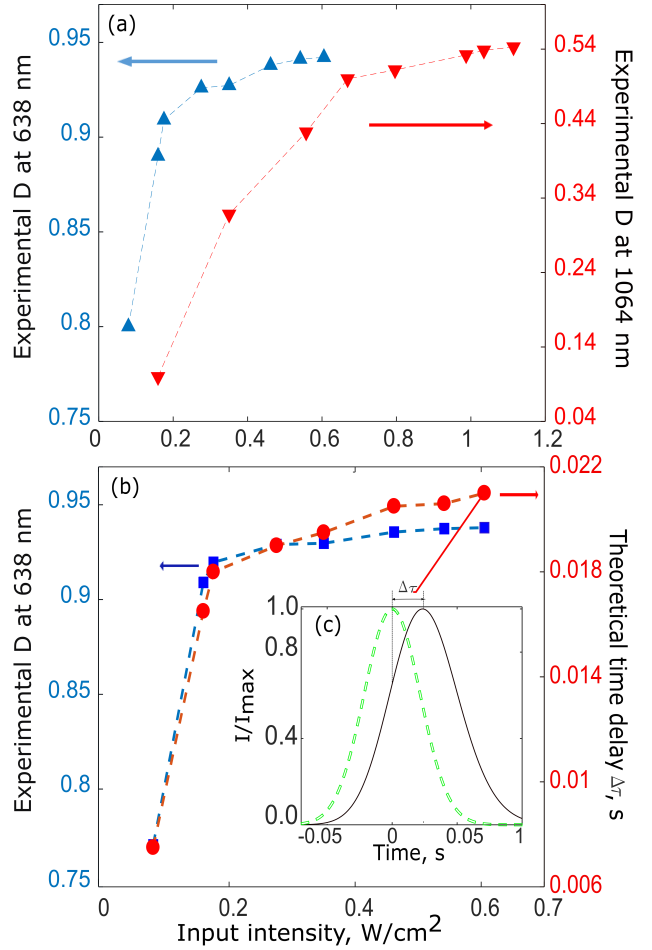


Figure 2: (a) Experimental depletion factor D in the visible (\blacktriangle) and infrared (\blacktriangledown) wavelengths according to the input intensities. (b) Theoretical time delay (\bullet) calculated with Eq. 4 for different depletion factors D (\blacksquare) at $\lambda = 638 \text{ nm}$. (c) Temporal envelopes of the input (green line) and transmitted (black line) pulses calculated with Eq. 4 for t_0 full width at half maximum of order of 0.02 s

In the following, we fix the input beam intensity so that we get the maximum fanning in the photorefractive crystal $D = 0.94$ at $\lambda = 638 \text{ nm}$ and $D = 0.54$ at $\lambda = 1064 \text{ nm}$ and we measure the output pulse delay in both cases. Fig. 3 shows an example of normalized input (black line) and output (red line) pulses for different input pulse durations. Fig. 3(a_i) ($i = 1, 2, 3$) shows the result of slow-down of light pulses when the SPS crystal is illuminated by a beam laser at $\lambda = 638 \text{ nm}$ when the input pulse of intensity $I_0 = 0.6 \text{ W/cm}^2$ enters in the sample with an incidence angle $\theta = 45^\circ$. Fig. 3(b_i) ($i = 1, 2, 3$) shows the result of slow-down of light pulses using a laser at $\lambda = 1064 \text{ nm}$ with $I_0 = 1.2 \text{ W/cm}^2$. In both cases, with the presence of the fanning in the crystal, the maximum of the output pulse is shifted in the time compared to the input pulse maximum. The

observed delay results from the photorefractive coupling of the input pulse with the beam fanning. Effectively, if we change the incidence angle or decrease the input intensity in order to decrease the fanning in the crystal, the pulse propagates in the crystal without any delay.

In Fig. 3(a₁) and Fig. 3(b₁) time delays $\Delta\tau = 113 \mu\text{s}$ and $\Delta\tau = 500 \mu\text{s}$ are observed respectively for pulse durations $t_0 = 600 \mu\text{s}$ and $t_0 = 2.5 \text{ ms}$ that are shorter than the SPS response time. In that case, the output pulses are delayed but significantly widened and distorted. When the input pulse duration is larger than or equal to the time response of the crystal, the output pulse is much less distorted and is delayed with a time-delay increasing with the input pulse duration. This is true both for the visible and infrared wavelengths.

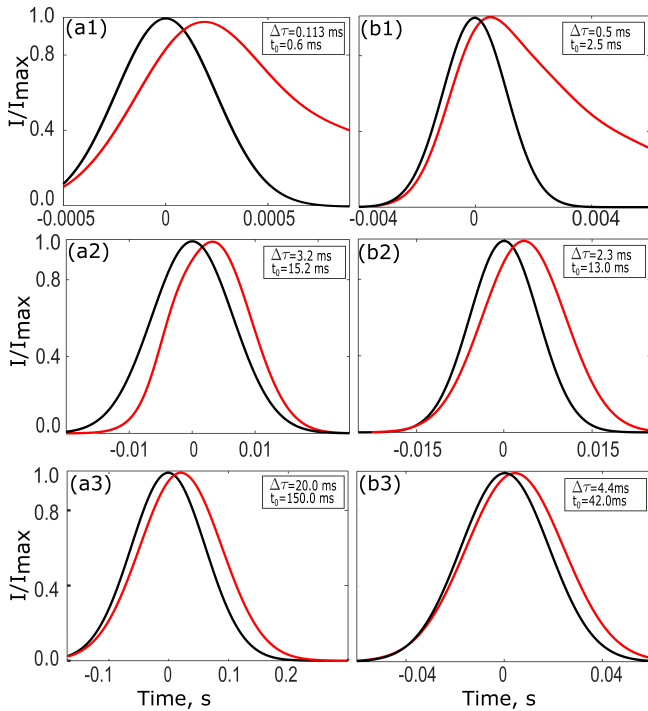


Figure 3: Experimental temporal envelopes of the normalized input pulse (black line) and output pulse (red line) as a function of the time for $\lambda = 638 \text{ nm}$ and input pulse intensity $I_0 = 0.6 \text{ W/cm}^2$ (a_i) and $\lambda = 1064 \text{ nm}$ with $I_0 = 1.2 \text{ W/cm}^2$ (b_i) with $i = 1, 2, 3$. (a₁) and (b₁) Input pulses durations $t_0 = 600 \mu\text{s}$ and 2.5 ms shorter than the response time of the crystal leading to deceleration given by $\Delta\tau = 113 \mu\text{s}$ and $\Delta\tau = 500 \mu\text{s}$. (a₂) and (b₂) Input pulses durations $t_0 = 15.2 \text{ ms}$ and 13 ms around the response time of the crystal leading to deceleration given by $\Delta\tau = 3.2 \text{ ms}$ and $\Delta\tau = 2.3 \text{ ms}$. (a₃) and (b₃) Input pulses durations $t_0 = 150 \text{ ms}$ and 42 ms greater than the response time of the crystal leading to deceleration given by $\Delta\tau = 20 \text{ ms}$ and $\Delta\tau = 4.4 \text{ ms}$.

In Fig. 4(a) and Fig. 4(d), we plot the time delay $\Delta\tau$ for pulses respectively emitted at $\lambda = 638$ and $\lambda = 1064 \text{ nm}$. As shown, in both cases, the time delay increases with the input pulse duration. Also, the time delay values achieved in the visible range are larger than those measured in the infrared range for the same input pulse duration. For $\lambda = 638 \text{ nm}$, $\Delta\tau$ varies from $39 \mu\text{s}$ to 20 ms while, for $\lambda =$

1064 nm , it varies from $80 \mu\text{s}$ to 8 ms .

Next, we analyze the variation of the output pulse broadening as a function of the input pulse duration. This is shown in Fig. 4(b) and Fig. 4(e), for $\lambda = 638$ and $\lambda = 1064 \text{ nm}$ respectively where we plot R as the ratio between the full output and input pulse width at half maximum. It should be noted that in the ideal case when the pulse is transmitted without broadening, this ratio is equal to 1. In both visible and infrared wavelength cases, the output pulse broadening is found to be larger for pulse duration smaller than or equal to time response of the crystal. For example, in Fig. 4(e), we distinguish indeed two situations: 1) for $0.08\tau < t_0 < 0.2\tau$, the ratio R varied from 1.5 to 2.1 which shows an important enlargement of the pulse that increases with t_0 , 2) for $t_0 > 0.2\tau$, R decreases until reaching the ideal case for pulses greater than 20 ms .

Fig. 4(c,f) then plots the fractional delay FD as a function of the input pulse duration. The fractional delay is defined by the ratio between the delay and the output pulse full width at half maximum. It varies between 0.05 and 0.4 for $\lambda = 638 \text{ nm}$ and the largest fractional delay value achieved at $\lambda = 1064 \text{ nm}$ is of order of 0.2 for pulse duration $t_0 = 9.4 \text{ ms}$. The systematic analysis of Fig. 4 shows that the slow-light performances at $\lambda = 1064 \text{ nm}$ are slightly lower than those achieved at visible wavelength. This reduced performance is due to the reduction of the coupling strength between the input beam and the beam fanning, i.e. lowering the D value of Eq. 4, when operating at infrared wavelengths.

The experimental setup described above may be used to generate both slow and fast light. This is possible because of the self-compensating response of the SPS crystal, which results from the presence of two types of charge carriers in the material with different time responses (a fast one and a slow one) [10]. Fig. 5 shows both theoretical and experimental results of the output pulse acceleration achieved when the c-axis of the SPS crystal is rotated to 180° . The result of Fig. 5(a) is obtained using Eq. 4 for $D = -0.64$ and -0.91 . By rotating the crystal, the energy transfer switches from pump to signal to the opposite, and as a result, instead of the depletion of the input beam, we note the output pulse amplification. As shown in Fig. 5(a) the delay value changes its sign and increases with the absolute value of D . Fig. 5(b) shows an experimental result of fast light with an input pulse duration of the order of $t_0 = 200 \mu\text{s}$ and $\Delta\tau = -10 \mu\text{s}$.

In conclusion, we have described a new mechanism for slow light at room temperature, which exploits the beam fanning in a photorefractive crystal. The slow light performances have been analyzed in depth for both visible and infrared wavelengths. The beam fanning varies with the beam intensity and with the incidence angle, hence tailoring the group velocity of the transmitted light pulse. The comparison of the results obtained for the two wavelengths shows that the slow light performances are slightly worse for infrared wavelength. For example, the fractional delay is twice larger for pulses emitted with a laser in the

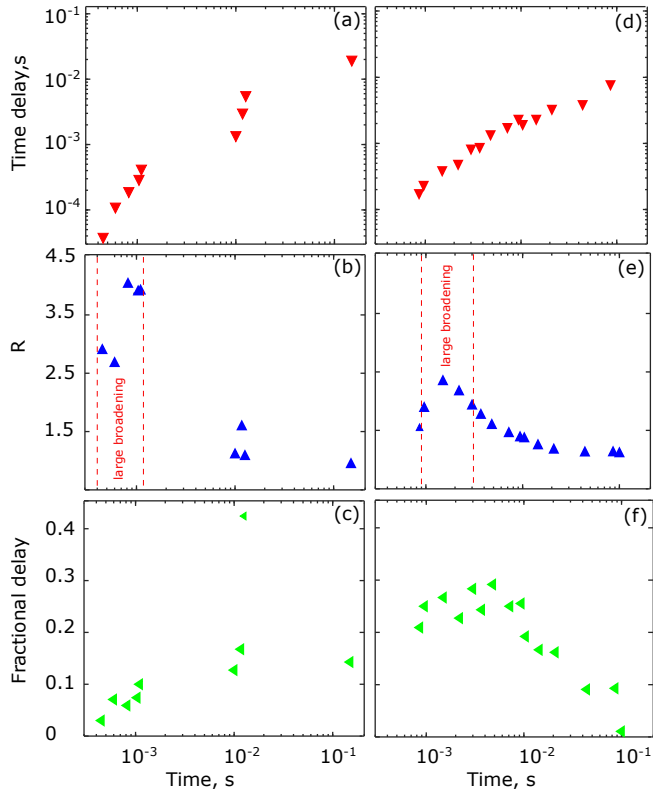


Figure 4: Performances of slow light as function of the input pulse durations for laser beam at $\lambda = 638 \text{ nm}$, input pulse intensity $I_0 = 0.6 \text{ W/cm}^2$ and $\tau = 10 \text{ ms}$ (a,b,c) and for laser beam at $\lambda = 1064 \text{ nm}$ with $I_0 = 1.2 \text{ W/cm}^2$ and $\tau = 13 \text{ ms}$ (d,e,f). (a) and (d) Time delay. (b) and (e) Ratio between the output and input pulse durations. (c) and (f) Fractional delay.

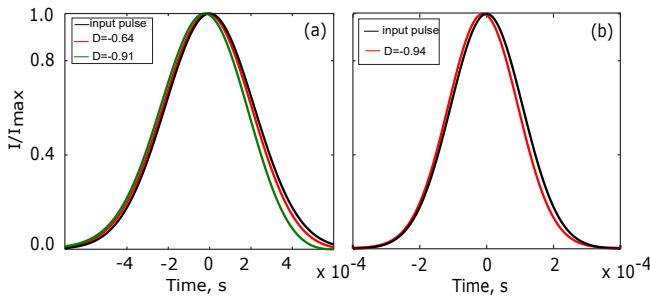


Figure 5: Temporal envelopes of the normalized input pulse and output pulse as function of the time. (a) Theoretical advancement of an input pulse of duration $t_0 = 500 \mu\text{s}$ by using Eq. 4, $\Delta\tau = 10 \mu\text{s}$ and $-25 \mu\text{s}$ are obtained respectively for $D = -0.64$ and -0.91 . (b) Experimental pulse light advancement at 1064 nm when the SPS is rotated through 180° , $t_0 = 200 \mu\text{s}$ with $\Delta\tau = -10 \mu\text{s}$.

visible wavelength range compared to the one for infrared pulses. In addition, the analysis of the temporal broadening of the output pulse shows that the best fractional delay values are achieved for pulse durations close to crystal time response. We demonstrate slow light of 13 ms single pulse with $v_g < 80 \text{ cm/s}$ and FD max equal to 0.4, which is very close to the state of the art performances we achieved earlier [?] with a much more complex conventional wave mixing approach. Slow light of input pulses

with much smaller pulse durations would require reducing the photorefractive crystal response time, for example by increasing the input pulse intensity.

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