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# Slow light using photorefractive nonlinear optics

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Slow and fast light are achieved in two experiments using SPS photorefractive crystal at room temperature. We report that the photorefractive gain achieved by the two wave mixing (TWM) method can control the group velocity of the transmitted light pulses at visible wavelength. It is shown theoretically and experimentally that the time delay and the shape of the output pulse change as a function of the photorefractive gain. The beam fanning has also been used to control the velocity propagation of a single light pulse in the same crystal at  $\lambda = 1064 \text{ nm}$ . Depending on the orientation of the polar axis, it is possible to accelerate or decelerate a short pulse with duration of order of  $\mu\text{s}$  in the crystal.

Slow light, photorefractive crystal, two wave mixing, photorefractive gain, beam fanning, depletion factor

## 1 INTRODUCTION

Deceleration of light group velocity has some potential for future applications such as optical delay lines and buffer memories in optical communication networks [1]. Slow light is characterized by a very small group velocity ( $v_g \ll c$ ) which can be achieved in high dispersion nonlinear materials such as optical fibers [2], photonic [3, 4] or photorefractive crystals [5–9]. Recent studies have shown that the two waves mixing (TWM) method can be used to strongly improve the photorefractive crystal dispersion and reduce light propagation velocity at room temperature [6]. The TWM consists in the coupling of strong pump beam and probe signal to modulate the refractive index and leads to the output pulse amplification, resulting in the generation of a photorefractive gain  $\Gamma$ . Using this method, group velocities lower than  $0.025 \text{ cm/s}$  and  $0.9 \text{ cm/s}$  were respectively achieved in  $\text{BaTiO}_3$  [7] and  $\text{Sn}_2\text{P}_2\text{S}_6$  (SPS) [6] crystals.

The delay is usually accompanied by the measurement of the achievable bandwidth of the output signal, in order to present a more complete evaluation of the slow light performances. The photorefractive crystal suffer from high dispersion when the light pulse group velocity is low which causes the widening and distortion of the output pulse and limits its data rates [10]. Usually, this parameter is characterized by the fractional delay FD which is the ratio between the time delay and the output pulse full-width at half maximum (FWHM). The optimization of two-wave mixing in the SPS crystal was used to provide a solution to the problem of pulse widening. Then FD of the order of 0.79 [6] was measured for a pulse duration of the order of  $100 \text{ ms}$ .

In this work, we present two experimental methods for slowing down or speeding up an optical pulse in SPS photorefractive crystal at room temperature. Unlike the  $\text{BaTiO}_3$ , this crystal is known for its fast response time of the order of  $10 \text{ ms}$ , which makes it possible to process shorter pulses and its large gain in the visible and infrared domains [11]. First, using the TWM method, the SPS crystal can slow down the light Gaussian pulses with durations of order of  $14 \text{ ms}$  close to the SPS response time. Both experimental and theoretical studies show that the time delay and the shape of the transmitted pulse change as a function of the photorefractive gain. In the second part, the beam fanning in the SPS photorefractive crystal has also been used to slow-down a single light pulse. The beam fanning occurs when a single optical passes through the crystal and scatters from the crystal imperfections. The coupling between the fanning and the input beam gives rise to noisy refractive index gratings and causes the depletion and slowing down the output beam. Here, a group velocity deceleration and acceleration have been observed for pulse durations of order of  $\mu\text{s}$  and  $\text{ms}$ . We show that both the delay and the advancement depend on the crystal orientation and the input pulse durations.

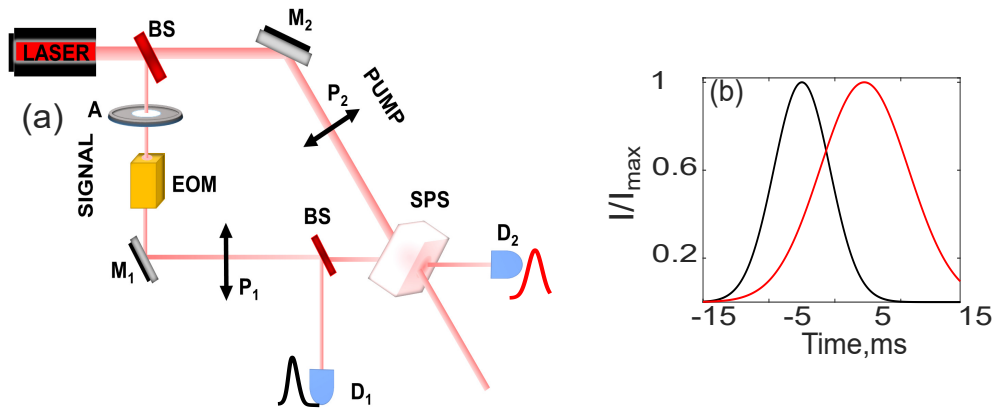
## 2 Slowdown of pulse with duration close to SPS response time

In this section, we investigate the performance of slow light in photorefractive TWM configuration. The setup of Fig. 1(a) makes use of a  $0.5 \text{ cm}$ -thick z-cut  $\text{Sn}_2\text{P}_2\text{S}_6$  (SPS) sample and a Crystal laser LC Model DL at  $632 \text{ nm}$ . The laser

beam is split into two parts, a pump and signal. The signal beam is modulated by a Newfocus Model 4002-Visible Phase Modulator (EOM) to be in the Gaussian shape. The pulse gets amplified inside the photorefractive crystal because of its interference with the pump with different intensities. The intensity of the input and of the output pulses is detected with two amplified photodetectors  $D_{1,2}$  and analyzed by an oscilloscope.

By analyzing the intensity evolution measured by  $D_{1,2}$ , we observe that the transmitted pulse is delayed by comparison to the reference pulse. As shown in Fig. 1(b), the maximum of the output pulse duration is about 10 ms (red line) and is shifted in time with  $\Delta\tau = 9.4$  ms compared to the input one (black line). As we show in [6], the obtained experimental delay depends on the coupling strength between the pump and the signal beams or the photorefractive gain. For the characterization of the delay as a function of the photorefractive TWM gain  $\Gamma$ , we fix the input pulse duration to 14 ms close to the crystal response time and we analyze the evolution of the transmitted pulse for different values of  $\Gamma d$ , with  $d$  is thickness of the crystal. This included studies of the delay, the full output pulse width at half maximum (FWHM) and the fractional delay FD. The measurements results are compared with the theoretical ones calculated by using the following equation [5]

$$A(d, t) = A_0 \frac{T_0}{2\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-0.5\omega^2 T_0^2 + \frac{\Gamma d}{1-i\omega\tau} - i\omega t} d\omega \quad (1)$$



**Figure 1:** (a) Two Wave Mixing setup in the photorefractive SPS crystal with a time response  $\tau = 10$  ms and laser at 638 nm ; A is the attenuator, EOM is the electrooptic modulator,  $D_{1,2}$  are the amplified detectors,  $M_{1,2}$  are mirrors and BS beam splitters. (b) Experimental results of the temporal envelopes of the normalized input (black line) and output (red line) pulses as a function of the time for full input pulse duration at half maximum (FWHM)  $t_0 = 10$  ms,  $\Delta\tau = 9.7$  ms.

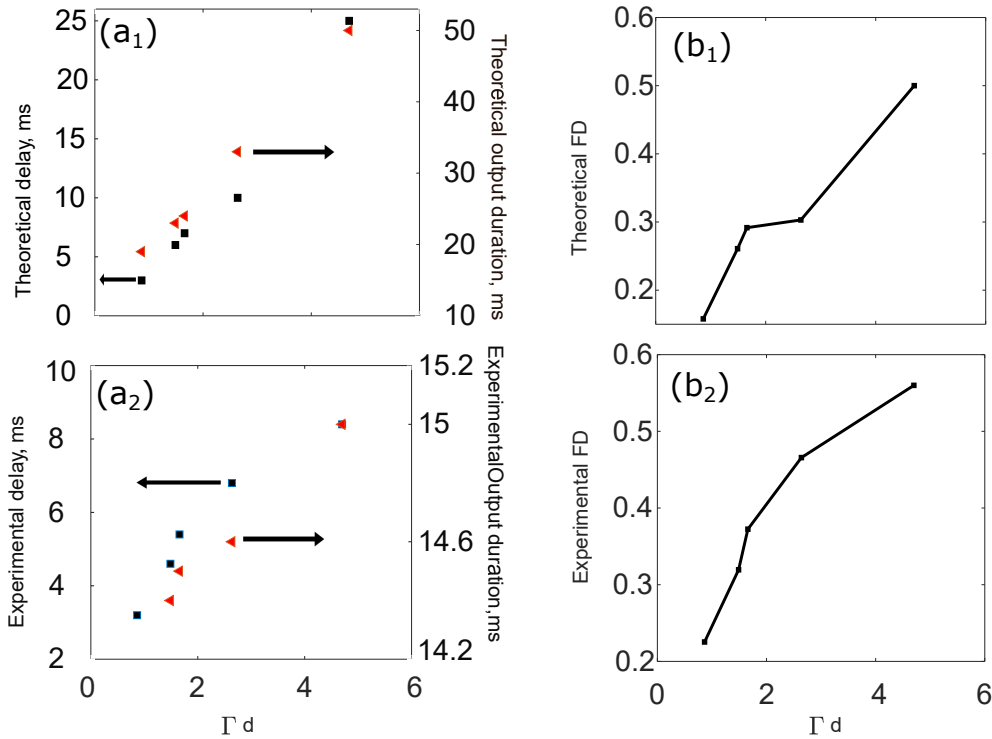
The output pulse amplitude  $A(d, t)$  of Eq. (1) depend on the time  $t$ , the photorefractive gain  $\Gamma d$ , the  $1/e$  half-width of the pulse intensity  $T_0$  and the input amplitude  $A_0$ . The numerical simulations of the delay and the duration of the output pulses as a function of the gain are presented in Figs. 2(a<sub>1</sub>) and 2(b<sub>1</sub>). The delay is found to increase with increasing the photorefractive gain . Furthermore, for sufficiently large values of  $\Gamma$ , the delay can be higher than the input pulse duration. Also, the output pulse width is modified compared to the input one because of its broadening which increases with  $\Gamma d$ . From Fig. 2(a<sub>1</sub>), the input pulse widens by almost three times its duration for  $\Gamma d = 4.7$ . The resulting fractional delay (FD) is shown in Fig. 2(a<sub>1</sub>). The value of theoretical FD increases with  $\Gamma d$  and its maximum value is about 0.5.

Now, if we analyze the experimental results, we note that the behaviors of the curves of Fig. 2(a<sub>2</sub>) is the same as in Fig. 2(a<sub>1</sub>). On the other hand, for the same value of  $\Gamma d$ , the measured values of delay and widening of the output pulse are less important than those calculated with Eq. (1). The output pulse amplitude  $A(d, t)$  of Eq. (1) depend on the time  $t$ , the photorefractive gain  $d$ , the  $1/e$  half-width of the pulse intensity  $T_0$  and the input amplitude  $A_0$ .

The results plotted in the right column in Fig. (2) demonstrate that the fractional delay increases also with the photorefractive gain. The curves in Figs. 2(b<sub>1</sub>) and 2(b<sub>2</sub>) show that the values of the experimental fractional delay are almost the same as those obtained theoretically. The maximum FD of order of 0.5 and 0.56 are respectively obtained theoretically and experimentally for  $\Gamma d = 4.7$ . The FD values do not exceed the unit due either to the large widening of the output pulse (theoretical case) or to the small values of the delay (experimental case).

### 3 Slow and fast light using photorefractive beam fanning

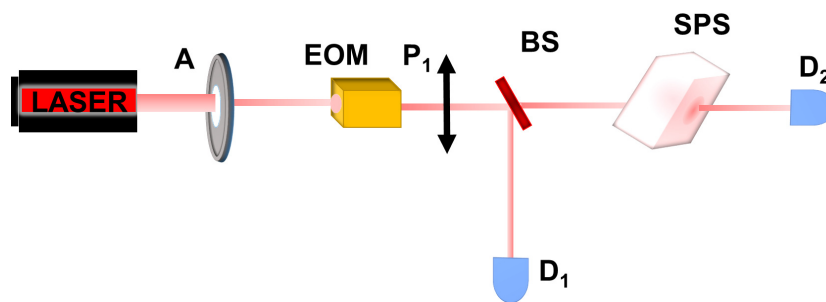
The SPS photorefractive crystal has already been used for slow light in the visible range using the two [6,7] or four [12] wave mixing method . In this section, we propose the slow and the fast light propagation scheme using the beam fanning



**Figure 2:** Slow light performances as function of  $\Gamma d$  for a full input pulse duration at half maximum  $t_0 = 14$  ms and 0.5 cm– SPS crystal with response time  $\tau = 10$  ms. (a<sub>1</sub>) and (b<sub>1</sub>) Theoretical results (a<sub>2</sub>) (b<sub>1</sub>) experimental result. (a<sub>i</sub>) Time delay  $\Delta\tau$  and output pulse duration, (b<sub>i</sub>) fractional delay.

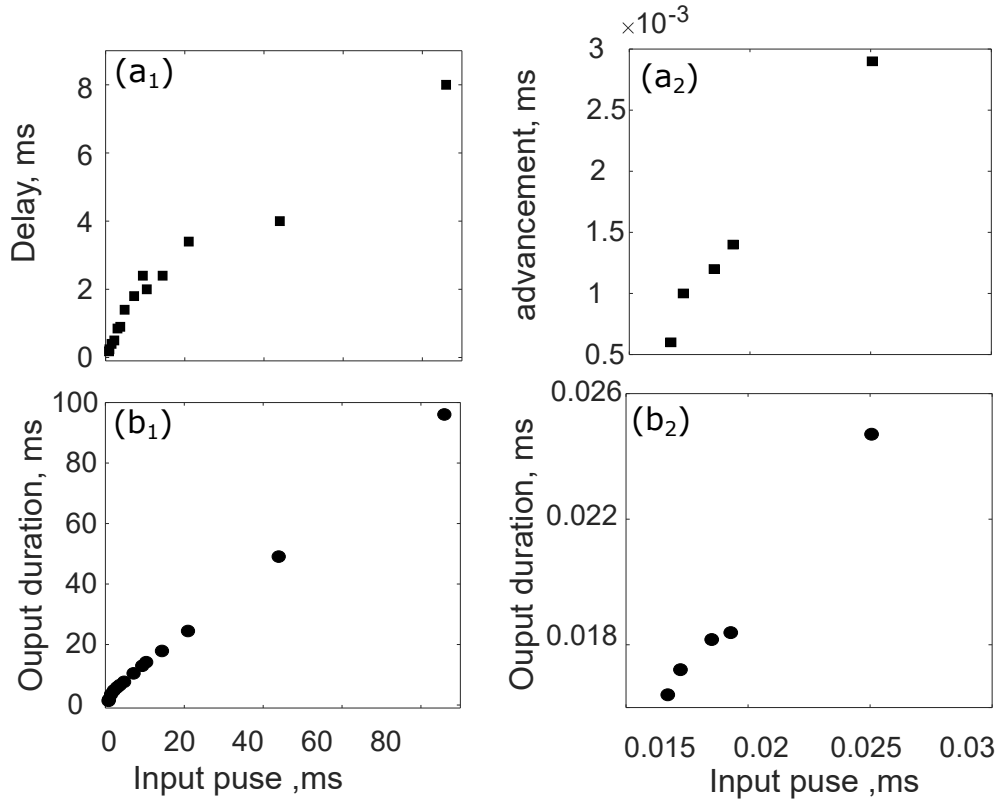
in the SPS photorefractive crystal at 1064 nm wavelength. We experimentally study the slowing down and the speeding up of shorter pulses of order of  $\mu s$  and  $ms$ . This process is easily achieved by the scattering of a single light beam in an asymmetrical way [13] and it can be observed in all crystal possessing large photorefractive gain  $\Gamma$ . On the other hand, it was reported that the presence of two types of charge carriers in the SPS photorefractive crystal [5, 6], provide two different response times (slow and fast response) known as "self compensation response" [5, 6, 14]. The presence of this response in the crystal can control the dispersion and group velocity of the pulse at the output of the crystal. Indeed, by changing the orientation of the polar axis of the crystal, it is possible to slow down or speed up the velocity light propagation simultaneously.

To control the light velocity propagation using the beam fanning, we change the visible laser of the above experience by a Crystal laser LC Model IR-700 at 1064 nm and we turn off the pump beam as shown in Fig. (3). We choose the incidence angle  $\theta = 45^\circ$  between the input beam and the SPS c-axis to get the maximum fanning in the direction of the transmitted pulse. The input pulse power was adjusted by the attenuator  $A$  to maintain a constant intensity  $I_0 = 1.2$  W/cm<sup>2</sup> of throughout the experiment. In these conditions, a noisy refractive index grating is created in the crystal via the TWM between the fanning and the input beam.



**Figure 3:** Setup of the slow light using the beam fanning in 0.5 SPS crystal with response time  $\tau = 10$  ms performed with a laser at 1064 nm.  $A$  is the attenuator, EOM is the electrooptic modulator,  $p_1$  is the polarizer, BS is the beam splitter  $D_{1,2}$  are the amplified detectors.

In the last conditions, a noisy refractive index grating is created in the crystal via the TWM between the fanning and the input beam. Also, the interference between the beams causes energy transfer beam coupling between the two beams [15] and the depletion of the transmitted pulse.



**Figure 4:** ( $a_1$ ,  $b_1$ ) Performances of the slow light as function of the input pulse durations for laser beam at  $\lambda = 1064 \text{ nm}$ , the input intensity  $I_0 = 1.2 \text{ W/cm}^2$  and  $D = 54$ . ( $a_2$ ,  $b_2$ ) Performances of the fast light as function of the input pulse durations when the SPS is rotated through  $180^\circ$  and  $D = -54$ . ( $a_1$ ) delay, ( $a_2$ ) advancement, ( $b_1$ ) and ( $b_2$ ) output pulse durations in the case of the slow and fast light respectively.

The variation of this depletion allows to measure fanning strength defined by the depletion factor  $D$  [16]. At the same time, the maximum of the output pulse is delayed compared to the reference one. The left column in Fig. (4) represents the measured performance of the slow light achieved for depletion factor of order of 0.54 and different values of the full input pulse width at half maximum  $t_0$ . The delay and the output pulse duration depend on  $t_0$  and from Fig. 4( $a_1$ ), we note that for large  $t_0 \gg 50 \text{ ms}$ , the time delay increases slowly which reduces the performance of slow light. The maximum fractional delay measured in these experimental conditions is of order of 0.2.

Now, we rotate the polar axis of the crystal by  $180^\circ$  to change the direction of energy transfer between the input beam and the fanning or the sign of  $D$ . For  $D = -0.54$ , the same experiment ensures pulse amplification and its acceleration at the output of the SPS crystal. The performances of the fast light are plotted in Figs. 4( $a_2$ ) and 4( $b_2$ ). As shown in Fig. 4( $a_2$ ), the advancement is observed for short pulse durations of order of  $\mu\text{s}$ . the advancement values vary from  $0.5 \mu\text{s}$  to  $3 \mu\text{s}$  for  $t_0$  which vary between  $15 \mu\text{s}$  to  $30 \mu\text{s}$ .

## 4 Conclusion

In summary, we have shown the photorefractive gain achieved through TWM can be used to slow down light pulses of durations close photorefractive response to the time of the crystal (here  $\tau = 10 \text{ ms}$ ) and with FD of max 0.56.

In addition instead of using wave mixing with an additional pump laser, we can efficiently use the photorefractive beam fanning to generate wave mixing and slow down or speed up light pulses.

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