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Slow light of dark pulses in photorefractive crystal

Nacera BOULDJA^{1,2,*}, Alexander Grabar³, Marc SCIAMANNA^{1,2} and Delphine WOLFERSBERGER^{1,2}

¹Chair in Photonics, CentraleSupélec, LMOPS, F-57070 Metz, France

²Université Lorraine, CentraleSupélec, LMOPS, F-57070 Metz, France

³Institute of Solid State Physics and Chemistry, Uzhhorod National University, Pidhirna 46, 88000 Uzhhorod, Ukraine

*nacera.bouldja@centralesupelec.fr

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Slowdown of Gaussian "dark pulses" in photorefractive crystal using a two-wave mixing method is shown at room temperature. In agreement with our theoretical model, the experiment shows the dependence of the "dark pulse" delay and the group velocity values on the photorefractive gain Γ and the input pulse width t_0 . The use of "dark pulses" allows to improve the time delay values and achieve maximal fractional about 1 for a pulse duration close to the crystal response time.

Slow light in dispersive nonlinear media was actively studied theoretically and experimentally [1–5], including in photorefractive (PR) materials [?, 6–10]. The two-wave mixing (TWM) process in PR crystal yields amplification of the output pulse during the recording of the photorefractive grating. Simultaneously this modifies the light dispersion inside the crystal, hence reducing the group velocity of the output amplified pulse down to 1 *cm/s* in BaTiO₃ [11] and Sn₂P₂S₆ [9] at room temperature. The four-wave mixing effect can also be used to decelerate the light velocity both of the transmitted and the phase conjugate waves [12]. The output pulse delays vary as a function of the PR nonlinearity [13], the crystal response time, the input pulse duration [7] and the photorefractive gain Γ [9]. Small values of group velocity (large delays) are achieved for large Γ values. However, the dispersion inside the crystal limits the delay bandwidth product because of the broadening of the output pulse.

Previous studies of slow light used Gaussian pulses because it is better suited to numerical calculations and easier to process than other pulse shapes. However, experimental and numerical studies have shown that the dark pulse or "Gaussian holes" can be more stable and less sensitive to noise in optical fibers than the Gaussian light pulses. For example, the dark soliton can be interesting for long distance optical communications [14] due to its stable propagation in optical fibres under the influence of noise. Since their first observation [15], the dark pulses have attracted great interest, particularly for studying the propagation of solitons in the optical fiber [16, 17] and in Bose – Einstein condensate [18]. Dark pulses arise in many distinct areas of physics: coherent quantum control of two-photon transitions in Caesium (Cs) [19], time-resolved x-ray spectroscopy [20], generation of Kerr combs in normal-dispersion microresonators with mode-interaction assisted

excitation, and mode-locking transitions [21]. The use of dark pulses has been recently suggested in slow light systems including in the plasmas [22] and insulator-insulator-metal plasmonic waveguides [23]. It has been analytically and numerically demonstrated that the dispersion of the output signal can be compensated by using Kerr dielectrics and dark solitons, hence being of interests for high-bit-rate telecommunications [23].

In this work, we investigate theoretically and experimentally how dark pulses may be decelerating in a PR crystal at room temperature. First, we developed an analytical model describing the temporal envelope of the dark pulse propagating through the PR crystal. As for the Gaussian light pulses, the model shows that the delay and shape of the output dark pulse change as a function of the TWM gain and the input pulse duration. Using the TWM between the dark pulse and a continuous pump beam, delays greater than the input pulse duration can be reached. For *ms* pulse duration, the corresponding delays are larger than those we have reported in [9] for Gaussian pulses and the fractional delay is also larger close to 1. To analyze the delay performances of slow dark pulse in the PR material, the numerical calculations are implemented using the experimental parameters for a Te-doped Sn₂P₂S₆ crystal. Let us consider the input dark pulse $A(0, t)$ as following:

$$A(0, t) = \sqrt{A_0^2 - A_0^2 \exp\left(-\left(\frac{t}{t_1}\right)^2\right)} \quad (1)$$

Here A_0 and t_1 are respectively the amplitude and $1/e$ half-width of the input pulse intensity. Using the Taylor expansion, the Eq.1 becomes:

$$A(0, t) = A_0 \left(1 - \sum_{n=0}^{\infty} a_n \exp \left(-2n \left(\frac{t}{t_1} \right)^2 \right) \right) \quad (2)$$

where a_n is given by:

$$a_n = \frac{(2n)!}{2^{2n}(2n-1)(n!)^2} \quad (3)$$

The propagation of the dark pulse in the photorefractive crystal with thickness d after the interference with a continuous pump wave is expressed as follows:

$$A(d, \omega) = A_{\omega}(0) e^{gf_{\omega}} \quad (4)$$

where $A_{\omega}(0)$ is the Fourier transform of $A(0, t)$, $g = \Gamma d$ is the dimensionless parameter conventionally referred to as the coupling strength with Γ being the PR gain, d being the crystal thickness and f_{ω} [24] is the characteristic response function. By using the inverse Fourier transform, the output dark pulse amplitude $A(d, t)$ transmitted through the PR crystal is given by:

$$A(d, t) = A_0 \int_{-\infty}^{\infty} (\delta(\omega) e^{gf_{\omega}}) d\omega - A_0 \frac{t_1}{2\sqrt{\pi}} \sum_{n=0}^{\infty} a_n \int_{-\infty}^{\infty} e^{-0.5n\omega^2 t_1^2 + gf_{\omega} - i\omega t} d\omega \quad (5)$$

We use the expression of the output signal (Eq. (7) in Ref. [24]) and Eq. (5) to plot respectively the temporal envelope of bright [Fig. 1(a)] and dark [Fig. 1(b)] pulses calculated for $|\Gamma d| = 6.62$ and full input width at half maximum $t_0 = 60$ ms. By analyzing the profiles of the normalized pulse intensities we can retrieve the output pulse delay $\Delta\tau$ which is the time shift between the maximum or (minimum) between the input and output light pulses or (dark pulses). The result shows that for the same t_0 the minimum of the output dark pulse (Fig. 1(b)) is more delayed than to the output bright pulse maximum (Fig. 1(a)). For $t_0 = 60$ ms, the bright and the dark pulses are respectively delayed by $\Delta\tau = 67$ ms and $\Delta\tau = 77$ ms for $\Gamma d = |6.62|$. To

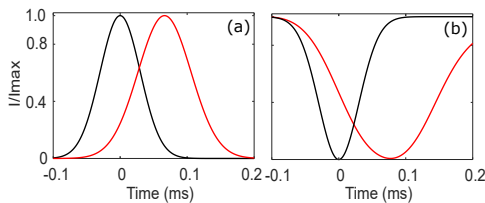


Figure 1: Temporal envelopes of the normalized input (black line) and output (red line) pulses for input full pulse width at half maximum $t_0 = 60$ ms and $|\Gamma d| = 6.62$, (a) time delay $\Delta\tau = 67$ ms for the Gaussian light pulse and (b) $\Delta\tau = 77$ ms for the dark Gaussian pulse.

illustrate the dependence of the time delay versus the TWM gain Γ , we plot in Fig. 2 the temporal profile of the input

and output intensities for $t_0 = 60$ ms for three values of $|\Gamma d| = 5, 8, 10$. As for the bright pulses, it is clearly seen that the dark pulse delay can be controlled by the gain. Both delay and output pulse width increase with increasing Γd values. For $|\Gamma d| = 5, 8, 10$, the transmitted pulse delays are $\Delta\tau = 50, 80, 100$ ms respectively. Also, Figs. (1,2) show that the transmitted pulse broadens when propagating through the PR crystal. This broadening increases with the increase of the PR gain value. For $|\Gamma d| = 5, 8$ and 10 , the durations of the output pulse become $120, 130$ and 150 ms respectively.

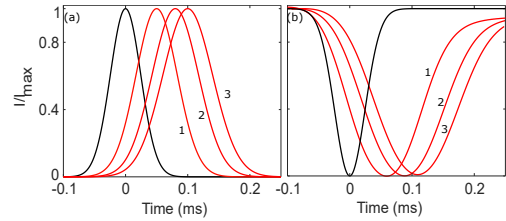


Figure 2: Temporal envelopes of the normalized input (black line) and output (red line) pulses for input pulse duration $t_0 = 60$ ms. (a) time delay $\Delta\tau = 50, 80, 100$ ms for the Gaussian light pulse and (b) $\Delta\tau = 58, 88, 106$ ms for the dark Gaussian pulse (1) $|\Gamma d| = 5$, (2) $|\Gamma d| = 8$ and $|\Gamma d| = 10$.

Below we present the results of experimental studies of the slow dark pulses using the setup presented in Fig. 3. The setup is similar to that used in [9]. The measurements are performed with a laser at $\lambda = 638$ nm with intensity of 3.8 W/cm² and a 5 mm-thick Sn₂P₂S₆:Te PR crystal. The electro-optic modulator which is controlled by a signal generator generates a bright or dark pulses by a change of the electric signal phase (the phase difference between a dark and bright pulse is 180°).

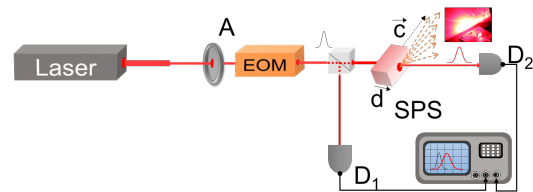


Figure 3: Experimental setup; BS is the beam splitter, A is the attenuator, EOM is the electrooptic modulator, $D_{1,2}$ are the detectors, M is the mirror, θ is the incidence angle and d is the crystal thickness

With this setup, we study first the experimental performances of the slow dark pulses in Sn₂P₂S₆ for the full input pulse duration at half maximum $t_0 = 10$ ms as a function of the TWM gain. To measure Γ , we change the pump and signal ratio and we measure the amplification of the output signal which gives the value of the gain. The results are shown in Fig. 4. Fig. 4(a) presents the normalized input and output pulse intensities for two experimental values of the gain $\Gamma d = 2$ and $\Gamma d = 2.9$. As is shown, the delay $\Delta\tau$ between the minimum of the input and output pulse changes with Γd . The transmitted pulse propagates in the crystal without any broadening for $\Gamma d = 2$ and when

Γd increases to 4.6, the output pulse duration $t_{out(FHWM)}$ changes from 10 ms to 28 ms. As is presented in Fig. 4(b), beyond $\Gamma d = 2.4$, the measured delay $\Delta\tau$ is larger than the dark pulse duration t_0 and a maximum value of 16.5 ms is measured for $\Gamma d = 4.6$, which is larger than the delay reported in [9] for the same input pulse duration. Fig. 4(c) shows the variation of the output pulse duration as a function of Γd . Note that the output pulse broadening increases weakly for small values of Γd and becomes stronger for $\Gamma d > 2.9$. Fig. 4(d) shows the measured fractional delay (FD) which is the ratio of the delay to the output full pulse width at half maximum, as function of Γd . We see that FD varies from 0.3 to 0.6. It increases with the delay until reaching the maximum at $\Gamma d = 2.4$ and decreases with the enlargement of the output pulse.

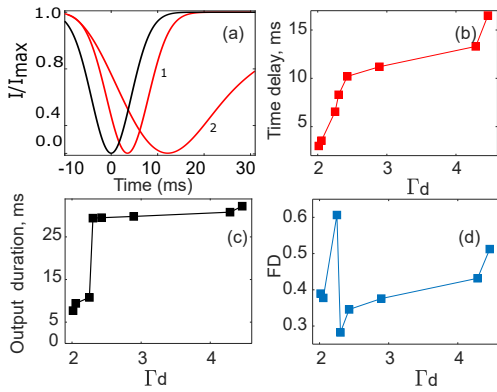


Figure 4: Performances of the slow dark pulse as function of Γd . (a) Temporal envelopes of the normalized input (black line) and output (red line) pulses for input pulse duration $t_0 = 10$ ms and $\Gamma d = 2$ (1) and $\Gamma d = 2.9$ (2). (b), (c) and (d) respectively: Time delay $\Delta\tau$, output pulse duration $t_{out(FHWM)}$ and fractional delay FD as function of Γd .

Now, as reported in [9], we analyze how the delay varies with the input duration for large TWM $\Gamma d = 5$. This Γd value is achieved for a very weak dark pulse intensity, i.e the ratio between the pump and the signal is of order $7 \cdot 10^3$. The curves (a–c) in Fig. 5 show the profiles of the normalized input and output pulse intensities for three input pulse durations. For example, at $t_0 = 10.3$ ms close to the crystal response time $\tau = 10$ ms the output pulse of duration $t_{out} = 15.7$ ms is delayed by $\Delta\tau = 7.9$ ms. Fig. 5(b) presents a case where the delay $\Delta\tau = 28$ ms is greater than the input pulse duration $t_0 = 23.5$ ms. If we increase the input pulse duration, the delay increases with t_0 , and a delay of the order of 146 ms is measured for a pulse duration of order of 480 ms (Fig. 5(c)). Therefore there is a range of input pulse durations for which the delay reaches a maximum value relatively to t_0 .

The variation of the delay, the output pulse duration and the corresponding FD with respect to the input pulse durations are plotted in Fig. 6. Fig. 6(a) shows that delay values increase for the short input pulses durations $t_0 < 250$ ms decreasing to zero. A maximum delay value of order of 156 ms corresponding to the envelop group velocity $v_g =$

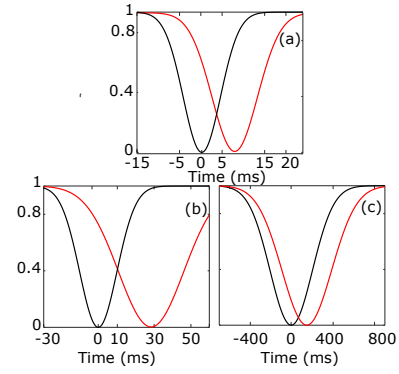


Figure 5: Temporal envelopes of the normalized input (black line) and output (red line) pulses for $\Gamma d = 5$ cm⁻¹, (a) time delay $\Delta\tau = 7.9$ ms, $t_0 = 10.3$ ms and $t_{out(FHWM)} = 15.7$ ms, (b) $\Delta\tau = 28$ ms, $t_0 = 23.5$ ms and $t_{out(FHWM)} = 56.8$ ms and $\Delta\tau = 146$ ms, $t_0 = 480$ ms and $t_{out(FHWM)} = 570$ ms.

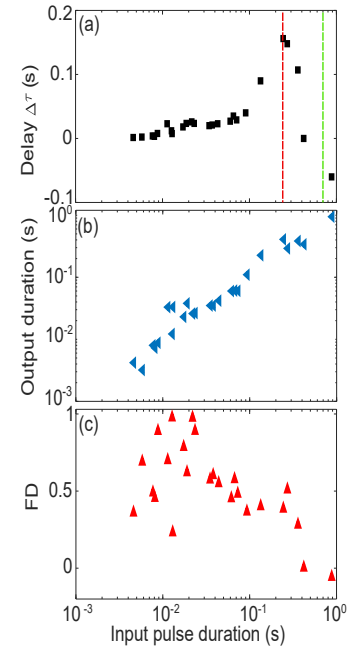


Figure 6: Performances of the slow dark pulses according to the input pulse duration t_0 and $\Gamma d = 5$. (a) Delay curve, (b) output pulse durations and (c) fractional delay. Dotted red line present the position of the maximum delay. Dotted green line present the position of negative delay values

3.2 cm/s is measured for input pulse duration $t_0 = 240$ ms. Also, for pulse durations higher than 880 ms, the delay values become negative which cause the acceleration of the output dark pulse. This case is possible because of the $\text{Sn}_2\text{P}_2\text{S}_6$ self-compensation in PR response [?]. The light acceleration can be observed by rotating the c-axis of the crystal by 180° or by increasing the input pulse duration greater than 800 ms. The output dark pulse time width versus the input pulses durations are plotted in Fig. 6(b). We note the enlargement of the output pulse duration for higher Γd values. For example, the input pulse of $t_0 =$

19 ms is slowed-down by $\Delta\tau = 23$ ms and its duration is almost doubled at the output of the crystal. Knowing the output pulse duration and the pulse delay, we can compute in Fig. 6(c) the fractional delay. Fig. 6(c) shows that the FD is maximum for a given input pulse duration t_0 which is close to the response time of the crystal τ . When $t_0 \ll \tau$ and increasing t_0 , the delay remains quite constant while the broadening of the output pulse increases, hence decreasing FD. When $t_0 \gg \tau$ and increasing t_0 , the delay increases much slowly than the increase of the broadening of the pulse, hence also decreasing FD. An optimal value of FD is therefore achieved for an intermediate value of t_0 close to τ .

In summary, we have studied the slow down of dark pulses using TWM in the $\text{Sn}_2\text{P}_2\text{S}_6:\text{Te}$ photorefractive crystal at room temperature. In addition to the experiments, the numerical calculations illustrate the performances of pulses deceleration including the time delay, the resulting distortion and the fractional delay. The results show that the delay increases with the input duration and also with the nonlinear gain Γd . The experimental results confirm the validity of the theoretical model. It is shown that the dark pulse is more delayed than bright pulse [9] for input pulse duration in the range $0 < t_0 < 100$ ms. A maximum time delay of 156 ms is achieved for input dark duration $t_0 = 240$ ms, corresponding to a group velocity of $v_g = 3.2$ cm/s. Increasing Γd leads to longer delay but the dark output pulse also propagates in the PR crystal with a larger distortion. Finally, the fractional delays 1 have been obtained for input pulse duration t_0 around the crystal PR response time $t_r = 10$ ms, a situation for which the delay $\Delta\tau$ is larger than t_0 .

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