Photorefractive solitons and light-induced resonance control in semiconductor CdZnTe

Tal Schwartz, Yaniv Ganor, Tal Carmon, Raam Uzdin, Sharon Shwartz, and Mordechai Segev

Physics Department and Solid State Institute, Technion–Israel Institute of Technology, Haifa 32000, Israel

Uri El-Hanany

Imarad Imaging Systems, Ltd., Rehovot 76124, Israel

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We demonstrate the formation of (1 + 1)- and (2 + 1)-dimensional solitons in photorefractive CdZnTe:V, exploiting the intensity-resonant behavior of the space-charge field. We control the resonance optically, facilitating a 10-μs soliton formation times with very low optical power. © 2002 Optical Society of America

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Optical spatial solitons and self-trapping of beams have been investigated for almost four decades. Much of the progress in this field was made in the past 10 years, partly following the discovery of photorefractive solitons,[1–6] which made possible solitons with very low power levels, as well as soliton experiments in bulk media. Photorefractive solitons, and the waveguides they induce, combine properties offering interesting applications: reconfigurable directional couplers,[7] beam splitters,[8] waveguide switching devices,[9] and tunable waveguides for second-harmonic generation[10] and for optical parametric oscillation.[11] In general, however, the formation time of solitons in most photorefractives is rather long, except when very high intensities are used.[12] This is because the photorefractive nonlinearity relies on charge separation, for which the response time is inversely proportional to the product of the mobility and the optical intensity, and the mobility in photorefractive oxides is low ($\sim$1 cm^2/V s). In principle, photorefractive semiconductors have high mobility and could offer formation 1000 times faster than other photorefractives. However, the electro-optic coefficient in these semiconductors is tiny, which implies that solitons that are as narrow as $\sim$20 optical wavelengths necessitate very large applied fields, making soliton formation in them almost impossible.[13] But, in some of these materials (InP, CdZnTe) that have both holes and electrons as charge carriers, a unique resonance mechanism enhances the space-charge field by as much as ten times the applied electric field. This enhancement yields large enough self-focusing effects that can support narrow spatial solitons. The resonant enhancement of the space-charge field was first observed in photorefractive two-wave-mixing in such materials,[14,15] and has led to the observation of solitons in photorefractive InP,[16,17] and to their theoretical explanation.[18]

Resonant enhancement of the space-charge field occurs in materials with both types of charge carrier, both of which are excited from a common trap level: One is excited optically, and the other is excited by temperature. At steady state, when a focused beam illuminates a biased crystal of this kind, and the beam intensity is such that the excitation rates are comparable, the concentrations of both free carriers at the illuminated region decrease drastically.[18,19] The intuitive explanation for this is as follows: Under proper conditions,[18,20] the ratio between the concentrations of electrons and holes is equal to their ratio in the absence of light and thus has a constant (coordinate-independent) value. The net excitation rate of the traps is the difference between the thermal (holes) and optical (electrons) excitation rates. At resonance, the net excitation rate goes to zero. At the same time, at steady state the excitation rate must be equal to the recombination rate, which, in turn, is proportional to the free-charge concentration. Hence, at resonance (when the excitation rates of holes and electrons are comparable) the free-charge concentration goes to zero. Consequently, the local electric field is highly enhanced because the current at steady state must remain constant throughout the crystal. For a given temperature, this enhancement occurs at a specific intensity (the resonance intensity), for which the thermal and optical excitation rates are comparable. It is a resonant enhancement, although it is an intensity resonance and not an atomic resonance. The enhanced electric field compensates for the smallness of the electro-optic coefficient and permits a sufficiently large change in the refractive index to support narrow solitons. Solitons based on the resonance enhancement in photorefractive semiconductors have thus far been demonstrated experimentally only in InP:Fe,[16,17] for which the thermal excitation rate of electrons resonates with the optical excitation rate of holes in the close vicinity of a resonance intensity. This mechanism could facilitate narrow and fast solitons in photorefractives, but unfortunately, a new problem arises: the electron excitation rate is determined by temperature, so the value of the resonance intensity is prefixed to be very low ($\sim$30 m W/cm^2 at $T = 300$ °K). This means that the peak intensity of solitons in that material is also destined to be $\sim$30 m W/cm^2, which inhibits the exploitation of the ability for short formation times. Increasing the temperature could offer some improvement, as it shifts the resonant intensity to higher values, but most applications cannot afford temperatures much higher than room temperature. Thus, it is highly desirable to increase the value of the resonance intensity to much higher values by means other than temperature. This increased resonance

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intensity will allow solitons at higher intensities and facilitate much shorter formation times. Furthermore, it is difficult to control the resonance through temperature (because of its high sensitivity), whereas all-optical control of the resonance can be easy and very accurate.

Here we demonstrate the formation of (1 + 1)-dimensional [(1 + 1)D] and (2 + 1)-dimensional [(2 + 1)D] solitons in another photorefractive semiconductor material, CdZnTe:V, and show optical control over the resonance intensity, facilitating formation times of 10 μs with very low optical power.

CdZnTe:V has an intensity-resonance mechanism similar to that of InP:Fe, with an important difference: The electrons and the holes exchange roles.[21] Electrons are optically excited by a 1.3-μm (or shorter) wavelength, whereas holes are thermally excited. But the holes can also be excited optically by an ~1.5-μm wavelength beam.[22] We use this capability to increase (and control) the hole excitation rate considerably by uniformly illuminating the crystal with such a beam. This background beam sets the resonance intensities to much higher values than temperature-driven resonance, thereby shortening the formation time to 10 μs with soliton intensity of ~20 W/cm^2 and background intensity of ~1 W/cm^2.

Our experimental setup resembles that of Refs. 16 and 17. The CdZnTe:V crystal is situated on a temperature-control device, stabilizing the crystal temperature to 21 °C. The soliton-forming beam comes from a cw 936-nm-wavelength Ti:sapphire laser. We carry out two sets of experiments, demonstrating (1 + 1)D and (2 + 1)D solitons. In the (1 + 1)D case, the laser beam is focused by a cylindrical lens to an ~15-μm FWHM beam that is uniform in the other transverse dimension. In the (2 + 1)D case, the beam is focused by a spherical lens to a 15-μm FWHM circular beam. In both cases the beam is linearly polarized along the (110) direction and is propagating in the (1$\bar{1}$0) direction. The external bias field is applied along the (001) direction. In the absence of an applied field, the beam diffracts to approximately three times its input FWHM after 5-mm propagation. The input and output beams are imaged onto a CCD camera.

Typical results with (1 + 1)D and with (2 + 1)D solitons are shown in the top and bottom rows of Fig. 1, respectively. Shown are [(a), (d)] photographs and beam profiles of the input beams, [(b), (e)] output soliton beams when the intensity and the applied fields are adjusted to the appropriate values, and [(c), (f)] linear diffraction in the absence of an applied field. The (1 + 1)D soliton [Fig. 1(b)] is at an applied field E_0 = 1.8 kV/cm, and the (2 + 1)D soliton of Fig. 1(e) is at E_0 = 9.4 kV/cm, both with no background illumination. In both cases, the data clearly show nice, undistorted narrow beams that are as narrow as the input beam. Note that the centers of the soliton beams in these cases are shifted (self-bent) from the center of the corresponding diffracting beam by 15 and 30 μm.[23] (the shift of the 2D solitons is larger because the 2D solitons necessitate a higher applied field).

To illustrate the resonant self-focusing behavior, we perform a set of experiments with all parameters kept constant and varying only the intensity (Fig. 2). All the data in this figure are without background illumination, so the natural (thermal) resonance intensity is ~1.5 mW/cm^2. In Fig. 2, (a)–(e) show experiments with a 15-μm input beam and E_0 = 6 kV/cm. The output beam in (a) is far below resonance, and it shows some fanninglike features (the intensity spread to the right). At higher intensities it self-focuses (b), until it forms a soliton (c) when the peak intensity is in the range 0.45–1.5 mW/cm^2. The reason for this somewhat wider range of intensities is the presence of fairly high absorption (2.2 cm^{-1}), which means that the ratio between the resonance intensity and the intensity of the beam varies throughout propagation. At the resonance intensity and slightly above it, the beam breaks in two (d) because in this range the beam induces a waveguide that is shifted away from the beam center.[12] As the intensity is further increased (e), the induced waveguide moves further away from the beam, until it no longer affects the beam. The trend with a 2D beam is similar: The beam displays fanninglike features at intensities far below resonance (f), solitons form at the proper intensity range (h), and the beam is distorted at higher intensities (i), until at high enough intensities (j) the nonlinearity no longer affects the beam. The data in (f)–(j) were taken at E_0 = 9.4 kV/cm.

Finally, we show how the background intensity determines the resonance. We carry out a set of experiments with a 17-μm circular input beam and E_0 = 6 kV/cm. To isolate the control over the resonance, we vary the background intensity while keeping the input (soliton-forming) beam shape and the applied field fixed and adjust the intensity of the input beam until a soliton forms. Figure 3 shows typical results with 2D solitons for various resonant intensities that are induced via the background beam. At the

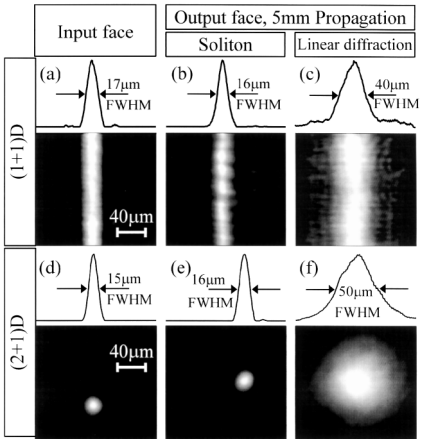

Fig. 1. Observation of self-trapping in CZT. A 17-μm FWHM (1 + 1)D input beam (a) is self-trapped with E_0 = 1.8 kV/cm (b). The peak intensity at the input face of the crystal is 1.5 mW/cm^2. When E_0 = 0, this beam diffracts (c) to 40 μm. A circular 15-μm FWHM input beam (d) is self-trapped (e) with E_0 = 9.4 kV/cm. The peak intensity at the input face is 3.4 mW/cm^2. When E_0 = 0, this beam diffracts (f) to 50 μm.

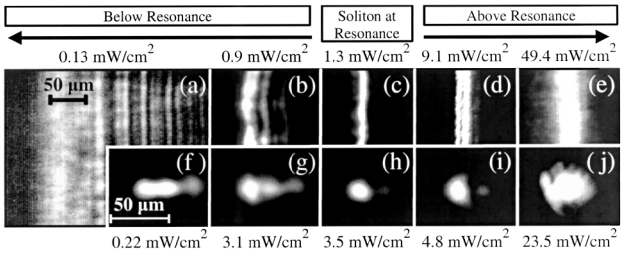

Fig. 2. Self-focusing dynamics of (1 + 1)D (above) and (2 + 1)D (below) beams, as a function of input intensity. With the beams width and resonance intensity fixed, the beams' intensities are successively increased. The focusing effect increases with the intensity [(a)–(c) and (f)–(h)] until it reaches its maximum strength [(c), (h)]. Then, at higher intensities, the self-focusing effects decrease [(d), (i)] until they are nonapparent [(e), (j)].

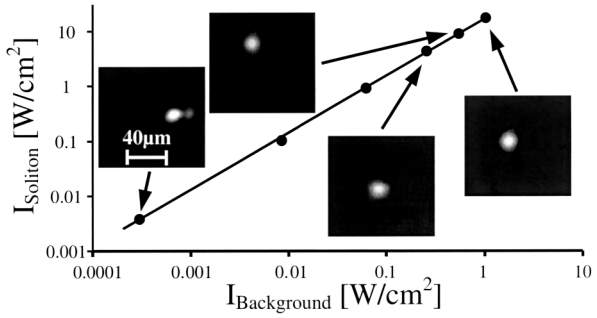

Fig. 3. Peak intensity of a soliton at 0.936 μm as a function of the background intensity at 1.48 μm. The insets show the intensity of the 17-μm FWHM soliton beam exiting the crystal at various intensities.

highest-intensity point the resonance intensity is ~1000 times higher than the thermal resonance intensity. This shows that we can generate solitons in a wide range of intensities by optically controlling the resonance accurately. We carry out similar experiments with a 1D beam, and the trend is similar. The response time at the point of the highest resonance intensity is measured to be 10 μs for a 17-μm FWHM circular beam with ~46-μW power (peak intensity, ~17 W/cm^2). This response time is 1000 times faster than the response time of solitons of the same intensity in strontium barium niobate. Yet we emphasize that to form solitons at this speed in CdTe one must increase the resonance intensity from its natural (thermal) level by 10^3 times, which is exactly what we did. We envision that in the near future, light emerging from ordinary optical fibers carrying (temporal) data will be used to form spatial solitons. The average optical power emerging from such fibers is a few milliwatts, which when distributed across a 10-μm FWHM circular soliton beam can lead to formation times as low as 100 ns.

In conclusion, we have reported the observation of (1 + 1)D and (2 + 1)D solitons in CdZnTe:V, which has a resonant photorefractive nonlinearity. We have shown how to control the resonance intensity of the nonlinearity by applying background illumination at a wavelength different that that of the soliton. This approach makes possible narrow solitons with intensities much higher than those produced by the thermal excitation alone. Optical regulation of the resonance is a crucial step toward CdZnTe-based applications, because it permits short response times and because the system becomes temperature independent. We estimate that by using light beams emerging from ordinary fiber communication links we can form photorefractive solitons in CdZnTe within 100 ns.

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19. Note the difference from the screening nonlinearity which supports solitons,[8] for which the free-charge concentration at illuminated regions increases.
20. In our CdZnTe crystals, $L_E/KL_D{}^2 \cong 200$, where L_E and L_D are the drift and diffusions lengths, $1/K$ is taken as half the solitons' FWHM. This indicates that the solitons form well inside the drift regime.
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