Self-deflection and all-optical beam steering in CdZnTe

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We report on the experimental observation of very large self-deflection of optical beams, along with all-optical steering, and electro-optic beam deflection. We observe as many as 27 resolvable spots of deflection at 1-W/cm^2 intensity. These deflections arise from enhanced photorefractive effects in CdZnTe:V, giving rise to optically induced index changes in excess of 0.08, which is to our knowledge the strongest nonlinearity ever reported for any bulk semiconductor. © 2004 Optical Society of America

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Since it was predicted,[1] self-deflection of optical beams has been considered one of the most exciting manifestations of nonlinear optics: A single beam propagating in a nonlinear medium develops an asymmetric profile and consequently curves (and carves) its own trajectory. If self-deflection had been accomplished with low power levels, at fast response times, and with many resolvable spots, this fascinating process would have already found its way into commercial products, in applications ranging from optical interconnects to laser printers and optical scanners. Unfortunately, experimental demonstrations of self-deflection of optical beams have been scarce, exhibiting few resolvable deflection spots. (A resolvable deflection spot is defined as the deflection angle divided by the diffraction angle of the finite beam.[2]) Thus far, self-deflection has been demonstrated in NaCl (Ref. 3) and CdSSe (Ref. 4) crystals, liquid CS_2 (Ref. 5), sodium vapor,[6] and nematic liquid-crystal films.[7] In all these the number of resolvable spots was small, typically two or three, with the exception of sodium vapor, which had eight. Furthermore, all these experiments required high intensities, ranging from 200 W/cm^2 in sodium[6] to 400 MW/cm^2 in NaCl (Ref. 3). All of these early demonstrations of self-deflection suffered from major distortions of the beam profile, which limited the deflection angle. Furthermore, the deflected beam was always accompanied by a long nondeflected "tail" that limited the actual number of resolvable spots.

Here we report on the observation of very large self-deflection of optical beams. The self-deflection arises from enhanced photorefractive effects in CdZnTe:V, resulting in as many as 27 resolvable deflection spots at 1-W/cm^2 intensity. Our results show more than three times as many resolvable spots as in any self-deflection result ever reported to our knowledge and at an intensity that is 200 times lower. These deflections arise from enhanced photorefractive effects in CdZnTe:V, giving rise to optically induced index changes in excess of 0.08, which is to our knowledge the strongest nonlinearity ever reported for any bulk semiconductor. In contrast with previous work our deflected beam has a symmetric structure throughout almost the entire deflection range. The nonlinear effects supporting our self-deflection arise from a space-charge field, enhanced through simultaneous excitations of both electrons and holes, which in the past has led to efficient two-wave mixing[8,9] and narrow solitons.[10–13] The large space-charge field results in a very large index change that depends highly on the intensity of the deflected beam, hence the self-deflection. The deflection can be controlled through the intensity of a second (background) beam at a different wavelength; thereby the process also allows for all-optical control of one beam with another. The deflection can also be controlled through the bias electric field applied to the crystal; thus the same process also facilitates electro-optic deflection. However, in a sharp contradistinction with traditional electro-optic deflection, which yields 1–5 resolvable spots,[2] our process yields >25 spots.

Our system is sketched in Fig. 1. A broad collimated signal beam (0.8 mm FWHM) from a Ti:sapphire laser at 900 nm is launched into a 5-mm-long crystal and propagates along its ⟨110⟩ direction. Our nonlinear crystal is CdZnTe (CZT, 1% Zn) doped with vanadium at a 10^{16}-cm^{-3} concentration. The output beam is captured by a lens ($f = 50$ mm) and focused to an 11-μm FWHM spot at the focal plane of the lens, from where it is imaged onto a CCD camera. The temperature of the crystal is stabilized at 294 K to control the density of its free charge carriers arising from thermal excitations. In addition to the self-deflected signal beam, the crystal is also illuminated uniformly by another beam at a 1527-nm wavelength from a diode laser. This background beam is used to all-optically control the deflection of the signal beam

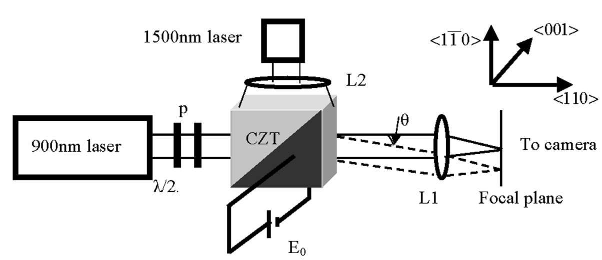

Fig. 1. Setup: A 900-nm beam is passed through a wave plate and a polarizer to control its intensity and polarization. The CZT crystal is illuminated uniformly by a 1527-nm beam and biased by a dc field applied through triangular parallel electrodes. Lens L1 Fourier transforms the angular deflection into a shift at the focal plane.

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through the excitation of a uniform density of charge carriers.[13] The two ⟨001⟩ faces of the crystal are connected to a bias electric field E_0, which is applied through electrodes in the form of equilateral 45° triangles covering two parallel halves of the interfaces (similar to the scheme used for electro-optic steering of quadratic solitons[14]). The signal beam is polarized either in the ⟨001⟩ or in the ⟨1$\bar{1}$0⟩ direction. When $E_0 = 0$, the refractive index is uniform everywhere in the crystal, and the signal beam is propagating on axis. When E_0 is on, a large space-charge field builds up between the electrodes and modifies the refractive index. The index change at any point depends on the local field, which in turn depends on the signal and background intensities, and whether that point is between the triangular electrodes (as the space-charge field is negligible in regions not between electrodes). Hence the optical intensity and the bias field give rise to a prismlike index change, and the beam propagating in the crystal experiences a different refractive index (a different phase delay) at different heights in the ⟨1$\bar{1}$0⟩ direction. This tilts the beam wave front by an angle θ (Ref. 2) and deflects the beam (Fig. 1). The number of resolvable deflection spots is given by $N = |\theta/\theta_{\mathrm{Beam}}|$, where θ_{Beam} is the diffraction angle of the finite signal beam. We find that the deflection depends on three variables: the intensities of the signal and background beams, I_s and I_b, respectively, and the applied field E_0. When the background intensity and the bias field are set anywhere in the (large) appropriate parameter range, we observe self-deflection of the signal beam. The intensity of the signal beam alone determines its trajectory.

Experimental results are shown in Fig. 2. Figures 2(b) and 2(d) show photographs of the self-deflected signal beam for various signal beam intensities, taken with $I_b = 0.05$ W/cm^2 and at $E_0 = 8$ and 4 kV/cm, respectively. Here the signal beam is polarized in the ⟨1$\bar{1}$0⟩ direction. The photographs are taken at the focal plane of the output lens, where each resolvable spot is 11 μm FWHM, and the maximum deflection is 304 μm, yielding 27 resolvable spots. Surprisingly, the deflection is in both transverse directions (in contrast with ordinary electro-optic beam deflection[2]). In angular terms the output beam is deflected by as much as 3.5 mrad, and the diffraction angle is 0.12 mrad. The maximum deflection is limited by distortion of the deflected beam, however, in contrast with all previous experiments; here the beam is almost undistorted for at least the first 20 resolvable spots. Figures 2(a) and 2(c) show the number of resolvable spots for the same E_0 as in 2(b) and 2(d), respectively, for three values of I_b. The deflection angle seems to depend linearly on the signal intensity I_s for our entire measurement range.

Figure 2 displays self-deflection of the signal beam, yet the deflection also depends on the intensity of the background beam. We therefore test for all-optical deflection of the signal beam by varying the intensity of the background beam I_b while keeping E_0 and I_s unchanged. Typical results (taken with $E_0 = 4$ kV/cm and two I_s values) are shown in Fig. 2(e) and indicate that the deflection of the signal beam depends linearly on I_b. That is, the all-optical deflection of a signal beam by another (background) beam is linear in the intensity of the control beam, just as the self-deflection of a signal beam depends linearly on its own intensity. The third variable controlling the deflection is the applied field E_0. We measure the deflection of the signal beam as a function of E_0 while keeping I_s and I_b fixed. The results are shown in Fig. 2(f), with $I_s = 1.24$ W/cm^2 and $I_b = 0.05$ W/cm^2, respectively. The nonlinear index change Δn arises from electro-optic effects and as such could be sensitive to the polarity of the applied field (with respect to the crystalline ⟨001⟩ axis) and to the polarization of the signal beam. The experimental findings are surprising. If the dominant electro-optic effects were the Pockels effect, one would expect a linear dependence of the deflection on E_0 and observe positive and negative deflections corresponding to positive and negative fields with respect to ⟨001⟩. As shown in Fig. 2(f), the dependence is quadratic in E_0 while showing a difference between positive and negative fields. This implies that the space-charge field values contributing to the deflection are sufficiently large so that the dc Kerr effect, which is a third-order nonlinearity, is dominant. The contribution of the Pockels effect is manifest in increasing (decreasing) the deflection at positive (negative) field values. This said, we do not observe negative deflection in our configuration: Even at low E_0 giving rise to the first point, the underlying space-charge field is sufficiently large so that the third- (not second-) order nonlinearity is dominant. We also find that the deflection is almost insensitive to the polarization of the signal beam, which can be polarized in either the ⟨001⟩ or the ⟨1$\bar{1}$0⟩ direction. The difference between the deflections of the two

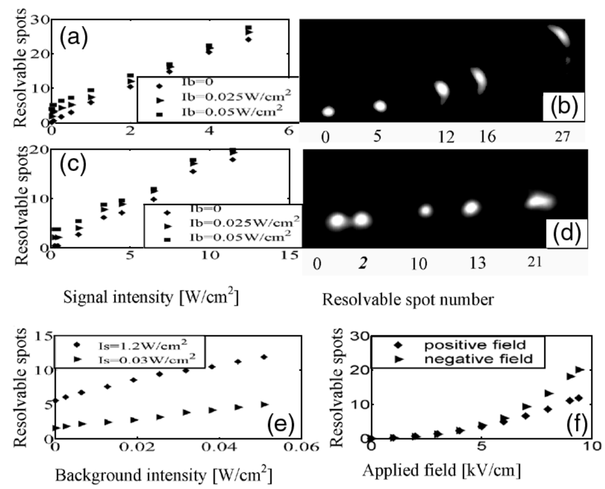

Fig. 2. Experimental self-deflection results. (a), (c) Number of resolvable spots versus intensity of the deflected (signal) beam for three values of the background intensity, taken at $E_0 = 8$ and 4 kV/cm, respectively. (b), (d) Photographs of the self-deflected beam, taken from (a) and (c) with $I_b = 0.05$ W/cm^2. (e) Number of resolvable spots versus the intensity of the background beam for two values of the signal intensity, taken at $E_0 = 4$ kV/cm. (f) Number of resolvable spots versus applied field for both field polarities, taken at $I_s = 1.24$ W/cm^2 and $I_b = 0.05$ W/cm^2.

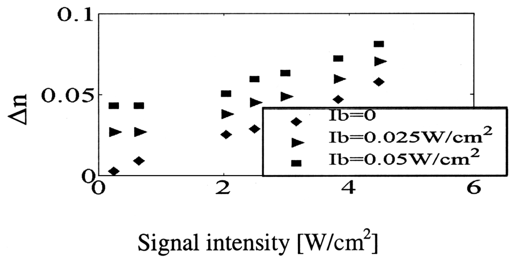

Fig. 3. Index change versus signal intensity for three values of background illumination, taken at $E_0 = 9$ kV/cm.

orthogonally polarized beams is less than 4%, which is greater than the experimental error but altogether very small. For most applications this polarization insensitivity is an important asset.

The large optical self-deflection of the signal beam relies on a very large Δn. One can deduce Δn from the deflection angle, but it is much more accurate to measure it interferometrically. Moreover, interferometric methods that employ plane waves are less affected by beam distortions (that naturally occur in self-deflection experiments, which inherently rely on inducing an asymmetry in the beam profile). Hence, in interferometric experiments we are able to measured higher Δn values than in self-deflections. We construct a Mach–Zehnder interferometer and substitute the nonlinear crystal in one of its arms. We illuminate the crystal uniformity with a broad signal beam, set the values of I_b and E_0, and measure the shift of the interference fringes (at the interferometer output) as a function of I_s. From the shift of the fringes we find Δn directly. The results are shown in Fig. 3 for three different values of I_b with $E_0 = 9$ kV/cm, and they show a very large value of Δn, roughly 0.08. This is to our knowledge the largest value ever obtained with any bulk semiconductor. Furthermore, we do not observe saturation of Δn, because the upper limit on its measurement is set by fragmentation of the signal beam. In fact, Δn is so large that, had it come solely from the Pockels effect, the corresponding field would have to be 1300 kV/cm, which is 150 times larger than E_0. In practice the dependence of Δn on E_0 is mostly quadratic [Fig. 2(f)], but even so, the space-charge field is greatly enhanced over E_0 (although we cannot determine the actual internal field because the parameters of the dc Kerr effect in this crystal are unavailable).

To summarize the experimental findings, we demonstrated very large self-deflection of an optical beam, deflection of one beam by another beam, and electro-optic beam deflection in photorefractive CdZnTe:V. We measure a very large nonlinear index change that arises from both the Pockels and the dc Kerr effects. The deflection is linear in the intensities of the signal (deflected) beam and the background (control) beam. These results indicate a very large enhancement of the (internal) space-charge field—possibly by orders of magnitude. In principle, these effects should be explained by the charge-transport theory in photorefractive semiconductors with both types of charge carriers.[9,12] In fact, our experiments were designed relying on the understanding gained from the spatial solitons in these materials,[12,13] and we expected a large resonant enhancement of the space-charge field. However, some of the experimental findings presented here are at odds with this theory. Most important, we do not observe any resonance: Δn and the space-charge field increase monotonically with the intensities of both the signal and the background beams. This is a sharp contradistinction with all two-wave mixing[9] and soliton[10–13] experiments in these materials, where a well-defined intensity resonance was observed. In our deflection experiments, as well as in our interferometric measurement, Δn and the internal field continue to increase with increasing intensities with no indication of any resonance. Furthermore, these experiments did not indicate any saturation, although saturation is most likely present at sufficiently large intensities, beyond our measurement range. Clearly, our results cannot be explained by the theories developed for two-wave mixing[9] and spatial solitons[12] in these materials.

In conclusion, we reported on the observation of large self-deflection, all-optical beam steering, and electro-optic beam deflection in photorefractive CdZnTe:V. To our knowledge, this is the largest optical self-deflection ever observed. These effects could be used for various applications, including those requiring high-speed beam steering, because photorefractive effects in such crystals were observed at submicrosecond scales even at low power.[13]

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