Spatial modulation instability driven by light-enhanced nonlinearities in semiconductor CdZnTe:V crystals

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We present the experimental observation of spatial modulation instability in photorefractive semiconductor crystals (CdZnTe:V), where the optical nonlinear effects are enhanced by light. We find that the total refractive index change can be expressed as sum of a uniform index change, which can exceed the value of 0.003, and a local index change which is limited to $\approx 1.6 \times 10^{-4}$. However, only the later, arising from the intensity-enhanced photorefractive effect, contributes to the formation of the modulation instability. Finally, we find that the refractive index change experiences large temporal fluctuations induced by the combination of uniform cw illumination and applied electric field. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2982084]

Photorefractive effects in semiconductors have been widely investigated, mainly because of their potential use in fast nonlinear all-optical devices.[1] A photorefractive material exhibiting a large nonlinear response combined with a fast response time could lead to valuable applications. Photorefractive semiconductors, featuring high mobility of charge carriers, indeed respond faster than other photorefractives for the same light intensity. However, the electro-optic effect in semiconductors is small,[2] thus a very large field should be established within the material to obtain a significant photorefractive response.[3] To overcome this obstacle, several techniques for enhancing the space charge field in photorefractive semiconductors have been developed,[1,4] demonstrating enhanced two-wave mixing gain and narrow spatial solitons.[1,5–12] Both phenomena rely on charge separation driven by nonuniform illumination. The enhancement in both cases displays an intensity-resonance (a maximum in the nonlinear response) when the excitation rates of electrons and holes are comparable.[1,5–12] In contrast to that, we have recently demonstrated huge all-optical steering and electro-optic deflection of *uniform* beams in a photorefractive semiconductor, CdZnTe:V (CZT:V). We found, through interferometry, that the large beam deflection is supported by refractive index changes in excess of 0.008.[13,14] These findings cannot be explained by "usual" electro-optic effects because the field required to support such index changes would be high above dielectric breakdown. Furthermore, we have found that the index change is proportional to the light intensity in all regimes investigated, not displaying any intensity-resonance. Finally, our experiments were performed with uniform beams, hence cannot be explained by standard photorefractive models relying on photoexcitation, charge separation, and retrapping because the optical excitation is uniform in space. This raises the question: could the symmetry-breaking effects that give rise to such a large index change arise from small local fluctuations in the refractive index or the beam intensity?

Here, we address this question and study whether the crystalline symmetry breaking can enhance the photorefractive effect in CZT:V. Both effects exhibit light-induced enhancement of the nonlinear index change, hence it is natural to ask whether the effects arise from the same physical origin. We therefore measure the local and nonlocal contributions to the nonlinear index change and their dependencies on the optical intensity. For this purpose, we experiment with *induced modulation instability* (MI) and compare between the refractive index change underlying the MI gain and the uniform refractive index change occurring naturally in the same experiment.

The reasoning for using MI for this study warrants a discussion. When a broad beam (plane wave) is propagating in a nonlinear material exhibiting a self-focusing nonlinearity, it typically breaks into filaments. This effect, known as spatial MI, occurs because a plane wave is unstable in a self-focusing medium; hence, small perturbations upon the wave are enhanced, eventually evolving into a periodic pattern. MI has been observed in many nonlinear systems,[15,16] usually under conditions similar to those supporting bright solitons. Here we use induced MI. We launch a broad beam modulated by small periodic perturbation (with visibility of ~3%) whose periodicity can be tuned. We turn the nonlinearity on, measure the visibility enhancement, and extract the nonlinear index change responsible for the MI gain.

Our setup is sketched in Fig. 1. A 5 mm width beam ("signal beam") at $\lambda = 980$ nm wavelength is launched into a Michelson interferometer with a variable attenuator in one of its arms. We set the attenuation to obtain a plane wave modulated by a small perturbation at the interferometer output and image this intensity structure onto one of the (110) faces of a $5 \times 5 \times 5$ mm^3 CZT:V crystal ("input face"). The opposite (110) face ("output face") is imaged onto a charge coupled device (CCD) camera. The crystal is biased by a dc voltage across its ⟨001⟩ direction, and a second beam ("background beam") at $\lambda = 1550$ nm illuminates the crystal uniformly along its $\langle 1\bar{1}0 \rangle$ direction.

We first launch a signal beam with zero modulation (a plane wave) and set the signal and background intensities, as well as the applied field, to the values supporting solitons in the same crystals.[8] Under such conditions, one would expect to observe MI: some periodic modulation of the intensity at the crystal output face. Surprisingly, no pattern forms under these conditions. Moreover, even when we vary the intensi-

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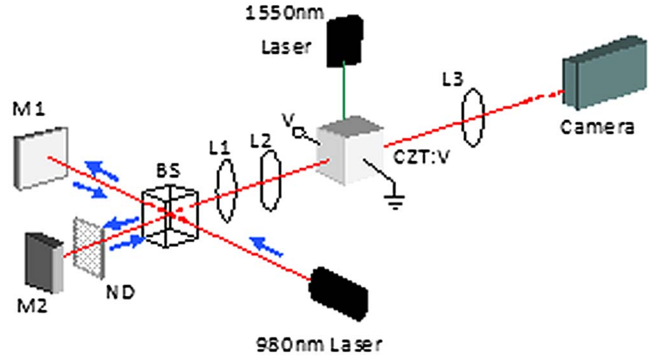

FIG. 1. (Color online) Experimental setup. A 5 mm width beam from a $\lambda = 980$ nm diode laser is passed through a Michelson interferometer with a neutral density filter at one of its arms. The output intensity of the interferometer is imaged onto the (110) face of a CZT:V crystal, resulting in a "plane wave" with a small amplitude perturbation propagating along the $\langle 110 \rangle$ crystalline direction. The crystal is illuminated uniformly by 1550 nm beam propagating in the $\langle 1\bar{1}0 \rangle$ direction.The crystal is biased by a dc field applied in the $\langle 001 \rangle$ direction. The intensity at the output face of the crystal is imaged onto a CCD camera.

ties of the two beams and the applied field value, the output intensity remains uniform. This suggests that the MI gain accumulated in our CZT:V crystal is too weak to be observed. In such cases, it is useful to conduct the experiments with induced-MI. We extract the MI gain g at the output face from the experimental data and the expression $I = I_0[1 + m\cos(k_x x)e^{gL}]$, where I_0 is the intensity of the plane wave, m is the modulation depth at the input face, k_x is the wavenumber of the modulation, and L is the length of the crystal. (Note that the background illumination dramatically reduces the absorption of the signal beam; this "light-induced transparency" effect is taken into account when we calculate the MI gain). Using this technique of induced MI, we do measure gain, but the gain coefficient is small, and it is difficult to quantify the dependence of the gain on the intensity or on the applied field. However, we find experimentally that if the background beam is modulated temporally at frequencies of 2–4 Hz, the gain nearly triples, and its dependence on the beams' intensities (or on the applied field) becomes clear. Accordingly, all the results presented below are obtained with a temporally modulated background beam. A typical pattern of induced MI with a period of 75 μm is shown in Fig. 2(a). For comparison, we also present [Fig. 2(b)] the output pattern for spontaneous MI. One can recognize the traces of a pattern also in Fig. 2(b), but it is not clear if its

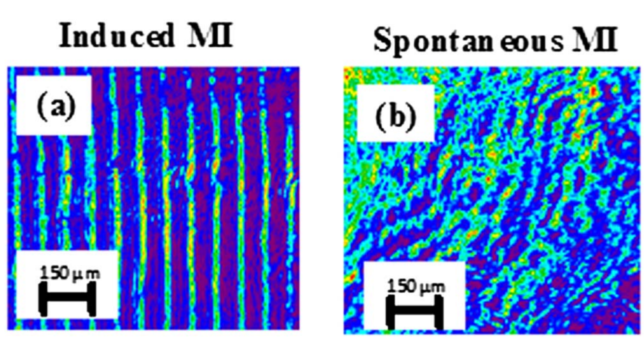

FIG. 2. (Color online) Photographs of the MI pattern emerging at the output face of the CZT:V taken at signal intensity of 1.6 mW/cm^2, background intensity of 15 mW/cm^2, modulated at frequency of 3 Hz, and applied electric field of 8 kV/cm. (a) Induced MI for transverse wave number of 0.08 μm^{-1}. (b) Spontaneous MI pattern.

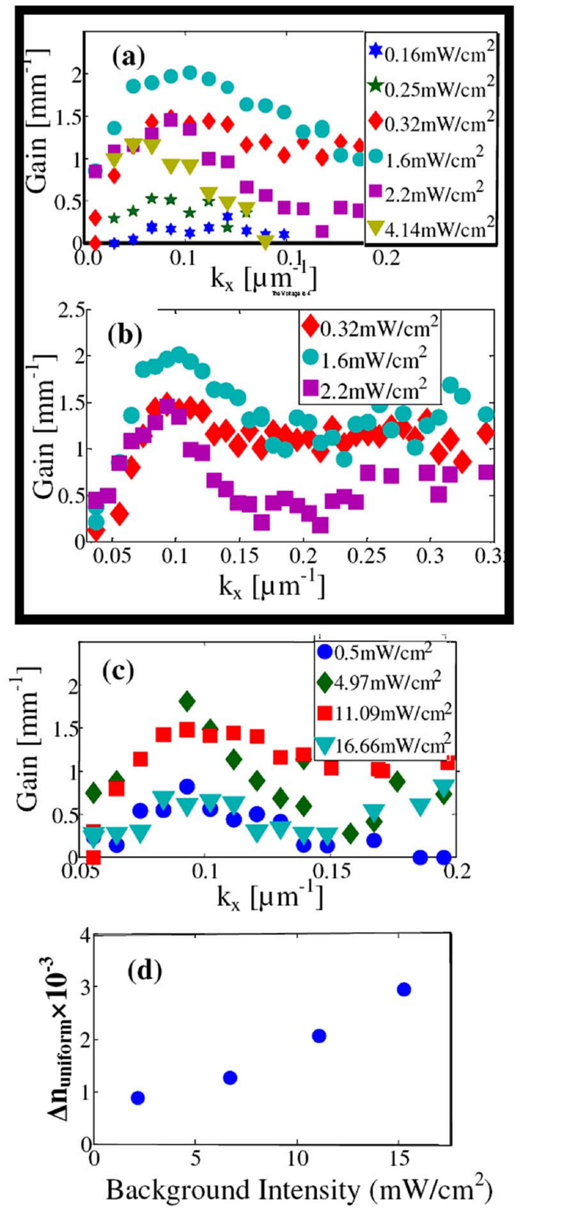

FIG. 3. (Color online) Experimental results: [(a) and (b)] MI gain vs transverse wave number for different values of signal beam intensity, all measured at an applied electric field of 8 kV/cm and background intensity of 15 mW/cm^2. (b) MI gain vs transverse wave number for three different values of signal beam intensity, (c) MI gain vs transverse wave number for four different values of background beam intensity, all measured at applied electric field of 8 kV/cm and signal intensity of 0.2 mW/cm^2. (d) Uniform effective–refractive change vs background intensity, measured interferomentrically at signal intensity of 0.2 mW/cm^2 and applied electric field of 8 kV/cm.

origin is truly spontaneous (random noise) or these features reflect inhomogeneities at the crystal input face.

The gain coefficients measured for several values of signal intensity at an applied field of 8 kV/cm and background intensity of 15 mW/cm^2 are plotted in Figs. 3(a) and 3(b), as a function of the transverse wave number k_x. It is clear from Fig. 3(a) that, for low signal intensities, the gain increases with increasing intensity until it reaches a maximum value at 1.6 mW/cm^2, above which it decreases with increasing intensity. This behavior is characteristic for the intensity-resonance effect observed with solitons and two-wave mixing in photorefractive semiconductors.[1,5–10] We recheck this resonant behavior by varying the intensity of the background beam at a fixed signal intensity of 0.2 mW/cm^2 and an applied field of 8 kV/cm. Indeed, the results plotted in Fig. 3(c) show again that, for background intensities below 11 mW/cm^2, the gain increases with intensity until reaching its maximum value, above which it decreases with increasing intensity. Analyzing Figs. 3(a)–3(c), we find that the maximum gain value is 2 mm^{-1} and it is obtained at a wave number of 0.1 μm^{-1}. We estimate the maximum refractive index change from the maximum gain value. When the visibility of MI pattern is small (i.e., the regime of exponential gain), the gain coefficient is related to the index change through $\Delta n_{eff} = g\lambda/(4\pi)$,[15] which leads to an effective refractive index change of $\approx 1.6 \times 10^{-4}$.

This value of refractive index responsible to MI, 1.6×10^{-4}, is almost 100 times smaller than the value measured with a uniform beam in our previous experiment.[13,14] It is therefore reasonable to examine whether the periodic index change supporting MI resides on top of a large uniform index change. For this purpose, we perform interferometric experiments with a uniform (nonmodulated) signal beam under the exact same supplementary conditions (signal and background intensities and applied field) used to obtain maximum gain in MI experiments [see Fig. 3(a)]. The index change is calculated from the phase shift measured interferometrically. The results showing the uniform effective index change $\Delta n_{uniform}$ versus background intensity are plotted in Fig. 3(d). This figure reveals that $\Delta n_{uniform}$ depends nearly linearly on the background intensity, reaching the large value of $\approx 3 \times 10^{-3}$. Clearly, the index change underlying MI is superimposed on a 20 times higher uniform index change. These results suggest that the total index change in CZT:V comprises of two terms: $\Delta n_{eff} = \Delta n_{uniform} + \Delta n_{local}$. Here, $\Delta n_{uniform}$ is the large uniform index change associated with crystalline symmetry breaking, which depends on the average light intensity and seems to be of a nonlocal nature hence not contributing to MI, whereas Δn_{local} varies from one point to another, depending on the local intensity. When the amplitude of the signal beam is spatially modulated, Δn_{local} follows the modulation and enhances it, giving rise to the MI pattern. Supporting evidence for the existence of two separate mechanisms arrives also from the comparison between the characteristic response time for symmetry breaking and the modulation time we use here. While the former is ~5 s, the temporal modulation yielding the highest gain is 3 Hz, i.e., the formation time for the local refractive index change is ~15 times faster. Hence, there are two separate processes giving rise to the index change: symmetry breaking, which is slower but yields a very large nonlocal index change, and a smaller, spatially local, index change, occurring within fractions of a second. The MI process arises from the latter.

Our experiments reveal another feature of the MI in CZT:V, whereas induced-MI yields a clear periodic pattern [Fig. 2(a)], spontaneous MI results in a pattern with no clear periodicity [Fig. 2(b)]. The underlying reason has to do with the temporal variation in the evolving MI pattern. While experimenting with spontaneous MI, we notice that the spatial perturbations fluctuate in time. This temporal variation is probably due to high-field domains traveling across the crystal, a phenomenon known for high-resistance semiconductors, which is observed when high electric field is applied.[17] Under our experimental conditions, for the illumination intensities used (<20 mW/cm^2), the response time is rather slow (~0.5 s). When the response time of the nonlinearity is slower than the traveling time of the domains, MI is suppressed and its gain curve versus wave number becomes broad, resulting in a wide range of spatial frequencies exhibiting similar gain values.[18] When this happens, the MI process is not dominated by a single spatial frequency, and the MI pattern has no clear periodicity. Rather, since spontaneous MI is initiated by noise comprising many spatial frequencies, all growing at the same rate, the output pattern is complex, representing a superposition of all spatial frequencies displaying an appreciable gain. The flattening of the MI gain curve is actually observed in our induced-MI experiments: as clearly shown in Fig. 3(b), spatial frequencies higher than 0.2 μm^{-1} yield gain comparable to the maximum gain. This feature, of a flat gain curve for spatial frequencies above a certain value, stands in a sharp contrast with all MI experiments (and theories) for Kerr or saturable (e.g., photorefractive, liquid crystals, etc.) media, which always exhibit a cutoff frequency above which MI is suppressed.[18]

In summary, we presented the observation of spatial MI effects in photorefractive semiconductors. Comparing the effective refractive index change supporting the MI to the uniform index change caused by uniform illumination suggests that the total index change in CdZnTe:V is the sum of two contributions with different time constants: a very large uniform component, reaching values of $\approx 3 \times 10^{-3}$, and a local index change whose value is limited to $\approx 1.6 \times 10^{-4}$. This suggests that MI here is driven by the intensity-enhanced photorefractive effect, with a moderate (~4) enhancement of the index change, whereas the huge uniform term in the index change originates from crystalline symmetry breaking, hence the associated enhancement is ~100.

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