High photorefractive gain at counterpropagating geometry in CdTe:Ge at 1.064 μm and 1.55 μm

Konstantin Shcherbin

Institute of Physics, National Academy of Sciences, Prospekt Nauki 46, 03028 Kiev, Ukraine
(kshcherb@iop.kiev.ua)

Received 9 October 2008; revised 26 November 2008; accepted 5 December 2008;
posted 8 December 2008 (Doc. ID 102599); published 8 January 2009

Recording of efficient reflection holograms is achieved in CdTe:Ge at $\lambda = 1.064\,\mu$m and $\lambda = 1.55\,\mu$m. The gain factor measured at both wavelengths for counterpropagating two-beam coupling considerably exceeds the absorption constant and transcends all values previously reported for semiconductors with no external field. The dependences of the gain factor on intensity and grating spacing are studied. Some crystal characteristics are estimated in the frame of a single band, one mobile species approximation of space-charge formation. The homogeneity of photorefractive properties in the crystal volume is demonstrated. © 2009 Optical Society of America

OCIS codes: 160.5320, 190.5330, 190.7070.

1. Introduction

Photorefractive semiconductor crystals, such as GaAs, CdTe, and InP, are well suited for telecommunication systems because they are sensitive in the infrared region of the spectrum. An additional significant advantage of these materials is a fast response when compared with photorefractive wide-band-gap crystals. On the other hand, the smaller electro-optic coefficients of semiconductors result in a smaller refractive index modulation and, therefore, in a smaller diffraction efficiency and a two-beam coupling gain factor. Furthermore, the latter important characteristics decrease with the wavelength for a fixed refractive index change, as the nonlinear phase shift is inversely proportional to the wavelength. In other words, the photorefractive response of semiconductors in the infrared wavelength range is reduced when compared with the response of crystals with similar characteristics in the visible region of the spectrum. This unfavorable feature, along with smaller electro-optic coefficients, makes any improvement to the response of photorefractive semiconductors very important.

The photorefractive response can be improved when the space-charge field is increased by an external electric field. A dc field [1,2], a high frequency [2,3], or a low-frequency [4] ac field may be used, but these techniques have particular difficulties. The use of a dc field requires the homogeneous illumination of the crystal to prevent an undesirable formation of the large-scale space-charge distribution of the field across the cross section of the crystal with high photoconductivity. Quite often, it is almost impossible to apply a field with high amplitude to semiconductors with relatively high conductivity of the order of 10^{-6}–10^{-9} $(\Omega \times \mathrm{cm})^{-1}$. When an ac field is used, the frequency of the field must be much larger than the reciprocal relaxation time of the crystal, which falls to microsecond range or even less. Application of a high voltage with such a high frequency is a difficult engineering task. This is why the increase of the photorefractive response of semiconductors with no external field remains an important task.

For the diffusion process of recording (when no external field is applied to the crystal), the maximum space-charge field may be reached in the reflection geometry [2] when nearly counterpropagating recording beams are directed into the sample through opposite faces. This is possible if the effective trap concentration is high enough to ensure efficient space-charge formation at small grating spacing.

0003-6935/09/020371-04$15.00/0
© 2009 Optical Society of America

However, the photorefractive semiconductors often do not meet this requirement. In this work it is demonstrated that doping of CdTe with germanium allows the effective recording of reflection gratings at two important wavelengths, $\lambda = 1.064\,\mu$m and $\lambda = 1.55\,\mu$m. The two-beam coupling gain factor measured at both wavelengths is, to the best of our knowledge, the largest ever reported for any photorefractive semiconductor with no electric field and exceeds the values previously reported for CdTe by more than two times for $\lambda = 1.064\,\mu$m [5] and by nearly 1.5 times for $\lambda = 1.55\,\mu$m [6].

2. Experimental Setup

Cadmium telluride is the most promising semiconductor for photorefractive recording with no electric field as it exhibits the largest electro-optic coefficient amongst other semiconductors [7]. In this work CdTe:Ge, which is a particularly promising semiconductor [8], has been studied. The crystal was grown by a modified Bridgman process at Chernivtsy National University, Ukraine. The CdTe is deliberately germanium-doped to ensure a high effective trap concentration: germanium was added in the melt in a concentration of the order of $10^{19}\,\mathrm{cm}^{-3}$. The single-crystal sample is cut along the $[1\bar{1}0]$, [001], and [110] crystallographic axis and has dimensions $3.8\,\mathrm{mm} \times 3.5\,\mathrm{mm} \times 6.8\,\mathrm{mm}$, respectively. Each face of the crystal is optically finished. The absorption constant of the sample $\alpha \approx 1.7\,\mathrm{cm}^{-1}$ is measured at $\lambda = 1.064\,\mu$m and $\alpha \approx 0.6\,\mathrm{cm}^{-1}$ at $\lambda = 1.55\,\mu$m.

The experimental setup is shown schematically in Fig. 1. Either a YAG: Nd^{3+} laser operating at $1.06\,\mu$m or a laser diode emitting at $1.55\,\mu$m, both continuous wave single frequency, serves as a light source. The output laser radiation is divided by a beam splitter (BS) into two beams, I'_{S0} and I'_{P0}, with intensity ratio $\beta \approx 1:20$. The shutter (SH) allows control of the presence of the pump beam. To study gratings recorded with copropagating beams, both beams are sent to the crystal through the same input face parallel to the (110) crystallographic plane as shown in Fig. 1(a). The plane of incidence corresponds to the $(1\bar{1}0)$ plane. For recording of reflection gratings, two nearly counterpropagating beams, I'_{S0} and I'_{P0}, are sent to the sample through opposite faces parallel to the (001) plane [see Fig. 1(b)]. In such a manner, the grating vector **K** is always kept parallel to the [001] direction. The polarization of the light is perpendicular to the plane of incidence, i.e., it is parallel to the $[1\bar{1}0]$ direction. The effective electro-optic coefficient is equal to the handbook electro-optic coefficient r_{41} in this case for two-beam coupling in codirectional as well as in counterdirectional geometry.

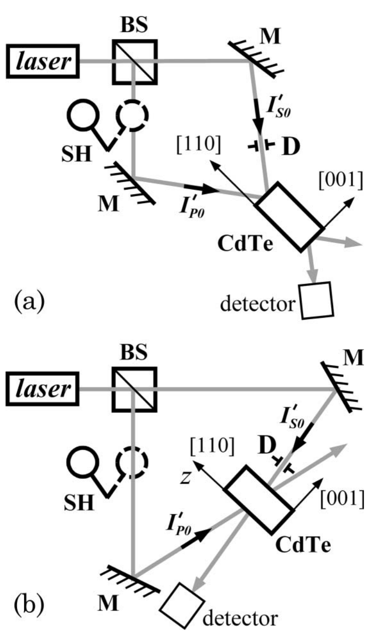

Fig. 1. Experimental setup for (a) copropagating and (b) counterpropagating two-beam coupling.

The unexpanded beams of half-width Gaussian intensity distribution $w \approx 2.4\,\mathrm{mm}$ are used in the experiment. To ensure grating recording with better homogeneity of intensity, the diaphragm D with diameter $d = 1.4\,\mathrm{mm}$ is placed in the path of a signal beam in front of the crystal at a distance of 4 cm. In this way the grating recording by beams at the top of the Gaussian distribution is achieved. The use of a wider pump beam as compared to the signal also ensures the complete overlap of the beams at copropagating geometry when beams intersect in the crystal at a relatively large angle.

3. Experiment and Discussion

The two-beam coupling gain factor $\Gamma = (1/l)\ln(I_S/I_{S0})$ is measured in the experiment, where I_S and I_{S0} is the intensity of the transmitted signal beam in the presence of a pump beam and with a blocked pump, respectively, and l is the interaction length. First, the dependence of the gain factor on incident light intensity was measured at both wavelengths for counterdirectional two-beam coupling. The results are presented in Fig. 2. The gain factor increases as intensity increases and nearly reaches a saturated value at intensity $I = 1500\,\mathrm{mW/cm^2}$ for $\lambda = 1.064\,\mu$m and $I = 500\,\mathrm{mW/cm^2}$ for $\lambda = 1.55\,\mu$m. The direction of energy transfer is unchanged at both wavelengths, which indicates that the main charge carriers are the same. They are the holes, according to the charge transport model for CdTe:Ge [9,10]. When the crystal is rotated by 180° in such a way that the [001] axis reverses direction, the direction of energy transfer is inverted, i.e., the weak signal beam is attenuated and the negative gain factor is measured. The modulus of the gain is the same for amplification and attenuation geometry with the same experimental conditions. This indicates the photorefractive recording with no contribution from an absorption grating.

For a simple one-band, one-level model of the photorefractive effect, the intensity dependence of the gain factor is given as [11]

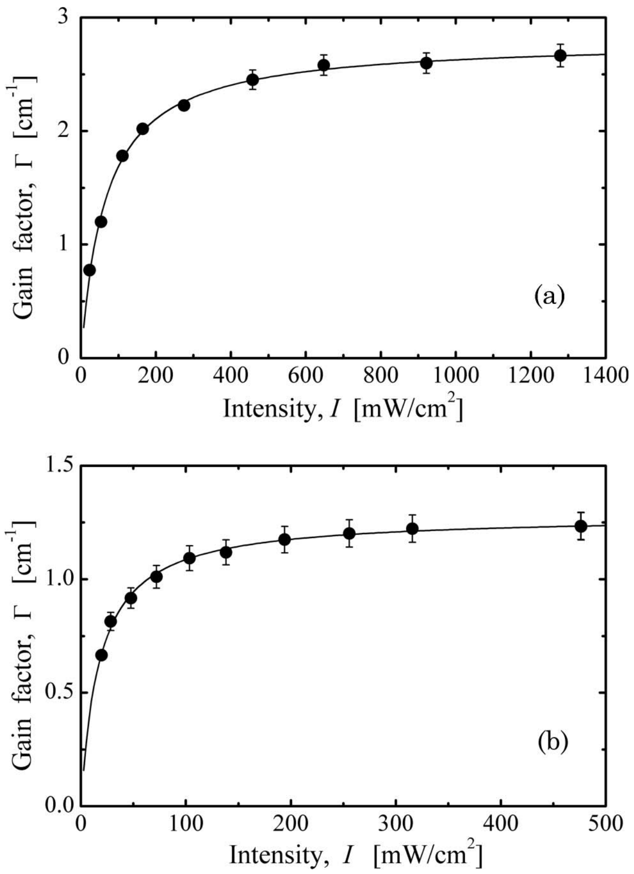

Fig. 2. Intensity dependences of the gain factor measured for counterpropagating geometry at (a) $\lambda = 1.064\,\mu$m and (b) $\lambda = 1.55\,\mu$m; circles—experimental data, solid lines—best fit by Eq. (1).

$$\Gamma = \frac{\Gamma_0}{1 + \sigma_D/(\kappa I)}, \tag{1}$$

where Γ_0 is the saturated value of the gain factor, σ_D is the dark conductivity, and κ is the specific photoconductivity. The solid curves in Fig. 2 represent the best fit to the experimental data by Eq. (1) with $\Gamma_0 = 2.8\,\text{cm}^{-1}$ and $\sigma_D/\kappa = 66\,\text{mW/cm}^2$ for $\lambda = 1.064\,\mu$m and $\Gamma_0 = 1.28\,\text{cm}^{-1}$ and $\sigma_D/\kappa = 17.8\,\text{mW/cm}^2$ for $\lambda = 1.55\,\mu$m. It could be expected that the ratio σ_D/κ is larger for the longer wavelength as photoconductivity typically decreases with wavelength. The larger ratio σ_D/κ at $\lambda = 1.064\,\mu$m observed in the experiment can be explained by electron-hole competition when secondary charge carriers are photoexcited and partially compensate the primary grating recorded by the main charge carriers. Secondary charge carriers are photoexcited more effectively at $\lambda = 1.064\,\mu$m. Hence the larger intensity is necessary to reach saturation of the gain factor on intensity. In spite of the fact that electron-hole competition is inherent to CdTe:Ge and several species are involved in space-charge formation [9,10], the dependence (1) describes well the experimental data. The estimations made for the ratio σ_D/κ should be considered as an "effective" ratio of the dark conductivity and specific conductivity made in the frame of a single charge carrier model for the crystal with bipolar conductivity.

To determine the grating spacing dependence of the gain factor, the intensity dependences of the gain factor were measured in copropagating geometry for different crossing angle between recording beams. The gain factor for intensity saturation conditions was evaluated from these dependences. The grating spacing dependences of the gain factor for intensity saturation conditions are presented in Fig. 3 for $\lambda = 1.064\,\mu$m and $\lambda = 1.55\,\mu$m.

According to the theory [2], the gain factor decreases at large grating spacing as

$$\Gamma = \frac{4\pi^2 n^3 r_{\text{eff}} \xi k_B T}{\lambda e} \frac{\Lambda}{\Lambda^2 + \ell_S^2}, \tag{2}$$

where Λ is the grating spacing, r_{eff} is the effective electro-optic coefficient ($r_{\text{eff}} = r_{41}$ in the present two-beam coupling geometry), k_B is the Boltzmann constant, T is the absolute temperature, n is the refractive index, e is the electron charge, ξ is the electron-hole competition factor taking into account a possible compensation of the main grating by the minority carriers, and the Debye screening length ℓ_S is given by $\ell_S^2 = (4\pi^2 \varepsilon\varepsilon_0 k_B T)/(e^2 N_{\text{eff}})$, where ε is the dielectric constant of the material, ε_0 is the

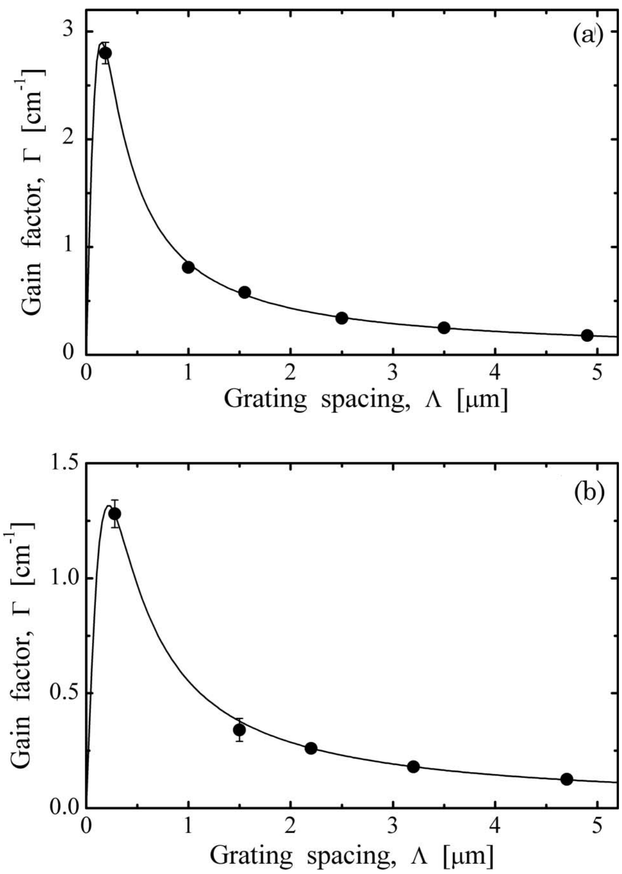

Fig. 3. Grating spacing dependences of the gain factor measured at (a) $\lambda = 1.064\,\mu$m and (b) $\lambda = 1.55\,\mu$m; circles—experimental data, solid lines—best fit by Eq. (2).

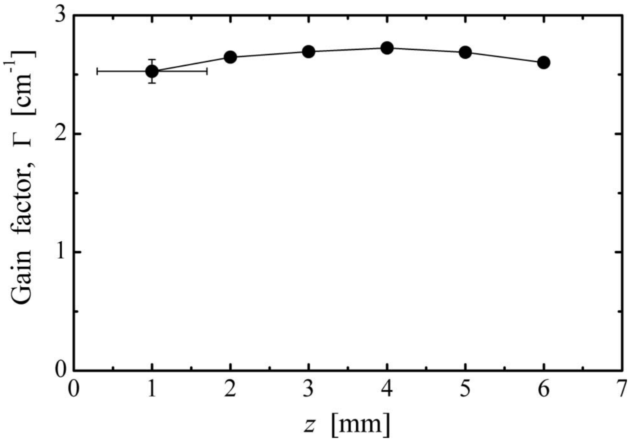

Fig. 4. Scan of the gain factor along z axis parallel to [110] direction measured at $\lambda = 1.064\,\mu$m for counterpropagating geometry.

electric permittivity of free space, and $N_{\rm eff}$ is the effective trap density.

The solid lines in Fig. 3 represent the best fit to the experimental data by Eq. (2) with $\ell_S = 0.15\,\mu$m ($N_{\rm eff} \approx 2.4 \times 10^{16}$) and $\xi = 0.66$ for $\lambda = 1.064\,\mu$m and with $\ell_S = 0.22\,\mu$m ($N_{\rm eff} \approx 1.1 \times 10^{16}$) and $\xi = 0.7$ for $\lambda = 1.55\,\mu$m. The electro-optic coefficient $r_{41} = 6.1$ pm/V [7] and the refractive indexes $n = 2.82$ at $\lambda = 1.064\,\mu$m and $n = 2.74$ at $\lambda = 1.55\,\mu$m [12] were used to get fitting parameters. As for intensity dependences of the gain factor, the estimated characteristics should be considered as "effective" characteristics because several defect and impurity centers and both types of charge carriers are involved in space-charge redistribution in differently doped CdTe [9,10,13]. At the same time, the simplest approximation of charge transport considering one type of carrier and one photorefractive center qualitatively perfectly explains the experimental results.

Cadmium telluride usually exhibits nonuniformity of photorefractive properties in the crystal volume, which introduces significant limitations for practical applications. To determine the distribution of photorefractive properties in the studied sample, the crystal was mounted on a translation stage allowing translational displacement along the z axis parallel to the [110] crystallographic direction [see Fig. 1(b)]. The gain factor as a function of displacement measured at $\lambda = 1.064\,\mu$m for the counterpropagating geometry is shown in Fig. 4. The gain factor remains nearly the same within experimental error. The experimental data demonstrate the homogeneity of the excellent photorefractive properties in the volume of studied CdTe:Ge crystal.

4. Conclusion

In conclusion, it has been demonstrated that doping of cadmium telluride with germanium may ensure a high effective trap concentration sufficient for the recording of efficient reflection holograms. To the best of our knowledge, the gain factor reached for counterpropagated two-beam coupling exceeds previously reported results by more than two times for $1.064\,\mu$m recording and nearly 1.5 times for $1.55\,\mu$m recording. The gain factor at both wavelengths considerably transcends the absorption constant: $\Gamma \approx 2.8\,\mathrm{cm}^{-1}$ and $\alpha \approx 1.7\,\mathrm{cm}^{-1}$ at $1.064\,\mu$m; $\Gamma \approx 1.3\,\mathrm{cm}^{-1}$ and $\alpha \approx 0.6\,\mathrm{cm}^{-1}$ at $1.55\,\mu$m. The uniformity of the photorefractive properties in the crystal volume is demonstrated experimentally. The crystals with such characteristics are perfect candidates for applications such as laser ultrasonics receivers, laser intracavity filters, and others.

The CdTe:Ge crystal was supplied by Z. I. Zakharuk and I. M. Rarenko. The author is grateful to S. Bozhko and K. Eveson for technical assistance.

References

1. J. P. Huignard and A. Marrakchi, "Coherent signal beam amplification in two-wave mixing experiments with photorefractive $Bi_{12}SiO_{20}$ crystals," Opt. Commun. **38**, 249–254 (1981).
2. M. P. Petrov, S. I. Stepanov, and A. V. Khomenko, *Photorefractive Crystals in Coherent Optical Systems* (Springer-Verlag, 1991).
3. S. I. Stepanov and M. P. Petrov, "Efficient unstationary holographic recording in photorefractive crystals under an external alternating electric field," Opt. Commun. **53**, 292–295 (1985).
4. A. V. Khomenko, A. López Navarro, M. García-Zárate, and K. Shcherbin, "Optically stimulated electron-hole resonance in photorefractive CdTe with a low frequency ac field," J. Opt. Soc. Am. B **24**, 2172–2176 (2007).
5. K. Shcherbin, A. Shumeljuk, S. Odoulov, P. Fochuk, and G. Brost, "Relaxation of photorefractive gratings in cadmium telluride crystals," Proc. SPIE **2795**, 236–243 (1996).
6. A. Godard, G. Pauliat, G. Roosen, and É. Ducloux, "Relaxation of the single-mode emission conditions in extended-cavity semiconductor lasers with a self-organizing photorefractive filter," Appl. Opt. **43**, 3543–3547 (2004).
7. K. Tada and M. Aoki, "Linear electro-optic properties of ZnTe at 10.6 microns," Jpn. J. Appl. Phys. **10**, 998–1001 (1971).
8. K. Shcherbin, "Recent progress in semiconductor photorefractive crystals," in *Photorefractive Materials and Their Applications II*, P. Günter and J.-P. Huignard, eds. (Springer, 2007), pp. 391–418.
9. B. Briat, K. Shcherbin, B. Farid, and F. Ramaz, "Optical and magnetooptical study of photorefractive germanium-doped cadmium telluride," Opt. Commun. **156**, 337–340 (1998).
10. B. Briat, F. Ramaz, B. Farid, K. Shcherbin, and H. J. von Bardeleben, "Spectroscopic characterization of photorefractive CdTe:Ge," J. Cryst. Growth **197**, 724–728 (1999).
11. N. V. Kukhtarev, V. B. Markov, S. G. Odoulov, M. S. Soskin, and V. L. Vinetskii, "Holographic storage in electro-optic crystals. II. Beam coupling—light amplification," Ferroelectrics **22**, 961–964 (1979).
12. D. T. F. Marple, "Refractive indexes of ZnSe, ZnTe, and CdTe," J. Appl. Phys. **35**, 539–542 (1964).
13. L. A. de Montmorillon, Ph. Delaye, G. Roosen, H. Bou Rjeily, F. Ramaz, B. Briat, J. G. Gies, J. P. Zielinger, M. Tapiero, H. J. von Bardeleben, T. Arnoux, and J. C. Launay, "Correlation between microscopic properties and the photorefractive response for vanadium-doped CdTe," J. Opt. Soc. Am. B **13**, 2341–2351 (1996).