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# Solid-state characterization of CdTe:Sn as a medium for adaptive interferometry

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## ABSTRACT

Two-wave mixing adaptive interferometer based on photorefractive crystal allows for compensation of temporal disturbances in ambient environment and operation with speckled beams. The crystal should exhibit large effective trap density, low dark conductivity and large photoconductivity. Deliberately doped semiconductor may meet these requirements. In the present work the photorefractive, spectroscopic and magneto-optical study of CdTe:Sn is performed aiming to estimate these characteristics and to describe the space-charge formation. The photon energies for optical ionization/neutralization of the tin ions are estimated. The crystal is characterized as a medium for two-wave mixing adaptive interferometer with excellent performance.

**Keywords:** Cadmium telluride, photorefractive effect, photorefractive semiconductor, two-wave mixing, adaptive interferometer, doped semiconductor

## 1. INTRODUCTION

Adaptive interferometers based on two-wave mixing (TWM) on dynamic holograms allows for remote detection of surface vibrations caused by ultrasonic waves. They can process speckled beams scattered from rough surfaces and compensate for ambient environmental perturbations. Furthermore they can be made to operate intrinsically in quadrature without need for external path length stabilization. In such interferometers a dynamic grating serves as an adaptive beam-splitter[1-3]. As the grating is dynamic, it adapts to the relatively slowly varying wave front of the object beam caused by undesired external perturbations, ensuring continuous compensation for them. However, the grating may be considered as being fixed for the fast phase variations related to ultrasonic vibrations, thereby enabling conversion of phase modulation to intensity modulation.

The adaptive interferometers have been demonstrated with dynamic gratings recorded in different materials and devices including liquid crystal light valves[4] and gain medium[5]. The operation with digital holography has also been studied[6]. If digital holography is still clearly inferior to its analog form[7], dynamic holograms in photorefractive crystals appear to be the most relevant to the application[8]. Among all photorefractive materials, only fast photorefractive semiconductors can compensate for the full bandwidth of mechanical and optical disturbances in the outside ambient because of their short response time[9]. An additional significant advantage of photorefractive semiconductors is their sensitivity in the near infrared. This makes them compatible with many available lasers and telecommunication components.

Photorefractive recording involves a chain of different physical processes[10,11]. When a photorefractive crystal is illuminated by an interference pattern formed by the recording beams, more free charge carriers are photoexcited from donors in the bright fringes, as it is shown schematically in Fig. 1. The carriers diffuse in the dark areas where they are trapped by charge acceptor states. As a result a spatial charge distribution $\rho(x)$ is created. Owing to the Pockels effect, the electric field of the space-charge $E_{SC}(x)$ induces a refractive index modulation $\Delta n(x)$. In this way the index grating is created. The recording light diffracts from the grating giving rise to different optical effects and various applications[10-12].

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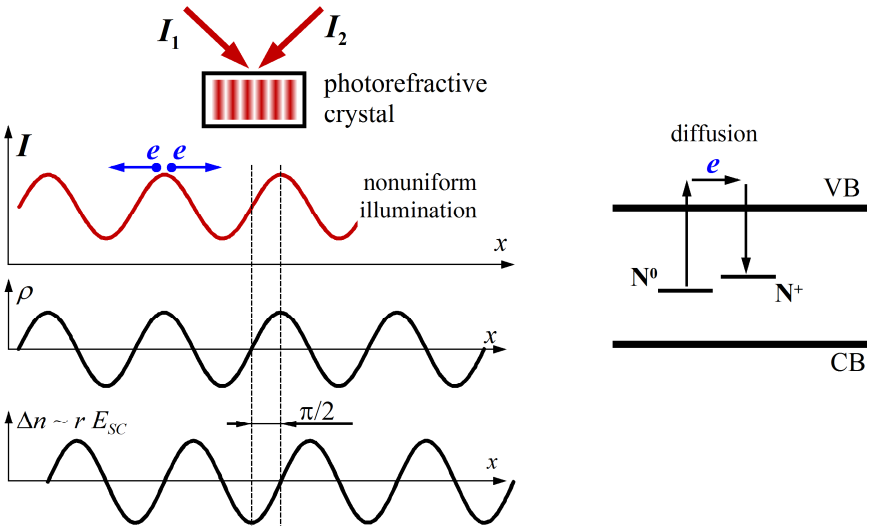


Figure 1. Schematic representation of the photorefractive recording.

Therefore the photorefractive material needs to be electro-optic with a large enough electro-optic coefficient. It should exhibit a low dark conductivity to be able to collect a space charge, but have a photoconductivity at the wavelength of operation. A large density of donors is necessary to supply the photoconductivity, while a large trap density is required for space charge formation. Generally, the same impurity or defect center in different charge states may serve as a donor and trap. Also, the free photo-excited carriers may be electrons or holes.

CdTe is the best material for adaptive interferometers because of the largest electro-optic coefficient among all semiconductors. It is sensitive at the eyesafe wavelength $\lambda$ = 1550 nm, where modular and cost-effective telecommunications components are available. Some unique specially selected CdTe samples demonstrate the largest for semiconductors gain factor in photorefractive two-beam coupling at $\lambda$ = 1064 nm and $\lambda$ = 1550 nm[13]. The key feature for large donor and trap density is appropriate doping. Three elements are used mainly for enhancement of the photorefractive response of CdTe. These are vanadium[14], germanium[13] and tin[15]. If a comprehensive study of the space charge formation in vanadium[16] and germanium[17] doped crystals gave an understanding of the main processes involved long time ago, a similar study of CdTe:Sn was performed only recently[7]. In the present, work we extend results of this study and characterize CdTe:Sn as a material for TWM adaptive interferometry.

## 2. EXPERIMENTAL RESULTS AND DISCUSSION

The studied CdTe:Sn crystals were grown in Chernivtsy National University, Ukraine. The samples are rectangular in shape with typical dimensions 1×0.5×0.5 cm$^3$. The input optically polished faces are parallel to (110) plane, while the side faces are parallel to (001) plane. In the experiments requiring an external field, a voltage is applied to electrodes deposited on the side faces, forming an electric field $E_0$ along [001] axis. The crystals are deliberately doped. The initial tin concentration in the melt $N_{Sn} = 2.5\times10^{19}$ cm$^{-3}$. A dark conductivity is estimated $\sigma_D < 1.7\times10^{-9}$ (Ohm×cm)$^{-1}$.

### 2.1 Photorefractive properties at 1064 nm

Experimental set-up is shown schematically in Fig. 2. Continuous-wave laser radiation is divided by a beam splitter BS into two beams $I_S^0$ and $I_P^0$ with intensity ratio $\beta = I_P^0/I_S^0 \approx 100$. Both unexpanded beams enter the crystal through the face parallel to (110) plane, so that the grating vector **K** is parallel to the [001] direction. The light polarization is perpendicular to the plane of incidence, i.e., it is parallel to [110] direction. The effective electro-optic coefficient is equal to the handbook value $r_{41}$ in this geometry. The total light intensity is up to 500 mW/cm$^2$. To control the intensity, a variable attenuator is used. A phase electro-optic modulator EOM is used to control the grating recording and erasure.

It introduces in the pump wave packets of high-frequency sinusoidal oscillations $\varphi(t) = \Delta\varphi\sin(2\pi ft)$ with amplitude $\Delta\varphi$ = 2.4 rad (the first zero of the zero order Bessel function $J_0(\Delta\varphi) \approx 0$). Such phase modulation stops the grating recording keeping the same averaged light intensity in the sample[7]. The gain factor $\Gamma = (1/d)\ln(I_S/I_S^0)$ is measured, where $I_S^0$ and $I_S$ are the signal beam intensities behind the crystal with and without the fast phase modulation, respectively, and $d$ is the interaction length.

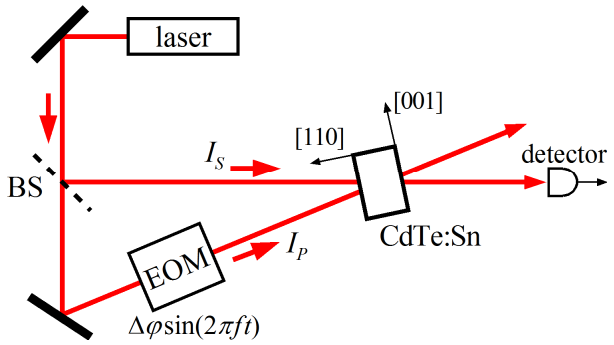


Figure 2. Experimental setup; BS – beam-splitter, EOM – electro-optic modulator.

The photorefractive recording is a light-induced process, which saturates with intensity. Therefore a certain intensity is necessary for grating formation with maximum index modulation. To estimate this intensity the gain factor is measured as a function of total light intensity at grating spacing $\Lambda$ = 1.1 μm. Experimental data are shown in Fig. 3(a) by diamonds.

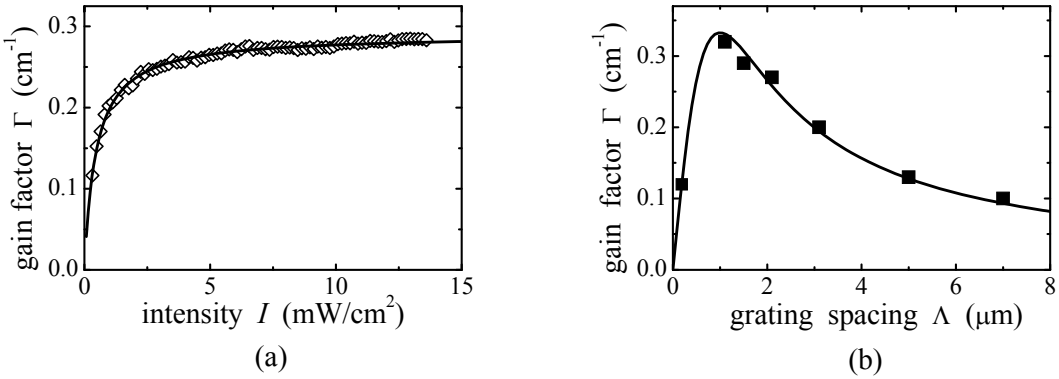


Figure 3. Gain factor versus (a) – recording light intensity, $\Lambda$ = 1.1 μm; (b) – grating spacing.

The gain factor approaches saturation at quite small intensity $I$ = 3 mW/cm$^2$. For a simple one-level model of the photorefractive recording the intensity dependence of the gain factor has the form[18]

$$\Gamma = \Gamma_0 / \left(1 + \sigma_D / (\kappa I)\right), \qquad (1)$$

where $\Gamma_0$ is the gain factor in saturation, $\sigma_D$ is the dark conductivity, and $\kappa$ is the specific photoconductivity. The line in Fig. 3a represents the best fit of Eq. (1) to the experimental data with $\Gamma_0$ = 0.29 cm$^{-1}$ and $\sigma_D/\kappa$ = 0.46 mW/cm$^2$. The latter parameter has an important physical meaning. It defines the intensity, at which the photoconductivity becomes equal to the dark conductivity. The value, which is more than one order of magnitude better than that reported for CdTe:Ge[13], demonstrates large photo-sensitivity of CdTe:Sn.

The maximum gain factor is reached in the diffusion mode of recording at a grating spacing equal to the Debye screening length[10] $\ell_S$

$$\Gamma = \frac{4\pi^2 n^3 r}{\lambda} \xi \frac{kT}{e} \frac{\Lambda}{\Lambda^2 + \ell_S^2}, \qquad (2)$$

where $n$ is unperturbed refractive index, $r$ is electro-optic coefficient ($r = r_{41}$ in the present two-beam coupling geometry), $k$ is the Boltzmann constant, $T$ is the absolute temperature, $e$ is the electron charge, $\xi$ is the electron-hole competition factor, which takes into account a possible compensation of the main grating by secondary charge carriers, $\ell_S^2 = (4\pi^2 \varepsilon \varepsilon_0 kT)/(e^2 N_E)$, $\varepsilon$ and $\varepsilon_0$ are the dielectric constants of material and vacuum, respectively, and $N_E$ is the effective trap density. To estimate the Debye screening length and the effective trap density the gain factor is measured versus grating spacing. Experimental data are shown in Fig. 3b by squares. The line shows best fit of Eq. (2) to the experimental values with $\ell_S = 1$ μm ($N_E = 6.2\times10^{14}$ cm$^{-3}$) and $\xi = 0.52$. Thus, analysis of the photorefractive measurements allows for estimation of the crystal characteristics and predicts that increase of the effective trap density is effective way for strengthening the photorefractive response in CdTe:Sn.

### 2.2 Magneto-optical study

A deeper understanding of the space charge formation and identification of the centers involved in the process may help to find ways for increasing of the effective trap density. Spectroscopic and magneto-optical studies are held for that purpose.

At least two tin related centers are expected in CdTe:Sn. These are the neutral $Sn^0$ ($Sn^{2+}$ in the ionic notation) and the ionized $Sn^+$ ($Sn^{3+}$). The ionized $Sn^+$ is paramagnetic. Therefore it can be identified with magneto-optical techniques. One of the techniques is the magnetic circular dichroism (MCD). MCD measures the absorption difference $\Delta\alpha$ for the clockwise and counterclockwise circularly polarized light in the presence of a magnetic field $B$ aligned along the light propagation. It resolves the absorption bands related to paramagnetic species at low temperature. The MCD spectrum measured at $T = 1.4$ K under magnetic field $B = 2.5$ T is shown in Fig. 4a. The negative band with a minimum at photon energy $E = 1.14$ eV is of particular interest because the levels in the middle of the gap are important for photorefraction.

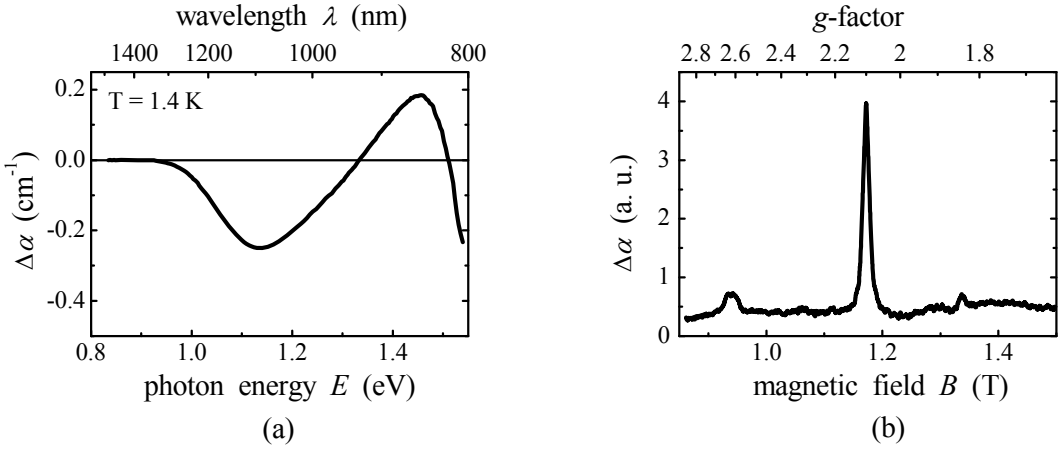


Figure 4. (a) – MCD spectrum measured at $T = 1.4$ K with $B = 2.5$ T; (b) – ODMR measured with photon energy $E = 1$ eV in the presence of microwaves with $f = 34.45$ GHz.

Optical Detection of Magnetic Resonance (ODMR) can assign the MCD band to a particular impurity center. ODMR measures MCD signal at a fixed wavelength as a function of magnetic field in the presence of microwaves. When Zeeman splitting matches the microwave photon energy, a resonant absorption of the microwaves occurs. A dip in the smooth curve $\Delta\alpha = f(B)$ is observed. The Landé $g$-factor can be evaluated from the resonance magnetic field. Then the absorption band can be attributed to particular paramagnetic center with known $g$-factor.

To identify the MCD band at $E = 1.14$ eV the ODMR is measured with photon energy 1 eV in the presence of microwaves with frequency $f = 34.45$ GHz. The dependence shown in Fig. 4b exhibits sharp resonance at $B \approx 1.18$ T,

which corresponds to $g$ = 2.1. Paramagnetic tin $Sn^+$ in CdTe has been identified earlier by EPR[19] with the isotropic Landé factor $g$ = 2.101. Therefore the MCD band at $E$ = 1.14 eV can undoubtedly be attributed to recharging of the ionized tin $Sn^+$ into its neutral state $Sn^0$. The free holes are generated in this case under illumination.

The results of the magneto-optical experiments together with the data of photo-induced absorption studied in CdTe:Sn[7] allows for estimation of the optical ionization energy $E$ = 1.09 eV for tin in neutral state, $Sn^0$. Additional photorefractive experiments show that the main charge carriers participating in the grating recording at $\lambda$ = 1064 nm are holes. Strong overlapping of two absorption bands related to tin in different charge states results in strong electron-hole competition ($|\xi| < 1$) during the grating recording and explains moderate gain factor reported for the crystal. The larger gain factor can be reached with proper compensation of the influence of one of the species. An appropriate co-doping or modification of the crystal growth technique can be used for the suppressing destructive influence of secondary carriers.

### 2.3 Two-wave mixing adaptive interferometer with CdTe:Sn

Optical excitation energies for tin in different charge states fits perfectly to the radiation with $\lambda$ = 1064 nm. Taking into account that the absorption bands related to the tin in semiconductor CdTe are broad at room temperature, we can expect effective photorefractive recording at $\lambda$ = 1550 nm (photon energy $E$ = 0.8 eV). To test this assumption we study TWM adaptive interferometer at this wavelength.

The experimental set-up is similar to that shown in Fig. 2, which is used for photorefractive experiments at $\lambda$ = 1064 nm, with the following modifications. A continuous wave single frequency laser diode emitting at $\lambda$ = 1550 nm serves as a light source. The intensity ratio of the recording beams $\beta \approx 10$. An external dc voltage is applied to the side faces of the crystal, forming an electric field along [001] axis. The EOM simulates ultrasonic surface displacements introducing in the signal wave fast phase modulation $\varphi(t) = \Delta\varphi \sin(2\pi f t)$ with low amplitude ($\Delta\varphi$ = 0.15 rad << $\pi$/2 rad) and high frequency ($f$ = 50 kHz >> $1/(2\pi\tau_{SC})$, $\tau_{SC}$ is response time of the grating). The phase modulation is transformed into intensity modulation of the signal beam behind the crystal. The amplitude of intensity modulation is measured at different experimental conditions.

An important feature of the adaptive interferometer is the ability to compensate for perturbations in environment. It is characterized by frequency range of the compensation, which can be represented by the amplitude of intensity modulation versus modulation frequency. Such dependence measured at grating spacing $\Lambda$ = 55 μm with dc field $E_0$ = 6 kV/cm and total light intensity $I$ = 30 mW/cm$^2$ is shown in Fig. 5a. The amplitude of intensity modulation $\Delta I_S$ is normalized by the intensity of the signal $I_S^{mean}$ measured with no phase modulation.

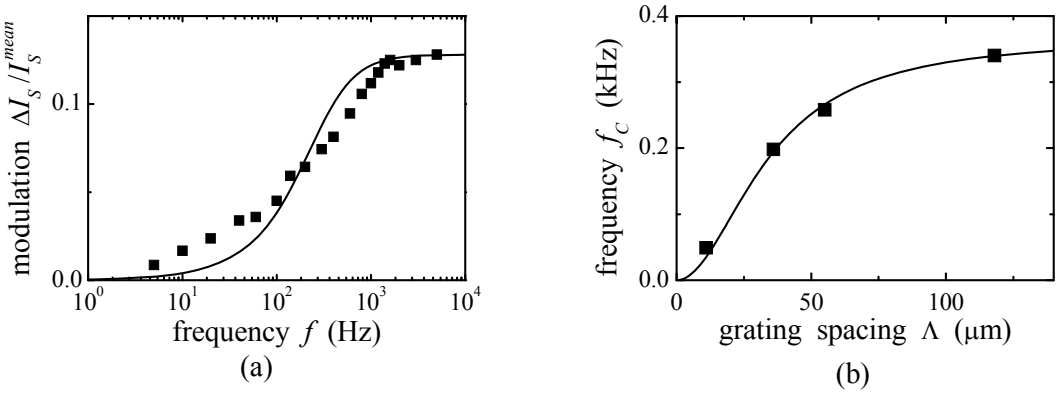


Figure 5. (a) – intensity modulation at the output of TWM interferometer versus frequency of the input phase modulation; (b) – cutoff frequency versus grating spacing.

The dependence in Fig. 5a has the typical shape of high-pass filter with cutoff frequency $f_C \approx 200$ Hz, which is defined at half level of the maximum intensity modulation at high frequency $\Delta I_S^{sat}$. For a simple one-center model of the space charge formation it has the form

$$\Delta I_S = \Delta I_S^{sat} \frac{2\pi f \tau_{SC}}{\sqrt{1+\left(2\pi f \tau_{SC}\right)^2}}. \quad (3)$$

The line in Fig. 5a represents the best fit of Eq. (3) to the experimental data with $\tau_{SC}$ = 500 μs and a maximum modulation amplitude $\Delta I_S^{sat}/I_S^{mean} \approx 0.13$. The low frequency tail with increased response may be explained by a complex process of the space charge formation, which becomes more complicated at $\lambda$ = 1550 nm. The increased response at low frequency can perhaps be suppressed by temperature control of the crystal slightly above the room temperature, as it has been demonstrated for CdTe:Ge[20].

The photorefractive response time $\tau_{SC}$ changes strongly with the grating spacing[10]. For the diffusion length smaller than the drift length $L_D = (\mu\tau kT/e)^{1/2} << L_E = \mu\tau E_0$, the grating response time $\tau_{SC} = \tau_M(1 + 4\pi^2K^2/\Lambda^2)$, where $\mu$ and $\tau$ are the mobility and lifetime of free charge carriers and $\tau_M$ is the dielectric response time of the crystal. Correspondingly, the cutoff frequency changes with the grating spacing as[20]

$$f_C = \frac{1}{\sqrt{3}} \frac{1}{2\pi\tau_M\left(1+4\pi^2 L_E^2/\Lambda^2\right)}. \quad (4)$$

Therefore the study of cutoff frequency versus grating spacing may give information about the diffusion length and dielectric response time of the crystal. Such an experimental dependence is presented in Fig. 5b by squares. The line represents fitting calculation according Eq. (4) with $\tau_M$ = 250 μs, $L_E$ = 5.4 μm. The product $\mu\tau = 9\times10^{-8}$ cm$^2$/V is estimated from the drift length.

The sensitivity of the adaptive interferometer to a small surface displacement is characterized usually by the relative detection limit. It is defined as the ratio of sensitivity of an adaptive interferometer to that of a classical lossless interferometer operating with plane waves. Assuming the losses of adaptive interferometer are minimized by means of antireflection coatings, etc., the relative detection limit can be estimated experimentally[8]

$$\delta_{rel} = \frac{\exp(\alpha d/2)}{\left|\sin(\gamma" d)\right|}, \quad (5)$$

where $\alpha$ is the absorption constant and $\gamma"$ is the coupling constant of the local grating in dc-biased CdTe:Sn. The relative sensitivity $\delta_{rel}$ = 2.3 is estimated using the measured absorption $\alpha d \approx 0.4$ and coupling strength $\gamma" d \approx 0.56$ achieved with $E_0$ = 8 kV/cm. This relative detection limit is equal to the value reported for CdTe:Ge[20], which is the best to our knowledge ever reported for adaptive interferometers at $\lambda$ = 1550 nm. Thus CdTe:Sn demonstrates excellent performance in TWM adaptive interferometer.

## 3. CONCLUSIONS

A comprehensive study of CdTe:Sn crystal using dynamic holography, optical spectroscopy and light-induced spectroscopy, MCD and ODMR shows that the space-charge formation is occurring within one-center model of the photorefractive recording. Analysis of the experimental results allows for estimation of optical activation energies of tin impurity center in two charge states: $E$ = 1.09 eV for $Sn^0$ and $E$ = 1.14 eV for $Sn^+$. Different characteristics expressing charge transport in CdTe:Sn ($\ell_S$, $N_E$, $L_E$, $\mu\tau$, $\kappa/\sigma_D$) are evaluated. While CdTe:Sn demonstrates moderate photorefractive coupling constants with no external field, these coupling constants are achieved at low intensity of couple of mW/cm$^2$. Such large photosensitivity and fast response makes CdTe:Sn promising material for applications. It is shown that adaptive interferometer with CdTe:Sn demonstrates good frequency response and the best sensitivity at $\lambda$ = 1550 nm. In addition, our studies show that a larger photorefractive response is expected in CdTe:Sn with reduced impact of the tin impurity center in one of its charge states. A targeted modification of the crystal synthesis process should be explored for such improvement of photorefractive CdTe:Sn.

## 4. ACKNOWLEDGEMENTS

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