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Dynamic light beam deflection caused by space charge waves in photorefractive crystals

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Abstract. During holographic recording in photorefractive crystals (BSO, BGO, and BTO) by an oscillating interference pattern we observe a strong dynamic deflection of the laser beams reflected from the crystal's surface. The theoretical treatment shows that this new effect is associated with a nonlinear interaction of space charge gratings resulting in a quasi-homogeneous oscillating space charge field which provides deformations of the crystal via the piezoelectric effect.

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The process of hologram recording in photorefractive materials comprises the build-up of an electric space charge field [1, 2]. For the simplest case, i.e., a sinusoidal interference pattern with a low contrast, the spatial variation of this field also has a sinusoidal shape (below we will call this kind of variation a grating). A space charge field grating causes a corresponding grating in the refractive index and a periodically modulated mechanical tension and a deformation because photorefractive crystals exhibit both the electrooptic and the piezoelectric effect. To a vast extend, investigations of photorefractive crystals have been devoted to light diffraction from a refractive index grating. There are also several publications concerning the diffraction of light from a crystal surface relief grating induced by the piezoelectric effect. In [3], for example, diffraction from a surface grating in a static regime of recording was studied, and in [4] the technique of phase-modulated laser beams was used to investigate dynamic effects. The theory of surface relief gratings has been recently published [5].

In this article we describe a new phenomenon, namely dynamic deflection rather than diffraction of the light beams incident on the crystal surface. The investigations are carried for when the holographic grating is recorded with use of a spatially oscillating interference pattern.

1 Experimental method

The experimental setup is shown schematically in Fig. 1. A diode-pumped, frequency-doubled Nd:YAG cw laser (Coherent DPSS 532-400) with an output power of 400 mW is used to record the holograms. The laser beam is expanded and split into two parts (reference beam R and signal beam S) and the phase of the signal beam is modulated sinusoidally with the amplitude $\Theta = 0.5$ rad and the frequency Ω by an electrooptic modulator. To register the beam deflection, the part of the R or S beam reflected at the crystal surface can be utilized. We did this at the initial stage of our investigations, but it turned out that using an additional probe beam with low light intensity provides many practical advantages. Therefore, we finally used a He:Ne laser with an output power of less than 1 mW for the measurements. To register the beam deflection, the power of the probe light reflected at the crystal surface is detected by a photoreceiver and analyzed by a lock-in amplifier. We use a photoreceiver with an aperture that is

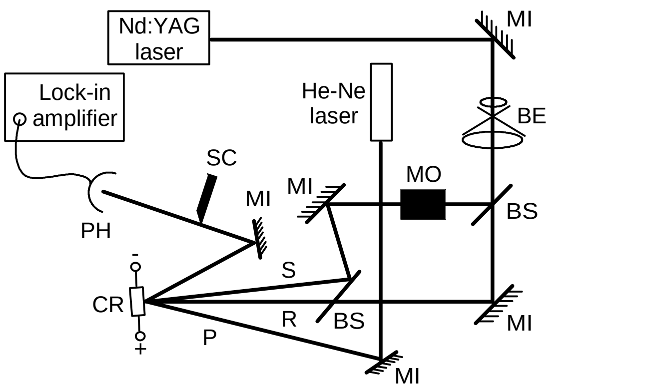

Fig. 1. Experimental setup. The power of the reflected probe beam P is detected while a hologram is recorded with an oscillating interference pattern created by the signal beam S and the reference beam R. MI mirror; BE beam expansion with spatial filtering; BS beam splitter; MO electrooptical modulator; CR crystal; SC screen; PH photoreceiver

larger than the cross section of the probe beam. Furthermore, a screen is installed in front of the photoreceiver which shadows approximately 60%–70% of the probe beam diameter. This allows us to detect temporal variations in the light power incident on the photoreceiver when the angle of reflection of the probe beam is modulated.

Measurements are made with three kinds of crystals: $Bi_{12}GeO_{20}$ (BGO), $Bi_{12}SiO_{20}$ (BSO), and $Bi_{12}TiO_{20}$ (BTO). To avoid possible effects induced by light beams reflected from the rear face of the crystals (because these beams can record additional gratings) we chose samples with non-polished rear faces. In this case the light is only scattered and not reflected at the rear faces. The dimensions of the crystals used are about 4 mm × 3 mm × 2.5 mm in all cases. The front faces are parallel to the crystallographic (110) plane; the applied electric field $\boldsymbol{E}_0$ and the grating wave vector $\boldsymbol{K}$ are chosen along the [001] direction and the polarization of the recording and probe light beams is parallel to $[1\bar{1}0]$.

2 Experimental results

The effect of beam deflection is registered for all crystals and the main results are qualitatively quite similar. Because of space limitations we will present mainly the experimental results for the BGO sample.

The dependence of the output signal magnitude U_{out} on the frequency Ω of phase modulation for the BGO and BSO crystals is shown in Fig. 2 for the same experimental conditions (external electric field $E_0 = 11\,kV/cm$, spatial frequency $\nu = K/2\pi = 30\,mm^{-1}$, contrast ratio $m = 0.35$, intensity of recording light $I_0 = 170\,mW/cm^2$ and intensity of probe light $I_p = 12\,mW/cm^2$). The solid lines are theoretical dependences calculated using (3) with the fit parameters $\mu\tau = 3.1 \times 10^{-11}\,m^2/V$ and $\tau_M = 1.4 \times 10^{-4}\,s$ for BGO and $\mu\tau = 3.2 \times 10^{-11}\,m^2/V$ and $\tau_M = 0.8 \times 10^{-4}\,s$ for BSO. Here $\mu\tau$ denotes the mobility–lifetime product and τ_M the Maxwell relaxation time.

Figure 3 presents the dependence of the resonance frequency Ω_r on the spatial frequency $\nu = K/2\pi$ and on the externally applied electric field E_0 for BGO. The solid lines represent theoretical calculations according to (6) with the same set of fit parameters ($\mu\tau = 4.0 \times 10^{-11}\,m^2/V$ and $\tau_M = 1.6 \times 10^{-4}\,s$) for both dependences. Taking into account the experimental errors, these values are in good agreement with the parameters obtained from the fit of the resonance curve in Fig. 2.

In Fig. 4 the amplitute of the output signal $U_{out}(\Omega_r)$ at the resonance frequency is plotted versus the contrast ratio m and the solid line is a calculation assuming a pure quadratic dependence. One can see a very good agreement between the experimental data and the calculation for values up to $m \approx 0.5$.

A linear increase of the maximal output signal $U_{out}(\Omega_r)$ with increasing ν is observed in the case of our particular experimental conditions ($E_0 = 11\,kV/cm$, $m = 0.35$, $I_0 = 170\,mW/cm^2$) only for spatial frequencies up to $\nu = 35\,mm^{-1}$. For higher values of ν the signal no longer grows linearly and for $\nu > 60\,mm^{-1}$ it even decreases. Additionally, we found that the output signal grows quadratically in E_0. We

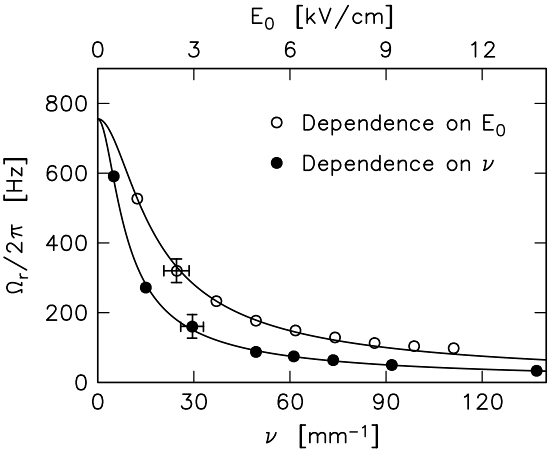

Fig. 3. Resonance frequency $\Omega_r/2\pi$ in dependence on the spatial frequency ν and the electrical field E_0 for the BGO sample. For the dependence on ν the electric field is $E_0 = 8.6\,kV/cm$ and for the dependence on E_0 the spatial frequency is $\nu = 43\,mm^{-1}$. The light intensities and the contrast ratio are the same as in Fig. 2. The *solid lines* are calculated from (6) with the fit parameters $\mu\tau = 4.0 \times 10^{-11}\,m^2/V$ and $\tau_M = 1.6 \times 10^{-4}\,s$

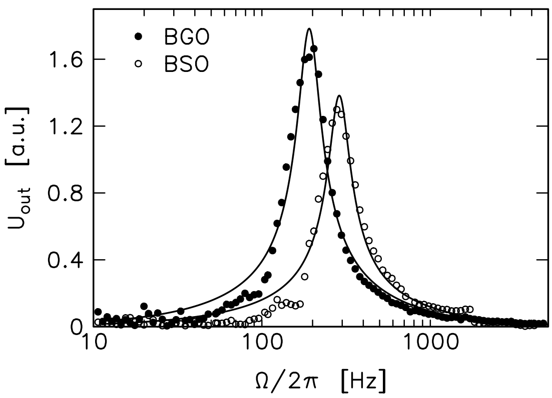

Fig. 2. Dependence of the output signal U_{out} on the frequency $\Omega/2\pi$ of phase modulation for the BGO and BSO samples. The total intensity of the recording beams is $I_0 = 170\,mW/cm^2$ with a contrast ratio $m = 0.35$; the intensity of the probe beam is $I_p = 12\,mW/cm^2$; the applied electric field is $E_0 = 11\,kV/cm$; the spatial frequency of the grating is $\nu = K/2\pi = 30\,mm^{-1}$. The *solid lines* show the theoretical dependences according to (3)

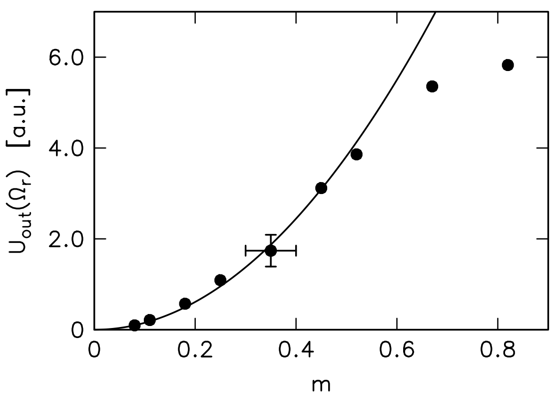

Fig. 4. Maximal output signal $U_{out}(\Omega_r)$ as a function of modulation index m for the BGO crystal. The experimental parameters are: $E_0 = 11\,kV/cm$, $\nu = 30\,mm^{-1}$, $I_0 = 170\,mW/cm^2$, $I_p = 12\,mW/cm^2$. The *solid line* is a fit assuming a pure quadratical dependence for small values of m

also studied the dependences of Ω_r on the total light intensity I_0 of the recording beams and observed a relation $\Omega_r \propto I_0$.

Finally, we would like to emphasize that after removing the screen, no frequency dependence of the output signal can be registered. If the screen is used, the signal-to-noise ratio in the measurements is as high as 50 for optimal experimental conditions, although a small contrast ratio ($m = 0.35$) is used.

3 Discussion

Deflection of the light beam reflected from the crystal can be the result of a displacement or a deformation of the sample surface, which acts as a deformable mirror. As we have shown, this displacement or deformation oscillates in time and can appear in piezoelectric crystals due to an oscillating homogeneous (or quasi-homogeneous) electric field inside the crystal. However, the existing theory for the calculation of the space charge electric field leads to the conclusion that the homogeneous component ($K = 0$) of the space charge field must be zero ($E_{sc}(K = 0) = 0$). When an external electric field is applied to the crystal the sample is connected to a voltage source and the homogeneous component of the electric field inside the crystal is completely determined by the external field E_0. Another situation must be considered if the crystal is connected to a current source, which means that the total current through the sample is constant. However, even in the last case a theoretical analysis in the linear approximation, i.e. a small value of m so that all effects of the order of m^2 can be neglected, shows that there is also no reason for a spatial homogeneous component of the space charge field. Therefore we consider the problem in a nonlinear approximation where the usual set of equations [6] is used, but the requirement of a constant total current is imposed. Then the total current density reads

$$J = \varepsilon\varepsilon_0 \frac{\partial E(x,t)}{\partial t} + j(x,t) = \text{const.} \tag{1}$$

Here $\varepsilon\varepsilon_0$ is the dielectric permittivity, $j(x,t)$ is the current density corresponding to the charge carriers, and $E(x,t)$ is the electric field inside the crystal. It is assumed that the recording light intensity pattern is described by

$$I(x,t) = I_0[1 + m\cos(Kx + \Theta\cos\Omega t)]\,, \tag{2}$$

with $m \ll 1$ and $\Theta \ll 1$. We neglect the diffusion process and consider $E_0 \ll E_q$ where E_q is the saturation field. Then, solving the Kukhtarev equations [6] (using (1) and (2)) in the same way as described in [7] yields the following expression for the oscillating homogeneous component of the space charge field:

$$E_{sc}(K = 0, t) = E_0\Theta m^2 d\; f(\omega)\cos(\Omega t + \varphi)\,, \tag{3}$$

where

$$f(\omega) = \omega\left[\frac{1 + \omega^2/4}{(1+\omega^2)[1 + 2\omega^2(1-d^2) + \omega^4(1+d^2)^2]}\right]^{1/2}, \tag{4}$$

$\omega = \Omega\tau_M$ (τ_M is the Maxwell relaxation time), $d = KL_0$ ($L_0 = \mu\tau E_0$ is the drift length with the mobility μ and the lifetime τ of the charge carriers), and

$$\tan(\varphi) = \frac{2 - \omega^2(3 + 2d^2) - \omega^4(1+d^2)}{\omega[5 + \omega^2(1-d^2)]}\,. \tag{5}$$

It follows from (3) that $E_{sc}(K = 0, t)$ has a resonance-like dependence on Ω with the resonance frequency

$$\Omega_r \approx \frac{1}{\tau_M\left[1.66 + (KL_0)^2\right]^{1/2}}\,. \tag{6}$$

Note that the value of the amplitude of the oscillating homogeneous component of the space charge field can reach high values. For instance, at reasonable experimental conditions ($m = 0.35$, $\Theta = 0.5$, $E_0 = 12\,\text{kV/cm}$ and $d = 5$) this amplitude is $|E_{sc}(K = 0, t)| = 1.5\,\text{kV/cm}$ at the resonance frequency.

Qualitatively, the nature of $E_{sc}(K = 0, t)$ can be explained as follows. Under illumination of the crystal by an oscillating interference pattern, standing and moving components of any grating (space charge waves [8]) arise inside the crystal. The standing components contain a term $m\exp(\mathrm{i}Kx)$, while the moving components contain a term $m\exp[-\mathrm{i}(Kx - \Omega t)]$. If we consider a nonlinear interaction between the standing and the moving components we must take the product of these terms and we obtain an expression which contains the term $m^2\exp(\mathrm{i}\Omega t)$ and therefore does not depend on the spatial x coordinate.

The electric field $E_{sc}(K = 0, t)$ results in an oscillating displacement ΔT of the crystal (110) surface through the piezoelectric effect:

$$\Delta T(t) = Td_{14}E_{sc}(K = 0, t)\,. \tag{7}$$

Here T is the thickness of the crystal (spatial dimension in the [110] direction) and d_{14} is the piezoelectric constant ($d_{14} = 40.5 \times 10^{-12}\,\text{C/N}$ for BSO [9], $48.2 \times 10^{-12}\,\text{C/N}$ for BTO [9], and $33.9 \times 10^{-12}\,\text{C/N}$ for BGO [9]). For $T = 2.5\,\text{mm}$ we obtain a value of ΔT of the order of 10 nm at $\Omega = \Omega_r$ and $E_0 = 10\,\text{kV/cm}$. The displacement of the crystal surface causes a shift in the reflected beam of $\Delta l = 2\Delta T\sin(\alpha)$, where α is the angle of incidence of the probe laser beam. Finally the output signal (in relative units) can be written as

$$U_{out} \approx I_p RD\Delta l\,, \tag{8}$$

where I_p is the intensity of the probe light, R is the reflectivity of the crystal, and D is the diameter of the probe beam. A comparison of (8) with the the experimental data reveals a very good agreement for the functional dependences of Ω_r on K, E_0, and I_0. In the latter case we assume $\tau_M \propto I_0^{-1}$, which means that the Maxwell relaxation time is completely determined by the photoconductivity. The theory describes the dependences of the magnitude of the output signal on m, E_0, and K quite well for certain intervals of these values ($m < 0.5$, $\nu = K/2\pi < 35\,\text{mm}^{-1}$, $d > 1$) as can be seen from the Figs. 2, 3, and 4. A discrepancy between theory and experiment for other values of m and K is not surprising because the theory has been developed for $m \ll 1$ and for the case $\Theta m^2 d \ll 1$. In the other case, $\Theta m^2 d \geq 1$, the alternating component of the space charge field will be equal or even higher than the applied field, which has no physical meaning.

However, an estimation of the absolute value of the output signal shows that it is approximately two orders of magnitude higher than that predicted by (8). A more probable, effective mechanism for an enhancement of the output signal is a spatial inhomogeneity of the surface displacement.

The reasons for inhomogeneity in the displacement are the clamping of the crystal in the holder and inhomogeneity of the internal electric field. On the one hand, we have experimental evidence for the influence of the clamping: we observe that the amplitude of the registered signal changes if the conditions concerning the fixing are changed. On the other hand, there are obvious sources for inhomogeneity in the electric field, e.g., inhomogeneity in the intensity of the incident light beams and also non-ohmic electrode contacts (see, for instance, [2], Chapt. 4.6). The existence of strongly blocking electrode contacts can also be a reason for using the model where the crystal is connected to a current source. If we assume inhomogeneity in the displacement of the order of $\Delta T/L$ (where L is the spatial dimension of the crystal in the direction of the electric field), the reflected light beam will be deflected by an angle $\delta \approx \Delta T/L \approx 10^{-5}$ and the laser spot position on the photoreceiver will oscillate with the amplitude $\Delta l_S \propto \delta S$ where S is the distance between the crystal and the photoreceiver. The enhancement of the output signal is then given by $\Delta l_S/\Delta l = S/L$. In our case, $S = 2$ m and $L = 4$ mm and thus $\Delta l_S/\Delta l \approx 10^2$. This estimation leads to the correct order of magnitude of the output signal value and the assumption of an inhomogeneous displacement agrees with preliminary experiments, which showed that the signal increases with increasing distance S and that the signal depends on the position of the probe beam on the crystal surface. A rigorous analysis of the nature of inhomogeneity in the electric field and of the crystal surface displacement is now in progress and will be published elsewhere. The assumption of an inhomogeneous electric field will also allow us, under certain conditions, to use successfully the model with a crystal connected to a voltage source as well.

Finally, we would like to mention that we use the term ‘deflection’ of the light beam, but in the case of an inhomogeneous deformation also focusing and defocusing of the beam is possible.

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