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NONLINEAR OPTICAL PHENOMENA

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Nonlinearity of the photorefractive response upon two-beam interaction in a bismuth silicon oxide crystal in an alternating electric field

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Abstract. Nonlinearity of the photorefractive response is studied experimentally and theoretically upon two-beam interaction of light waves in a bismuth silicate crystal placed in an external meander electric field. The experimental data are shown to be in good agreement with a model, taking into account the influence of the second harmonic of the space-charge field on a photorefractive grating. The concentration of acceptors in a crystal and a product of the mobility of charge carriers by their recombination time are estimated from a comparison of the experimental and calculated data.

The interaction of light waves in photorefractive crystals plays an important role in the development of devices for optical data processing [1, 2]. The dynamical range of such devices is determined by the nonlinearity of processes taking place both upon the charge transfer in a crystal under the action of an inhomogeneous light field and the power redistribution between interacting light beams [3 – 5]. The increase in the photorefractive response of crystals produced by applied external electric fields [3, 6, 7] enhances the role of nonlinearity. In particular, this is manifested in the decrease in the fundamental harmonic amplitude upon generation of higher space harmonics, and sometimes of subharmonics of a photorefractive grating [3, 5, 8 – 10].

Brost [5] has considered successively all the nonlinearities in sillicon oxide crystals placed in an alternating electric field using the numerical analysis of constitutive equations and coupled-wave equations, which take the nonlinearity of the space charge field into account with the help of an empirical correction function. A simpler, but consistent, approach is to consider the second harmonic [8, 10, 11], which, in the case of a moderate contrast of the interference pattern ($m \leqslant 0.5$) produced by the interacting beams, affects the amplitude of the fundamental harmonic of the space-charge field most strongly.

This paper is devoted to the experimental and theoretical study of nonlinearity of the photorefractive response upon two-beam interaction of light waves in a $Bi_{12}SiO_{20}$ crystal placed in an external electric field.

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We used a standard experimental scheme of two-beam interaction at a wavelength of 633 nm (Fig. 1) in a photorefractive crystal of sizes 3.5, 5, and 6 mm along the crystallographic directions [110], [$\bar{1}$11], and [1$\bar{1}$2]. The absorption coefficient of a crystal sample was $\alpha = 0.5$ cm^{-1} and the rotatory power $\rho = 22$ angular degree mm^{-1}. The emission from a He – Ne laser was split into two beams with a beamsplitter 1. The intensity I_s of a signal beam was reduced by a factor of 10 – 2500 with neutral light filters. The signal and reference beams reflected by mirrors 3 and 4, respectively, crossed within a sample, being polarised along the [111] crystallographic direction. The signal-beam intensity I_s behind crystal 5 was measured with a calibrated photodiode 6.

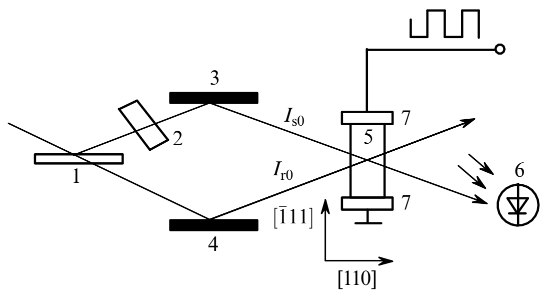

Figure 1. Schematic of the experimental setup: (1) beamsplitter; (2) light filter; (3, 4) mirrors; (5) crystal sample; (6) photodiode; (7) electrodes.

The spatial period of the grating Λ was varied by changing the convergence angle of the beams so that the bisectrix of this angle would coincide with the normal to the input [110] face of the sample and the lattice vector would coincide with the [$\bar{1}$11] axis. The high meander voltage at frequency $f =$ 2750 Hz was applied across the crystal ($\bar{1}$11) faces using copper electrodes 7. The electric field amplitude in the crystal was $E_0 = 10$ kV cm^{-1}.

The stationary intensities of the signal beam behind the crystal in the presence of pumping [$I_s^p(d)$] and in its absence [$I_s^0(d)$] were used to measure the two-beam gain:

$$\Gamma = \frac{1}{d} \ln \left[\frac{I_s^p(d)}{I_s^0(d)} \right] . \tag{1}$$

The experimental dependences of the two-beam gain on the ratio $\beta = I_{r0}/I_{s0}$ of the pump and signal beam intensities for spatial periods of the grating $\Lambda = 15$ and 28 μm are presented in Fig. 2 (circles and squares). Note that the gain close to the limiting one is achieved in a sample under study for $\beta > 10^3$. Note also that we did not observe the generation of space subharmonics by the photorefractive grating even

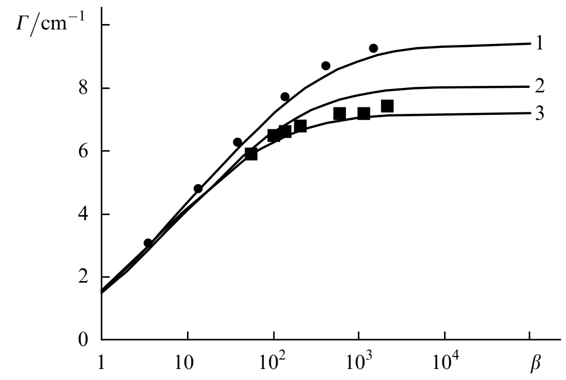

Figure 2. Experimental (circles and squares) and theoretical (curves) dependences of the gain Γ on the ratio β of intensities of writing light beams in a bismuth silicate crystal for the photorefractive grating period Λ = 15 (1), 7 (2), and 28 μm (3). The theoretical curves correspond to the following parameters of the crystal: $\mu\tau_r = 5.5 \times 10^{-12}$ m^2 V^{-1}, $N_a = 4.3 \times 10^{21}$ m^{-3}, $r_{ef} = 4.25 \times 10^{-12}$ m V^{-1}.

for $\beta \approx 1$. The gain was independent of the total light intensity $I_0 = I_r + I_s$, which was varied from 1 to 100 mW cm^{-2}. This suggests that in our analysis we can use the single-level band transfer model [12] and models of the nonlinear photorefractive response based on it, which consider only the contribution of the fundamental and second harmonics to the space-charge field of the grating [11].

We will consider the nonlinearity resulting in the decrease in the efficiency of the two-beam coupling with increasing power of the signal beam using the known equations for the coupled waves with intensities I_s and I_r [5]:

$$\frac{dI_s}{dz} = i\left(\frac{2\pi}{\lambda} n_0^3 r_{ef} \frac{E_1}{m}\right)\frac{I_r I_s}{I_r + I_s} - \alpha I_s\ ,$$
$$\frac{dI_r}{dz} = -i\left(\frac{2\pi}{\lambda} n_0^3 r_{ef} \frac{E_1}{m}\right)\frac{I_r I_s}{I_r + I_s} - \alpha I_r\ , \tag{2}$$

where n_0 and r_{ef} are the refractive index and the effective electrooptical constant of a crystal; $m = 2(I_r I_s)^{1/2}(I_r + I_s)^{-1}$ is a contrast of the interference pattern depending on z; and $E_1(m)$ is the amplitude of the first harmonic of the space-charge field. Shandarov et al. [11] have obtained the equations relating the amplitudes E_1 and E_2 of the first and second harmonics with the contrast m in a crystal in a high-frequency meander field in the following form

$$\frac{m}{4E_0}\left[K(L_{dr} + 2L_a) + 2K^3 L_{dr} L_s^2\right]E_1^2 - i\left[1 + K^2\left(L_{dr}L_a\right.\right.$$
$$\left.\left.+ L_s^2 + L_d^2\right)\right]E_1 + \frac{1}{E_0}\left[K(L_{dr} - L_a) + 5K^3 L_{dr} L_s^2\right]E_1 E_2$$
$$- i\,\frac{m}{2}\left(1 + 6K^2 L_{dr} L_a + 8K^2 L_s^2\right)E_2 + m\left(\frac{E_0^2}{E_\mu} + E_d\right) = 0\ ,$$

$$E_2 = \left\{-m\left(1 + 6K^2 L_d^2 - K^2 L_s^2\right)E_1 - i2\left[K(L_{dr} - L_a)\right.\right.$$
$$\left.\left.+ 2K^3 L_{dr} L_s^2\right]E_1^2 E_0^{-1}\right\}\left\{2\left[1 + 4K^2\left(L_{dr}L_a + L_s^2 + L_d^2\right)\right]\right\}^{-1}, \tag{3}$$

where $L_e = \mu\tau_r E_0$ and $L_d = (\mu\tau_r k_B T/e)^{1/2}$ are the drift and diffusion lengths; $L_s = [k_B T\varepsilon/(e^2 N_a)]^{1/2}$ is the Debye screening length; $L_a = \varepsilon E_0/(eN_a)$; $K = 2\pi/\Lambda$; $E_\mu = (K\mu\tau_r)^{-1}$ and $E_d = Kk_B T/e$ are the strengths of the drift and diffusion fields; μ and τ_r are the mobility and the recombination time of the charge carrier; k_B is the Boltzmann constant; T is the absolute temperature; ε is the static dielectric constant of the crystal; N_a is the acceptor concentration; and e is the elementary electric charge. Eqns (3) were derived by neglecting the contribution from higher harmonics to the space-charge field, assuming that $E_d \ll E_\mu$ and $E_d \ll E_0$.

Fig. 2 also shows the results of a numerical analysis of the dependence of the two-beam gain on the ratio of the pump and signal beam intensities behind the crystal performed using Eqns (2) and (3). The best agreement between the experimental data (circles and squares) and the calculated curves 1 and 3 is observed for the following parameters of the crystal: $\mu\tau_r = 5.5 \times 10^{-12}$ m^2 V^{-1}, $N_a = 4.3 \times 10^{21}$ m^{-3}, $r_{ef} = 4.25 \times 10^{-12}$ m V^{-1}. Curve 2 corresponds to the spatial period of the grating $\Lambda = 7$ μm.

It follows from Fig. 2 that the two-beam gain in a $Bi_{12}SiO_{20}$ crystal for the interaction length $d = 3.5$ mm only slightly depends on the signal intensity if the pump intensity exceeds the signal intensity more than by a factor of 10^3. The spatial-frequency characteristic of the two-beam coupling is distorted due to nonlinearity of the photorefractive response [3, 5]. Fig. 3 shows the dependences of the two-beam gain on the spatial period of the grating calculated from Eqns (2) and (3) for the crystal studied at $E_0 =$ 10 kV cm^{-1}. Curve 1 corresponds to the linear theory of formation of the space-charge field, when nonlinear terms containing mE_1^2, E_1E_2, and mE_2 in Eqn (3) can be omitted. However, even for $\beta = 10^3$ ($m = 0.006$), the two-beam gain near the optimum spatial period of the grating is more than 2 cm^{-1} lower than its value obtained from linear theory. The increase in the amplitude of the signal beam is accompanied not only by the decrease in the maximum gain Γ_{max} but also by a broadening of the spatial frequency band where the efficiency of the two-beam coupling gain does not exceed the specified efficiency.

Thus, we have studied the experimental dependence of the two-beam gain on the ratio of the input signal and pump intensities in a $Bi_{12}SiO_{20}$ crystal in an external meander field. We have estimated the concentration of acceptors in the crystal and the product of the mobility of charge carriers by their recombination time from a comparison of our experimental data with the theoretical model, which takes into account

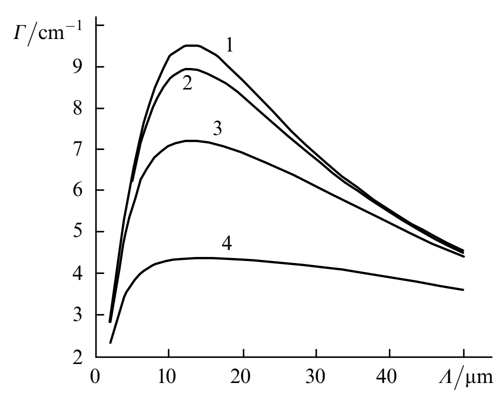

Figure 3. Dependences of the gain Γ on the photorefractive grating period Λ in a bismuth silicate crystal calculated using a linear theory (1) and for $\beta = 1000$ (2), 100 (3), and 10 (4) for $\mu\tau_r = 5.5 \times 10^{-12}$ m^2 V^{-1}, $N_a = 4.3 \times 10^{21}$ m^{-3}, $r_{ef} = 4.25 \times 10^{-12}$ m V^{-1}.

the nonlinearity of the two-beam coupling and the influence of the second harmonic of the space-charge field on the photorefractive grating.

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