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Two-beam coupling on the reflection grating in a $Bi_{12}TiO_{20}$ crystal

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***Abstract*. The results of experimental investigations of the dynamics of two-beam amplification on a reflection holographic grating and photoinduced absorption of light at $\lambda = 633$ nm in the (100) cut of a $B_{12}TiO_{20}$ crystal are presented. The numerical analysis of coupled-wave equations taking into account the absorption of light and the vector nature of the coupling in a gyrotropic cubic crystal with a given orientation is carried out. The processing of the experimental data using the scalar approach shows that the two-beam gain on a diffusion-type reflection grating in the $B_{12}TiO_{20}$ crystal may achieve 4.7 cm^{-1}, while the additional absorption induced by light amounts to 0.65 cm^{-1}.**

Keywords: *reflection holographic grating, two-beam coupling, photorefractive effect.*

The interest in sillenite crystals is due to the possible application of their photorefractive properties in optical data processing and phase conjugation of light beams as well as in holographic interferometry and optical sensors [1 – 3]. Transmission holographic gratings in which the angle between the light beams forming them in a crystal is much smaller than 90° are of special importance in this respect.

It was shown in Ref. [4] that the diffraction efficiency of hologram recording in a $Bi_{12}TiO_{20}$ crystal with orthogonal propagation of recording beams can be quite high ($\eta \approx 30\,\%$). For reflection holographic gratings formed in the (111) cut of a $Bi_{12}TiO_{20}$ crystal using counterpropagating light beams, $\eta = 0.14\,\%$ for $\lambda = 633$ nm [5]. The two-beam coupling on reflection gratings in the (100) cut of doped $Mn{:}Bi_{12}TiO_{20}$ and $Cd{:}Bi_{12}TiO_{20}$ crystals was studied in Ref. [6]. The lower optical activity of $Bi_{12}TiO_{20}$ made it possible to obtain the gain of the signal beam more than double the value for bismuth silicate.

A typical feature of $Bi_{12}TiO_{20}$ crystals is a considerable photoinduced absorption of light at 633 nm [7, 8], which may lead to noticeable changes in the dynamics of two-beam amplification enhancement as well as in its steady-state value. In this work, the dynamics of two-beam amplification on a reflection grating and of photoinduced absorption of light in the (100) plane of undoped bismuth titanate is studied experimentally.

We studied an undoped $Bi_{12}TiO_{20}$ single crystal grown from the high-temperature melt. The sample with optically polished (100) faces had thickness $d = 3.46$ mm and specific optical rotation $\rho = -6.5°\ mm^{-1}$ ($\lambda = 633$ nm). The experimental setup is shown schematically in Fig. 1. The uncollimated light beam from a He – Ne laser ($\lambda = 633$ nm) with an output power of ~ 40 mW was attenuated to the required level with the help of neutral light filters. The polarisation vector of incident radiation was oriented at 60° to the [010] axis at the input face of the crystal ($x = -d$) by a polariser. A small wedge ($\sim 0.5°$) between the sample faces made it possible to separate in space the light beams with intensities I_r and I_s reflected from the input and output faces of the sample, respectively. The intensities I_p and I_s of the light beams passing through the crystal and reflected from its output face, respectively, were measured with the help of photodiodes FD1 and FD2. In the interval between experiments, the crystal was isolated from ambient light by a lightproof box.

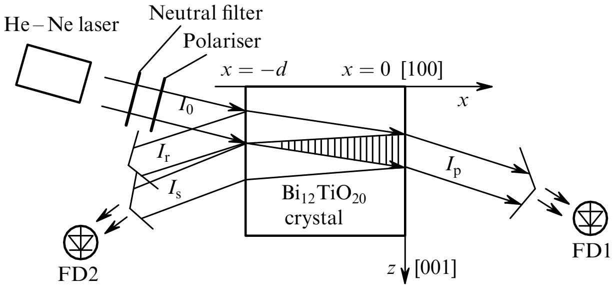

Figure 1. Schematic of the experimental setup.

Typical time dependences of the normalised beam intensity $I_p(t)$ and $I_s(t)$ observed after switching on the incident beam with $I_0 = 10$ mW cm^{-2} are shown in Fig. 2. The decrease in I_p, which is five times as large as I_s, may be due to photoinduced light absorption during the population of shallow trapping levels [7, 8]. The light beam reflected from the output face interferes with the incident beam and creates a reflection holographic grating in the photorefractive $Bi_{12}TiO_{20}$ crystal due to the diffusion mechanism of charge

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carrier redistribution. This grating is displaced relative to the interference pattern by a quarter of spatial period, which leads to efficient energy transfer from the incident to the reflected beam [1]. The dependence $I_s(t)$ presented in Fig. 2 shows that the gain for the given beam on the reflection grating increases with time and considerably exceeds the photoinduced absorption in the crystal. It should be emphasised that the value of I_p decreases with time not only due to photoinduced absorption, but also due to diffraction losses on the reflection hologram.

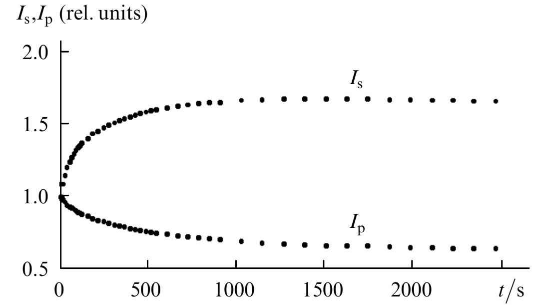

Figure 2. Normalised time dependences of the intensities of transmitted (I_p) and signal (I_s) beams for the input intensity $I_0 = 10$ mW cm^{-2}.

The light fields of the beams propagating in the crystal can be written as the superposition of natural waves:

$$\boldsymbol{E}_p(x) = [C_{p1}(x)\boldsymbol{e}_1 \exp(-ik_0 n_1 x) + C_{p2}(x)\boldsymbol{e}_2 \exp(-ik_0 n_2 x)] \exp\left(-\frac{\alpha}{2}x\right), \tag{1}$$

$$\boldsymbol{E}_s(x) = [C_{s1}(x)\boldsymbol{e}_1^* \exp(ik_0 n_1 x) + C_{s2}(x)\boldsymbol{e}_2^* \exp(ik_0 n_2 x)] \exp\left(\frac{\alpha}{2}x\right), \tag{2}$$

where $\boldsymbol{e}_{1,2} = (\boldsymbol{y}_0 \pm i\boldsymbol{z}_0)/\sqrt{2}$ are the polarisation vectors; $n_{1,2} = n_0 \pm \rho/k_0$ are the refractive indices; $k_0 = 2\pi/\lambda$; and n_0 and α are the refractive index and the absorption coefficient of the crystal, respectively. We can prove that in the case of linear polarisation of the light beam incident on the input face of the crystal, the amplitudes of natural waves satisfy the conditions $C_{p2} = C_{p1}^*$, $C_{s2} = C_{s1}^*$. In this case, the coupled-wave equations describing the two-beam coupling on the reflection grating in an absorbing gyrotropic cubic crystal in the (100) cut for the purely diffuse mechanism of the photorefractive response have the form

$$\frac{dC_{p1}}{dx} = i\,\frac{\Gamma}{4}\,mC_{s1}\exp(i2\rho x)\exp(\alpha x), \tag{3}$$

$$\frac{dC_{s1}}{dx} = -i\,\frac{\Gamma}{4}\,mC_{p1}\exp(-i2\rho x)\exp(-\alpha x), \tag{4}$$

where

$$m = \frac{C_{s1}C_{p1} + C_{s1}^* C_{p1}^*}{|C_{p1}|^2\exp(-\alpha x) + |C_{s1}|^2\exp(\alpha x)}$$

is the contrast of the interference pattern in the crystal and Γ is the exponential two-beam gain.

By expressing the complex amplitudes of natural waves in terms of the intensities $\tilde{I}_p(x)$ and $\tilde{I}_s(x)$ and phases $\varphi_{s1}(x)$ and $\varphi_{p1}(x)$ in the crystal, we obtain from the system of Eqns (3) and (4)

$$\frac{d}{dx}(\tilde{I}_s\tilde{I}_p) = -\frac{\Gamma}{2}\tilde{I}_s\tilde{I}_p\{\sin[2(\varphi_{s1} + \rho x)] - \sin[2(\varphi_{p1} - \rho x)]\}, \tag{5}$$

$$\frac{d}{dx}(\tilde{I}_p - \tilde{I}_s) = -\alpha(\tilde{I}_p + \tilde{I}_s). \tag{6}$$

In the absence of coupling ($\Gamma = 0$), the phases $\varphi_{p1}^0(x)$ and $\varphi_{s1}^0(x)$ of natural waves are independent of coordinate x and are determined by the angle θ_0 formed by the vector polarisation of the incident wave with the [010] axis of the crystal at its output face $x = 0$: $\varphi_{p1}^0 = \varphi_{p1}(0) = \theta_0$, $\varphi_{s1}^0 = \varphi_{s1}(0) = -\theta_0$. It follows from this that the optimal orientation for the grating in the (100) cut is the orientation of the polarisation vector of the incident wave along the {011} direction ($\theta_0 = 45°$). Gyrotropy suppresses the efficiency of the two-beam coupling the more strongly, the larger the crystal thickness. The numerical analysis of the system (3), (4), which exactly takes into account the vector nature of the coupling for the $Bi_{12}TiO_{20}$ sample under study ($\rho = -6.5°$ mm^{-1}, $d = 3.46$ mm, $\Gamma = 3.9$ cm^{-1}, $\alpha = 1.05$ cm^{-1}), indicates that for the optimal polarisation, the function

$$\Delta(x) = \sin[2(\varphi_{s1}(x) + \rho x)] - \sin[2(\varphi_{p1}(x) - \rho x)]$$

appearing in Eqn (5) varies from $\Delta(0) = 2$ to $\Delta(-d) = 1.65$. If we disregard its dependence on the coordinate x and replace it by a certain mean value $\tilde{\Delta}$, the system of Eqns (5) and (6) becomes closed and its integrals can be obtained in the form

$$\tilde{I}_s(x)\tilde{I}_p(x) = \tilde{I}_{s0}\tilde{I}_0\exp(-\tilde{\Gamma}x), \tag{7}$$

$$x = -\frac{1}{\tilde{\Gamma} + 2\alpha}\ln\left[\frac{\tilde{I}_p^2(x)}{\tilde{I}_0^2}\exp(\tilde{\Gamma}x)\right] + \frac{2\tilde{\Gamma}}{\tilde{\Gamma}^2 - 4\alpha^2} \times \ln\left[\frac{(\tilde{\Gamma} - 2\alpha)\tilde{I}_p^2(x)\exp(\tilde{\Gamma}x) - (\tilde{\Gamma} + 2\alpha)\tilde{I}_{s0}\tilde{I}_0}{(\tilde{\Gamma} - 2\alpha)\tilde{I}_0^2 - (\tilde{\Gamma} + 2\alpha)\tilde{I}_{s0}\tilde{I}_0}\right], \tag{8}$$

where $\tilde{\Gamma} = \Gamma\tilde{\Delta}/2$, $\tilde{I}_{s0} = \tilde{I}_s(0)$; and $\tilde{I}_0 = \tilde{I}_p(0)$.

Fig. 3 shows the dependences $\tilde{I}_s(x)\tilde{I}_p(x)$ and $\tilde{I}_p(x)$ obtained from the numerical solution of the system of Eqns (3), (4) (curves *1* and *3*) and (7), (8) (curves *2* and *4*) for the $Bi_{12}TiO_{20}$ crystal with the above parameters and $\tilde{\Delta} = 1.82$. A comparison of these curves shows that the scalar model of coupling on the reflection grating is a good approximation for thin crystals with the (100) cut with a small specific rotation. For this reason, Eqns (7), (8) and Fresnel formulas were used for determining the time dependences of the gain Γ and the photoinduced variation of the absorption coefficient $\Delta\alpha = \alpha(t) - \alpha_0$ from the experimental values of I_0, $I_s(t)$ and $I_p(t)$. The results of these calculations are presented in Figs 4 and 5 for the input intensities $I_0 = 2$, 4, and 10 mW cm^{-2}. Since the incident beam polarisation differed from the optimal polarisation ($\theta_{opt} \approx 67°$), we assumed in our calculations that $\tilde{\Delta}/2 = 0.85$ (this value was obtained from the numerical solution of the system of Eqns (3), (4).

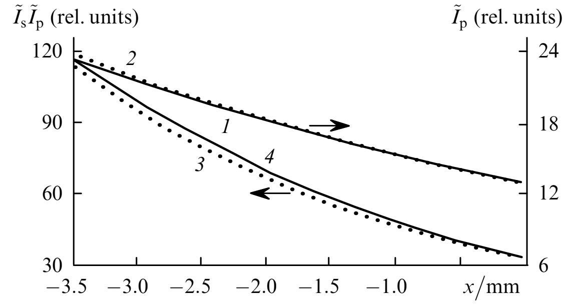

Figure 3. Intensity $\tilde{I}_p$ of the transmitted beam (*1*, *2*) and the product of intensities $\tilde{I}_s\tilde{I}_p$ (*3*, *4*) as functions of x obtained from a numerical analysis of the system of equations (3) and (4) and from the solution of Eqns (7) and (8) for $\tilde{I}_{p0} = 13.1$ and $\tilde{I}_{s0} = 2.55$.

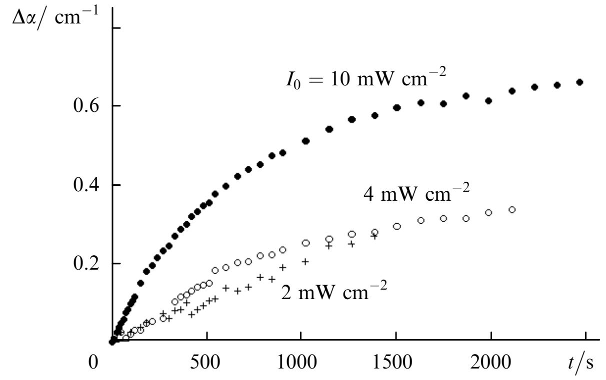

Figure 4. Dynamics of photoinduced variation in the absorption coefficient for various intensities of the incident beam.

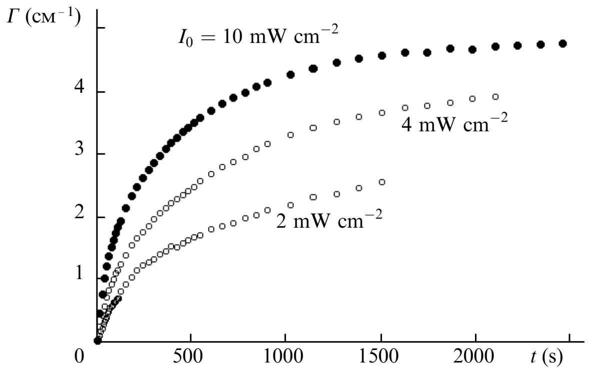

Figure 5. Dynamics of the time variation in the two-beam gain for various intensities of the incident beam.

It should be noted that photoinduced absorption and two-beam amplification do not attain steady-state values over a period of $t \sim 40$ min even for $I_0 = 10$ mW cm^{-2} (see Figs. 4 and 5). The observed variation in the absorption coefficient $\Delta\alpha \sim 0.65$ cm^{-1} exceeds the initial absorption $\alpha_0 \sim 0.4$ cm^{-1} in an unexposed $Bi_{12}TiO_{20}$ sample. The relaxation of the absorption coefficient to the initial value required several days of holding the crystal in the dark. Note that the error in the determining of $\alpha(t)$ from Eq. (4) increases with decreasing intensity of the pump beam due to an increase in the error of measurements. Consequently, the curve in Fig. 4 for the input intensity $I_0 = 2$ mW cm^{-2} reflects the dynamics of variation of photoinduced absorption only qualitatively.

Thus, the relative intensities of the beam reflected from the inner face of the undoped $Bi_{12}TiO_{20}$ crystal in the (100) cut and the beam transmitted through it change simultaneously due to the photoinduced absorption of light and its diffraction from the reflection hologram. The gain of light on such a grating formed due to the diffusion mechanism of recording may be as high as $\Gamma = 4.7$ cm^{-1}.

References

1. Petrov M P, Stepanov S I, Khomenko A V *Fotorefraktivnye kristally v kogerentnoi optike* (Photorefractive Crystals in Coherent Optics) (St. Petersburg: Nauka, 1992)
2. Stepanov S I *Repts. Progr. Phys.* **57** 39 (1994)
3. Kamshilin A A, Jaakelainen T, Khomenko A V, Garcia-Weidner A *Appl. Phys. Letts.* **67** 2585 (1995)
4. Kamshilin A A, Miridonov S V, Miteva M G, Mokrushina E V *Zh. Tekh. Phys.* **59** 113 (1989)
5. Kukhtarev N, Chen Bo Su, Venkateswarlu P et al. *Opt. Commun.* **104** 23 (1993)
6. Mallick S, Miteva M, Nikolova L *J. Opt. Soc. Am. B* **14** 1179 (1997)
7. Shandarov S, Reshetko A, Emelyanov A et al. *Proc. SPIE Int. Soc. Opt. Eng.* **2969** 202 (1996)
8. Kobozev O V, Shandarov S M, Kamshilin A A, Prokofiev V V *J. Opt. A: Pure Appl. Opt.* **1** 442 (1999)