Experimental and theoretical investigations of the gain dependence at two-wave interaction on the thickness and orientation angle of the Bi$_{12}$GeO$_{20}$ crystal

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Abstract. Experimental studies of the dependence of object wave gain at two-wave interaction on the effective thickness of cubic photorefractive optically active crystal Bi$_{12}$GeO$_{20}$ were performed using only one (110)-cut crystal sample. It is shown that the obtained experimental results can be satisfactorily theoretically interpreted taking into account the inverse piezoelectric and the photo-elastic effects in addition to the traditionally considered electro-optical one.

1. Introduction
Photorefractive sillenite crystals Bi$_{12}$SiO$_{20}$ (BSO), Bi$_{12}$GeO$_{20}$ (BGO) and Bi$_{12}$TiO$_{20}$ (BTO) have found application in many holographic devices. This is caused by the high photosensitivity of such crystals and other unique their properties. To increase the efficiency of practical use of these crystals, it is of interest to experimentally and theoretically study the gain dependence of an object light wave in two-wave interaction on the thickness of the crystalline sample.

2. Experimental method
We carried out this investigation for (110)-cut BGO crystal using only one sample 16 mm thick. The realization of such experiment has been possible with the use of trapezoidal intersection geometry of the reference and object light beams in the crystal. This geometry was first advanced in [1–3] also for studies of the gain in sillenite crystals. However, it is important to note that in these studies only such spatial orientations of the crystals with respect to the holographic grating vector $\mathbf{K}$ were considered for which this vector was perpendicular or parallel to the [001]-crystallographic direction.

This made it possible to eliminate the inverse piezoelectric and photoelastic effects (hereinafter it abbreviated as "piezoelectric effect") from the theoretical calculations for $\mathbf{K}[001]$ and neglect the piezoelectric effect at $\mathbf{K} \perp [001]$. Therefore, we considered other orientations of the BGO crystal relative to the plane of propagation of light beams and showed the importance of taking into account
the piezoelectric effect. Note that the trapezoidal geometry was first used to experimentally study the dependence of the diffraction efficiency of holograms on the thickness of the BSO crystal in [4].

3. The experimental conditions and parameters of BGO crystal
During the experiments with BGO at a wavelength \( \lambda = 632.8 \) nm, the ratio of the intensities of object S and reference R light beams before entering the crystal \( \frac{I_S}{I_R} \) was approximately equal to 0.25. The Bragg angle \( \theta_0 \) outside the crystal was 15°. The spatial orientation of the crystal relative to the plane of propagation of the light beams, determined by the angle \( \theta \), corresponded to [4], as well as the choice of the direction of the azimuth of the linear polarization \( \Psi_0 \) of the beams.

In the theoretical calculations, the following parameters of the BGO crystal were used: specific rotation of the plane of polarization \( \rho = 363 \) rad/m; refractive index \( n = 2.54 \); electro-optical coefficient \( r_{41} = -3.4 \times 10^{-12} \) m/V; coefficients of elasticity \( c_1 = 12.8 \times 10^{10} \) N/m\(^2\), \( c_2 = 3.05 \times 10^{10} \) N/m\(^2\), \( c_3 = 2.55 \times 10^{10} \) N/m\(^2\); piezoelectric coefficient \( e_{14} = 0.99 \) C/m\(^2\); photoelastic constants \( p_1 = -0.136 \), \( p_2 = -0.103 \), \( p_3 = -0.091 \), \( p_4 = -0.0134 \).

4. Obtained experimental results and their comparison with theoretical ones
The obtained experimental and theoretical results of studying the dependence of the object light wave gain \( \gamma \) on the effective thickness \( d \) of the BGO crystal, in particular, for \( \theta = 70° \) and 250° at \( \Psi_0 = 0 \) and 90°, are shown in figure 1.

![Figure 1](image)

**Figure 1.** Dependences \( \gamma(d) \) for the crystal of the BGO (110)-cut with \( d_0 = 16 \) mm: dashed line – theory for \( e_{14} = 0 \), solid line – theory for \( e_{14} \neq 0 \); □ – experiment

As can be seen from Fig. 1, only additional accounting of the piezoelectric effect leads to reach agreement between theoretical and experimental results.

5. Conclusion
Thus, the inclusion of piezoelectric effect leads to the most efficient use of the BGO crystal in holographic applications.

This effect should be taken into consideration in the theoretical determination of the optimal conditions of the two-wave interaction in the investigated crystal (for example, by choosing the optimal values of \( \theta, \Psi_0 \), and \( d \), at which the maximum gain of the object light wave is reached).
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