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Wavefront conjugation by mixed holographic gratings in an optically active photorefractive piezoelectric crystal

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Received July 31, 2024
Revised August 23, 2024
Accepted September 8, 2024

Regularities of wavefront conjugation in contradirectional four-wave mixing by mixed holographic gratings in $Bi_{12}SiO_{20}$ crystal of (001), (110) and (111) cuts have been considered. Dependences of the reflection coefficient optimized with respect to the crystal orientation angle and azimuth of linear polarization of the light beams on the recording medium thickness have been investigated. It has been shown that the maximum intensity of the phase-conjugated light beam is achievable for the crystal sample of (110) cut. Combinations of the crystal thickness and orientation angle, as well as of the light beam polarization azimuths, at which the highest diffraction efficiency gets achieved have been determined.

Keywords: wavefront conjugation, reflection coefficient, photorefractive crystal, light beam.

DOI: 10.61011/TPL.2025.01.60145.20078

In the case of contradirectional degenerate four-wave mixing (FWM) in a cubic photorefractive crystal (PRC), two transmission and four reflection volume holographic gratings (hereinafter referred to as gratings) may be simultaneously recorded [1]. In addition to conventional phase gratings formed by modulating the crystal refraction coefficient, in the crystal there may be recorded amplitude gratings formed due to modulation of the recording medium absorption coefficient under the action of the electric field of spatially separated charges [2]. The additional diffraction contribution of the amplitude gratings significantly affects the efficiency of light beam diffraction on gratings, which leads to variations in orientation dependences of the signal beam diffraction efficiency and gain during conventional two-wave mixing. In scientific literature, the grating formed in PRC by modulating its permittivity and nonlinear absorption is usually referred to as mixed [3].

Intensity of the conjugated wave in FWM on photorefractive dynamic phase gratings may be significantly increased by selecting optimal holographic experiment conditions [4–6]. As shown in [4], reflection coefficient of PRC of $\bar{4}3m$ symmetry class may be significantly increased at fixed light beam polarization azimuths by selecting optimal orientation angles. In PRC of 23 symmetry class, the conditions for self-excitation of mutually conjugated light waves on dynamic transmission gratings depend on recording medium thickness d and crystal specific rotation ρ [5]. At low specific rotation (e.g. in crystal $Bi_{12}TiO_{20}$, $\rho \approx 6.3°$/mm) the threshold generation conditions change slightly with increasing thickness d. In optically active photorefractive media with high specific rotation ρ (e.g., in crystal $Bi_{12}SiO_{20}$ (BSO), $\rho \approx 22°$/mm), the conditions for self-excitation of mutually conjugated light waves largely depend on thickness d. The reflection coefficient during FWM on dynamic reflection gratings in the BSO crystal of (001) cut changes with increasing crystal thickness; if the optimal light beam polarization azimuths for a crystal more than 3 mm thick are selected, the reflection coefficient may exceed 100% [6].

The FWM conditions providing the highest reflection coefficient under the condition when the mixed gratings are formed in PRC of 23 symmetry class have been studied in [7]. There have been established the thickness d values at which the reflection coefficient optimized with respect to light beam polarization azimuth ψ reaches its highest values during the wavefront conjugation in the BSO crystal of (001) cut. In this study, investigation [7] was evolved: there were found the conjugated-light-beam reflection coefficients R^{opt} optimized with respect to three parameters (light beam polarization azimuth ψ, orientation angle θ and crystal thickness d); as a result of comparative analysis of dependences $R^{opt}(d)$ obtained for the crystal samples of (001), (110) and (111) cuts most commonly used in holographic experiments, conditions for achieving the greatest diffraction efficiency were revealed.

Schematic diagram of contradirectional FWM, BSO crystal material parameters, and characteristics of light beams with wavelength $\lambda = 632$ nm, which were used in calculations, are described in [7]. Dependences $R^{opt}(d)$ and $R(\theta, \psi)$ were obtained by numerically integrating the coupled wave equations presented in [8]. In calculations, linear polarization azimuths of co-propagating pump and signal beams were taken equal to ψ, and polarization azimuth of the pump beam fed from the crystal opposite side was found from condition $\psi_2 = -\psi + \rho d$. In this case, the propagating beams remain polarized parallel to each other, and modulation depth of the induced interference patterns is optimal. Parameter R^{opt} for fixed thickness d

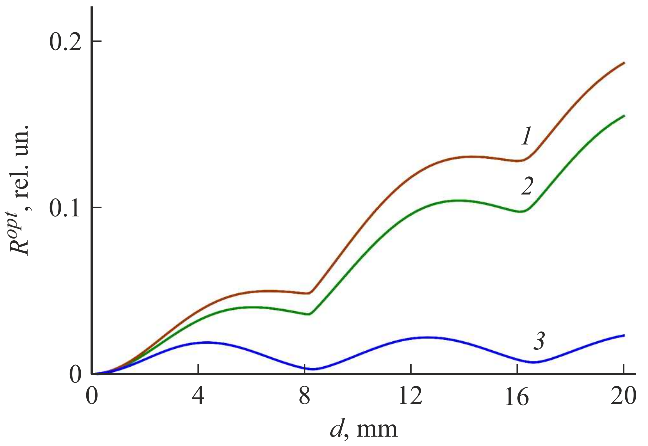

Figure 1. Maximum reflection coefficients R^{opt} versus thickness d calculated for different cuts of BSO crystals. *1* — (110), *2* — (111), *3* — (001).

was chosen as the highest reflection coefficient R found by searching through parameters ψ and θ. The calculations took into account the diffraction contributions of secondary gratings arising as a result of the conjugated beam mixing with the pump and signal beams. Spatial shifts of the interference patterns with respect to relevant amplitude gratings were assumed to be zero, while that with respect to phase gratings was taken as $\pi/2$.

As shown in Fig. 1 for the considered crystal cuts, optimized reflection coefficients R^{opt} increase with increasing thickness d. Dependences $R^{opt}(d)$ are wave-like, which is caused by the influence of the BSO crystal optical activity. At any thickness from the $0 < d \leqslant 20$ mm range, the highest values of R^{opt} are achieved for the sample of (110) cut. The R^{opt} values close to the largest ones may be obtained for the crystal of (111) cut. If the crystal thickness is less than 2 mm, then the difference between the R^{opt} values for the samples of (110) and (111) cuts does not exceed 13%. The greatest difference in the R^{opt} values reaches 24% and corresponds to such d values at which rotation angles of the light beam polarization planes under the influence of optical activity during their propagation in the crystal are $\rho d = 180°$ ($d = 8.1$ mm) and 360° ($d = 16.2$ mm). The optimized reflection coefficient achievable in the crystal of (001) cut is significantly lower than that for the crystal of (110) cut. Even in relatively thin crystals ($d \leqslant 2$ mm), the R^{opt} values achievable for the sample of (110) cut may be up to 37% greater than for the sample of (001) cut. In extreme cases, when thickness d is 8.1 and 16.2 mm, the difference between the R^{opt} values obtained for the samples of (110) and (001) cuts is 95%.

Each $R^{opt}(d)$ dependence in Fig. 1 exhibits in the

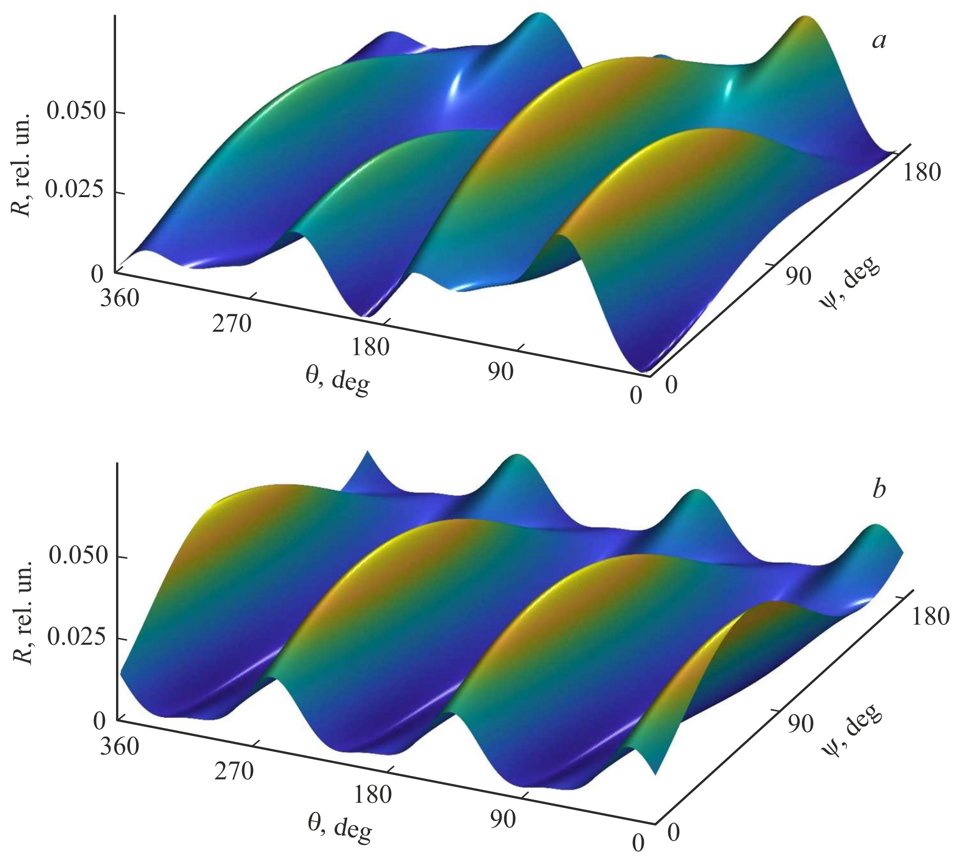

Figure 2. Reflection coefficient R versus polarization azimuth ψ and orientation angle θ calculated for the BSO crystal 6.6 mm thick. *a* — (110), *b* — (111).

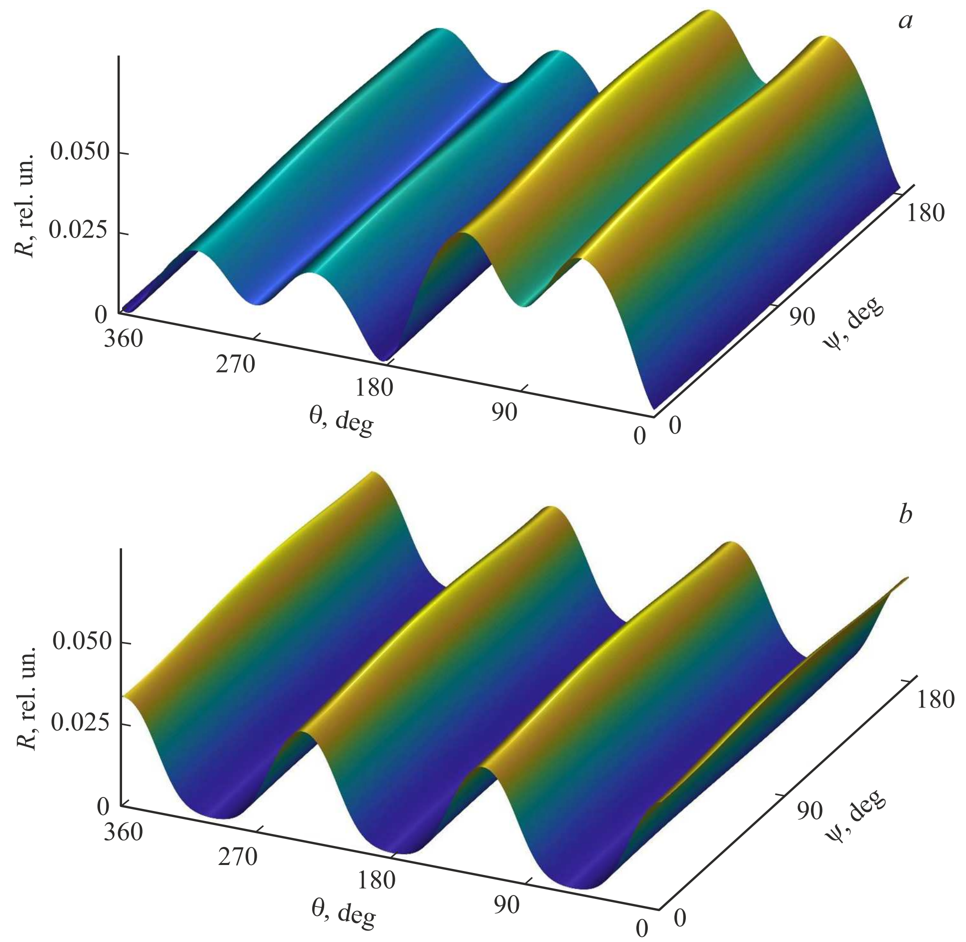

Figure 3. Reflection coefficient R versus polarization azimuth ψ and orientation angle θ calculated for the BSO crystal 8.1 mm thick. a — (110), b — (111).

$0 < d \leqslant 8.1$ mm interval a single local maximum. For the sample of (110) cut, the highest value of the optimized reflection coefficient ($R^{opt} = 0.05$) is achieved at the thickness of $d = 6.6$ mm. For the sample of (111) cut, R^{opt} in the local maximum at $d = 6$ mm is 20% less and equals $R^{opt} = 0.04$. For the sample of (001) cut, local maximum of dependence $R^{opt}(d)$ corresponds to the thickness of $d = 4.1$ mm; in this case, $R^{opt} = 0.018$. The difference in the d values at which the highest R^{opt} values are achieved for the given cuts is induced by an additional diffraction contribution caused by interaction of the pump and signal beams with the mixed grating amplitude components.

In the $8.1 < d \leqslant 16.2$ mm range, the highest values of R^{opt} are achieved at $d = 14.2$ mm for the sample of (110) cut ($R^{opt} = 0.13$) and $d = 13.8$ mm for the sample of (111) cut ($R^{opt} = 0.1$). Comparing the R^{opt} values in the first and second local maxima of dependences $R^{opt}(d)$ calculated for the samples of (110) and (111) cuts, we can see that the largest reflection coefficient increases by approximately 2.5 times. The highest $R^{opt} = 0.021$ for the sample of (001) cut is achieved at $d = 12.5$ mm; it is approximately equal to the R^{opt} value in the first local maximum of dependence $R^{opt}(d)$. This stems from the fact that, when a conjugated wavefront is formed in the sample of (001) cut, the greatest contribution is made by the reflection gratings whose diffraction efficiency decreases significantly with increasing d under the influence of strong optical activity inherent to the BSO crystal (see, e.g. [8]).

Figs. 2 and 3 demonstrate surface images illustrating the reflection coefficient R dependences on polarization azimuth ψ and orientation angle θ; the images were obtained for crystals 6.6 and 8.1 mm thick, respectively. The highest R value in the $R(\psi, \theta)$ curve is optimized reflection coefficient R^{opt} for the crystal of corresponding thickness d. As Figs. 2 and 3 show, combinations of polarization azimuth ψ and orientation angle θ at which R^{opt} is achieved may vary significantly depending on the crystal cut and thickness.

For the crystal 6.6 mm thick, the $R(\psi, \theta)$ dependences take the form of hump-shaped surfaces with clearly visible local maxima. For the sample of (110) cut, R^{opt} gets achieved at $\psi \approx 90^\circ$ and $\theta \approx 135^\circ$ (Fig. 2, a). This means that to achieve a greater efficiency of the wavefront conjugation, the co-propagating pump and signal beams should be polarized perpendicular to the plane of incidence, while the pump beam fed to the crystal from the opposite side should be polarized at $\psi_2 = 55^\circ$ to the plane of incidence. At the same time, the crystal should be oriented so that the angle between the [100] and [010] axes and plane of incidence is 45°. The conditions for achieving R^{opt} for the crystal of (111) cut (Fig. 2, b) differ from those shown in Fig. 2, a: the co-propagating pump and signal beams are to be polarized at 66° to the plane of incidence, while the [100] or [010] axis is to lie in the plane of incidence.

For the crystal 8.1 mm thick, shapes of surface images illustrating dependencies $R(\psi, \theta)$ are qualitatively different: they acquire a wave-like structure. Reflection coefficients close to R^{opt} may be achieved only by optimally selecting orientation angle θ and are almost independent of polarization azimuth ψ. For the crystal of (110) cut, maximum R are achievable when $\theta = 45, 135^\circ$. If the orientation angle is shifted by 180°, local maxima are also achieved in dependence $R(\psi, \theta)$, but R decreases twofold. For the crystal of (111) cut, the R^{opt} values may be obtained for $\theta = 0, 120, 360^\circ$, which corresponds to the third-order-symmetry rotation axis.

Thus, if the recording medium thickness, polarization azimuth and orientation angle are selected optimally, the highest (among the cases considered) intensity of the conjugated beam during FWM in the BSO crystal gets achieved for the sample of (110) cut. In the $0 < d \leqslant 8.1$ mm range, the highest reflection coefficient may be obtained at $d = 6.6$ mm, while that in the $8.1 < d \leqslant 16.2$ mm range occurs at $d = 14.2$ mm. If the crystal of (111) cut is used, a reflection coefficient comparable to that for the crystal of (110) cut may be obtained provided the optimal FWM conditions are selected. The orientation angle and polarization azimuth at which the highest diffraction efficiency is achievable on mixed gratings in the crystals of (110) and (111) cuts are strongly dependent on the crystal thickness, which is due to a large specific rotation of the BSO crystal.

Acknowledgements

The author expresses his gratitude to the Reviewers for careful reading and useful discussion of the manuscript, which contributed to improving the scientific level of the study.

Funding

The study was supported by the Belarus Republic Ministry of Education (Contract № 1410/2021 of 22.03.2021) in the framework of State Research Program № 6 „Photonics and electronics for innovations" for 2021–2025 (Assignment 6.1.14).

Conflict of interests

The author declares that he has no conflict of interests.

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