OPTICAL KERR EFFECT IN PHOTOREFRACTIVE $Bi_{12}SiO_{20}$ CRYSTAL[1]

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We present the experimental evidence for the strong optical Kerr effect in photorefractive $Bi_{12}SiO_{20}$ crystals. Our theoretical analysis shows an enhancement of the diffraction efficiency caused by the optical Kerr effect, when the photorefractive grating in this crystal is illuminated by high-intensity pulsed light.

Introduction

Sillenite crystals as a photorefractive medium have been the subject of many investigations because of their high sensitivity and speed. It is well known that the response time of a photorefractive crystal varies as the inverse of light power, permitting the efficient recording of phase gratings by the interference of light beams of a wide range of intensities from nW to MW. Although the biggest part of the investigations of photorefractive crystals was done with low-power, quasicontinuous light beams, the photorefractive effect generated in $Bi_{12}SiO_{20}$ (BSO) and other photorefractive crystals ($LiNbO_3$, GaAs, InP, CdTe, $BaTiO_3$) at high fluences with short pulses has been reported [1—4]. In all cases, the crystal response was attributed to the charge separation caused by the inhomogeneous illumination of the crystal, which leads to the photoinduced space-charge field. We present here the results of two-wave self-diffraction experiments in the nanosecond regime at 1.06 μm wavelength in photorefractive BSO crystals, with the goal to analyze how the wave polarization affects the diffraction efficiency. We have found experimentally the considerable self-diffraction when two interacting beams have mutually orthogonal polarizations. The interference of such waves yields the modulation of polarization, while the intensity of the resulting electromagnetic wave is constant. Obviously, the photorefractive effect cannot be responsible in this case for the diffraction of the interacting waves. We explained the self-action of the two waves with orthogonal polarizations as a result of their diffraction on a refractive index grating associated with third-order nonlinear susceptibility of the crystal, known as optical Kerr effect. This effect and the photorefractive effect are considered both as a manifestation of refractive index nonlinearity. Nevertheless, the physical mechanisms of these effects are completely different. The difference determines essential distinctions between properties, characteristics, and mathematical descriptions of the effects [5, 6]. In particular, the refractive index change induced by the photorefractive effect depends on the intensity modulation, while, in the case of the optical Kerr effect, it depends on the intensity and polarization of a wave. The dependence on polarization explains the interaction of two orthogonally polarized waves in Kerr media. Direct experimental comparison of the self-diffraction shows that the optical Kerr effect in BSO crystals is thousand times stronger than that in the well-known Kerr medium CS_2. To our knowledge, the observation of the Kerr effect in sillenite crystals has not been reported in the literature. We believe that this founding is essential for applications of BSO and possibly other sillenite crystals. We present here the results of numerical investigations of the short pulse propagation through nonlinear optical media, which possess simultaneously the optical Kerr and photorefractive effects. We show that the diffraction efficiency of a photorefractive grating should be considerably enhanced due to the crystal's Kerr nonlinearity, when the light fluence is high enough. This effect can be used to control high-energy light pulses by a low-power light signal.

Experiments

We conducted two-wave self-diffraction experiments using the geometry shown in Fig. 1. The disk-shaped BSO crystal sample had a thickness of 1 mm along [110] axis. In some experiments, the crystal was replaced by a cuvette with CS_2 with the same thickness of the liquid. The experiments with CS_2 gave us the possibility of a

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[1] This article is dedicated to Professor Marat Soskin on the occasion of his 75th birthday.

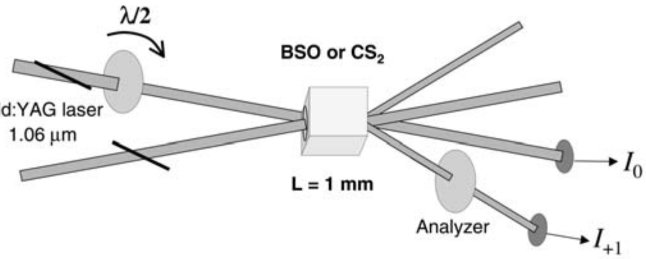

Fig. 1. Schematic of the experimental setup

direct comparison between a BSO crystal and CS$_2$which is the well-characterized Kerr medium. A Q-switched Nd:YAG laser that delivered 5 ns pulses at 1.06 μm with linear polarization was used as a light source. The polarization of one of the beams was rotated by a $\lambda/2$-plate before it entered into the nonlinear medium. The diffracted and transmitted beam intensities were measured with or without polarization analyzer in front of a photodetector. The dependence of the total self-diffraction intensity on the angle between the polarizations of interacting beams measured without polarization analyzer is shown in Fig. 2. The arrows point at the diffraction values obtained when two beams have mutually orthogonal polarizations. To exclude the photorefractive effect from the consideration, it was carefully checked that the intensity modulation vanishes at the marked points. Qualitatively similar results were also obtained in the experiments with CS$_2$, which is the well-known non-photorefractive medium with the optical Kerr effect. The assumption that the Kerr effect is responsible for the self-diffraction of waves with orthogonal polarizations was supported by the numerical analysis of the two-wave mixing in Kerr media. The method used for the calculations will be discussed below. The numerical results predict a similar polarization dependence of self-diffraction, as shown in Fig. 2.

We got another evidence for the Kerr effect in a BSO crystal in the measurements of the diffraction efficiency as a function of the crystal orientation in respect to the light polarization plane. As well known, the photorefractive index modulation is due to the linear electro-optic effect and so depends on the mutual orientation of the crystal and the light polarization. At the same time, the optical Kerr effect in a cubic crystal as well as in isotropic media does not depends on the orientation of the polarization plane. In our experiments, this dependence was not detected that gives us an additional weighty argument in favor of the Kerr effect.

Fig. 3 shows both the experimental and numerical results for two polarization components of the diffracted light as a function of the angle between the input polarizations of the interacting beams. One of the components is parallel to the polarization of the pump beam with fixed polarization, whereas other is orthogonal to it. The good agreement between the numerical and experimental results confirms that the contribution of the photorefractive grating in self-diffraction is negligible in our experiments for all polarization angles. Nevertheless, in other experiments with short pulses, the contributions of both effects should be commensurable and both of them have to be considered simultaneously for the correct interpretation of the results.

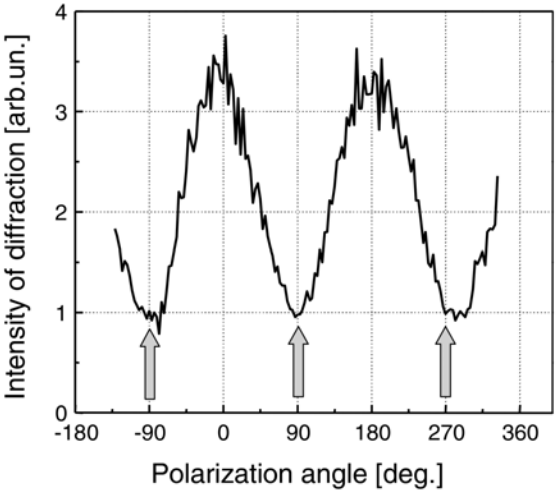

Fig.2. Intensity of a diffracted beam as a function of the angle between two linear polarizations of interacting beams measured with a BSO crystal. Similar result was obtained in the experiment with CS$_2$

Enhancement of Photorefractive Modulation by the Optical Kerr Effect

According to the experimental data presented above, the illumination of our BSO sample by the nanosecond pulses at λ=1.06 μm does not result in a noticeable photorefractive effect. At the same time, the crystal has good photorefractive sensitivity to the light from the green-red range of the spectrum and demonstrates considerable optical Kerr effect. In this connection, a following question arises: how the optical Kerr effect should affect the diffraction efficiency of a prerecorded photorefractive grating? Some works related to this problem have been published. The dependence of the diffraction efficiency of a photorefractive grating on the fluence has been observed in the early work, where the pulsed readout from the

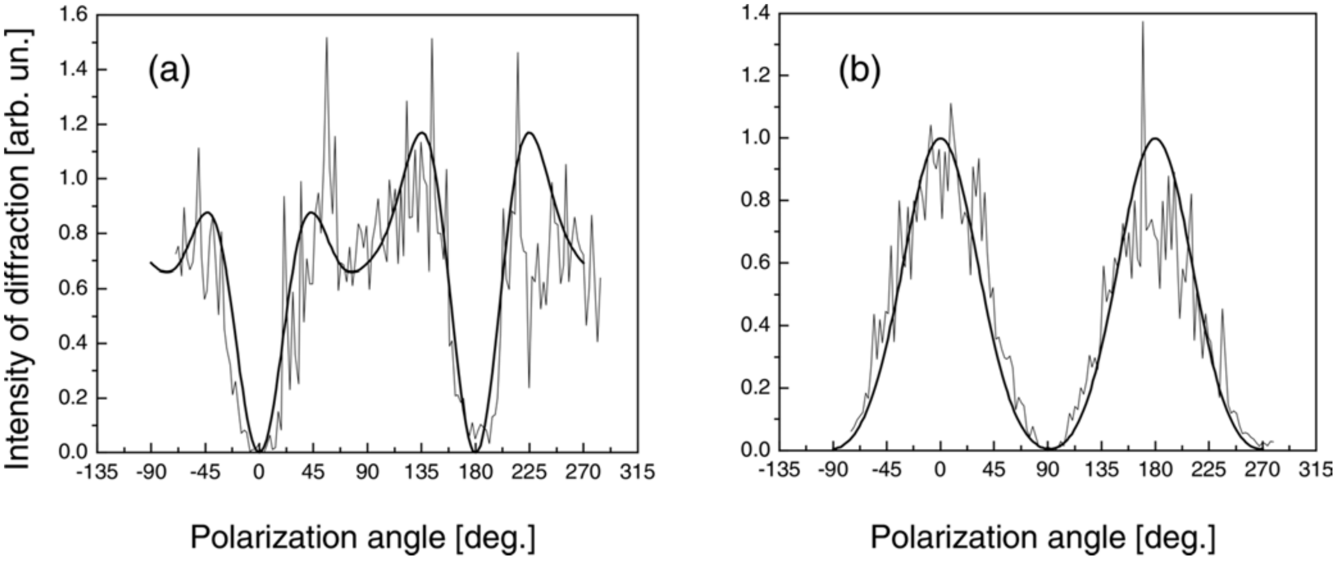

Fig. 3. Intensities of the orthogonal (a) and parallel (b) polarization components of the diffracted beam. The fair-curves represent the numerical results

photorefractive space light modulator PRIZ was investigated [7]. However, in this work, green light ($\lambda = 0.53$ μm) was used for the readout and the results were explained by "an ultra fast photorefractive effect". In a later work, the propagation instability of the wave with polarization modulation was theoretically predicted in media with the optical Kerr effect [8]. It was pointed out that this instability should be a cause for the fluence dependence of the photorefractive grating diffraction efficiency. In the present work, to answer the foregoing question, we analyzed numerically the vectorial three-wave mixing and propagation of a wave with polarization modulation in optical Kerr media.

For our numerical calculations, we used the two-dimensional beam propagation method (BPM). This method was developed first in underwater acoustic and seismology, where waves propagate in an essentially inhomogeneous medium. Later, the BPM was adapted to a large variety of optical problems. In particular, BPM has been used in photorefractive nonlinear optics [9—13]. BPM is a stepwise algorithm consisting essentially of replacing the wave propagation in an inhomogeneous and/or nonlinear medium by the propagation through a sequence of homogeneous thin layers with phase/polarization correction after each layer. These corrections introduce the entire information about the optical inhomogeneity and nonlinearity of a layer by a single phase and polarization correction. We used the same classical BPM algorithm as in our previous works, where the steady-state wave propagation in photorefractive crystals was analyzed [12, 13]. In this work, we modified only the matrix operator which was used for the phase correction of each of two polarization modes. Thus, the results of calculations are valid only when the response time of the Kerr medium is much longer than the pulse duration. The typical response time of the Kerr medium is a few picoseconds, so our calculations are reliable if the pulse is longer than approximately 100 picoseconds. The phase increments of two circularly polarized modes were calculated as [5]

$$\Delta\varphi_\pm = \frac{12\pi}{n_0\lambda}\left[\chi_{1122}\left|E_\pm\right|^2 + \left(\chi_{1122}+\chi_{1221}\right)\left|E_\mp\right|^2\right], \quad (1)$$

where $\Delta\varphi_+$ and $\Delta\varphi_-$ are the phase increments for the right-hand and left-hand circular polarization modes, respectively, E_+ and E_- are the complex amplitudes of the polarization modes, and χ_{ijkl} are the elements of the third-order susceptibility tensor.

Let us first examine the vectorial three-wave mixing in nonlinear Kerr media to determine the optimum wave polarization for the maximization of energy exchange between the strong pump wave and two weak waves which propagate symmetrically on both sides from the pump beam. The two weak waves should be considered as the ±1 diffraction orders of the grating, while the strong central wave as the 0-order. The calculations were done for the pump/weak wave intensity ratio $\beta = 100$, the thickness of nonlinear media $L = 1$ mm, and nonlinear third-order susceptibility $\chi^{(3)} = 1.9 \cdot 10^{-12}$

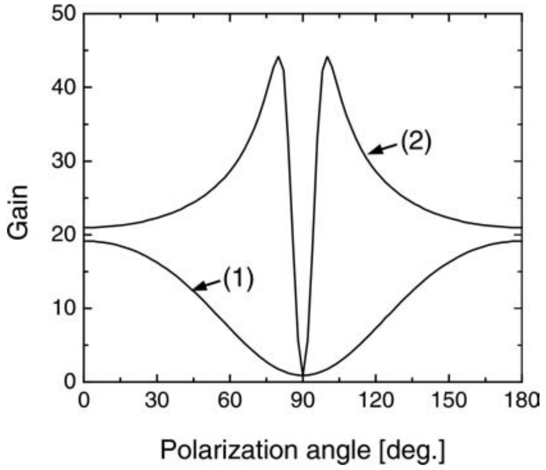

Fig. 4. Gain factor as a function of the input polarization angle for the fluences: 30 MW/cm^2 (*1*), 60 (*2*)

esu, which corresponds to CS$_2$ [5]. All three waves had linear polarization at the input plane of the nonlinear medium, and the polarization plane of both weak waves had the same angle in respect to the pump beam. The interference pattern of these three beams in general had both the intensity and polarization modulation. The angle between the pump and weak beam was 1.5° that corresponds to the special frequency of the interference pattern $f = 50$ mm^{-1}. Fig. 4 shows the gain as a function of the angle between the polarization plane of the pump and weak wave at two different overall fluences, 30 and 60 MW/cm^2. The gain was calculated as a ratio $g = I(L) \setminus I(0)$, where $I(L)$ and $I(0)$ are the intensities of the weak wave at the output and input of the nonlinear medium, respectively. One can see that the optimum polarization of the pump beam depends on the fluence. At low fluences, the maximum gain is reached with similar polarizations of all three waves, when the intensity modulation of the interference pattern is the most important factor for the refractive index modulation. The optimal angle approaches 90° with the increment of the fluence, through there is no gain of the weak wave at any fluence, when the pump wave has orthogonal polarization. The fluence dependence of the optimal polarization should be explained by the periodic character of energy exchange with the period which depends on polarization. Thus, the change of polarization allows an adjustment of the energy exchange period and the length of the sample of a nonlinear medium. The periodic energy exchange in the photorefractive two-wave mixing has been discussed previously [14, 15].

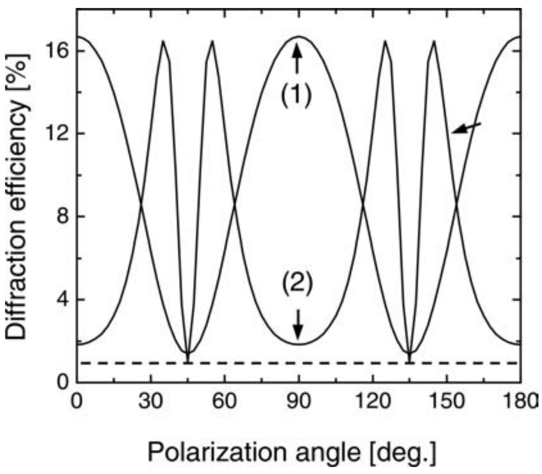

Fig. 5. Diffraction efficiency of the photorefractive grating enhanced by the optical Kerr effect. The fluence is 30 (*1*) and 60 MW/cm^2 (*2*). The dashed line shows the diffraction efficiency without enhancement

The results presented in Fig. 4 demonstrate an opportunity of light amplification in optical Kerr media. However, these data are not enough for a proving of the effect of diffraction enhancement in thin cubic photorefractive crystals, where the readout light experiences the phase and polarization modulation without intensity modulation. To provide the evidence for such an effect, we examined, as a model, the cubic crystal with a photorefractive grating, which is prerecorded in a thin layer near the crystal input face. In this model, the grating was readout by a strong wave at $\lambda = 1.06$ μm, which did not affect the photorefractive grating amplitude. In the thin layer, the readout wave experiences the phase/polarization modulation without any intensity modulation. The modulation should be enhanced due to the optical Kerr effect during the following propagation in the crystal volume. The typical crystal configuration was chosen for our calculations with the light propagation direction along the crystal axis [110] and the wavevector of the prerecorded grating along $[\bar{1}10]$ axis. This configuration yields the same amplitude of refractive index modulation, $|\Delta n_x| = |\Delta n_y|$, for both linearly polarized electro-optic modes with $\Delta n_x = -\Delta n_y$. The diffraction efficiency of a thin photorefractive grating does not depend in this case on the polarization of the readout light. Thus, the polarization dependence of the diffraction efficiency obtained in our numerical experiments has to be attributed only to the diffraction enhancement associated with the optical Kerr effect. These dependences are shown in Fig. 5. They were calculated using the same values of fluences, spatial frequency, and nonlinear third-order susceptibility as to obtain the results presented in Fig.4. The polarization angle is defined here as an angle between the polarization plane and $\left[\bar{1}10\right]$ direction, which coincides with the wavevector of the photorefractive grating. The diffraction efficiency of the photorefractive grating without enhancement was 1%. As one can see in Fig. 5 for both fluences, 30 and 60 $\mathrm{MW/cm^2}$, our calculations gave approximately the same, 16-times diffraction efficiency enhancement factor. In the crystal configuration which we discuss here, the principal axis of the index ellipsoid is directed at the 45°-angle counted from $\left[\bar{1}10\right]$ direction. At the zero polarization angle, two linear polarization modes have similar amplitudes at the crystal input, and the diffracted light has the orthogonal polarization in respect to that of the incident wave, because $\Delta n_x = -\Delta n_y$. In accordance with the results presented in Fig. 4, the enhancement factor has maximum at high fluences, when the polarization angle is close to 0°. When the polarization angle is ±45°, the readout light has the polarization that coincides with one of the polarization modes. So the light diffracts without polarization change, which allows the maximum enhancement at a lower fluence.

Conclusions

In this work for the first time to our knowledge, we have reported the experimental observation of the self-diffraction of two beams with orthogonal polarizations in the photorefractive BSO crystal. This observation can be explained by the beam interaction caused by the optical Kerr effect. We are planning the exact measurements of the third-order susceptibility of a BSO crystal in our future experiments. Nevertheless, the direct experimental comparison of two-beam self-diffraction in BSO and CS_2 indicates that the optical Kerr effect in BSO has a considerable value and should be an important factor in the experiments with short pulses. Our numerical analysis using BPM demonstrates that the diffraction efficiency of the photorefractive grating in cubic crystals can be noticeably enhanced with a pulsed readout due to the optical Kerr effect.

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ОПТИЧНИЙ ЕФЕКТ КЕРРА У ФОТОРЕФРАКТИВНОМУ КРИСТАЛІ $Bi_{12}SiO_{20}$

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Резюме

Наведено експериментальні дані, які свідчать про наявність сильного оптичного ефекту Керра у фоторефрактивному кристалі $Bi_{12}SiO_{20}$. Проведений теоретичний аналіз показав підвищення дифракційної ефективності, зумовлене оптичним ефектом Керра, при освітленні фоторефрактивної гратки в цьому кристалі потужним імпульсним світлом.