Anisotropic diffraction of light by volume holographic grating in birefringent photorefractive crystals with extended wavelength range

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Abstract: The properties of anisotropic diffraction of light by volume holographic grating in birefringent photorefractive crystals are discussed. This diffraction takes place when the refractive index for diffracted light is different from the refractive index for incident light. It is found that in some special geometry of wavevector diagram the diffraction becomes less sensitive to the wavelength mismatch of Bragg condition. The wavelength range may extent in several times the range of ordinary isotropic diffraction on the grating of the same spacing and thickness. Theoretical explanation of this phenomena and experimental results of widerange diffraction in $BaTiO_3$ photorefractive crystal are also presented.

OCIS codes: (050.7330) Volume holographic gratings; (260.1440) Birefringence

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1. Introduction

It is found in crystal optics that diffraction of light on periodic structure in optical anisotropic medium the polarization states of incident and diffracted lights may be different [1]. In the case when the incident and diffracted lights correspond to different refractive indexes of medium that kind of diffraction may be called as anisotropic diffraction. The properties of

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anisotropic diffraction are significantly different from that of ordinary diffraction in optically isotropic material. They are dependent on mutual orientations of the light and grating and have been studied well in acoustoptics [1-4] as well as in photorefractive nonlinear optics [5-7]. In both cases, the main characteristics can be described by using the momentum conservation law and the coupled mode theory of volume gratings [8-11].

Here we present the investigations of a special kind of light diffraction on holographic grating in uniaxial crystals. In this special geometry of wave vector diagram the diffraction becomes less sensitive to the wavelength mismatch of Bragg condition while different wavelengths are diffracted to different directions.

2. Widerange diffraction in uniaxial crystals

Unlike isotropic media, the wave vector surface in uniaxial crystals is split into two shells corresponding to the ordinary and extraordinary linearly polarized light waves. Let us assume that the diffraction takes place in the plane orthogonal to the optic axis of a crystal and all wave vectors lie in that plane. In that case the cross section of refractive surfaces represents two circles. From momentum conservation law it follows that the diffraction takes place and reaches the maximum of efficiency when the Bragg condition is satisfied. In other words, the triangle consisting of incident light wave vector, diffracted light wave vector and grating vector should be complete (Fig.1).

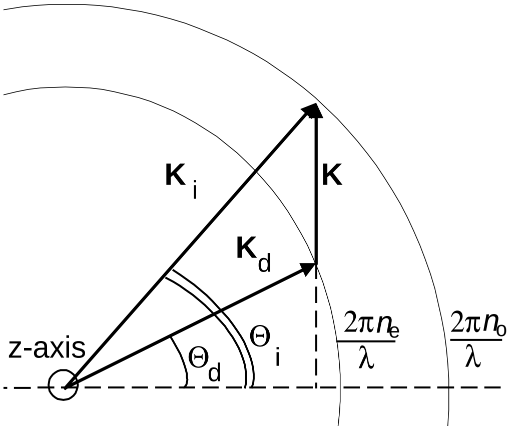

Fig.1 Wave vector diagram of anisotropic diffraction in (x,y) plane of uniaxial crystal

From these simple argumentations we can write the Bragg condition for the anisotropic diffraction in (x, y) plane of uniaxial crystal [1, 3]

$$\begin{cases} \sin\Theta_i = \dfrac{\Lambda}{2n_o\lambda}\left(n_o^2 - n_e^2 + \dfrac{\lambda^2}{\Lambda^2}\right) \\ \sin\Theta_d = \dfrac{\Lambda}{2n_e\lambda}\left(n_o^2 - n_e^2 - \dfrac{\lambda^2}{\Lambda^2}\right) \end{cases}, \tag{1}$$

where n_o and n_e mean refractive indexes for ordinary and extraordinary polirized light waves respectively, λ is a light wavelength, Λ is a grating spacing, Θ_i and Θ_d determine the angles of incident and diffracted light waves related to the straight line which is orthogonal to grating vector (Fig.1).

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Let us fix the grating spacing Λ. Now we can draw the dispersive curves or the dependences Θ_i and Θ_d as functions of wavelength λ. For example, for barium titanate crystal two dispersive curves are plotted in Fig. 2.

It is clear to see that dispersive curve for the incident light has an extreme point when the diffracted light passes through zero degree. This extreme point can also be found by using equation (1). It happens when the wavelength corresponds to the following equation [1, 3]

$$\lambda_o = \Lambda\sqrt{n_o^2 - n_e^2}\ . \tag{2}$$

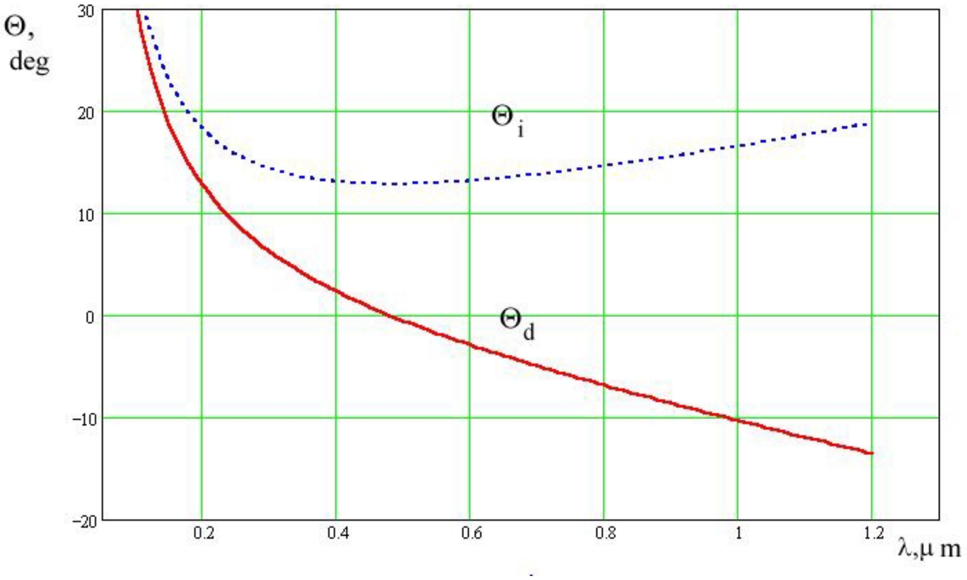

Fig.2. The dispersive curves of anosotropic diffraction on the grating with spacing Λ=0.9 μm in (x,y) plane of $BaTiO_3$ crystal (n_o=2.458, n_e=2.399))

Couple mode analysis shows that if equation (2) is satisfied and the incident angle is chosen to be at the extreme point of dispersive curve (Fig.2) the diffraction becomes less sensitive to the wavelength mismatch. The half-power passband can be calculated as [2]

$$\Delta\lambda_{anis} = \sqrt{\frac{\lambda^3}{L\Delta n}}\ , \tag{3}$$

where Δn is crystal's birefringence, L is grating thickness. If we compare (3) with the expression for the passband of isotropic diffraction [8]

$$\Delta\lambda_{is} = \frac{\lambda^2 \cos\Theta_i}{2Ln\sin^2\Theta_i} \tag{4}$$

we see that anisotropic diffraction has much wider wavelength range. The extension coefficient is equal to

$$\frac{\Delta\lambda_{anis}}{\Delta\lambda_{is}} = \frac{2n\sin^2\Theta_i}{\cos\Theta_i}\sqrt{\frac{L}{\lambda\Delta n}}\ . \tag{5}$$

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It is seen that in practical cases the coefficient (5) may reach several times and that makes incident wavelength range a significant value. For example, for $BaTiO_3$ phororefractive crystal with parameters ($L=5$ mm, $\lambda=507.5$ nm, $n_o=2.458$, $\Delta n=0.059$ and $\Theta_i=6.33$ deg) the range of anisotropic diffraction is 21 nm where as the range of isotropic one is only 0.85 nm. The extension coefficient in that case according to (5) is equal to 25 times.

3. Experimental setup and results

To prove the theoretic formulas and to show the phenomena of widerange anisotropic diffraction we constructed the setup (Fig.3). We used Argon laser in multi-line regime that irradiates 3 lines (488, 501 and 514 nm). We split the laser light into two beams.

The first one is used for recording the grating. By using a prism we select only one wavelength (514 nm), expand the beam size and realize the two beam interference scheme that is usually used in holographic experiments. The power of each writing beam is 20 mW. The polarization is linear and corresponds to ordinary polarized light (horizontal plane in Fig.3). The mixing angle inside the medium is equal to 12.66 deg. That was chosen to record the grating with a spacing of $\Lambda=948$ nm to satisfy the condition (3) at 507.5 nm wavelength.

The second one is used for reading the grating simultaneously with the recording process. We expand the beam size and illuminate the crystal. A reflection mirror mounted on a rotating stage is used for tuning the angle of incidence of the reading beam.

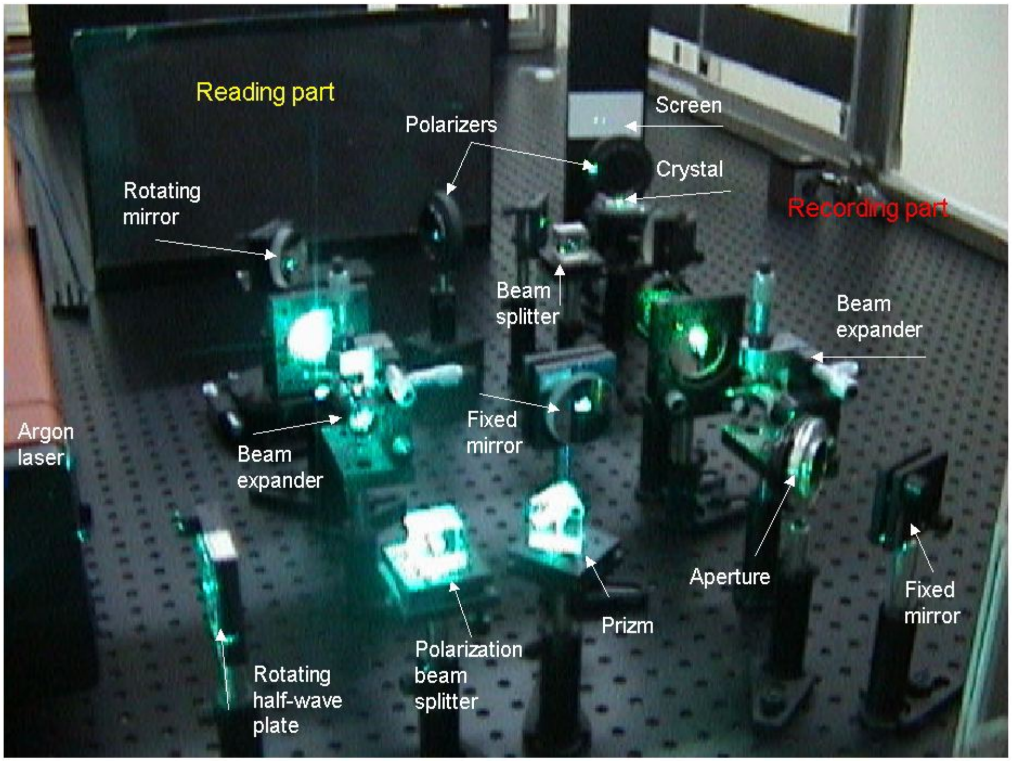

Fig.3. Experimental setup

In our experiments we used $BaTiO_3$ crystal with sizes 5×5×6 mm. The grating thickness equals to 5 mm. The photos of diffracted images are shown in Fig.4. It is important to note that the anisotropic diffraction with high efficiency for two wavelengths (514, 501 nm) has been achieved simultaneously.

The maximum of measured diffraction efficiency in $BaTiO_3$ was 30% for 514 nm line. From these experimental results it is possible to estimate that the wavelength range of diffraction is at least no less than the spectral distance between the laser lines and is equal to 13 nm. It is in good agreement with theoretical formula (3).

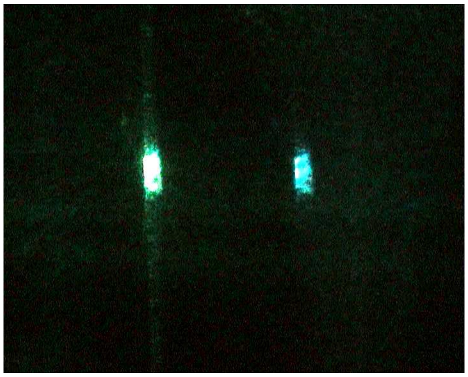

Fig.4 The photos of diffracted images of widerange anisotropic diffraction in $BaTiO_3$ crystal, (1.5 MB) Movie of two-diffracted spots

It is also important to note another interesting phenomena. When we measured the dependence of diffraction efficiency on incident angle (or so-called angle characteristic of diffraction) we applied 3 wavelength light of Argon laser at the same incident angle and changed that angle by rotating a mirror (Fig. 3). We have found that when the mirror had been rotating the diffracted spots from two different wavelengths (514 and 501 nm) appear and disappear simultaneously and reach the maximum of efficiency at the same incident angle. The dynamic behavior of the diffracted spots has been captured to a video camera and the movie is also presented in Fig.4.

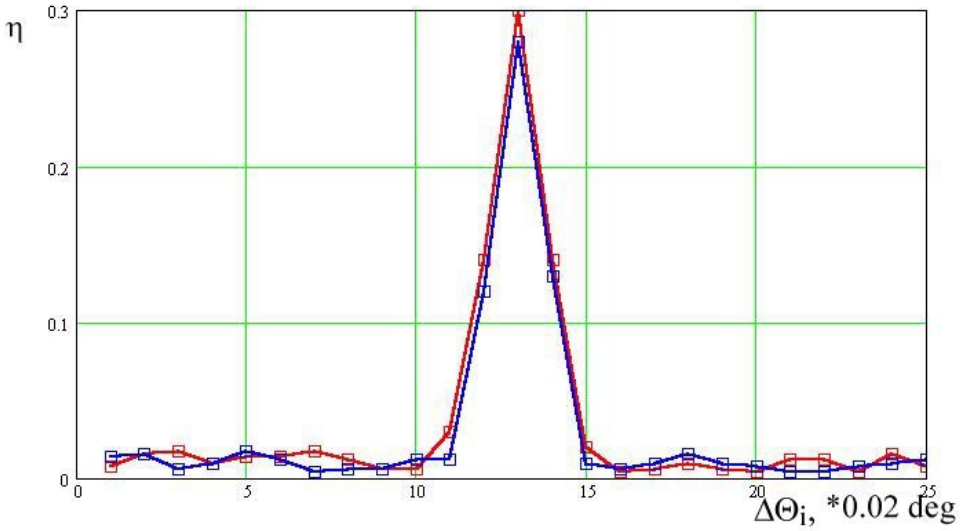

Fig.5. The angle characteristic of widerange anisotropic diffraction in $BaTiO_3$ crystal for two different wavelengths (red-for 514 nm, blue-for 501 nm)

In addition, the angle characteristic of anisotropic diffraction in $BaTiO_3$ was measured and plotted in Fig.5. It is seen that the full width of incident angle at the half-power points of

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the Bragg condition is about 0.04 degree which is close to the theoretical value (0.03 degree) obtained by using Bragg matching condition.

Our results show that phenomena of anisotropic diffraction is very different compared to the isotropic one. In isotropic case, when several wavelengths are incident to thick volume grating the maximum of diffraction efficiency at each wavelength is observed at different incident angles because of the Bragg matching condition. In our special geometry of anisotropic diffraction, the Bragg matching condition may be satisfied at two different wavelengths simultaneously.

4. Conclusion

We investigated the properties of anisotropic diffraction of light by volume holographic grating in birefringent photorefractive crystals. We have found that in some special geometry of wavevector diagram when the incident angle corresponds to the extreme point (Fig.2) the diffraction becomes less sensitive to the wavelength mismatch. Our experimental results of widerange diffraction in $BaTiO_3$ photorefractive crystal designing at the central wavelength of 507.5 nm show that for the grating thickness 5 mm the wavelength range exceeds 13 nm. That extends in several times the range of ordinary isotropic diffraction on the grating of the same spacing and thickness. This phenomena of widerange diffraction could be used in optical demultiplexer designing and opens the new possibility of using the phorefractive crystals in dense wavelength division multiplexing (DWDM) applications.

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