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Spatial Sensitivity Characterization of the Photorefractive $Bi_{12}TiO_{20}$ Crystal by Anisotropic Self-Diffraction at $\lambda = 0.633\mu m$

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We show in this paper a holographic characterization of the photorefractive sensitivity by the spatial light modulation dependence in the $Bi_{12}TiO_{20}$ crystal. The experiments were perforined in diffusion only Bragg regime and exploit the anisotropic self-diffraction properties of the material. Through the well known condition $KL_D = 1$, we obtain an evaluation of the diffusion transport length L_D in the low frequency domain. The experimental limitations found in the holographic testing routines of spatial sensitivity in high frequency domain are theoretically explained. It is also indicated the best conditions based on spatial frequencies for fast response of the material as optical holographic processor.

I. Introduction

The photorefractive material is a very interesting nonlinear register media with high spatial resolution and sensitivity in real time holographic recording. This material is systemstically employed for generation and controlling of the volume phase holograms for many scientific and tecnological purposes. In these materials, the well described[1] combination of photocondutivity and linear eletrooptic effect produces a refractive index modulation due to the projection of an interferente pattern of light into the crystal.

It is well known from theory[2] related with the photorefractive effect that the maximum sensitivity response to the spatial light modulation is reached for $KL_D = 1$, and that the increasing of the K value from this condition to saturation values results in reduced sensitivity. Here, $K = 2\pi/\Delta$ (A is the grating spacing) is the spatial frequency and L_D the diffusion transport length for no applied external electric field. Recently[3], this condition was employed to check positively the measured L_D valu:. It was proposed[4] a new complete holographic experiment exploring the anisotropic self-diffraction properties to determine some intrinsic parameters in BSO-type crystals.

This work shows an experimental characterization of the photorefractive sensitivity by the spatial light modulation dependence in the $Bi_{12}TiO_{20}$ crystal. We determine the diffusion transport length L_D of the sample, which was illuminated with $\lambda = 0.633\mu m$ from a He-Ne laser light source.

II. Spatial sensitivity in the photorefractive material

In the photorefractive crystal, the photocondutivity allows photoelectric carrier displacements, and the subsequent trapping produces a spatial charge distribution. So, a refractive index modulation is produced via linear eletrooptic effect. All the process of the volume phase hologram formation is described by the space charge field E_{sc}. The holographically generated sinusoidal phase grating is obtained when the interference pattern of light

$$I(x) = I_0(1 + m\cos Kx) \qquad (1)$$

of period $\Lambda = 2\pi/K$ and modulation rate m, is projected onto the (110) face of the crystal sample in a transverse eletrooptic configuration[5,11] with the x axis parallel to the [110] crystal axis. In this case, the space charge field E_{sc} during the grating formation or in the grating decay has an exponential behaviour[6] in the time domain characterized by the constant[7]

$$S = I(q\mu_\tau\phi/\epsilon h\nu d)(1 + K^2 l_s^2)/(1 + K^2 L_D^2) \qquad (2)$$

for no external applied electric field. In this expression I is the effective absorved irradiance in the experiment, q is the electric charge, $\mu_\tau = L_E/E$ is a *specific drift length*, ϕ is the quantum efficiency of the photoelectron generation, ϵ is the electric permitivity, d is the crystal thickness, $h\nu$ is the photon energy of incident light, l_s is the Debye screening length and finally L_D is the diffusion transport length.

In short, the space charge field is sinusoidal in the spatial domain with an exponential amplitude in the time domain with the constant defined by the Eq. **(2).**

The sensitivity of these materials is computed by the change rate of the photoinduced space charge field" amplitude $E_{sc}(t)$ in the beginning of the recording or in the beginning of the erasure of the hologram. In this sense, we are treating the photorefractive sensitivity as a velocity response of the space charge field in the grating formation. With the amplitude[7]

$$E_{sc}(t) = (D/\mu)K \exp(-St) \tag{3}$$

where $D/\mu = L_D^2/\mu_\tau$, and the definition of the sensitivity for the erasure"

$$W = -(\partial E_{sc}(t)/\partial t)_{t=0} \tag{4}$$

Using the Eq. (2) and the Eq. (3), we obtain the expression

$$W_n = W/I = (q\phi/\epsilon h\nu d)(1 + K^2 l_s^2)KL_D^2/(1 + K^2 L_D^2) \tag{5}$$

where W_n is the sensitivity normalized by effective absorbed irradiance in the crystal. The Eq. *(5)* expresses the spatial light modulation dependence of the photorefractive sensitivity.

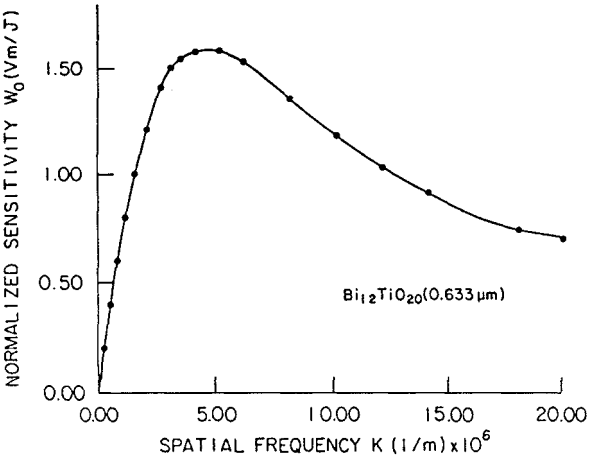

Figure 1.: Normalized sensitivity curve form $Bi_{12}TiO_{20}$ crystal at $\lambda = 0.633\mu$m using $L_D = 0.23\mu$m from Ref. *4*.

We assume that our analysis is made for the values of spatial frequencies in which the approximation

$$K^2 l_s^2 << 1 \tag{6}$$

must be considered. This is the usual interval of variation for practical purposes and corresponcls to the intermediate spatial frequencies. With this approximation the Eq. *(5)* becomes

$$W_n = (q\phi/\epsilon h\nu)KL_D^2/(1 + K^2 L_D^2) \tag{7}$$

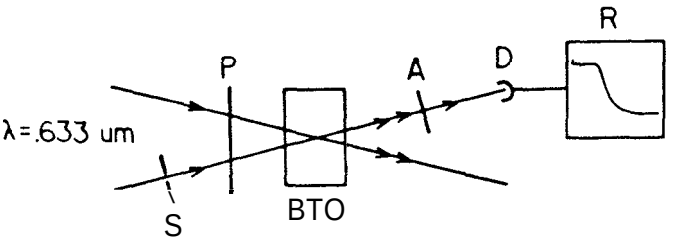

Figure 2.: Experimental setup. In this sketch, S is the mechanical shutter, P is a polarizer, **A** is a polarizer used as an analyser, D a photodetector and R is a fast graphic register.

which has one maximum value (see Figure 1) given by the condition

$$\partial W_n/\partial K = 0 \tag{8}$$

e.g., the maximum of the sensitivity for this interval is reached[2] for

$$KL_D = 1 \tag{9}$$

The well known result expressed in the last equation can be used as an additional testing for new experimental[3] determinations of L_D and it is in agreement with our experimental characterization curve which shows the maximum (see Figure *4)* foreseen by Eq. (9).

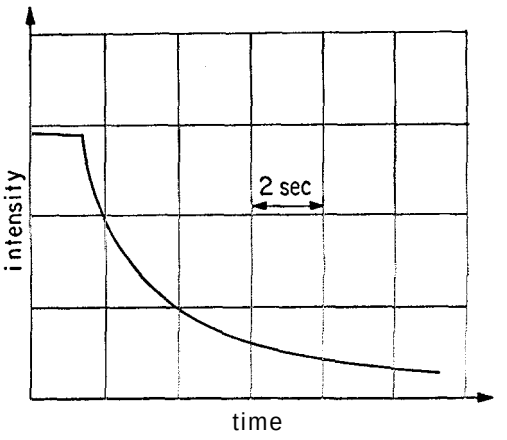

Figure **3.:** Typical experimental intensity in erasing of a photorefractive sinusoidal grating.

III. Spatial sensitivity in high **frequency** domain

Now, making a simple algebraic manipulation and introducing the trap density parameter by the definition

$$l_s^2 = \epsilon(K_B T/q^2 N_A) \tag{10}$$

then Eq.(5) beconies

$$W_n = (K_B T/q)(\phi/N_A h\nu d)H(K)\cdot(K^2 L_D^2)/(1+K^2 L_D^2), \quad (11)$$

where

$$H(K) = (1 + K^2 l_s^2)/K l_s^2.$$

In this last result assuming sufficiently high values of K, the factor

$$K^2 L_D^2/(1 + k^2 L_D^2) \simeq 1 \quad (12)$$

is an approximation factor. With no modification in the factor $H(K)$, :he sensitivity now is given by

$$W_n = (K_B T/q)(\phi/N_A h\nu d)(1 + K^2 l_s^2)/K l_s^2 \quad (13)$$

For this interval cf variation of K, using the Eq. (8), it is reached one value (maximum or minimum) of the sensitivity for which

$$KI, = 1 \quad (14)$$

On the other hand, the term $(1 + K^2 l_s^2)/K l_s^2$ in the Eq. (13), plotted in Figure 5, allows to conclude that the sensitivity corresponding to the conditions $K l_s = 1$ is the smaller value (minimum) reached in the high frequency domain. Therefore, the analysis shows that is possible to find the slower response time in the material for high spatial frequency, before the saturation limit of the material has been reached.

IV. Experimental characterization of the $Bi_{12}TiO_{20}$ Crystal by the spatial sensitivity

The experimental setup used for the photorefractive sensitivity characterization is illustrated in Figure 2. We used a BTO ($Bi_{12}TiO_{20}$) sample (10x8x4,8mm^3) grown in the A.F. Ioffe Physical-Technical Institute of Leningrad, USSR. It was illuminated by two beams of $\lambda = 0.633\mu$m of the He-Ne laser light source at 10 mW of nominal power, rxpanded, collimated at small beam diameter (4mm), in a similar experimental configuration used in Ref. 3. From the practical viewpoint, the main feature of this approach is the easy implementation of the experiinent. The simple detection of the diffracted beam is possible, in spite of the low diffraction efficiency in ε, purely diffusion recording mechanism, exploiting the anisotropic diffraction properties[8] of this material. So, if the polarization direction of interfering beams is parallel to the [001] crystai axis at the center of the crystal sample, in transverse electrooptic configuration, the polarization direction of the diffracted beam makes 90° with that of the transmitted beam. In this case, the difftacted beam is selected by an analyzer (see Figure 2), with the additional advantage of eliminating the possible background scattered noise increasing the SNR (Signal to Noise Ratio) of the

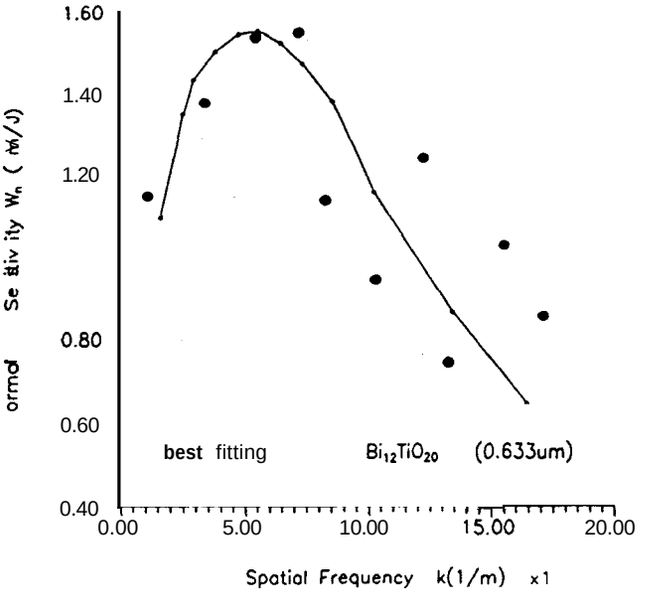

Figure 4.: Experimental curve fitting W_n *x* K, where W_n is given by Eq. (7).

holographic device. The sample used here has the light absorption coeficient a = 1.15 cm^{-1}, and the specific optical activity ρ = 1.25 cm^{-1}.

The decay constant S is obtained from data in pictures illustrated in Figure 3. This parameter is determined by the grating erasure for each K used in the experimental data in W_n *x* K plotted in Figure 4. The W_n values for construction of the characterization curve in Figure 4 are computed by Eq. (5), with the definition of S in Eq. (2), in the form

$$W_n = (K_B T/q)K(S/I) \quad (15)$$

In the last expression $K_B T$ is the Boltzmann factor, q is the electric charge and in our case $K_B T/q$ = 25.26 mV. The Figure 4 shows maximum value of sensitivity for one spatial frequency K = $2\pi/\Delta$. Therefore, this maximum value of the sensitivity, by the Eq. (8) allows to compute

$$L_D = 0.21\mu m. \quad (16)$$

Based on the data from Figure 4, we made the sensitivity characterization of the $Bi_{12}TiO_{20}$ crystal at $\lambda = 0.633\mu m$ as an optical holographic processor. The maximum in the sensitivity is $W_n = 1.55 V m J^{-1}$ with the spatial frequency K = $4.7 \times 10^6 m^{-1}$ or 748 lines/mm, that corresponds to the incident Bragg angle 8 = 13.69°. The minimum measured value of sensitivity corresponds to the spatial frequency K = $16.5 \times 10^6 m^{-1}$ or 2,626 lines/mm with the incident Bragg angle 8 = 56.22°.

V. Comments and Conclusion

According to the condition imposed by Eq. (8) applied in our experimental photorefractive sensitivity characterization curve, we computed the intrinsic

parameter L_D. Comparatively, our measured value is in good agreement with the values evaluated by others, using different methods with similar experimental conditions. Trofimov and Stepanov[10] reported $L_D = 0.3\mu$m measuring the sensitivity at the beginning of the writing-erasing cycle while Stepanov and Petrov[7] reported $L_D = 0.25\mu$m, using the gain factor dependence on the spatial frequency. Both experiments in a nonstationary holographic recording in an alternating electric field employing $Bi_{12}TiO_{20}$ crystal at $\lambda = 0.633\mu$m.

In the present work we show the photorefractive sensitivity characterization of an interesting photorefractive material and determine the usual interval in the spatial frequency domain in this sample for real-time holographic technological applications.

The experimental verification of the spatial frequency response of the photorefractive material was made by exploitation of the properties of the induced anisotropic self-diffraction[9]. This procedure allows an easy implementation of the experiment. From the practical viewpoint the main feature is the easy detection of the diffraction beams by a simple control and selection of the polarization direction of the light beams[3]. The system employs the two wave mixing configuration in diffusion only operation.

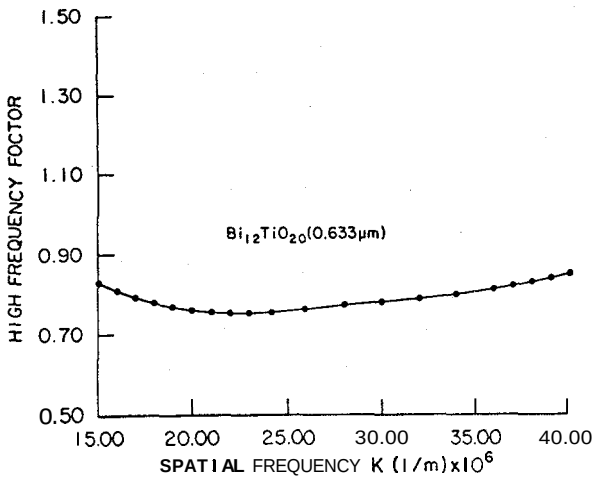

Figure 5.: High frequency factor for $Bi_{12}TiO_{20}$ crystal at $\lambda = 0.633\mu m$ using I, $= 0.042\mu m$ from Ref. 4.

We show that the sensitivity corresponding to the condition $Kl_s = 1$ is the smaller value reached in the high frequency domain. It occurs before the saturation limit of the material has been reached. There is a small variation of the sensitivity in a wide range of frequency as is ilustrated by the theoretical curve in the Figure 5. This foresight explains the experimental difficulty to determine with precision the minimum sensitivity in high spatial frequency domain. So, the measured values in this region with the holographic testing routine proposed here, cannot be used for this purpose. The system shows great diferences in the values of the sensitivity when the holographic gratings with small variations of spatial frequency are projected in the sample. This is probably due to the nearness of the limit of resolution of the material.

In summary, we show in this paper an experimental characterization of the photorefractive sensitivity by the spatial light modulation dependence of the $Bi_{12}TiO_{20}$ crystal. The holographic procedure used here is based on the anisotropic diffraction properties, within the diffusion only regime at illumination of $\lambda = 0.633\mu m$ by a low power He-Ne laser. From the experimental results we make an evaluation of the diffusion transport length L_D using the well known maximum condition $KL_D = 1$. This parameter plays an important role in real-time applications with photorefractive materials.

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