COMPLEX IMAGING OF PHOTOREFRACTIVE RECORDS

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Summary Commonly used diffraction method of photorefractive effect investigation does not give the complete information about properties of photorefractive record. Thus, the legitimate assumption arises that such a way of investigation cannot register manifestation of the all-possible mechanisms contributing to formation of the record in photorefractive medium. Therefore, the combining of various ways of registering the record is required. In order to do so, except the classical diffraction investigation of photorefractive effect we used also imaging of refractive index distribution in the record by means of interference as well as imaging the transmittance of the sample in the place of the record. This contribution also presents some results obtained by methods of photorefractive record registration mentioned above. As the photorefractive medium was used $Fe{:}LiNbO_3$ crystals.

1. INTRODUCTION

In principle, there are several ways to record optical fields. In general, for recording an optical field can be used the effect of modulation of the absorption coefficient as well as the modulation of refractive index of recording medium, respectively. In both cases one expects the figure of the change, which represents the record to be proportional to intensity of the recorded field in the given place. These ways of the record creation have some advantages and disadvantages. The disadvantages occur depending on the way we register the level of the modulation that makes the record, i.e. depending on the way we read the record. Therefore, it is very important to know what kind of the record is being investigated.

At first sight, it may be considered trivial to determine what kind of the record is dealt with. However, that is not the every case. It is so because records can be formed as a combination of refractive index modulation and modulation of coefficient of absorption, at least. Next, it might be considered trivial to find out whether the amplitude of modulation of the record we have is proportional to intensity of recorded field. At the same time, we bear in mind not only the question of the record linearity but also the question whether there is a proportionality between intensity of illumination and amplitude of modulation or proportionality between amplitude of the record and another quantity, e.g. derivative of the function describing intensity of illumination with respect to coordinate. The latter is the case of the standard model describing the origin of the record in photorefractive media [1]. As the values of the parameter depend on the character of the record in various ways it is needed to combine different ways to register the record when one wants to obtain the complex knowledge about record.

In order to achieve the complex image of photorefractive records in $Fe{:}LiNbO_3$ crystals we used not only the method based on monitoring the diffraction efficiency of created records [2] but also the imaging of refractive index distribution by means of interference [3, 4] as well as imaging the transmittance of the sample in the place of the record.

2. IMAGING BY MEANS OF DIFFRACTION OF LIGHT

Investigation of record by means of diffraction of light is effective especially when studying periodical records. As the record of light with harmonic distribution of intensity is the most often used for studying the recording process, therefore such a way of record investigation is natural and moreover, exclusively used. Periodical optical field can be very easy formed by interference of two coherent laser beams or by passing the beam of light through grating with harmonic distribution of transmittance.

In principle, whether one sees diffraction of light by the record which acts as an amplitude or phase object (grating) it can be recognized by dependence of diffraction efficiency on the amplitude of modulation. Diffraction efficiency of a harmonic amplitude grating with transmittance depending on coordinate as

$$T(x)=\frac{1}{2}\cdot\left(T_0+T_1\cdot\sin(K\cdot x)\right), \qquad (1)$$

where K is spatial frequency and $T_1 \le T_0$, grows monotonous with the level of modulation of transmittance. While dependence of diffraction efficiency of the phase grating on amplitude of modulation of phase (refractive index) is not monotonous. Fig. 1 shows the diffraction efficiencies for amplitude and phase grating as calculated from diffraction integral [5]

$$I_d(\theta,t)=I_0\cdot\left(\left|\int_S T(\xi,t)\cdot e^{i\cdot k\cdot\int_L \tilde{n}(\xi,t)dl}\cdot e^{-i\cdot k\cdot\xi\cdot\theta}d\xi\right|\right)^2, \qquad (2)$$

where $I_d(\theta,t)$ is the time dependent distribution of the light intensity formed by diffraction on the record in direction θ, I_0 is the light intensity in place of the zero diffraction order, $T(\xi,t)$ represents the modulation of transmittance and $\tilde{n}(\xi,t)$ describes modulation of the phase. In case of amplitude diffraction grating in integral (2) we have

$$\exp\left(i \cdot k \cdot \int_L \tilde{n}(\xi,t)dl\right) = 1 \cdot$$

In case of pure phase grating $T(\xi,t) = 1$.

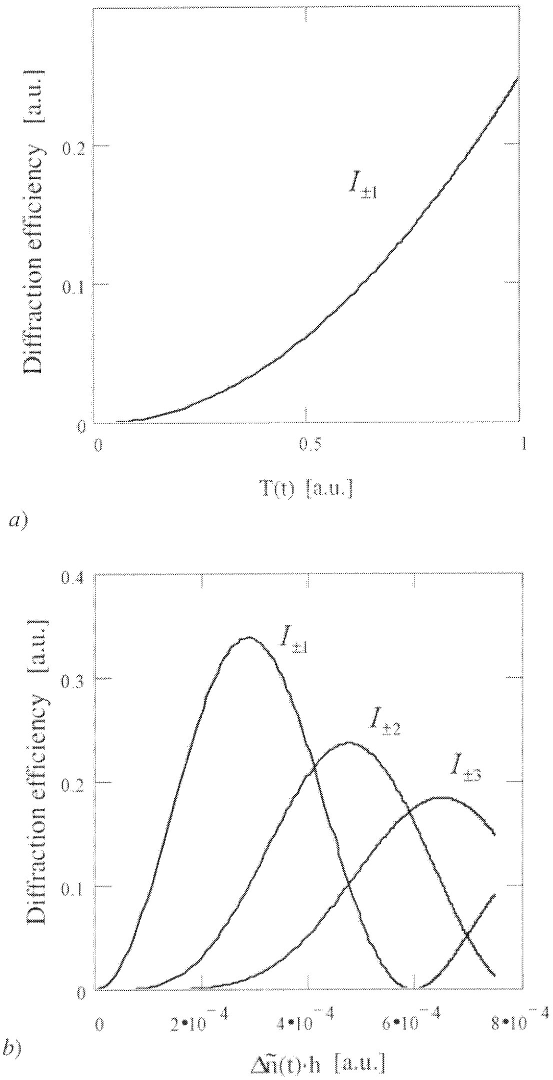


Fig. 1 *a) Diffraction efficiency of an amplitude grating in dependence on amplitude of modulation T(t).*
b) Diffraction efficiency of a phase grating in dependence on amplitude of modulation $\Delta n(t) \cdot h$.

Whether it is the case of amplitude or a phase grating (record) we cannot determine upon diffraction efficiency if we have only records with small amplitude of modulation. It is so because in both cases the dependence of diffraction efficiency on amplitude of modulation is quadratic (linear in amplitude). In addition, if we have the case record is realized by modulation of coefficient of absorption in a medium of finite thickness the situation will be even more complicated because in general, the transmittance as a function of coordinate will not be harmonic neither for harmonic modulation of coefficient of absorption. Furthermore, the coefficient of absorption can depend on illumination in two ways. Let the distribution of the intensity of light be

$$I(x) = I_0 + I_1 \cdot \sin(K \cdot x), \tag{3}$$

where $I_0 > I_1$. Using such illumination we can write for coefficient of absorption

$$\alpha(x) = \alpha_0 + \alpha_1 \cdot (1 + \sin(K \cdot x)). \tag{4}$$

This is true when the coefficient of absorption grows in all places due to illumination of the recording media. It happens when illumination causes the change of the state of the medium. For example, it could be the case of excitation of electrons (charge carriers, in general) into conduction band and consequent capture by traps (Fig. 2), which have grater cross-section for interaction with photons of illuminating light. Distribution of amplitude of reading beam after passing through the record with mentioned distribution of coefficient of absorption is

$$u(x) = u_0 \cdot \exp(-(\alpha_0 + \alpha_1(1 + \sin(K \cdot x)) \cdot h), \tag{5}$$

where u_0 is amplitude of the reading beam incident upon record, α_1 is the amplitude of modulation of absorption coefficient; h is the thickness of the medium. α is (approximately) harmonic only if $\alpha_1 << 1$.

As the α_1 enlarges during creation of the record, transmittance approaches to zero in places of maximal light intensity. For longer exposures this region enlarges and distribution of amplitude of transmittance becomes strongly anharmonic. Consequently, diffraction efficiency after reaching the maximum decreases and

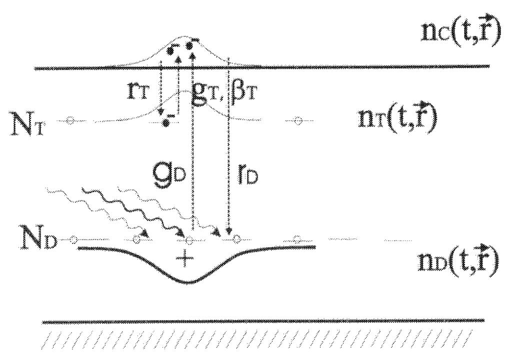


Fig. 2 Band model illustrating formation of amplitude grating by mechanism according to (4).

thus its dependence on exposure also for amplitude

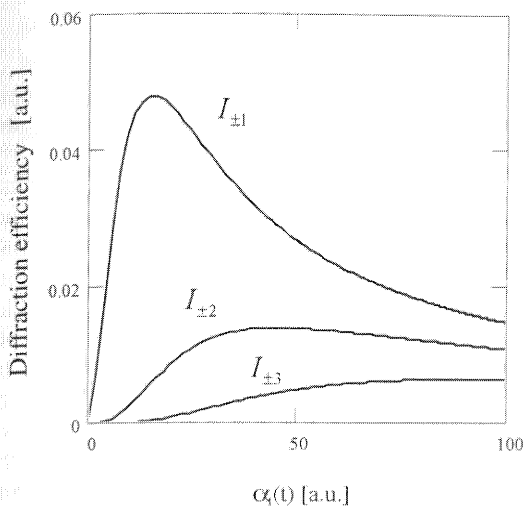


Fig. 3 *Diffraction efficiency of amplitude grating formed by modulation of coefficient of absorption according to* (4).

record is not monotonous (Fig. 3).

However, there are few mechanisms causing the absorption coefficient decreases due to illumination. This is the case, for example, when noticeable diffusion of carriers occurs in conduction band. Consequently, carriers may not be captured at the same place they were excited (Fig. 4). In this case the concentration of electrons in conduction band can be obtained from diffusion equation

$$D\frac{\partial^2 n(x)}{\partial x^2} - R\cdot n(x) = G\cdot I(x), \qquad (6)$$

where D is the diffusion coefficient, n (x) is distribution of electrons in conduction band, I (x) is intensity of illumination and G, R are generation and recombination factors, respectively. Solving equation (6) for harmonic illumination and assuming that G and R are constants (do not depend on n if induced changes of carriers concentration are small in comparison with concentration before illumination – n_0, or in comparison with concentration of empty traps) we get

$$n(x) = -\left(\frac{G\cdot I_0}{R} + \frac{G\cdot I_1}{D\cdot K^2 + R}\cdot \sin(K\cdot x)\right)\cdot \qquad (7)$$

It follows from (7)

$$\alpha(x) = \alpha_0 - \alpha_1\cdot \sin(K\cdot x), \qquad (8)$$

and one has to say there is no direct relationship between α_0 and α_1. The value of α_0 is determined by concentration of absorbing carriers before illumination

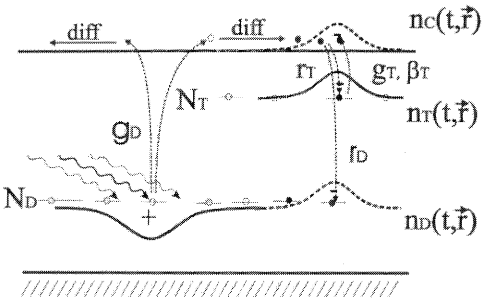


Fig. 4 *Band model illustrating formation of amplitude grating by mechanism according to* (8).

and amplitude of modulation α_1 is determined by their change induced due to illumination. It means there are some places occurred with decreased absorption. Diffraction efficiency for this case is in Fig. 5.

As can be seen from dependence of diffraction efficiency on exposure for phase grating (Fig. 1b) and amplitude grating (Fig. 1a, Fig. 3 or Fig. 5), the dependence is different. Diffraction efficiency for amplitude record possesses in the whole range of exposure one maximum at best, while diffraction efficiency for phase record (and for harmonic distribution of refractive index) is expressed by Bessel function and thus for the amplitude of modulation deep enough, reaches the maximal value several times.

However, for shorter exposures the record may not achieve such a modulation that makes the maxima of the dependence observable. In this case to score whether amplitude or phase grating is investigated, one can take into account the value of the (first) diffraction maximum for given dependence. The maximal value of diffraction efficiency for harmonic amplitude grating is 0.25 while it is 0.339 for phase grating.

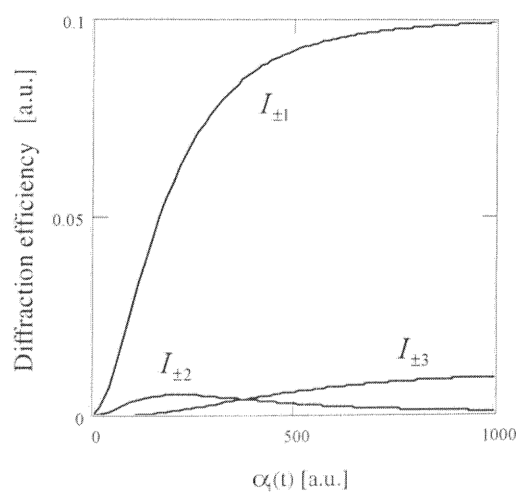


Fig. 5 *Diffraction efficiency for amplitude grating formed by modulation of coefficient of absorption according to* (8).

In a specific case, tracking the diffraction efficiency can give information that record is being formed by phase modulation along with the amplitude modulation. As shown in Fig. 1b, in case of pure phase grating exist such values of modulation for which diffraction efficiency reaches zero. This is not the case of the gratings, which are formed by combination of amplitude and phase modulation of the media. Fig. 6 shows diffraction efficiencies calculated from integral (2). Dependences are calculated for combination of phase and amplitude grating with mutual shift equal to zero (regions with maximal value of refractive index correspond to maxima of transmittance). Following, when investigating records which dependences of diffraction efficiency show existence of strong maxima and non-zero minima among them, one can expect such records to be combination of amplitude and phase grating.

It is evident from the text above that examining the

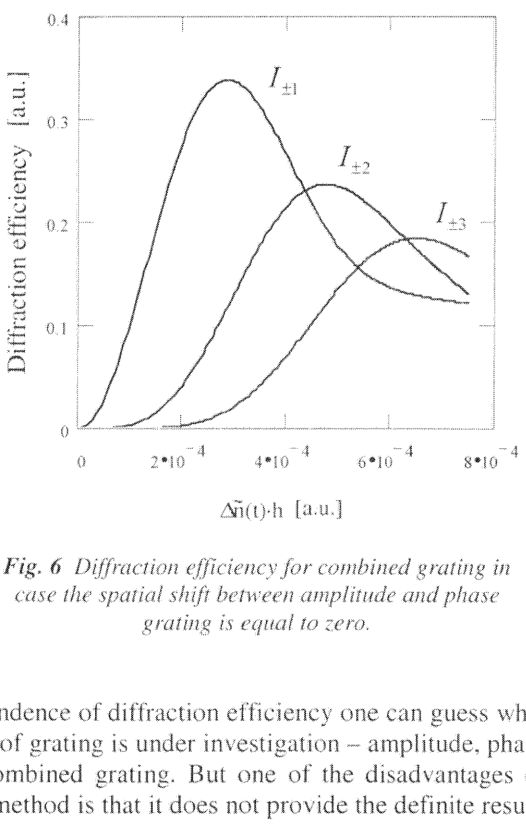


Fig. 6 *Diffraction efficiency for combined grating in case the spatial shift between amplitude and phase grating is equal to zero.*

dependence of diffraction efficiency one can guess what kind of grating is under investigation – amplitude, phase or combined grating. But one of the disadvantages of this method is that it does not provide the definite result. Another disadvantage of this method is that the intensity of diffracted beam carries information about the region containing the record (which was illuminated by reading beam) and thus, it cannot provide the information about local characteristic. It leads to fact that the shape of dependence of diffraction efficiency can inform about variability of the record amplitude but does not provide the information what is the dependence like. Moreover, it is not possible to determine from diffraction efficiency any potential spatial shift of the record. Thus, we cannot identify whether in case of harmonic record is its modulation proportional to function describing the distribution of illumination or its derivative with respect to coordinate. Hence, for complex investigation of the character of the record it is needed to add diffraction method by another methods.

3. INTERFERENCE IMAGING OF RECORDS

Imaging by means of interference of coherent light waves seems to be a suitable method for monitoring the changes in refractive index of thin, transparent materials. There is several ways possible to use interference of light waves for imaging of refractive index changes. We get the simplest way of imaging when use the interference of plane waves reflected from the front and rear surface of the thin and plane-parallel sample. Insufficient plane-parallelism of the sample makes the method hard to use. This disadvantage can be compensated to a great extent using Michelson or Mach-Zehnder interferometer (it results from design of the interferometer) – simply putting the sample into the arm of interferometer. Some advantages and disadvantages of the alternative ways of interference imaging as mentioned above is in detail discussed in [3].

As it was convenient our investigation of photorefractive records in Fe:LiNbO$_3$ crystals was based on using the Mach-Zehnder interferometer (Fig. 7).

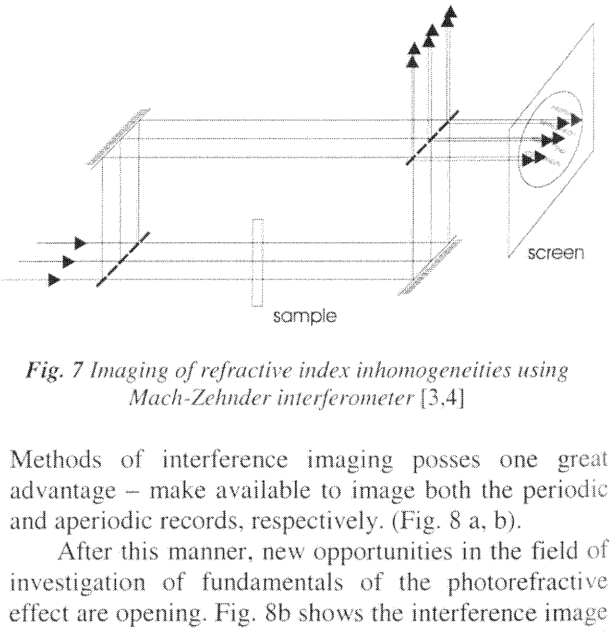
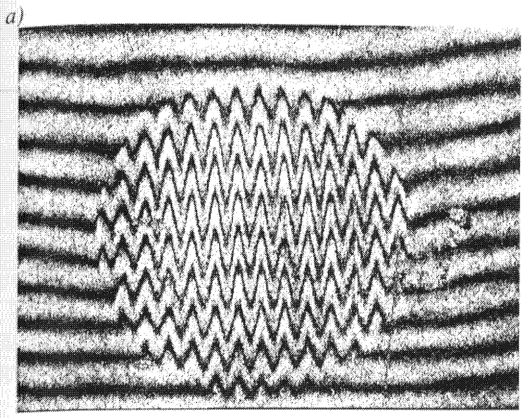


Fig. 7 *Imaging of refractive index inhomogeneities using Mach-Zehnder interferometer* [3,4]

Methods of interference imaging posses one great advantage – make available to image both the periodic and aperiodic records, respectively. (Fig. 8 a, b).

After this manner, new opportunities in the field of investigation of fundamentals of the photorefractive effect are opening. Fig. 8b shows the interference image of photorefractive record formed in Fe:LiNbO$_3$ crystal that is 1 mm thick. Recorded is the field, which was created by illuminating the slit 0.6 mm thick. As a source of light we used beam from Argon ion laser ILA 120 operating at a 488 nm. The intensity of the beam incident upon the crystal was about 10 mWmm^{-2} and recording time was 10 minutes. After that, we put the crystal with record into one arm of Mach-Zehnder interferometer and illuminated it by He-Ne laser. In order to illuminate also the further vicinity of the record we enlarged the diameter of the He-Ne laser beam using an optical expander.

a)



b)

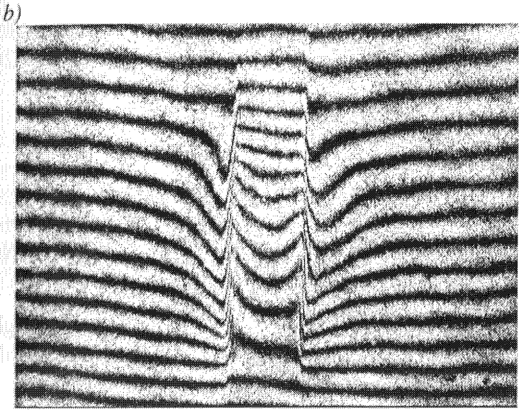


Fig 8 a) Interference image of the record of periodic optical field with period 150 μm. Optical field was delimited by circular aperture with diameter 2 mm during recording. b) Interference image of aperiodic field, which is realized by illuminating the 0.6 mm thick slit.

The result obtained from interference imaging of such a record is rather surprising. It is evident at first sight that distribution of refractive index in the region of the record does not correspond with distribution one can expect in case the modulation of refractive index in record is due to electrooptic effect [1, 6, 7, 8]. The character of distribution observed in our case is more like spatial distribution of the charge carriers caused by inhomogeneous illumination. This fact requires revaluating fundamental ideas about mechanism of photorefractive effect.

Exploiting the properties of Mach-Zehnder interferometer that follow from its design (ability to adjust the density of interference fringes and aligning them with respect to created refractive index inhomogeneity) and character of the aperiodic record, we can recognize the sign of the refractive index change in the place of the record. In order to do so, it is enough to review the interference image of known "perturbation". We have realized such a perturbation by means of a little spot of edible gelatine applied on a thin glass plate (Fig. 9).

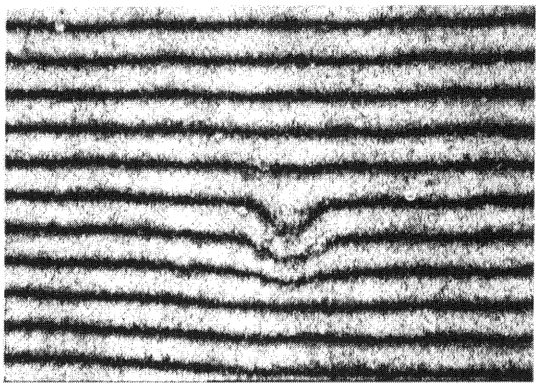


Fig. 9 Interference image of refractive index inhomogeneity that is realized by thin layer of gelatine applied on 1 mm thick glass plate.

We found out by help of this procedure the refractive index inside the illuminated region is lower than outside the region.

4. IMAGING THE TRANSMITTANCE

In principle, whether record is realized by phase or amplitude grating, one can find out also using the imaging of transmittance distribution. With convenience, it can be done by taking picture of the sample containing the record while there is a light source behind the sample illuminating the record (Fig. 10a). Another way is to use a small detector (or optical fibre and detector) and make a record of distribution of intensity of light that passes through the sample (Fig.

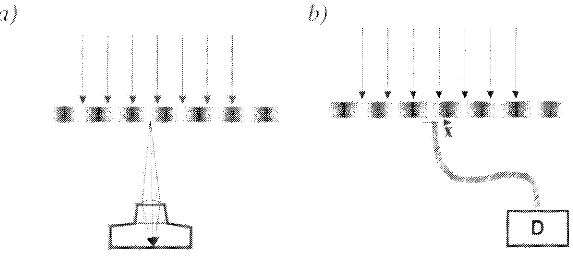


Fig. 10 Experimental set-up for imaging the amplitude record by taking pictures a) and using raster scanning b).

10b). At the same time we get also the distribution of transmittance.

In case the record is made by modulation of phase the amplitude of light after passing through sample does not depend on coordinate (homogeneous illumination is used and light is detected just behind the surface of the sample). In that case the picture would show homogeneous distribution of intensity of light. In case of amplitude record the amplitude of the light intensity would change depending on position.

However, when interpreting such records we have to be careful because also in case of phase grating one can get the distribution with variable amplitude. It will happen if we register the field distribution in the plane that is at a finite distance far from the surface of the sample. This will be due to interference of waves created by diffraction on the record (Fig. 11).

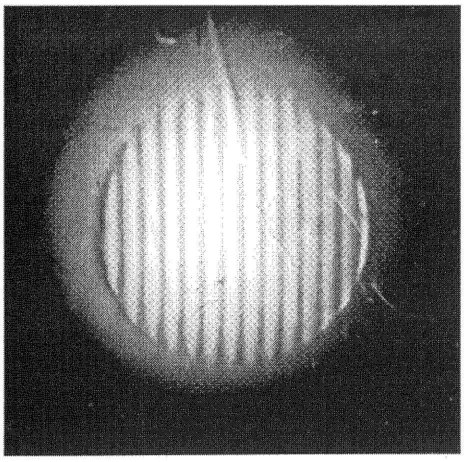


Fig. 11 *A photograph of the record of periodic field with period as great as 150 μm in 1 mm thick Fe:LiNbO$_3$ crystal*

On the other hand, in case of amplitude records (and inadequate illumination) we may not get the image of the record. The reason is that the amplitude of light after passing through the sample depends on integral of coefficient of absorption along the path of the beam. Thus, for example in case of an oblique incidence of light on periodical record (depending on one coordinate, only) we can get the homogeneous illumination. It will happen just in the moment when obliquely incident beam travels through integer number of periods of the record (Fig. 12.).

It follows from the text above that by imaging the

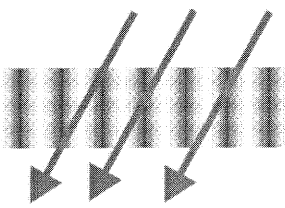


Fig. 12 *Illustration of the direction of illumination for case when information about modulation of absorption in recording medium is lost.*

field in the plane directly behind the planar record (i.e. infinitely thin record) one is able to determine whether amplitude or phase record is treated.

5. CONCLUSION

Analysing the properties of diffraction investigation, interference and amplitude imaging of optical field records show that none of discussed methods give complete information about properties of the record. In spite of this the most of works devoted to investigation of photorefractive records and the properties are limited to monitoring diffraction efficiency of created record [e.g. 9]. The consequence of such an incomplete investigation may be incorrect interpretation of the process of record creation as it is in case of description of the origin of records due to photorefractive effect. Images of photorefractive records used in this contribution show that records (modulation of refractive index of the medium) correspond to distribution of charge carriers and not to distribution of intensity of electric field that arises from those charges. It means the commonly used interpretation of photorefractive effect [1, 2, 10, 11] is not correct.

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