THE GENERATION OF HIGHER ORDER DIFFRACTION BEAMS BY PHOTOREFRACTIVE RECORD OF HARMONIC OPTICAL FIELD

N. Tarjányi, I. Turek

University of Žilina, Department of Physics, Veľký Diel SK-01 026 Žilina, Slovakia

Summary There are some results of investigation of photorefractive record of interference field created by two planar waves of Ar laser (488 nm) in LiNbO3:Fe presented in this work. Such record behaves as a phase diffraction grating. The time dependence of diffracted beam intensity informs about process of record creation. To read this record a weak beam of He-Ne laser (632.8 nm) was used. During recording and erasure process of the record, the intensities of the zero and intensities of higher orders on both sides of reading beam were detected. Experimentally obtained time dependences of intensities of diffracted beams were compared with dependences following from diffraction integral for harmonic phase grating. Quite small differences between measured and calculated dependences occurred. The differences show that there are some non-linear processes taking place at the record creation.

1. INTRODUCTION

A great number of papers have been addicted to existence of photorefractive effect (PRE) in $LiNbO_3$ crystals since its discovery in 1966 [1]. The reason is that the effect finds out the wide range of applications in different fields of technics, e.g. fabrication of optical filters [2, 3] or various diffraction components [4], but probably the most extended is the use in designing the hologram memories [5, 6, 7]. However, the interest in $LiNbO_3$ holds over also because of the unique combination of certain physical properties. The crystal is ferroelectric, pyroelectric and piezoelectric material with large electrooptic, acustooptic and photo elastic coefficients and shows the strong photorefractive and photovoltaic effect, too [8]. By doping with different impurities of various concentrations, it is possible to influence the properties of the crystal.

Due to recently developed technology, it is getting on to grow crystals with low concentration of intrinsic defects. It results in changing of some properties of the crystal. Such a $LiNbO_3$, called stoichiometric behaves rather different in comparison with the congruent $LiNbO_3$ although they are examined at the same external conditions [8]. It opens the door to basic research as well as to applied one.

2. EXPERIMENTAL STUDY OF PRE

The $LiNbO_3$ crystal doped with iron is being regarded as rather sensitive photorefractive material. That was one of the reasons we used just $LiNbO_3$:Fe to study the photo refractivity. Manufacturer (Crytur, Ltd., Turnov, Czech Republic) specifies the concentration of Fe in crystal by value 400 ppm. For experimental investigation, we used *y*-cut crystals ($10x10x1mm^3$) with polished surfaces.

Results of investigation were obtained by holographic method using the experimental setup the schematic drawing of which is shown in Fig. 1.

The arrangement consists of an Argon ion laser (*Ar L*) ILA 120-1, He-Ne laser (reading beam), optical beam splitter (*BS*), totally reflected prism (*P*), sample holder (*SH*), converging lens (*L*), filter (*F*), detectors (*D1*, *D2*), digital voltmeter (*DV*) to see the signal immediately and computer registering measured data (*PC*).

In order to suppress the in-homogeneity of the

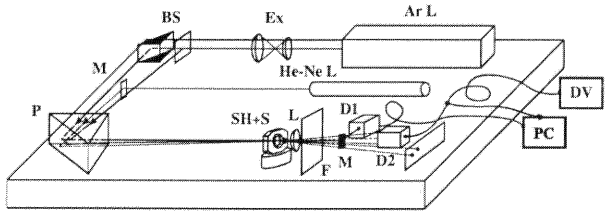


Fig. 1. Experimental setup.

optical field (Gaussian distribution of intensity in beams) we used the optical expander (*Ex*) expanding the diameter of the beam outgoing from Ar laser as much as twice of the reading beam diameter. Beam splitter divides the beam of Ar laser with intensity I into two parts I_O and I_R with ratio I_O/I_R =2/1. The state of polarization corresponds to an extraordinary beam in the sample. By tilting the semitransparent mirror, (that is a part of the beam splitter) one achieves the beams cross each other at a certain distance from the beam splitter. In the region of the overlapping, the optical field with harmonic dependence of coordinate is created. This is the consequence of the interference of two, mutually phase-shifted waves created by beam splitter from the original one wave coming out from the Ar laser:

$$I(\vec{r}) = I \cdot \left(1 + m \cdot \sin\left(\vec{K} \cdot \vec{r}\right)\right), \qquad (1)$$

where $I = I_O + I_R$ and $m = 2 \cdot \sqrt{I_O \cdot I_R} / I_O + I_R$ is the contrast of formed interference field.

In the space of existence of interference field the sample holder with crystal $LiNbO_3$:Fe is located.

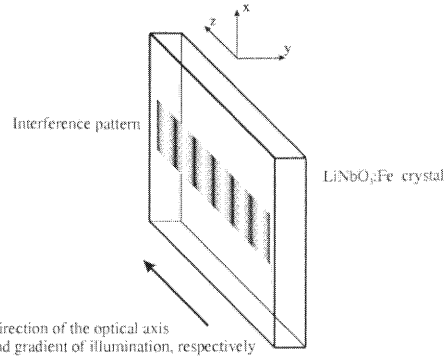


Fig. 2. Geometry in the place of the sample seating.

The crystal is oriented so that its optical axis is parallel to gradient of illumination (Fig. 2).

The choice of geometry mentioned above follows from the mechanism that causes photo refractivity. Due to in-homogeneous illumination of crystal by light with the proper wavelength charge carriers (electrons, eventually holes) are excited into the conduction (eventually valence) band. There they can diffuse and be recaptured by initial level or by another level (traps) in the band gap. This is how the spatial redistribution of the charge concentration originates. Along with the redistribution of charges, the electrostatic field inside the crystal is creating and growing up. The electric field then via the electrooptic effect induces the change of refractive index in the illuminated part of the crystal. Light induced change of refractive index represents the record of the optical field.

The magnitude of the refractive index change is proportional to electric field. As the crystal is an anisotropic material, the magnitude of the change will depend not only on the size but also on the direction of the electric field acting. The change of refractive index is described by the change of the impermitivity tensor:

$$\Delta\overline{\overline{\boldsymbol{B}}}\left(t,\vec{r}\right)=\Delta\left(1/\left(n\left(t,\vec{r}\right)\right)^2\right)_{ij},\ i,j=1,2,3.$$

In addition, in case of electrooptic effect we can write:.

$$\Delta\overline{\overline{\boldsymbol{B}}}\left(t,\vec{r}\right)=\overline{\overline{\boldsymbol{r}}}\cdot\vec{E}\left(t,\vec{r}\right), \qquad (2)$$

where $\overline{\overline{\boldsymbol{r}}}$ is the tensor of electrooptic coefficients and n represents the refractive index of material. As the r_{33} is the biggest of all coefficients, it is convenient to use such a cut of the crystal and geometry of experiment, that electric field will act along the optic axis (z axis) of the crystal.

During process of writing the record of interference field formed by two plane waves, these primary beams are diffracted. The record consisting of the region with periodic change of refractive index behaves as the phase diffraction grating with the time-dependent amplitude of modulation of optical path. The information about the amplitude one can obtain by analyzing the time dependence of the diffracted beam intensity as well as from the number of observable diffraction orders. The optical wave reading the record may be one of the two waves participating in the process of record writing (self diffraction) or the third, independent optical wave (reading beam).

In case, the record is created in a relatively thick crystal it can behave as the volume phase grating. If we use one of the beams creating record to read the record, analogue as in case of volume hologram we will see the change of intensity of conjugated diffraction orders. This will occur even though the optical field with harmonic distribution is being recorded.

If such a beam is used to read the record, the to two-wave mixing may occur. One can register this effect by flowing the power from one beam to the other. The effect is well known when studying volume holograms created in photorefractive materials [9, 10] and can lead to an amplification of the holographic record [11]. In our case, these effects would mean a considerable complication when investigating the processes of the photorefractive record formation.

Therefore, it is more adequate to use the light source with different wavelength to read the record and rearrange the geometry such, that the reading beam outgoing from the new source would perpendicular to the surface of the crystal.

To read the record in process of its formation we therefore used He – Ne laser (632.8 *nm*) (*He-Ne L*, Fig.1). Because there is no simple way to let the reading beam be perpendicular to the surface and do not change the geometry of experiment at the same time, we let the beam of He-Ne laser contain an angle with the normal of the sample in vertical plane. (In case of self-diffraction, there is an angle between interference fringes and reading beam lying in the horizontal plane).

It is well known that the record of non-homogeneous optical field can be erased by applying the homogeneous light (with the proper wavelength). As the light from He-Ne laser is able to create (then also erase) an optical record in $LiNbO_3$ crystals (although with low efficiency than it is in case of Ar laser), we used the intensities of reading beam as low as no observable erasure was present during whole exposure.

Investigating photo refractivity in $LiNbO_3$:Fe we used to record the interference field with period about 60 μm. The intensity of beams lettered I_O and I_R of Ar ion laser forming this field was approximately 3.5 mW/mm^2 and 2.1 mW/mm^2, respectively. The intensity of reading beam was in range (0.1 – 0.2) mW/mm^2 and the state of polarization of the beam corresponded to the extraordinary one. Using beam with this polarization the coefficient r_{33} is employed and consequently it leads to the maximal change in extraordinary refractive index of the crystal.

To read the intensities of the waves generated by diffraction on the record during the process of its creation we used two detectors with approximately identical properties (Fig. 3).

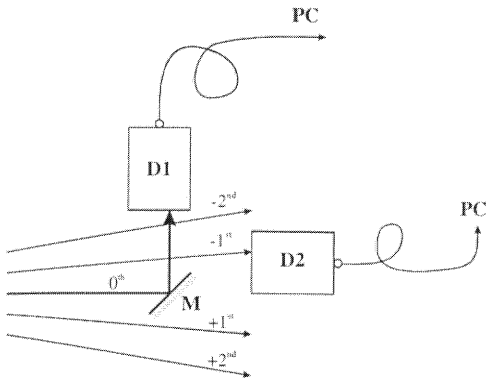
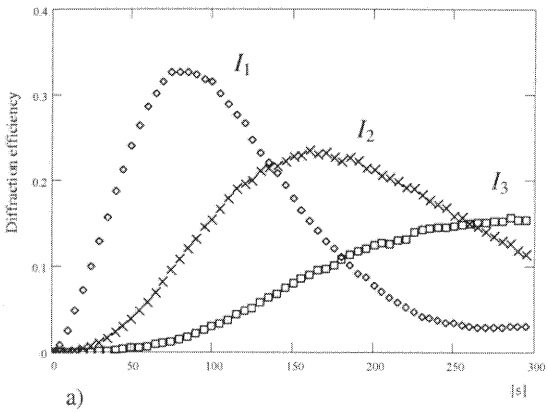
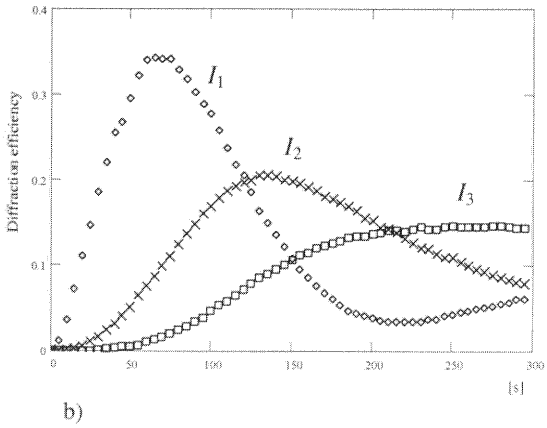


Fig. 3. Position of detectors.

Detector $D1$ scanned the intensity of the zero order and detector $D2$ scanned the intensity of the $\pm 1^{st}$, $\pm 2^{nd}$ and $\pm 3^{rd}$ diffraction orders accordingly its location. Accordingly, we could estimate the diffraction efficiency of measured diffraction orders (Fig. 4).



a)



b)

Fig. 4. The diffraction efficiency of -1^{st}, -2^{nd}, -3^{rd} diffraction maximum a) and $+1^{st}$,$+-2^{nd}$, $+3^{rd}$ diffraction maximum b) as the function of time.

Throughout those years we pay attention to field of photorefractive effect [12, 13], we have made hundreds of records. We have found out that the reproducibility of the measurements is about 85% - 90%. We can also say that the error of measurement is virtually the same and it does not depend on whether we create a new record whenever want to read the intensity of the couple of diffraction orders continuously or we create one record interrupted and we scan the intensity of desired higher orders during each interruption.

3. THE RECORD OF INTERFERENCE FIELD AS AN HARMONIC PHASE GRATING

When reading the record of the interference field formed by two plane waves in $LiNbO_3$:Fe crystal during its creation we observe not only the first order but also higher diffraction orders. The intensity of the r^{th} order as function of time depends on the character of $n(t,\vec{r})$ that is on the distribution of refractive index in time and space in region where the record is being located.

If we consider a distribution of refractive index as the harmonic function of coordinate, the intensity of the diffraction orders depending on the amplitude of modulation is expressed by the square of the Bessel function of the order r. The order of the Bessel function corresponds to order of diffraction. (Fig. 5).

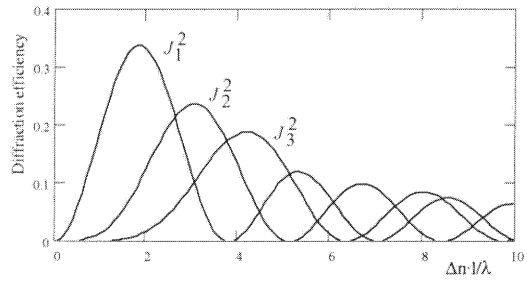


Fig. 5. Bessel functions representing the intensities of the first three diffraction maxima as function of amplitude of refractive index modulation. l is the thickness of the sample, λ is the wavelength of the recording light.

It can be shown [9] that amplitude of refractive index modulation during recording grows by the exponential law with τ as the time constant. If we consider the harmonic phase grating, for which the intensity of diffraction orders as the function of amplitude of refractive index modulation expresses the Bessel function of the relevant order, one can calculate the time dependence of the intensity of the desired diffraction order (Fig. 6).

By fitting the calculated curves on measured dependencies, one can obtain the amplitude of the refractive index modulation (amplitude of the record) as well as the time constant of the record formation. (Fig. 6, Fig. 7 and Tab.1).

The accuracy of these parameters depends on the match between calculated and measured dependencies.

In this case the dispersion of the values Δn and τ is caused besides the fluctuation of the power of laser source during the whole exposure time, also by the fact that in order to measure the intensity of the higher orders we created the new record on the non-illuminated place in the crystal. It means that each diffraction order in Fig. 6 and Fig. 7 belongs to different optical record. Nevertheless, all records were created at the same conditions.

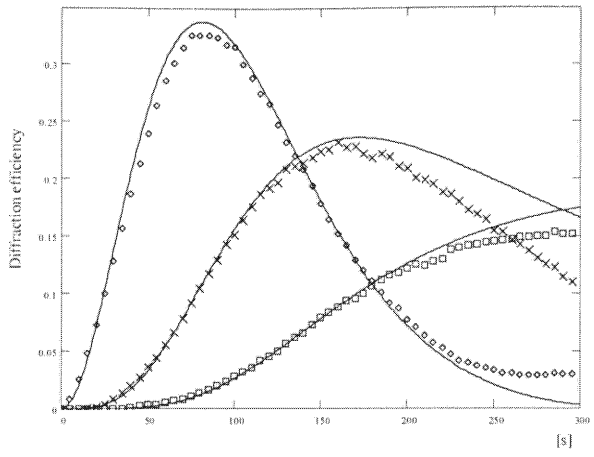


Fig. 6. Calculated —— and measured intensities of the -1^{st} (◊), -2^{nd} (x) and -3^{rd} (□) diffraction order as function of time.

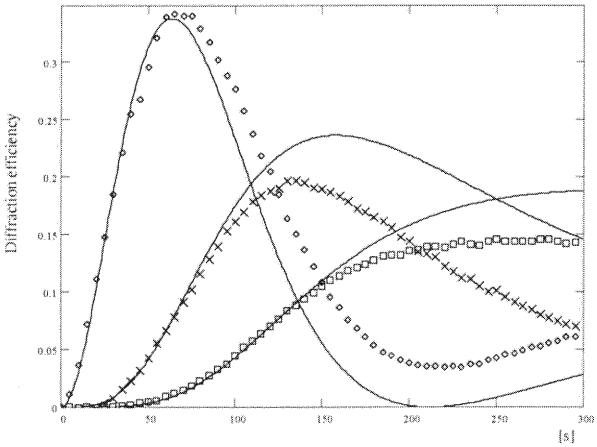


Fig. 7 Calculated —— and measured intensities of the $+1^{st}$ (◊), $+2^{nd}$ (x) and $+3^{rd}$ (□) diffraction order as function of time.

Tab.1.

Diffraction order	$+1^{st}$	$+2^{nd}$	$+3^{rd}$	-1^{st}	-2^{nd}	-3^{rd}
Δn ($x10^{-4}$)	7.4	6.8	7.1	6.5	6.7	6.7
τ [s]	130	132	130	140	140	140

4. CONCLUSION

During recording of interference field formed by two plane waves in $LiNbO_3$:Fe crystal we have observed except the first order also generating of high-order diffraction. The time dependencies of the first three orders were compared with calculated one for the harmonic phase grating. We got a good matching only in the region of short exposures. The longer exposure, the worse is matching. It means the record of the optical field with harmonic dependence on coordinate is not a harmonic phase grating for the whole duration of exposure. It is interesting to note that even if being in region of the short exposure (harmonic phase grating), there are observable also higher diffraction orders. It is in a contrary to an amplitude grating with harmonic distribution of transparency. The simple fitting of calculated dependencies on measured one allows to estimate the amplitude and the time constant of the record formation. The deviation between measured and calculated curves says there is an existence of nonlinear processes.

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