tainty in determining either of \( K \) and \( J_0(\xi) \). This treatment gives value of \( J_0 = 149.8 \text{ mT} \), providing the best fit for \( \eta = 0.18 \), and as final result \( J_0 = 150.2 \text{ mT} \). This is close to the value of 165 \text{ mT} as measured on the reference sphere by a vibration magnetometer method, see accompanying paper [J. Franek, R. Dosoudil, M. Ušaková] at this conference.

In Table 2 are calculated values of saturation magnetic polarization according above to presented method using (1) to (5).

<table>
<thead>
<tr>
<th>( J_0(\xi) ) (mT)</th>
<th>( J_0^{(1)} ) (mT)</th>
<th>( J_0^{(2)} ) (mT)</th>
<th>( J_0^{(3)} ) (mT)</th>
<th>( J_0^{(4)} ) (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.23</td>
<td>40.8</td>
<td>39.9</td>
<td>40.4</td>
<td>40.4</td>
</tr>
<tr>
<td>0.47</td>
<td>79.7</td>
<td>78.6</td>
<td>78.5</td>
<td>78.5</td>
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<tr>
<td>0.54</td>
<td>83.0</td>
<td>78.9</td>
<td>71.0</td>
<td>80.9</td>
</tr>
<tr>
<td>0.63</td>
<td>86.1</td>
<td>69.9</td>
<td>91.5</td>
<td>91.3</td>
</tr>
<tr>
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<td>101.5</td>
<td>101.3</td>
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</tr>
<tr>
<td>0.80</td>
<td>129.2</td>
<td>128.3</td>
<td>127.2</td>
<td>127.2</td>
</tr>
<tr>
<td>1.00</td>
<td>150.5</td>
<td>149.8</td>
<td>150.2</td>
<td>150.2</td>
</tr>
</tbody>
</table>

Note that (1) would assures \( J_0^{(2)} \) and \( J_0^{(3)} \) to be exactly the same values if instead of \( (B_0) \) rather \( B_0 \), was used in (2).

6. DISCUSSIONS AND CONCLUSIONS

Measurement of the reference ferrite sintered sample (a small ball with 100% filling) gave higher value \( B_0 = 312.2 \text{ mT} \) than should be expected, cf Tab.1. This sample prepared by grinding for hours in a ball mill may not be even a body of rotation, however, its aspect ratio 1.22 nearly corresponds to that of 1.12 at which this difference could be assigned to the ball demagnetising factor providing the bias field was directed along its shorter dimension. Since it is difficult to glue the ball with required orientation – a better solution is to master a "shift" allowing rotate the sample under measurement.

Another issue is the filling at least from two aspects: (i) it is troublesome to have prepared capsules with a higher filling factor – this can be circumvented by the described measurement method as far as the prediction of its properties is in question, (ii) the distribution of the powder particles and interactions of their aggregates are important, as well as how are they reflected in properties of the capsule (or another shape of the sample as a sheet etc.).

The measurement showed that something is likely be happening around from 0.5 < \( \xi < 0.7 \), as implied by the rippling character of the upper curve in Fig.5. The ferromagnetic resonance is influenced by internal magnetic field and this is highly affected not only by the shape of the sample but also the possible internal aggregates and their mutual interactions may play an important role. To certain extent the discrepancies or deviation from a straight line may explained by the surface roughness of capsules, particularly those with higher content of the ferrite powder.

We found interesting that the lower branch seems better to fit then the upper does, in spite of the lower absolute values. It seems plausible that there are quite different interactions to be expected in the respective positions. Much more "neighbours" may be found in position 2 (than in 1) in the direction along the wavelength and the field at the sample edges is different as depends on \( \xi \), co-ordinate.

The main goal of this approach was, however, not to attempt find a way how to determine the values of \( J_0 \) (since other methods are magnetic are as well cumbersome if using not homogenously magnetized samples) but also to get some information about the microwave properties of a "capsule" as prepared. By other words – to get evidence about \( \xi \) features of different compositions what is definitely not a simple question of the ferrite volume fraction in a polymer matrix due to the interactions of individual powder particles and their assemblies.

Acknowledgement

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REFERENCES


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

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Summary

There are some results of investigation of photorefractive effect of lithium niobate (LiNbO3) presented in this work. Such effect behaves as a phase diffraction grating. The time dependence of diffraction beam intensity informs about process of record creation. To read this record a weak He-Ne laser (632.8 nm) was used. During recording and erasure process of the record, the intensities of the zero and higher orders of both sides of recording beam were detected. Experimentally obtained time dependences of intensities of diffraction 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 added to existence of photorefractive effect (PRE) in LiNbO3, 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 LiNbO3 holds over also because of the unique combination of certain physical properties. The crystal is ferroelectric, pyroelectric and piezoelectric material with large electrooptic, acoustooptic 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. Thus, random sensitive photorefractive material. That was one of the reasons we used just LiNbO3: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 \( \eta \)-cut crystals (10x10x1mm) 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.

Fig. 1 Experimental setup.

The arrangement consists of an Argon ion laser (Ar L) I1A 120-1, He-Ne laser (reading beam), optical beam splitter (BS), totally reflected prism (P), sample holder (SH), converging lens (f 1, f 2, f 3), detectors (D), digital voltmeter (DV) to see the signal immediately and computer registering measured data (PC). In order to suppress the in-homogeneity of the optical field (Gaussion 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 \( \eta \) into two parts I1 and I2 with ratio \( \eta/I_2 = 2/1 \). 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: \( \eta(I) = 1 \cdot I_1 + m \cdot \sin (k \cdot x) \), (1)

where \( I = I_1 + I_2 \) and \( m = -2 \cdot \sqrt{I_1 / I_2} \cdot \sin (k \cdot x) \) is the contrast of formed interference field.

In the space of existence of interference field the sample holder with crystal LiNbO3: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 the gradient of illumination (Fig. 2).

The choice of geometry mentioned above follows from the mechanism that causes photo refractivity. Due to inhomogeneous 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 initial 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 impermeability tensor:

$$\Delta n(r) = \epsilon_0 \left( \epsilon(r) - 1 \right) \hat{r}$$

where $\epsilon$ is the tensor of electrooptic coefficients and $\epsilon_0$ represents the refractive index of material. $\epsilon_0$ 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, analogously 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 two-ray 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 hologram 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 be 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 LiNbO₃ 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 LiNbO₃Fe we used to record the interference field with period about 60 μm. The intensity of beams lettered I₀ and Iₐ of Ar ion laser forming this field was approximately 3.5 mW/mm² and 2.1 mW/mm², respectively. The intensity of reading beam was in range (0.1 - 0.2) mW/mm² and the state of polarization of the beam corresponded to the extraordinary one. Using beam with this polarization the coefficient $\epsilon_0$ 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).

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

When reading the record of the interference field formed by two plane waves in LiNbO₃:Fe crystal during its creation we observe not only the first order but also higher diffraction orders. The intensity of the $p$th order as function of time depends on the character of $n_0(\epsilon(r))$ 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. In the thickness of the sample, $A$ is the wavelength of the recording light.](image)

It can be shown [9] that amplitude of refractive index modulation during recording grows by the exponential law with $\tau$ 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 dependences, 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 dependences. In this case the dispersion of the values $A$ and $\tau$ 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.
The crystal is oriented so that its optical axis is parallel to the paper's axis of illumination (Fig. 2).

The choice of geometry mentioned above follows the mechanism that causes photo refractivity. Due to inhomogeneous illumination of crystal by light with the proper wavelength, light charges 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 permittivity tensor:

$$\Delta \varepsilon(x, y) = \frac{\varepsilon(x, y) - \varepsilon_0}{\varepsilon_0}, \quad i, j = 1, 2, 3.$$  

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

$$\Delta \varepsilon(x, y) = \frac{\varepsilon(x, y) - \varepsilon_0}{\varepsilon_0} = \frac{\sigma(x, y)}{\varepsilon_0},$$

where \( \varepsilon \) is the tensor of electrooptic coefficients and \( \alpha \) represents the refractive index of material. If the \( \varepsilon_0 \) 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 (2 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

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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 LN00 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 LN00:Fe crystals we used to record the interference field with period about 60 \( \mu m \). The intensity of beams lettered \( I_0 \) and \( I_0 \) of Ar ion laser forming this field was approximately 3.5 mW/cm\(^2\) and 2.1 mW/cm\(^2\), respectively. The intensity of reading beam was in range (0.1 – 0.2) mW/cm\(^2\) and the state of polarization of the beam corresponded to the extraordinary one. Using beam with this polarization the coefficient \( \bar{\rho} \) 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).

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 in transmission is virtually the same and it does not depend on whether we record 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 LN00:Fe crystal during its creation we observe not only the first order but also higher diffraction orders. The intensity of the \( L \) order as function of time depends on the character of \( \varphi(x, y) \) 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 \( \alpha \). The order of the Bessel function corresponds to order of diffraction (Fig. 5).

It can be shown [9] that amplitude of refractive index modulation during recording grows by the exponential law with \( \tau \) 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 \( a_i \) and \( \tau \) is caused neither by 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.
INTERFERENCE IMAGING OF REFRACTIVE INDEX DISTRIBUTION IN THIN SAMPLES

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Summary There are three versions of interference imaging of refractive index distribution in thin samples suggested in this contribution. These are based on imaging of interference field created by waves reflected from the front and the back sample surface or imaging of interference field of Michelson or Mach-Zehnder interferometer with the sample put in one of the interferometer’s arms. The work discusses the advantages and disadvantages of these techniques and presents the results of imaging of refractive index distribution in photorefractive record of a quasi-harmonic optical field in thin LiNbO$\text{3}$ crystal sample.

1. INTRODUCTION
There are some situations when it is needed to know the refractive index distribution in material under investigation. This is the case not only of controlling the technology of different crystals preparation but also the case of the studying the mechanisms being responsible for creation of different fields records in transparent materials. The interference imaging of refractive index appeared to be suitable for these objectives, namely if the imaging of the refractive index distribution in thin samples is of the interest.

In presented contribution, there are described in brief three versions of such imaging characterized by sufficient sensitivity and especially simplicity. This allows their use also in less equipped laboratories.

2. IMAGING BY INTERFERENCE OF WAVES REFLECTED FROM THE FRONT AND BACK SURFACE OF THE SAMPLE

We get the simplest imaging of refractive index distribution in plane waves reflected from the front and back surface of the thin and (at least approximately) plane-parallel sample. The basic setup of mentioned kind of imaging is shown in Fig. 1.

Several hundreds of millimeter, it is convenient to use laser light source to warrant the sufficient coherency of reflected waves [1]. When the diameter of the area to be displayed is larger than cca 2 mm, it is needed to append an optical expander to the laser source.

When using homogenous and plane-parallel sample, then the interference field is also homogenous. However, if there is a non-homogeneity characterized by changed value of refractive index of the sample, homogeneity of the interference pattern will also disturb. This is because the waves that pass through the sample in-homogeneity will be phase-shifted with respect to waves reflected from the front surface of the sample. The in-homogeneities that induce the phase shift of the wave reflected from the back surface of the sample greater than $2\pi$ will be shown by emerging of interference fringes.

When in-homogeneities of refractive index are small, or strictly speaking, if the dependence of refractive index on coordinates perpendicular to z-axis is slight, the existence of in-homogeneity will only slightly affect the direction of the beam reflected from the backside of the sample (z is the direction of light propagation and the direction of the normal to the surface of the sample, together). The layout of the interference fringes (distribution of the phase difference of the interfering waves) in the plane of the screen is then the direct image of the refractive index distribution in the sample. The difference in values of refractive index of places position of which corresponds to adjacent interference fringes is then

\[ \Delta n = \pi \ell / d, \]

where $d$ is the sample thickness.

The direct relation between interference field distribution and refractive index can only be expressed in the case when the refractive index doesn’t depend on coordinate $z$. In the opposite case only average value of refractive index change can be read from interference field distribution.

If the front and backside of the sample were planar but not parallel, the interference pattern would contain parallel interference fringes which density depends on the angle between these two surfaces. The existence of

![Fig. 1. A scheme of interference imaging by reflection from the front and back surface of the sample.](image)

4. CONCLUSION
During recording of interference field formed by two plane waves in LiNbO$\text{3}$:Fe crystal we have observed except the first order also generating of high-order diffraction. The time dependencies of the first three orders were computed 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.

REFERENCES