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 arm.

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 $LiNbO_3$ 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 by means of interference of 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

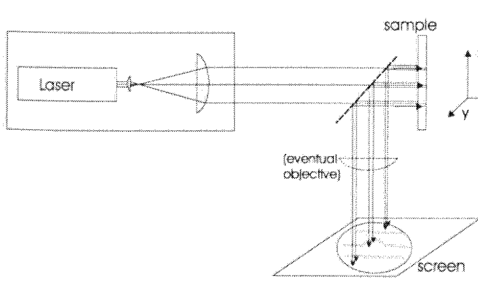

Fig. 1. A scheme of interference imaging by reflection from the front and back surface of the sample.

Fig.1. It consists of the plane wave source, semitransparent mirror, sample under test and the screen. In the case, the investigation of refractive index changes is focused on the small region of the sample it is convenient to use an objective for displaying the interference pattern with appropriate magnification. While investigating samples with thickness greater than several hundredths 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 homogeneous and plane-parallel sample, then the interference field is also homogeneous. 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 2π 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 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

$$\Delta n = \pi / d ,$$

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 potential in-homogeneities of refractive index causes an change of the interference fringes shape.

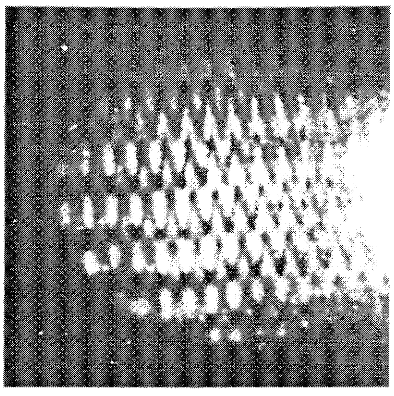

Fig. 2. An image of photorefractive record of the periodic optical field in $LiNbO_3$:Fe crystal. Thickness of the sample is 1mm. The period of the record is cca 0.1 mm.

The Fig. 2 shows how the change of refractive index affects the shape of the interference pattern. The pattern comes from the sample of $LiNbO_3$:Fe with slightly non-parallel front and back surfaces. The refractive index was changed by creation of photorefractive record of periodical (harmonic) optical field.

2.1. Imaging by interference of waves using an interferometer

Using an analogous way we can obtain the imaging of refractive index distribution in thin sample when it is put into one of the arms of Michelson or Mach-Zehnder interferometer (Fig. 3. and Fig. 4., [2]).

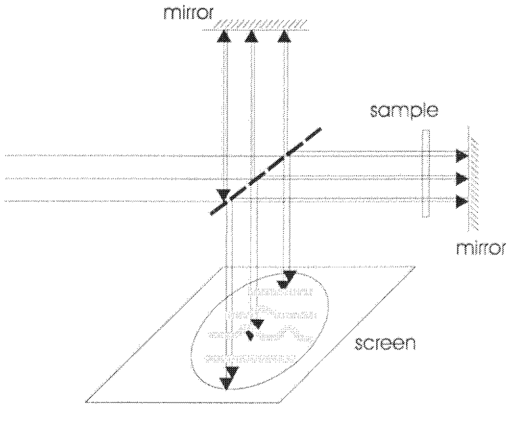

Fig. 3. Imaging of non-homogeneities of refractive index using Michelson interferometer.

The interference fringes depend not only on sample surfaces but also on inclination of the waves outgoing from arms of the interferometer. Consequently, the spacing and direction of the fringes can be changed by tilting one of the interferometer's mirror. It allows to modify the interference fringes according to the character of in-homogeneities in the sample (their slope).

The benefit of imaging of the sample in-homogeneities by changing the shape of the interference fringes (contrary to imaging by means of change of interference field intensity due to phase difference of interfering waves) will be evident especially at small changes of refractive index. It is due to fact that a little change of phase (considerably less than π) affects the intensity of interference field by rate dependent on phase difference. If the phase difference of the waves (interfering in the place without a defect) is close to 2π, the small change of phase affects the intensity only negligible. It is so because the derivative of intensity with respect to the change of phase at the place of maximum is equal to zero. The sensitivity to an in-homogeneity using this kind of imaging thus very slightly depends on the sample thickness. On the other hand the shift of the black fringes (phase difference equal to $\pi/2$) strongly depends on the phase shift caused by sample inhomogeneity.

2.2. Comparison of the benefits of mentioned techniques

When comparing the benefits of imaging the in-homogeneities with Michelson and Mach-Zehnder interferometer it should be mentioned two-times higher sensitivity for refractive index change in case when Michelson interferometer is used. This is because the beam is traveling through the sample twice. But a requirement is coupled herewith – the light has to pass the same way in the sample when going through in both directions, because only in this case the result gives the information about changes of refractive index in the places with defined coordinates x and y (coordinates according to Fig. 1.). The fulfillment of this requirement

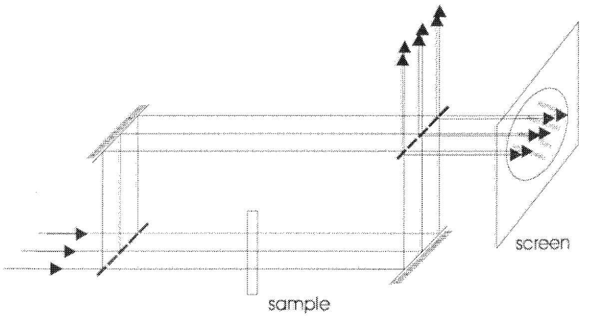

Fig.4. Imaging of non-homogeneities of refractive index using Mach-Zehnde interferometer.

is related to the impact of in-homogeneity on the direction of wave propagation. The better is the requirement fulfilled the weaker the in-homogeneities are (the less the derivative of refractive index with respect to coordinates) and the less the distance of the sample and mirror of the relevant arm of interferometer is. In an extreme, the change of direction of beam propagation could lead to complete loss of the image. This would happen if the displacement of the beam when coming back through the sample denoted the displacement from the region with maximum of

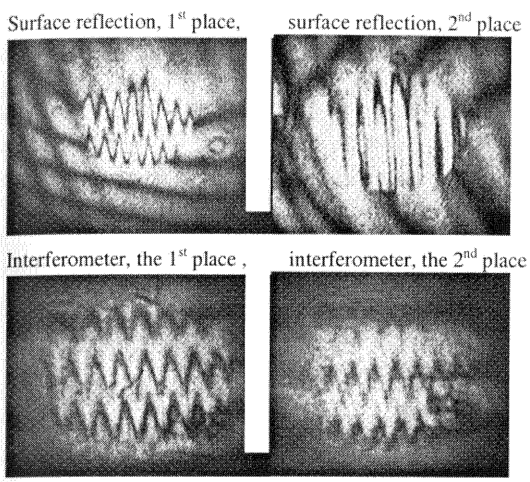

Fig. 5. The images of the records located in different places of the sample obtained using Mach-Zehnder interferometer and by technique of reflection from the front and back surface of the sample. It shows the possibility to control the direction and distance of the interference fringes when the interferometer is used. The period of the record is cca 0,22 mm.

refractive index to the region with the refractive index minimum. (We speak of the periodic change of refractive index what is the case of optical field recording, for instance (Fig. 5.)) Using the interference of waves reflected from the sample surfaces minimizes the distance between mirror and sample. Therefore it minimizes the influence of the change of the direction of beam propagation, too. It is minimized but not eliminated.

In case of Mach Zehnder interferometer the beam of light passes the sample only once thus potential change of direction of the beam propagation does not mean the averaging along different beam paths. However, also in case of Mach-Zehnder interferometer the change of direction of interfering waves propagation means some information loss. This loss of information is due to fact that the change of interference pattern intensity in certain place (as a consequence of the change of direction of beam propagation induced by non-homogeneity) is no more responding to the place where the change of the phase has occurred

The ultimate advantage of the first of techniques mentioned in the contribution is the simplicity. To perform this option one needs the light source with the length of coherence about several millimeters and a semitransparent mirror, respectively.

When investigating non-homogeneities of refractive index that depend on one coordinate only, we even do not need a semitransparent mirror. One has to place the sample such a way that beams incident upon the sample are not perpendicular to the surface and reflected beams are slightly deflected from the primary beam (beam outgoing from the laser source). It is possible to deflect these beams using a small mirror and by an objective display the interference pattern on the screen. The change of the path of the beam reflected from the sample's backside may cause the deformation of the image. To overcome this problem it is needed to choose the change of the sample orientation such a way, that the plane determined by the beam reflected and transmitted, respectively includes the direction of the zero change of refractive index. (Fig. 6).

2.3. Influence of multiple reflections

For all the three ways of interference imaging the image is distorted due to multiple reflections on the sample surfaces. In order to characterize the influence of these multiple reflections let us express the ratio between amplitude of the most intensive of the unwilling beams (from multiple reflected beams) and amplitude of the weaker one of those creating the primary interference pattern.

The ratio of the amplitudes is R_a^2 in the case of interference of waves reflected from the sample surfaces. R_a is the amplitude reflectivity of the sample. In case of Michelson interferometer there is, in addition to internal multiple reflections, also an unwilling beam created by reflection from the front surface of the sample and after passing through and reflection from the mirror there is another one being created by reflection from the back surface of the sample. This one is after

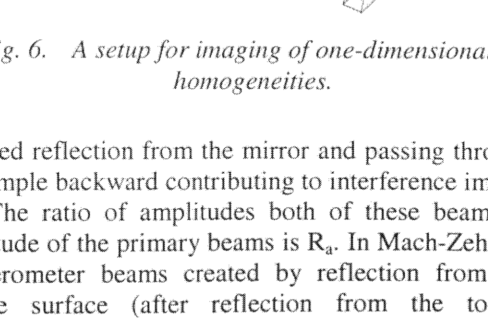

Fig. 6. A setup for imaging of one-dimensional in-homogeneities.

repeated reflection from the mirror and passing through the sample backward contributing to interference image, too. The ratio of amplitudes both of these beams to amplitude of the primary beams is R_a. In Mach-Zehnder interferometer beams created by reflection from the sample surface (after reflection from the totally reflecting and semitransparent mirror) leave the interferometer. Then, the most intensive beam of unwanted ones is that created by twofold internal reflection inside the sample. Alike in the case of interference of waves reflected from the surfaces, its intensity depends on R^2.

The amplitudes of the beams reflected from the front and back surfaces of the sample are not equal because the latter one of the beams is attenuated due to twofold transition through the front surface of the sample. Consequently, the ratio of their amplitudes in the location of the interference minimum is equal $1-Ra^2$. Ra^2 is the ratio between amplitudes of the reflected and incident beams, respectively. The intensity in the location of the interference minima is then $Im = Ir \cdot R^2$ and $I_M = Ir \cdot (2-R^2)$ in the place of interference maxima, where $Ir = I \cdot R$ and I is the intensity distribution in the beam that is illuminating the sample with optical record.

2.4. Enhancement of the image contrast

For purposes of exact interpretation of obtained image of interference field, it is useful if the minima of the interference pattern are displayed as thin dark fringes. This is the reason why it is convenient to display the image of the interference field with the maximum contrast. Taking into account the extreme situation, we can use the binary notation – full light and darkness. It is convenient to choose the discriminatory level as close to minimum of interference field intensity as possible. However, in case the non-homogeneous beam is used to illuminate the sample, the intensity in the location of the minima depends on the position of that place. Now, if we set the discriminatory level according to minima located in region of maximal intensity of illuminating beam (in the center of the beam in case of the beam with Gaussian distribution of intensity) we can not display the interference fringes in the region where the illumination is weaker (at the periphery of the field) (see Fig. 7)

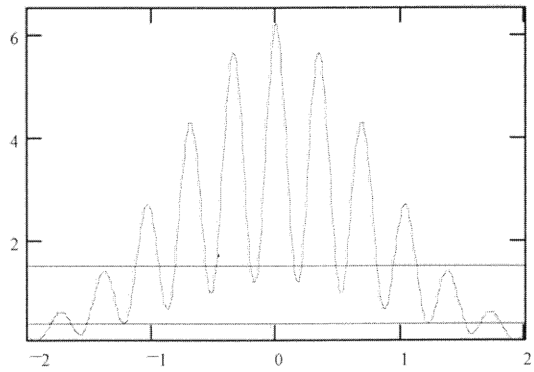

Fig. 7. Two values of the discriminatory level for binary notation of the interference field.

If the intensity of the interfering waves were the same, the intensity in the minimum of interference field would be zero. It mean's it would not depend on homogeneity of illuminating beam. Imaging a record using an interferometer enables to control the intensities of interfering waves by means of appropriate filters. One can doing this make the intensity be independent on the homogeneity of illuminating beam in the place of interference minimum. This is another advantage of imaging using interferometers when comparing with the imaging by means of interference of waves reflected from surfaces of the sample.

3. CONCLUSION

Following the description of three ways of interference imaging presented in this contribution, one can deduce the choice of the optimal setup depends on the value of refractive index of the sample and the range of the refractive index variation, which is going to be displayed, respectively. Samples with refractive index equal 2 or greater have the reflectivity coefficient greater than 0.3. It means that beams with amplitude determined by R (Michelson interferometer) significantly influence the interference image. The distortion may be as large as no imaging of in-homogeneities is possible. This is the reason why it is more convenient to use imaging by means of interference of waves reflected from the surfaces of the sample or imaging using Mach-Zehnder interferometer for samples with large refractive index. Though the imaging by interference of waves reflected from the surfaces is matchless the simplest one, the use of this technique (namely for imaging of one-dimensional non-homogeneities) needs the special form of the sample. The form of the sample assures that interference fringes are perpendicular to orientation of in-homogeneities. In that case, it will be advantageous to use Mach-Zehnder interferometer for samples with large refractive index or Michelson interferometer for samples with small refractive index.

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