Self-induced diffraction patterns in nonlinear Fabry-Perot interferometer on lithium niobate

V. Shandarov, A. Perin, V. Ryabchenok
Tomsk State University of Control Systems and Radioelectronics, Lenin Prospect 40, Tomsk, 634050, Russia
E-mail: shandarovvm@svch.rk.tusur.ru

Abstract. The effects of self-action of light fields within Fabry-Perot interferometers based on photorefractive lithium niobate plates both, of X- and Z- cuts are experimentally investigated. Formation of one-dimensional practically regular diffractive elements within the interferometers with slightly non-parallel input and output surfaces has been demonstrated at laser light wavelength of 532 nm. It has been found that these diffractive elements are formed due to the photorefractive response of the crystal to the steady-state optical interference patterns appeared within the interferometer at multiple reflections of light beam. From the Raman-Nath far field diffraction patterns the ordinary refractive index change within the interferometer on Z-cut crystal has been estimated.

1. Introduction

Light propagation in optically nonlinear medium may result in the conversion of the spatial and spectral structures of light fields due to the self-action effects. At the photorefractive nature of nonlinear response the spatial self-action of light may occur in the medium at optical powers of a microwatt level [1] that is very useful for the experimental studies. Very high optical nonlinearity results in the slow nonlinear response of photorefractive media that also brings the advantage to the time evolution study of light field self-action using simple and not too expensive tools. The most interesting among the spatial conversion effects for optical beams is the light localization in the form of spatial solitons that makes possible design of all-optical photonic elements and circuits with light controlled by light. Another result of similar effects relates to generation inside the nonlinear medium regular diffractive elements which also can be used for the light control needs. It should be noted that the boundaries of the nonlinear medium or interfaces between various materials may sufficiently vary the self-action characteristics of light fields. For example, generation of regular light patterns becomes possible in nonlinear optical cavities where the optical feedback comes into play [2 - 5]. Similar effects have been observed in photorefractive crystals and other nonlinear media with both, self-focusing and self-defocusing nonlinear response [2, 5].

In this work, we study the effect of self-formation of one-dimensional diffractive structures in photorefractive Fabry-Perot interferometers (FPI) with slightly non-parallel optical surfaces based on photorefractive lithium niobate (LiNbO₃) plates of two cuts.
2. Experimental setup and conditions
The X- and Z-cut LiNbO₃ plates with polished to optical grade largest opposite sides are used as Fabry-Perot interferometers in experiments. The plate dimensions are 1×15×10 mm³ along X, Y, Z axes for X-cut sample and 10×10×2 mm³ along X, Y, Z axes for Z-cut one. The Z-cut sample is doped with Fe ions (0.05%) during the crystal growth. Photorefractive properties of the X–cut sample result from the doping of its surface layer with iron (Fe) and copper (Cu) ions using the thermal diffusion of these impurities [6]. For this sample the thickness of Fe-doped and Cu-doped layers, where the photorefractive nonlinearity is high enough, make up 50 and 150 μm that is much less than the total thickness of the sample itself. The basic schematic of the experimental setup used to study the features of light field self-action in FPI is shown in Figure 1. Here a frequency-doubled continuous wave Nd³⁺:YAG laser, operating on a single longitudinal mode (light wavelength λ=532 nm, output power up to 50 mW), is used as a light source. The laser beam is collimated to necessary diameter (10 and 20 mm in various experiments) with a collimator built with two spherical lenses (CL). The central part of it with almost uniform intensity field is separated from the broad beam with a diaphragm to expose FPI. Using square shaped diaphragms, the transverse dimensions of light fields at the input surface of the crystal samples (LN) are provided as 3mm × 3mm or 5mm ×5mm. The light polarization corresponds to the extraordinary wave in the X-cut plate and to the ordinary wave in the Z-cut one. The light intensity of the input light field in most experiments on self-formation of diffractive structures in FPI is ~35 mW/cm². The FPI samples are placed over the linear positioning holders with micrometric control of their location. The light patterns at the output surface of FPI are imaged with the spherical imaging lens (SL) onto the sensitive plane of the laser beam analyzer BS-FW-FX33 (LBA) connected to the personal computer (PC). In experiments we study the temporal evolution of spatial distributions of light field intensity at the output surface of FPI and check the self-induced refractive index changes within the samples using the optical probing with both, broad and narrow light beams.

The optical probing method with a broad light beam exploits the effect of light diffraction on the diffractive structure. The analysis of far field diffraction patterns can confirm at this approach the occurrence of diffractive structures within the crystal sample and estimate the modulation depth of the sample refractive index by the nonlinearly generated diffractive element. The second approach is based on the optical probing of the diffractive element using light beam with its diameter less than spatial period of diffractive structure, as in the one of configurations of optical probing of surface acoustic waves [7].

3. Experimental results and discussions
As the result of FPI exposure with a laser beam, we observe generation of almost regular one-dimensional light patterns at its output surface. These patterns appear in near to 10 minutes for Z-cut sample and 30 minutes for X-cut one after the exposure start. They develop within the initial almost...
uniform light images. These light patterns point to the stationary spatial modulation of the material refractive index due to the photorefractive effect.

3.1. Light patterns at the output surface of FPI

To study the evolution of light patterns at the output surface of FPI’s, we use light field with almost uniform intensity over its cross-section with dimensions 3 mm x 3 mm. A part of light image at the input surface of FPI is shown in Figure 2a. At the initial stage (t=0) the light pattern at the output surface shows slight one-dimensional periodic modulation of its intensity because of the nonparallel input and output surfaces of the crystal plate (Figure 2b). But optical probe experiments do not find any periodic diffractive objects within FPI for this initial stage. In some minutes after the exposure start the increase of the intensity modulation depth in the light field at the crystal output surface is observed. It reaches some maximal depth in 50 – 60 minutes for the Z-cut sample and in 70 – 80 minutes for the X-cut FPI at input light intensity 35 mW/cm². The example of such light patterns observed at the output surfaces for the Z-cut FPI is shown in Figure 2c. The spatial period of the periodic light pattern is ~260 μm here and it does not depend on the incidence angle of the light beam to the input surface.

**Figure 2.** Light fields at the input and output surfaces of Z-cut FPI: a – the initial pattern at the input surface; b – light pattern at the output surface at t=0; c – light pattern at the output surface after FPI exposure for 25 minutes (input light field intensity 35 mW/cm²).

To reveal the mechanism of the light modulation depth increase, the optical probe of the FPI with narrow light beam (beam diameter at the input surface is 23 μm, λ=532 nm) is used. The exposed area of FPI is scanned with this probe beam along direction parallel to the “wave vector” of the light pattern. The crystal sample is moved with the micrometric accuracy with respect to the light beam in that case. As the intensity distribution within the cross-section of the probe beam as its peak intensity are investigated with LBA. Some results of this experiment are illustrated by Figure 3. The step of FPI movement with respect to the probe beam is 25 μm and the optical power of this beam is less than 0,01 mW to prevent photorefractive distortions of its intensity profile. The results demonstrate the dependence of the peak intensity of the probe beam on its location at scanning the single period of the diffractive structure within this FPI. The light patterns of the beam cross-sections for the uniform (unexposed) area of the crystal and for its different locations at the exposed area probing are shown here. It may be concluded that the beam peak intensity increases for its propagation along the central part of the region with increased refractive index that results in its self-focusing and the compression of its intensity cross-section in direction of light pattern “wave vector” (image “a”). Propagation of the probe beam in the slope part of this region results in its refraction with peak intensity decreasing and distortions of the intensity distribution within the probe beam cross-section (images “b” and “c”). The scanning of the total exposed area with narrow probe beam demonstrates practically periodic dependence of its peak intensity on the location within this area. The same results are observed for FPI based on X-cut LiNbO₃ crystal with some distinctions only in the quantitative characteristics of these effects. Thus, the results of experiments performed evidently show that practically periodic diffractive structure is generated within photorefractive FPI during its exposure with light field of uniform intensity distribution.
3.2. Far field diffraction of light on the diffractive structures within FPI

We also use another approach to study the diffractive structures induced within FPI. It is based on the diffraction of the broad light beam on the induced phase diffractive structure. The light patterns in the far field can inform in this case on spatial period of the structure and refractive index change within it. For this purpose the light beam of He-Ne laser (λ=633 nm) with diameter of 2 mm and optical power of 0.5 mW is used. Its polarization corresponds to the ordinary wave of the crystal. Far field of diffracted light is studied with LBA and intensities of diffraction maxima are measured with a silicon photodiode.

The diffraction patterns observed in experiments are illustrated by images in Figure 4. Here the left image corresponds to the light beam passed through unexposed Z-cut LiNbO3 based FPI. After FPI exposure for 30 minutes with light of λ=532 nm we observe in the far field the pattern with many diffraction maxima typical for Raman-Nath diffraction. The diffraction angle corresponds to the spatial period of the diffractive gratings of 270 μm. The ratio of the first and zero diffraction maxima intensities \( \eta_m \) depends on the refractive index change within the diffractive structure. This change \( \Delta n_0 \) is estimated using the known expression [8]:

\[
\eta_m = J_m^2(\delta) = J_m^2\left(\frac{2\pi d\Delta n_0}{\lambda \cos(\theta)}\right)
\]

where \( J_m \) is a Bessel function, \( d \) is a grating thickness, \( \Delta n_0 \) is a refractive index change, \( \lambda \) is wavelength, and \( \theta \) is the diffraction angle. For measured \( \eta_m=8\% \) and 2 mm FPI thickness we estimate the ordinary refractive index change value of induced within FPI grating as \( \Delta n_0=3.7 \times 10^{-5} \).
Similar effects of light diffraction we also observe for X-cut LiNbO$_3$ based FPI, but with slightly different diffraction angles.

![Figure 4](image)

**Figure 4.** Far field pattern of He-Ne laser beam diffraction on nonlinearly induced diffractive element in FPI. Left – light pattern before FPI exposure; right – the pattern after FPI exposure.

### 3.3. Discussions

The analysis of experimental results shows that diffractive structures are formed within FPI’s due to multiple reflections of light beam from its boundaries together with not ideally parallel input and output surfaces of FPI. The angles between these surfaces are measured as $46\pm5$ arc seconds and $40\pm5$ arc seconds for Z-cut and X-cut LiNbO$_3$ plates. The interference of almost co-propagating and almost counter-propagating coherent optical waves results in the formation of complicated three-dimensional (3D) steady-state light patterns within FPI. With taking into account the reflection coefficient value of light at the interface “lithium niobate - air”, the 3D interference pattern may be considered as the superposition of two 1D interference patterns. The first pattern is formed by two almost counter-propagating waves and the second one is formed by two almost co-propagating waves. In turn, these steady state light patterns may result in arising within FPI the photorefractive gratings. The estimations of spatial periods of similar gratings in FPI with non-parallel surfaces ($\beta=46$ arc seconds) give values of $\sim118$ nm for reflecting grating and $\sim0.3$ mm for transmitting grating. Because of the slow photorefractive nonlinear response of LiNbO$_3$ (more than 10 minutes in our experiments with optical powers used), formation of reflecting gratings requires experimental setup very stable mechanically and thermally, and their formation is not observed in the experiments. From the other side, the spatial period $\Lambda$ for transmitting photorefractive gratings is determined by the expression:

$$\Lambda = \frac{\lambda}{2n \cdot sin(2\beta)}$$

where $n$, the refractive index of LiNbO$_3$; $\beta$, the angle between input and output surfaces. For $\beta<1'$ this period $\Lambda=0.3$ mm and it corresponds to the spatial period value observed for the self-induced diffractive structures in our experiments.

### Conclusion

The formation of 1D diffractive structures within photorefractive Fabry-Perot interferometers based on lithium niobate has been demonstrated at light wavelength of 532 nm. It has been revealed that these structures are formed due to the photorefractive response of lithium niobate crystal to the three-dimensional steady-state light interference patterns which appear within the crystal plates because of their not ideally parallel optical surfaces. The effect observed may be useful for design of new nonlinear optical elements for the laser devices and for all-optical photonic components.

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