Investigation of influence incoherent background illumination on the nonlinear response of a lithium niobate crystal sample at low light intensity

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Abstract. The total compensation of nonlinear diffraction of coherent laser beams of He-Ne laser (wavelengths 633 nm) with diameters on full width of half maximum near to 15 - 20 μm due of assistance of incoherent background have been experimentally demonstrated. Incoherent background had a shorter wavelengths (455 – 465) nm and much lower intensity compared with coherent signal beam with wavelengths 633 nm. Obtained the dependences of the refractive index change in the LiNbO₃:Fe crystal under the conditions of such incoherent background.

1. Introduction

Effects of self-action may occur in nonlinear optical media. Depending on the response of the optical medium can be self-focusing and self-defocusing of light beams are possible besides in some conditions it consequences diffraction-less propagation of these beams accompanied with regimes of spatial solitons [1, 2]. The one of most unique materials among photorefractive crystals is lithium niobate (LiNbO₃) doped with some impurities, for example with iron (Fe), copper (Cu), manganese (Mn), cerium (Ce) and their combinations [3] The base response of the lithium niobate crystal is self-defocusing. To observe self-focusing of light beams instead their self-defocusing within LiNbO₃ crystal samples, the externally applied electric field, the thermo-optic and pyroelectric effects have been used [3 – 6]. For attain that we use one of alternative method, it's a use photovoltaic properties of this material by combinations of light fields with different wavelengths [7, 8].

The main aim of this work is experimental study of optical nonlinearity sign cross-over from self-defocusing to self-focusing in conditions of incoherent background within LiNbO₃:Fe sample.

2. Experimental conditions and results

Two distinct experimental approaches are used in our study. In our first experiment, we check value of refractive index change in LiNbO₃:Fe sample under influence of incoherent light produced by LED’s with central wavelengths of 455 nm, 470 nm, 525 nm. Along with this, light sources with different power and spatial coherence are used. This change is due to the photorefractive properties of Fe-doped LiNbO₃. The experimental setup exploits the interference between red beams reflected from the entrance and exit surfaces of LiNbO₃:Fe sample (Figure 1). Optical power of red beam used ranges from 10 to 20 μW at beam diameter near to 1 mm to exclude photorefractive self-action of this beam within the crystal. Red light propagates within the sample (LN) under small angle to crystal X axis. Interference patterns formed by partially reflected from the slightly nonparallel entrance and exit
surfaces of the sample. A phase of the light beam within the sample can vary in this scheme due to incoherent background influence or air temperature variation within the room.

LED with average $\lambda=455$ nm its light power obtains 0.5 W but angular divergence (FWHM) makes up $120^\circ$. In experiment used sample of LiNbO$_3$:Fe (0.005 wt%) with dimensions of $5\times10\times10$ mm$^3$ along X, Y, and Z axes. Light beam of He-Ne laser with linear polarization is incident onto the sample entrance surface (YZ plane) with angle $\sim 10^\circ$ to X axis in XZ plane of the crystal. Red beam polarization corresponds to the extraordinary wave of the crystal. Incoherent light is introduced into the sample through the back YZ surface of the sample. For introduce the background light into the crystal, we use hollow metal tubes with mirror-like internal surface. Observation of light pictures was made by means of the analyser of light beams.

Figure 1. A scheme of experiments on studies of incoherent background influence to the refractive index of LiNbO$_3$:Fe; He-Ne – helium-neon laser; LN – crystal sample; LED – light-emitting diode.

Some particular results on a change of interference pattern caused by reflections of He-Ne laser beam from the entrance and exit surfaces of LiNbO$_3$:Fe sample under its illumination with incoherent light are shown in Figure 2. The difference of these patterns is practically the same for all LED's used with only quantitative distinction of interference maxima shift velocity. Images in Figure 2 shows the fastest shift of interference maxima for using LED with 455 nm and optical power of 500 mW and with optical power of 633 nm He-Ne laser is $\sim 12 \mu$W. Due to the sample exposure for time near to 6 minutes we observe the spatial shift of interference maxima, within the whole light pattern, corresponding to phase change of red beam on $\pi$ in the sample. It is confirmed by intensity profiles of interference patterns at the start of incoherent illumination ($t=0$) and after 6 minutes of exposure (c and d of Figure 2).

Figure 2(a, b, c, d). Images of interference patterns of He-Ne laser beams reflected from entrance and exit surfaces of LiNbO$_3$:Fe sample for the background light wavelength 455 nm at initial moment (a) and at exposure time 6 minutes (b) and intensity profiles of these patterns along Z direction: (c) t=0; (d) t=6 minutes.
For LED's with a lower light intensity similar shift requires ~30 minutes of exposure. The results observed are explained by the arising of photovoltaic field $E_{pv}$ within LiNbO$_3$:Fe sample at its illumination by incoherent light with almost uniform intensity distribution over the sample surface. This electric field changes the material refractive indices by means of linear electro-optic (Pockels) effect on the value $\Delta n=-0.5n^2rE_{pv}$, where $n$ and $r$ are refractive index and electro-optic coefficient corresponding to light polarization and propagation direction. Accordingly, the phase shift of He-Ne laser beam within the sample changes on the value $k\Delta nL$, where $k$ is the wave number of light in free space and $L$ is the light propagation distance.

Figure 3 shown dependence of the change of the refractive index of the crystal from the time of exposure of incoherent background illumination LED with $\lambda=455$ nm and light power of 0.5 W. Experimentally observed shift of interference maxima gives value $\Delta n_e=(0.7 - 1.2) \cdot 10^{-4}$ for extraordinarily polarized light beam in LiNbO$_3$ crystal.

![Figure 3](image-url)

**Figure 3.** Graph of change in the refractive index of the photorefractive crystal of lithium niobate from time with incoherent background illumination LED with $\lambda=455$ nm and light power 0.5 W.

In our second experiment, we are possibility of red beam self-focusing using incoherent background (Figure 4). As incoherent background we use laser diode with wavelength 450 nm. The laser diode beam has elliptical shape with dimensions $\sim 4 \times 10$ mm$^2$ in its cross-section at the distance 60 centimeters from diode lens. The light beam of He-Ne laser with $\lambda=633$ nm is focused by $8 \times$ and $4 \times$ microscope objectives (SL) onto the input YZ surface of crystal sample. Light spot diameter (FWHM) makes up $\sim 15-20$ $\mu$m on this surface.

![Figure 4](image-url)

**Figure 4.** A scheme of experimental setup for investigation of red beam nonlinear diffraction in LiNbO$_3$:Fe: He-Ne, helium-neon laser; Laser, laser diode; BS, beam splitter; LED, light-emitting diode; SL, spherical lens; IL, imaging lens; LBA, CCD camera.
The light beam propagates practically along crystal X axis and increases its diameter to 40 – 60 μm at the sample exit surface due to natural diffraction. Light patterns from entrance or exit surfaces of sample are imaged by lens (IL) on laser beam analyzer (LBA). It is inserted into the sample along direction parallel to red beam propagation. Temporal dependences of red light patterns on the sample exit surface YZ are studied using LBA.

For the compensation of red beam natural (linear) diffraction requires increasing of background intensity which can be obtained with proper shaping of LED light field. Using laser diode with light wavelength 450 nm we also obtain the total compensation of nonlinear light diffraction caused by photovoltaic current produced within the crystal by narrow red beam and only very partial compensation of red beam linear diffraction. Background light is introduced into crystal sample along direction parallel to the signal (λ=633 nm) beam. Red beam power ~100 μW and its diameter is ~20 μm in that case. Power density of background light makes up about ~1 W/cm² and for red signal beam it is much higher again. Light images in Figure 5 show temporal evolution of light patterns for red beam at exit surface of the sample LiNbO₃:Fe without background and with background. It is seen that incoherent background with shorter wavelength than signal light beam, totally compensates the nonlinear diffraction of this signal beam at conditions described. And it is clear from analysis of these results that proper intensity of incoherent background will allow compensation of both, as linear as nonlinear beam diffraction that means stronger self-focusing of red beam.

![Figure 5(a, b, c, d, e, f). Images of light spots of red beam at exit surface of the sample at exposure beginning (a) and after some times when incoherent background is absent (b, c) and after start in conditions with incoherent background (d, e and f). Input FWHM is ~15 μm, red beam power is 20 μW, intensity of background with λ=450 nm is more than order less than average intensity of red beam.](image)

The graph shows the dependence of the width of the red beam of a He-Ne laser on time in conditions with background illumination and without it (Figure 6).
Figure 6. Evolution of beam diameter ($\lambda=633$ nm) for light propagation with no background ($\Diamond$) and with background ($\Delta$); $\lambda_{bg}=450$ nm; $d=20$ $\mu$m.

3. Conclusion
In conclusion, we have demonstrated that influence of spatially incoherent background with a more short wavelength on the narrow coherent signal beam with longer wavelength when it distributed in a LiNbO$_3$:Fe sample provides total compensation of nonlinear beam diffraction caused by photorefractive effect and partial self-focusing. It may create new configurations of all-optical photonic elements based on this crystal.

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