Pyroelectric generation of 2D spatial soliton sets in a bulk of lithium niobate crystal

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Abstract. The generation of two-dimensional bright spatial soliton sets in lithium niobate sample has been experimentally demonstrated at light wavelength of 532 nm, contribution of pyroelectric effect into nonlinear optical response of the crystal, and spatial modulation of one-dimensional beam along direction normal to the crystal optical axis. Diameters of soliton beams and channel waveguides formed within the crystal bulk by these solitons are near to 20 μm at light polarization corresponding to extraordinary wave of the crystal.

1. Introduction
Optical waveguide elements and waveguide structures with potential optical reshaping are important elements for photonic devices and systems. Such elements may be formed in electrooptic crystalline materials or layered structures exploiting the effects of spatial optical solitons. The one of most interesting electrooptic crystals promising for similar applications is lithium niobate (LiNbO₃). The nonlinear optical response of this crystal doped with some impurities like iron (Fe) or copper (Cu) is observed at very low light intensities [1 - 3]. However, this response is self-defocusing that allows formation only dark spatial solitons in this material at usual conditions. To overcome this limitation, the drift mechanism of charge carrier transport using at the photorefractive effect has been proposed to compensate large photovoltaic contribution into that transport [4]. This method is effective for crystals with low level of photorefractive impurities, but it requires high-voltage electric field applied to the crystal sample. Another approach to solve that problem with no external electric field is based on ferroelectric properties of LiNbO₃. Forming bright spatial solitons becomes possible when pyroelectric effect contributes to its nonlinear optical response [5 - 7]. Using this effect, one can form two-dimensional bright spatial solitons and, correspondingly, channel optical waveguides in LiNbO₃ crystals with low photorefractive sensitivity [5]. One-dimensional bright spatial solitons may form in LiNbO₃ due to its wavelength-dependent photovoltaic properties [8]. The main aim of our work is the study of generation of 2D spatial soliton sets in congruent LiNbO₃ bulk at contribution of pyroelectric effect into material nonlinear response using laser radiation with wavelength of 532 nm.

2. Experimental setup and experimental results
The schematic of experimental setup is shown in Figure 1. Laser beam (λ=532 nm) with polarization corresponding to extraordinary wave of crystal is focused with a cylindrical lens (CL) onto a surface of amplitude mask (AM) on a glass plate in order to illuminate it with elliptic light spot (see inset to Figure 1). The light field with periodic spatial modulation of its intensity along direction orthogonal to
crystal optical axis obtained after this mask is optically projected with spherical lens (L) onto the entrance surface of the crystal sample (LN), placed on a surface of Peltier heater (PE). The crystal temperature is measured with a non-contact infrared thermometer. Light field with smallest ellipse axis oriented parallel to crystal optical axis propagates within the crystal along its Y-axis through distance about 10 mm. The sample dimensions make up 4×10×4 mm³ along crystalline X, Y, Z axes. The spherical lens (L) forms the imaging of entrance or exit surfaces of the sample onto the sensitive matrix of a laser beam analyzer (BA). The light patterns from these surfaces are studied visually and saved as the files in a computer memory. These images are compared with those obtained in the same sample with no amplitude mask but at the same light power, polarization, and other experimental conditions.

### 2.1. Formation of sets of two-dimensional bright spatial solitons in a crystal bulk using spatially modulated light field

Transverse size of light field is increased during its propagation within the medium due to the natural light diffraction. The beam divergence may be compensated when self-focusing optical nonlinearity of the medium comes into play. It may be observed in photorefractive LiNbO₃ when photovoltaic mechanism of charge carrier transport is totally suppressed by another physical mechanism. To reverse the sign of LiNbO₃ optical nonlinearity, the contribution of that mechanism should exceed the photovoltaic current contribution into nonlinear optical response of LiNbO₃. As it has been mentioned, we can use for that purpose the pyroelectric properties of ferroelectric LiNbO₃.

To generate the set of 2D bright spatial solitons in LiNbO₃ sample, we use periodic spatial modulation of light intensity in direction normal to the optical axis direction in LiNbO₃. Some particular experimental results are illustrated by images in Figure 2. Image (2a) corresponds to the light pattern at the entrance surface of the sample and natural diffraction changes its width along crystal optical axis at the exit surface (Images 2b, 2c). The nonlinear diffraction increases light pattern size along that direction at the exit surface due to the photorefractive effect (Image 2d). To compensate both, nonlinear and linear light diffraction, we heat the crystal sample up to the temperatures (60 – 75)°C depending on light power which ranges from 1 to 10 mW. It is illustrated by image (2e) for light power 5 mW, light pattern dimensions of 20×1000 µm at the entrance surface, and sample temperature of 75°C. Corresponding intensity profiles of these patterns are shown in Figure 3.

![Experimental setup scheme. Inset demonstrates light field shape on AM surface.](image)
Figure 2. Light field images at the entrance surface of the crystal sample (2a), at its exit surface in linear regime (2b, c), in nonlinear regime (2d), and at the exit surface in conditions of total compensation of light field divergence along crystal optical axis (2e).

Figure 3. Intensity profiles of light fields at the entrance (3a), and the exit surfaces of crystal sample (3b–e). Letters correspond to situations, discussed in a capture to Figure 2.

These results clearly demonstrate formation of sets of 2D bright spatial solitons in the sample tested. It is due to the almost uniform crystal heating with Peltier element. The change of the sample temperature results in the change of spontaneous polarization $P_s$ of ferroelectric LiNbO$_3$ sample that generates within it the pyroelectric field $E_p$ [5]:

$$E_p = -\frac{1}{\varepsilon_0 \varepsilon_r} \frac{dP_s}{dT} \Delta T$$

(1)

Here $\varepsilon_0$ and $\varepsilon_r$ are the dielectric constants of vacuum and the crystal, and $\Delta T$ is a temperature variation in the illuminated part of material with respect to its initial temperature. By means of the crystal heating, the pyroelectric field $E_p$ lowers the refractive indices of the whole sample due to the linear electrooptic effect on value of $\Delta n=0.5n^3r_{eff}E_p$. Here $n$ is average refractive index for the linearly polarized light wave, and $r_{eff}$ is effective electrooptic constant. At the same time this pyroelectric field is screened in the illuminated area of the crystal sample due to the spatial redistribution of charge carriers existing in the illuminated area because of the photovoltaic current via light influence. The
experiments show that the steady-state formation of regularly separated 2D bright spatial solitons is generated when light beam is spatially modulated. We also study formation of 1D bright spatial soliton in the same crystal sample with light beam of Gaussian shape along direction normal to the optical axis. In that case the laser beam is directly focused onto the entrance surface of the sample. Some particular results of that experiment are shown in Figure 4. Here we also observe the linear diffraction of shit-shaped light beam at its propagation from the sample entrance (Image 4a) to its exit surface (Image 4b), the nonlinear contribution to the light diffraction due to the photorefractive effect (Image 4c), and the diffraction compensation by the pyroelectric effect (Image 4d) at the sample heating. However in the last image we observe separation of this shit-shaped light beam along its largest dimension to the almost regular structure of 2D spots. These spots correspond to separate 2D bright spatial solitons formed from 1D beam due to the spatial modulation instability \[9 - 11\]. It should be noted that this configuration of spatial soliton formation is very sensitive to the variations of experimental parameters. Using the spatially modulated light pattern for the spatial soliton excitation allows control of distances between separate 2D bright solitons.

![Figure 4](image)

Figure 4. Light field images at the entrance surface of the crystal sample (a), its exit surface in linear regime (b), at exit surface and photorefractive divergence (c), and at exit surface in conditions of beam separation on 2D spots due to the spatial modulation instability (d).

3. Conclusion

In conclusion, our experimental results demonstrate the possible generation of sets of 2D bright spatial solitons in LiNbO$_3$ samples with predicted distances between them due to the contribution of pyroelectric effect into its nonlinear optical response and spatial optical modulation of 1D light beam along direction normal to the crystal optical axis.

Acknowledgments

This study was carried out with the financial support of Ministry of Education and Science of Russia (within the task N 3.1110.2017/PCh of the project part).

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