Investigation of the interaction of a pair of bright optical spatial pyroelectric solitons during their in-phase propagation in an undoped lithium niobate crystal at a wavelength of 532 nm

A S Perin, M N Gapparova, D K Romanenko, A V Sokolnikov, D V Okunev and A E Mandel
Tomsk State University of Control Systems and Radioelectronics, Tomsk 634050, Russia
e-mail: perin.anton@gmail.com

Abstract. The formation of two-dimensional bright spatial solitons by in-phase laser beams with a wavelength of 532 nm propagating in the bulk of photorefractive lithium niobate crystal under the reversal of the sign of the nonlinear optical response of the material with the contribution of the pyroelectric effect has been experimentally demonstrated. It is shown that varying the distance between the beams at the input face of the crystal leads to the interaction of pyroelectric solitons, which allows the formation of non-rectilinear propagation paths of light beams.

1. Introduction

When laser beams propagate in an optically nonlinear medium, self-action effects may occur, the result of which is a change in the spatial structure of light fields [1-4]. The spatial self-action of light beams in such media can lead to their self-focusing or self-defocusing. A particular case of the self-action effect is the spatial optical soliton regime, in which the diffraction broadening of the light beam propagating in the medium is completely compensated by the nonlinearity of the medium. In applied terms, interest in such a regime is associated with the formation by spatial solitons of optical waveguides and nonlinear lenses [5, 6].

In some crystalline materials, a nonlinear optical response is manifested even at light intensities of several W/cm², which makes them attractive both in terms of studying the fine features of soliton phenomena and in the implementation of fully optical elements and devices of nonlinear optics and photonics [6-9]. One such material is a ferroelectric crystal of lithium niobate (LiNbO₃). The photorefractive optical nonlinearity of a lithium niobate crystal has a self-defocusing character, which leads to an increase in the diffraction divergence of laser beams propagating in the crystal [10]. The soliton regime of propagation of coherent light beams in a LiNbO₃ crystal can be achieved by the reversal of the sign of the nonlinear optical response of the material due to the pyroelectric and photorefractive effects interaction under conditions of uniform heating of LiNbO₃ samples [11, 12]. It was shown in [13] that, in the bulk of nominally undoped crystalline LiNbO₃ samples, the formation of single solitons and pairs of such solitons are possible due to the pyroelectric effect.

It is known that the coherent interaction of optical spatial solitons propagating in a nonlinear medium leads to a change in the distance between the centres of such beams [14]. It was shown in that in the case of propagation of solitons excited by light beams phase-shifted by π/2, they are repelled from each other, while in-phase generating light fields excite solitons, which are attracted during propagation.
This paper presents the results of studies of the formation and interaction of bright spatial optical solitons in a lithium niobate crystal while compensating for the diffraction divergence of laser radiation due to the pyroelectric effect under conditions of uniform heating of samples.

2. Experimental setups and conditions
In experiments on the formation and interaction of optical solitons, an undoped LiNbO$_3$ Z-section sample was used. The dimensions of the sample were $10 \times 4 \times 4$ mm$^3$ along the X, Y, Z axes, respectively. The light beam in the sample propagated in a direction parallel to the X axis. The polarization of the light field forming the soliton corresponded to an extraordinary wave in the crystal.

The experimental setup is shown in Fig. 1. The radiation source (1) in the experiments was a CW YAG:Nd$^{3+}$ solid-state laser with frequency doubling ($\lambda = 532$ nm). To form in-phase Gaussian light beams with a given waist diameter propagating in a crystalline sample in parallel directions, we used an optical system consisting of an amplitude diffraction grating (2), a spatial filter (4), and focusing lenses (3, 5, 6). After diffraction of laser radiation by an amplitude grating, maxima of $+1$ and $-1$ orders of magnitude were filtered from the light field by a spatial filter. Focusing lenses (3, 5, 6) with focal lengths $F_1$, $F_2$, and $F_3$ were respectively selected and placed so that the beams propagated in parallel and had a given distance between their centers and the required diameter of light spots on the input plane of the sample. The imaging lens (10) was used to scale the intensity distribution patterns on the front (input) and back (output) surfaces of the sample, which were studied, using a BS-FW-FX33 laser beam analyzer (11), coupled to a personal computer.

Figure 1. Scheme of an experimental setup for studying the formation and interaction of optical solitons.

In the experiments, the diameter of the light beam at the input surface of the crystal was $\sim 15$ $\mu$m in terms of half intensity. The distance between the centers of parallel light beams in the crystal was determined by the period of the diffraction grating and in different experiments varied in the range from 105 to 245 $\mu$m. The sample was moved in the transverse direction relative to the laser beams using a linear translator with micrometric positioning accuracy (7). The studied crystalline sample LiNbO$_3$ (8) was placed on the surface of the Peltier element (9), providing uniform heating of the sample. For better thermal transfer, a thin layer of heat-conducting paste was applied between the lower face of the crystal and the ceramic substrate of the heater. The remaining faces of the crystal had direct contact with the surrounding air. During the experiments, the crystalline sample was heated to the required temperature, the control of which was carried out by a non-contact infrared thermometer with an accuracy of $\pm 2$ °C.

Bright spatial optical solitons were excited in a lithium niobate sample by two in-phase laser beams obtained by spatial filtering of diffraction maxima. Due to the photorefractive effect, an electric field $E_{ph}$ arises in the illuminated region of the crystal, due mainly to the photovoltaic mechanism of redistribution of charge carriers. The self-defocusing nature of the photorefractive optical nonlinearity
of the LiNbO$_3$ crystal leads to the field-induced spatial charge of a nonlinear negative lens in the illuminated region [15]. The inhomogeneity of the refractive index leads to an increase in the diffraction divergence of the light beam.

In the case of two-dimensional Gaussian light beams, compensation of both linear and nonlinear light diffraction can be achieved by uniform heating of the crystalline sample. An increase in the crystal temperature leads to a change in its spontaneous polarization and the appearance of a pyroelectric field $E_{py}$, which lowers the refractive index of LiNbO$_3$. In the illuminated region, the pyroelectric field $E_{py}$ is compensated due to the photoconductivity of the medium, leading to drift redistribution of charge carriers. In this case, the refractive index in the illuminated region of the crystal changes less and turns out to be higher than that in the unlit region. Thus, the contribution from the photorefractive and pyroelectric effects under certain conditions leads to the appearance of a two-dimensional bright spatial soliton – the pyroelectric soliton, which eliminates the effect of diffraction spreading of the light beam [11].

In our experiments, the output power of the laser source was 400 $\mu$W. The diameters of the light beams formed by the optical system of the experimental setup at the input face of the crystal were 15 $\mu$m. The intensity of each of the light beams at the input face of the crystal was 50 W/cm$^2$. To establish the soliton regime, the sample was heated using a Peltier element to a temperature of 55 °C.

3. Experimental results and discussions

As a result of the interaction of in-phase bright spatial optical solitons, the centers of the soliton beams came closer together on the exit plane of the sample. In fig. 2 shows the patterns of the light field and the corresponding intensity distribution profiles, illustrating the approach of the solitons on the output face of the crystal for the case when the distance between the beams on the input face of the sample was 105 $\mu$m.

![Intensity distribution patterns and corresponding profiles of light beams at the input (a) and output (b) faces of the sample.](image)

**Figure 2.** Intensity distribution patterns and corresponding profiles of light beams at the input (a) and output (b) faces of the sample.

To identify the propagation features of in-phase bright spatial optical solitons in LiNbO$_3$, numerical simulation was performed using the propagating beam method (BPM) [16]) as applied to nonlinear waveguide structures in the paraxial approximation for the case of a nonlinear lossless medium with a modulated refractive index in the transverse direction.
As is well established, scalar wave propagation in a nonlinear one-dimensional waveguide array can be modelled within a paraxial approximation by:

$$i \frac{dE}{dx} + \frac{1}{2k} \frac{d^2 E}{dz^2} + k \frac{\Delta n(z) + \Delta n_{nl}}{n_s} E = 0.$$  

The propagation coordinate is along the $x$-axis, the amplitude of the electrical field is denoted by $E$, while $k = 2\pi n_s / \lambda$ represents the wave number. Here, $\lambda$ is the wavelength of the used light in vacuum while $n_s = 2.2355$ is the extraordinary refractive index of our lithium niobate substrate. The periodically modulated refractive index which defines the nonlinear waveguide array is denoted by $n(z)$ while $\Delta n_{nl}$ is the nonlinear refractive index change ($\Delta n_{nl} << n_s$). The periodically modulated refractive index can be well approximated by $n(z) = 2.2355 + 0.01035 \cos^2(\pi z/\Lambda)$, $\Lambda$ is period.

When modeling, it was accepted: undoped lithium niobate with an extraordinary refractive index of 2.2355 at a wavelength of 532 nm was used as a propagation medium; sample length 10 mm; type of nonlinearity – saturation-type photorefractive nonlinearity; diameter of light beams 15 microns; the distance between the centers of the beams on the input surface is 15 $\mu$m, 45 $\mu$m, 105 $\mu$m, 170 $\mu$m, 245 $\mu$m.

Figure 3a shows the experimental results and calculated data – the time dependences of the ratio of the distance between the centers of the light beams at the input ($H_{in}$) and output ($H_{out}$) planes of the sample propagating in the mode of in-phase bright spatial solitons. In figure 3b presents the intensity distribution patterns of optical solitons propagating at different initial distances between the centers of the beams at the input face.

**Figure 3.** Graphs of the dependence (a) of the ratio of the distances between the centers of light beams on the input face of the crystal ($H_{in}$) on the distance between the centers of light beams on the output face ($H_{out}$) over time. The results of numerical simulations (b) illustrating the patterns of the intensity distribution of optical solitons propagating at different initial distances between the centers of the beams at the input face of the sample.

The experimental dependences were constructed only for the distances between the beams of 245 $\mu$m, 170 $\mu$m, and 105 $\mu$m, which is due to the impossibility of the experimental implementation of the soliton propagation regime at a small distance between the beams due to the strong interference interaction between them. However, the BPM calculation data made it possible to construct the dependences for the distances between the beams of 45 $\mu$m and 15 $\mu$m, since the coherent nature of the light field of the beams was not taken into account in the calculations. Such a feature of the interaction can be eliminated by using incoherent light fields. The available experimental data are in satisfactory
agreement with the calculated values at the indicated distances between the beams. An analysis of the dependences (fig. 3a) shows that as the distance between the centers of the beams decreases, their attraction to each other increases sharply. Calculations show that when the distance between the beams is equal to their diameter (15 μm), the solitons approach each other within 5 s to a value of ~ 7.7 μm between their centers. The saturation region is determined by the geometric dimensions of the crystal and indicates that the beams reach the exit face of the sample.

4. Conclusion

Thus, we studied the formation and interaction of a pair of bright spatial solitons while compensating for the diffraction divergence of laser radiation under the conditions of the combined contributions of the photorefractive and pyroelectric effects to the nonlinear response of an undoped lithium niobate crystal at a wavelength of 532 nm. It was shown experimentally and by numerical simulation that the resulting perturbations of the optical properties of the medium lead to non-linear paths of propagation of light beams. This effect can be used to create optically reconfigurable waveguide elements or their arrays in such crystals, suitable for both long-term storage and operational optical reconfiguration of their topology.

Acknowledgments

This work was financially supported by the Ministry of Science and Higher Education as part of the state assignment for 2020 and by Russian Foundation for Basic Research and the government of the Tomsk region of the Russian Federation, grant № 18-42-703018. The experimental results were obtained using the equipment of the Center for Collective Use "Impulse" with the financial support of the Ministry of Science and Higher Education of the Russian Federation under agreement 075-15-2019-1644, project identifier RFMEFI62119X0029.

References

[1] Akhmanov S A, Sukhorukov A P and Khokhlov R V 1968 Soviet physics uspekhi 10 609–36
[2] Kivshar Y S and Stegeman G I 2002 Optics and Photonics News 13 59–63
[3] Perin A S, Trushnikov I A and Inyushov A V 2019 Ferroelectrics 544 54–61
[4] Pustozero A V, Perin A S and Shandarov V M 2019 Ferroelectrics 544 20–6
[5] Chen Z, Segev M and Christodoulides D 2012 Reports on Progress in Physics 75 086401
[6] Kivshar Y S and Agrawal G 2003 Optical solitons: from fibers to photonic crystals (Academic press) p 540
[7] Chen L and Reano R M 2012 Optics Express 20 4032–38
[8] Chauvet M, Bassignot F, Henrot F, Devaux F, Gauthier-Manuel L, Maillotte H and Sylvain B 2015 Opt. Lett. 40 1258–61
[9] Kip D 1998 Appl. Phys. B 67 131
[10] Petrov M P, Stepanov S I and Khomenko AV 1991 Photorefractive Crystals in Coherent Optical Systems (Berlin: Springer-Verlag) p 275
[11] Safioui J, Devaux F and Chauvet M 2009 Optics Express 17 205–12
[12] Ryabchenok V, Shandarov V and Perin A 2017 J. Phys.: Conf. Series 867 012026
[13] Perin A S, Ryabchenok V Y and Shandarov V M 2016 Joint IEEE Int. Symp. on the Applications of Ferroelectrics. Darmstadt, Germany, 21 August 2016 1–4
[14] Stegeman G I and Segev M 1999 Science 286 1518–23
[15] Shandarov V, Perin A and Ryabchenok V 2015 J. Phys.: Conf. Series 594 012036
[16] Stepić M, Smirnov E, Rüter C E, Prönneke L, Kip D and Shandarov V 2006 Phys. Rev. E 74 046614