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Change in the refractive index of a photorefractive crystal during formation of a spatially screened soliton

S.A. Assel'born, N.D. Kundikova, I.V. Novikov

***Abstract*. A change in the refractive index of a photorefractive barium-sodium niobate crystal in an alternating electric field during the propagation of intensity-modulated coherent radiation in it is studied. It is shown experimentally that a change in the refractive index in the soliton regime in a photorefractive crystal with a small nonlocal response is independent of the external-field amplitude and intensity-modulation depth.**

Keywords: *photorefractive crystal, spatial soliton, self-action of light, change in the refractive index of a medium.*

The study of formation and properties of optical spatial solitons in photorefractive media attracts interest because, to produce nonlinear effects in a photorefractive medium, the radiation intensity of only 100 mW cm^{-2} is required, which is considerably lower than radiation intensities needed, for example, for Kerr media. Due to low radiation intensities, solitons are actively used in optical communication lines [1].

Depending on the formation mechanism, several types of solitons are distinguished: quasi-stationary [2], screened [3], vector, photovoltaic and composite solitons. At present photorefractive screened solitons are being actively investigated [4].

Phenomena related to formation of the soliton regime in an alternating electric field, unlike a constant electric field, are not studied completely, although the use of an alternating external field instead of a constant field eliminates the influence of the internal inhomogeneity of the crystal conductivity and the nonuniformity of its background illumination on the external-field screening. The authors of paper [5] considered qualitatively the self-action of light in a photorefractive crystal in an alternating electric field in the case of synchronously modulated radiation intensity and studied the spatial self-phase modulation of coherent radiation in a $Ba_2NaNb_5O_{15}$ crystal (BNN). Later, the self-focusing effect was observed in this crystal [6]. An analytic expression for the spatial-charge field in a photorefractive crystal in an alternating electric field upon synchronous modulation of the radiation intensity was obtained in [7]. A photorefractive soliton in a crystal in an alternating electric field upon synchronous modulation of the radiation intensity was first observed in paper [8]. The results of the study of the influence of nonlinear responses of a photorefractive medium on formation of the soliton regime are presented in [9]. Variations in the refractive index during formation of the soliton regime have not been studied experimentally so far.

The aim of our paper is to investigate experimentally variations in the refractive index during the propagation of intensity-modulated coherent radiation in a photorefractive crystal in an alternating electric field.

Experiments were performed with a BNN crystal. The crystal length along the laser beam was 3.5 mm and in the electric field direction – 3 mm. Variations in the refractive index were investigated by using the experimental setup shown schematically in Fig. 1.

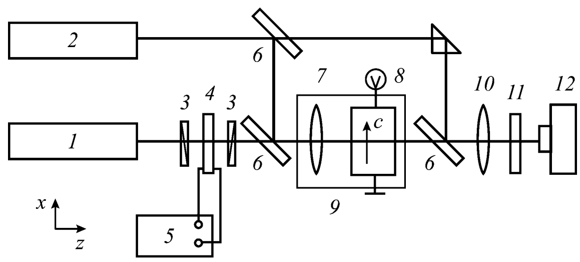

Figure 1. Scheme of the experimental setup: (*1*) He – Ne laser; (*2*) He – Cd laser; (*3*) crossed polarisers; (*4*) liquid-crystal cell; (*5*) low frequency oscillator; (*6*) semi-transparent mirrors; (*7*) short-focus lens; (*8*) photorefractive crystal; (*9*) translation stage; (*10*) objective; (*11*) blue-green filter; (*12*) CCD array; (*c*) optical axis of the crystal.

Radiation from 633-nm, 12-mW He – Ne laser (*1*), which was used to produce the soliton regime, propagated through liquid-crystal cell (*4*) mounted between two crossed polarisers (*3*). The liquid-crystal cell was connected with low frequency oscillator (*5*) (LFO) which generated a meander signal at a frequency of 50 Hz, which was used to modulate the radiation intensity at this frequency. To synchronise the modulation phase of the He – Ne laser radiation with the phase of the external alternating electric field, a delay was produced in the LFO. Focusing lens (*7*) and crystal (*8*) were mounted on platform (*9*), which could be moved along the laser beam (the *z* axis). The laser beam was focused by lens (*7*) with the focal distance 47 mm on the crystal so that the beam waist coincided with the front (input) face of the crystal.

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Variations in the refractive index of the crystal during formation of the soliton regime were studied by using 433-nm, 10-mW He – Cd laser (*2*). The radiation beam from this laser was split into two beams of approximately identical intensities to achieve the best contrast of an interference pattern obtained in a Mach – Zehnder interferometer. The use of the two lasers emitting at different wavelengths allowed us, with the help of a blue-green filter mounted in front of a CCD array, to record an interference pattern produced only by the He – Cd laser. To synchronise the modulation phase of radiations from He – Ne and He – Cd lasers with the external electric field frequency, a delay was produced in the LFO.

Figure 2 presents interference patterns produced in the BNN crystal by the 633-nm radiation with the intensity modulation depth $m = 0.73$ propagated in the crystal in the absence of an external alternating field and in the external field $E = 6$ kV cm^{-1}. To avoid the influence of the change in the refractive index at 433 nm caused by a linear electro-optical effect, the interference pattern was recorded immediately after switching off the external electric field.

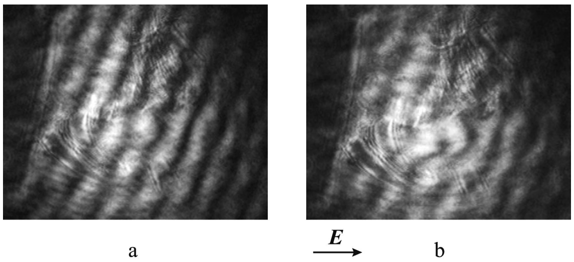

Figure 2. Interference patterns in the BNN crystal at $\lambda = 433$ nm at the intensity modulation depth $m = 0.73$ and the external electric field amplitude $E = 0$ (a) and 6 kV cm^{-1} (b).

It follows from Fig. 2 that, when the external field is switched on, the interference fringes experience nonuniform bending in the region of the self-focusing beam, while at the periphery the interference fringes are not displaced. The maximum displacement of the fringe is observed at the centre of the self-focusing beam and increases with increasing the external field amplitude. The dependence of the refractive index on the displacement of interference fringes was determined from the expression $\Delta n = h\lambda/L$, where h is the relative displacement of interference fringes and L is the crystal length along the laser beam.

Variations in the refractive index were studied at intensity modulation depths $m = 0.3$, 078, .86, 0.91, and 1. Figure 3 presents the dependences of the maximum change in the refractive index on the external field amplitude E for $m = 1$ and 0.78.

It follows from Fig. 3 that the maximum change in the refractive index during self-focusing increases with increasing the electric field amplitude E and modulation depth m. As shown in [9], the soliton regime is achieved for $E = 6.3$ kV cm^{-1} and $m = 1$, and also for $E = 8.4$ kV cm^{-1} and $m = 0.78$. One can see that the maximum change Δn_{max} in the refractive index during formation of the soliton regime in both cases is $\sim(1 \pm 0.05)\times10^{-4}$ and is independent of the external field amplitude E and the modulation depth m of the self-focusing beam intensity. According to [7], the field E_{sc} of a spatial charge in a photorefractive crystal in an alternating electric field upon synchronous modulation of

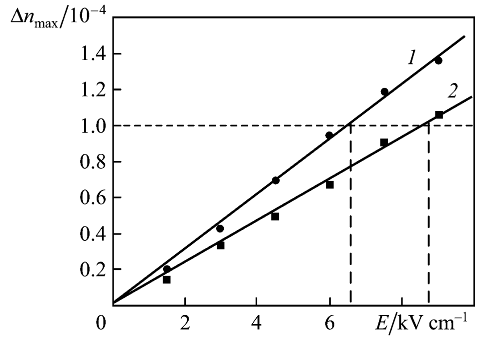

Figure 3. Dependences of the maximum change in the refractive index on the external field amplitude for radiation intensity modulation depths $m = 1$ (*1*) and 0.78 (*1*). The solid straight lines is a linear approximation.

the radiation intensity, which determines the change in the refractive index, has the local ($E_{sc}^{L} \propto Em$) and nonlocal ($E_{sc}^{NL} \propto L_e$) components. The electron drift length in the crystal under study is $L_e = \mu\tau_r E$, where μ is the mobility of charge carriers and τ_r is their recombination time; $\mu\tau_r \approx 2.7 \times 10^{-13}$ m^2 V^{-1} [10]. According to [9], for such an electron drift length, the nonlocal component does not affect the soliton regime formation. By using the values of E and m at which the soliton regime was achieved in our paper, we obtain $Em = (6 \pm 0.3)$ kV cm^{-1}. Because $\Delta n \propto E_{sc}$, the change in the refractive index corresponding to the achievement of the soliton regime is $\Delta n_{sol} \propto Em$ and, hence, is independent of E and m. Thus, the obtained result confirms once more that the local nonlinear response plays a decisive role in the soliton regime formation.

The maximum change Δn_{max} in the refractive index during formation of the soliton regime can be estimated as follows. Let us assume that a change in the refractive index has a step profile (as in a waveguide). By equating the diffraction angle of the beam inside material and the critical angle of the waveguide, we obtain $\Delta n_{max} = [0.61\lambda/(n_1 D)]^2 n_1/2$, where D is the beam diameter, defined as the beam width at the 1/e level of the maximum, and n_1 is the refractive index of the BNN crystal at $\lambda = 633$ nm. By substituting $D = 21$ μm and $n_1 = 2.2$, we obtain $\Delta n_{max} = 0.77 \times 10^{-4}$. These estimates are in good agreement with experimental results.

Thus, we have measured the change in the refractive index in a crystal for different amplitudes E of the external electric field and different modulation depths m of the self-focusing beam intensity. The change in the refractive index in a photorefractive crystal with a small nonlocal response after achievement of the soliton regime has been shown to be identical for any amplitudes of the external field and any modulation depths of the radiation intensity.

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