SOLITONS. BREATHERS

PACS numbers: 42.70.Nq; 42.65.Hw; 42.65.Tg
DOI: 10.1070/QE2008v038n09ABEH013734

Role of the local response of a photorefractive medium in the formation of a spatial screened soliton

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

***Abstract*. The propagation of intensity-modulated laser radiation in a barium – sodium niobate crystal is studied in an external electric field. The possibility of controlling a nonlinear local response of the crystal is demonstrated. It is shown experimentally that the conditions of formation of a one-dimensional spatial soliton can be changed by varying the nonlinear response of the crystal.**

Keywords: *photorefractive crystal, spatial soliton, self-action of light.*

Various manifestations of the self-action of light in photorefractive media (self-focusing, self-defocusing, self-bending [1], self-modulation, and the soliton regime) have been actively studied during the last decade [2]. These effects are used in optical switches, logic elements, multiplexers, and demultiplexers [3] and are also employed for data communication, storage and processing [3]. All these phenomena can be observed in photorefractive crystals at radiation intensities of ~ 100 mW cm^{-2}, whereas to observe nonlinear effects in Kerr media, considerably higher intensities of the order of 1 MW cm^{-2} are required.

There exist several types of solitons depending on the mechanism of their formation: quasi-stationary [4], screened [5], photovoltaic [6], composite [7] solitons and solitons in centrally symmetric media [8]. At present screened solitons in photorefractive media are being investigated most actively [9].

The formation of the soliton regime was studied in most cases in a constant electric field, whereas self-action effects in alternating electric fields were not investigated in detail. The use of an alternating external field offers a number of advantages compared to a constant field, eliminating the influence of the internal inhomogeneity of the crystal conductivity and the nonuniformity of its background illumination on the screening of the external field; in addition, in the case of synchronous modulation of the radiation intensity and external field, the nonlinear responses of the medium are increased.

S.A. Assel'born, N.D. Kundikova, I.V. Novikov University Academic Department of Nonlinear Optics, Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, and South Ural State University, prosp. Lenina 76, 454080 Chelyabinsk, Russia;
e-mail: igor_n@physicon.susu.ac.ru

Received 14 September 2007; revision received 3 March 2008
Kvantovaya Elektronika **38** (9) 859 – 861 (2008)
Translated by M.N. Sapozhnikov

The spatial self-phase modulation of light in a photorefractive crystal in an external alternating electric field was first observed in a barium – sodium borate crystal ($Ba_2NaNb_5O_{15}$, BNN) [10]. Consider the qualitatively possible mechanism of the spatial self-phase modulation of light in a photorefractive crystal [10]. Let us assume that an external alternating electric field is applied to the crystal. We will modulate the radiation intensity so that light is incident on the crystal only at instants when the direction of the external electric field vector is positive. Photoelectrons produced by light will move in the direction opposite to the electric field direction. Due to the capture of electrons by traps, the charge separation will occur in the crystal and the field E_{sc} of a spatially inhomogeneous charge will appear in the crystal volume. Due to the linear electrooptical effect, the refractive index n of the crystal will change by $\Delta n \sim E_{sc}$. During the next half-period, the field is directed to the opposite side and the crystal is not illuminated; therefore, it can be expected that the effect will be gradually accumulated, i.e. Δn will increases. The soliton regime can be obtained only if Δn is positive. The sign of Δn depends on whether the external electric field and incident radiation intensity change in phase or out-of-phase, other conditions being the same. In [10], both the decrease and increase in the refractive index n of the $Ba_2NaNb_5O_{15}$ crystal was observed. Radiation self-focusing [11] and one-dimensional spatial solitons were observed for the first time in this crystal as well [12].

The mechanism of spatial self-phase modulation of light, which was qualitatively considered in [11], was theoretically described in [13], where the conditions of formation of a one-dimensional refractive soliton were determined and the expression for the field E_{sc} of a spatially inhomogeneous charge was obtained in the case when the radiation intensity and amplitude of the external electric field were changed in phase:

$$E_{sc} = E_{sc}^{loc} + E_{sc}^{nloc} = -E\frac{mI}{I + I_d} - \frac{EL_e}{I + I_d}\frac{dI}{dx}. \qquad (1)$$

Here E is the amplitude of the external alternating electric field directed along the x axis (the optical axis of the crystal is also directed along the x axis); I is the beam intensity; I_d is the 'dark' illumination; L_e is the drift length of an electron; $m = (I^+ - I^-)/(I^+ + I^-)$ is the beam intensity modulation depth; and I^+ and I^- are the maximum and minimum intensities of the modulated beam [13]. One can see from expression (1) that, when the light intensity is modulated in phase with the alternating electric field applied to the crystal, along with the local component E_{sc}^{loc}, the nonlocal component E_{sc}^{nloc} of the response is also present, which is determined by the light field intensity gradient dI/dx. The local component E_{sc}^{loc} of the nonlinear response changes the efficiency of the beam self-focusing, while the nonlocal component E_{sc}^{nloc} causes the beam self-bending along the external field [13].

Thus, by changing the value of the local response, we can control the conditions of formation of a spatial screened soliton in the external alternating electric field during the propagation of light beam modulated in phase with the external field. It follows from expression (1) that the local response at the constant intensity is determined by the external electric field E and the radiation intensity modulation depth m; however, a change in the field E also causes a change in the nonlocal response. The latter change can be insignificant if the drift electron length L_e is small.

The aim of our paper is to study experimentally the possibility of controlling the conditions for formation of a spatial screened soliton in a photorefractive crystal in an external alternating electric field during the propagation of a light beam modulated by intensity in phase with the external field.

We performed experimental studies with a $Ba_2NaNb_5O_{15}$ crystal in which one-dimensional spatial solitons were observed for the first time [12]. The product of the mobility μ and recombination time τ_r of charge carriers in this crystal is $\mu\tau_r = 2.7 \times 10^{-13}$ m^2 V^{-1} [14]. According to the results obtained in [13], it can be expected that the beam displacement in the crystal cross section for such a value of $\mu\tau_r$ will be insignificant or absent at all. The crystal length along the laser beam was 3.5 mm and in the electric field direction – 3 mm.

Studies were performed by using the experimental setup shown schematically in Fig. 1. The 633-nm, 12-mW radiation from a He–Ne laser passed through a liquid-crystal cell placed between two crossed polarisers. The liquid-crystal cell was connected to a low-frequency generator forming a meander with a frequency of 50 Hz. The radiation intensity transmitted through the cell was modulated at this frequency. The modulation phase of the He–Ne laser radiation was synchronised with the phase of the external alternating electric field by decreasing the delay in the low-frequency generator. The laser beam was focused by a lens with a focal distance of 47 mm on a photorefractive crystal. The side faces of the crystal were covered with a conducting coating with electrodes glued to it with conducting cement, through which an alternating electric field was applied to the crystal. The focusing lens and crystal were mounted on a stage which could be moved along the beam (the z axis). The laser beam was focused by the lens on the crystal so that the waist coincided with the front (input) face of the crystal; the beam waist diameter was $D_1 = 21$ μm. If the external field was absent, the beam diameter at the crystal output was $D_2 = 30$ μm. The beam diameter was determined as the beam full width at half-maximum of its intensity. The measurement error determined by the resolution of a CCD array used in experiments was ~ 5 %.

The system for imaging the beam cross section in any cross section of the crystal with a six-fold magnification consisted of a fixed objective and a CCD array. The optical axis of the crystal (the c axis) coincided with the directions of the external electric field and incident radiation polarisation. The incident radiation polarisation was selected to provide the maximum change in the refractive index Δn [14].

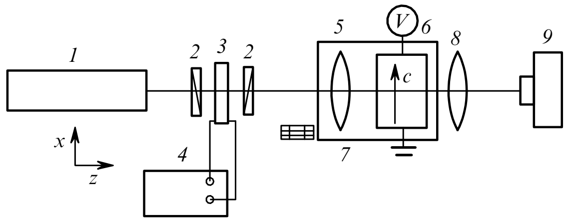

Figure 1. Scheme of the experimental setup: (*1*) He–Ne laser; (*2*) crossed polarisers; (*3*) liquid-crystal cell; (*4*) low-frequency generator; (*5*) short-focus lens; (*6*) photorefractive crystal mounted on translation stage (*7*); (*8*) objective; (9) CCD array; c is the optical axis of the crystal.

When an external alternating electric field with a frequency of 50 Hz was switched on in phase with the radiation intensity modulation and its amplitude was increased, the beam began to compress in the field direction. No change in the beam size in the perpendicular direction was observed (one-dimensional case). When a certain amplitude of the external alternating electric field was achieved, the beam cross sections on the input and output faces of the crystal became equal, i.e. the soliton regime appeared. As the electric field amplitude was further increased, the beam became diverging, i.e. self-focusing began to dominate over diffraction. No displacement of the beam centre in the electric field direction was observed. If the alternating electric field was switched on out-of-phase with the intensity modulation, the beam was broadened in this direction, i.e. in accordance with the results obtained in [10], the variation in the refractive index changed its sign.

The degree of beam self-focusing was characterised by the parameter $\alpha = D_1/D_2$. It is obvious that, if $\alpha < 1$, diffraction dominates over self-focusing, if $\alpha = 1$, the soliton regime is obtained, and if $\alpha > 1$, self-focusing dominates over diffraction. The beam diameter D_1 at the crystal input remained constant, while the beam diameter D_2 at the crystal output was measured for different external field amplitudes and different radiation intensity modulation depths. The amplitude E of the external alternating electric field was varied from zero to 9 kV cm^{-1} with a step of 1.5 kV cm^{-1}, while the intensity modulation depth m was arbitrarily set equal to 0.73, 0.78, 0.86, 0.91, and 1. These measurements gave the dependences of the beam self-focusing degree α on the external field amplitude E for different modulation depths m.

Figure 2 shows the dependence of the beam self-focusing degree α on the external field amplitude E for the intensity modulation depth $m = 0.91$. One can see that, as the electric field amplitude is increased, the self-focusing degree, which can be approximated by the linear dependence $\alpha = \alpha(E)$, increases.

Figure 3 presents the dependence of the beam self-focusing degree on the beam intensity modulation depth for the external filed amplitude 4 kV cm^{-1} (similar dependences were observed for other amplitudes). One can see that the beam self-focusing degree increases with increasing the intensity modulation depth m at the fixed external field amplitude E.

Thus, we have shown experimentally that the increase in the local nonlinear response, caused, according to (1), by the

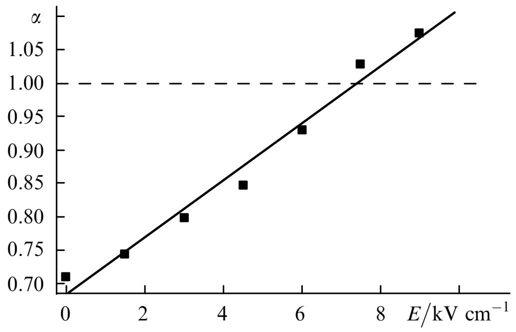

Figure 2. Dependence of the self-focusing degree $\alpha = D_1/D_2$ on the external field amplitude E for the intensity modulation depth $m = 0.91$.

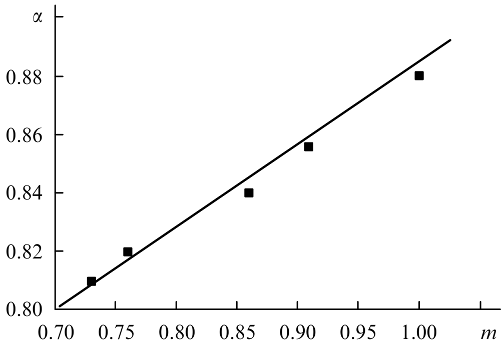

Figure 3. Dependence of the self-focusing degree α on the radiation intensity modulation depth m for the external field amplitude $E = 4$ kV cm^{-1}.

increase both in the beam intensity modulation depth m and in the external electric field amplitude E ($E_{sc}^{loc} \sim Em$), leads to the increase in the beam self-focusing degree. This corresponds to the theoretical results obtained in [13] and makes it possible to control experimentally the conditions of the soliton regime formation.

The field amplitude E_s at which the soliton regime is achieved ($\alpha = 1$) was determined for all modulation depths m from the dependence $\alpha(E)$ (Fig. 2). Figure 4 presents the dependence of the external field amplitude E_s required for obtaining the soliton regime on $1/m$. One can see that the external field amplitude required for obtaining the soliton regime linearly deceases with decreasing $1/m$. The results presented in Fig. 4 can be used to determine the amplitude of an external alternating electric field at which the soliton regime is achieved for the specified modulation depth.

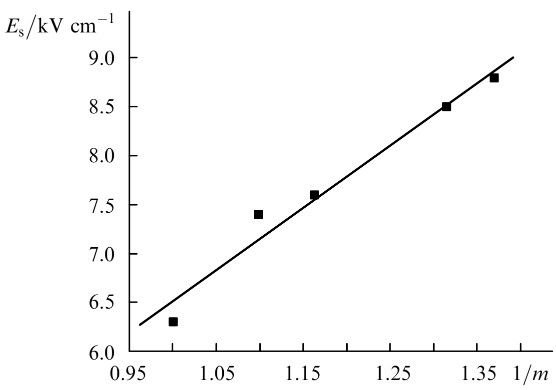

Figure 4. Dependence of the external field amplitude E_s required for obtaining the soliton regime on the inverse intensity modulation depth $1/m$.

Thus, we have shown experimentally that the increase in the local response of the photorefractive barium–sodium niobate crystal leads to the increase in the beam self-focusing degree. This allows one to control the formation of the soliton regime by varying the amplitude of an external alternating field and radiation modulation depth.

References

1. Petter J., Weilnau C., Denz C., Stepken A., Kaiser F. *Opt. Commun.*, **170**, 291 (1999).
2. Pettazzi F., Lehau G., Alonzo M., Sada C., Bazzan M., Argiolas N., Mazzoldi P., Chauvet M., Vlad V., Petris A., Fazio E. *Proc. SPIE Int. Soc. Opt. Eng.*, **6183**, 618319 (2006).
3. Garcia-Quirino G., Iturbe-Castillo M., Vysloukh V., Sanchez-Mondragn J., Stepanov S., Lugo-Martnez G., Torres-Cisneros G. *Opt. Lett.*, **22**, 154 (1997).
4. Segev M., Crosignani B., Yariv A., Fischer B. *Phys. Rev.*, **68**, 923 (1992).
5. Shin M., Leach P., Segev M., Garrett M., Salamo G., Valley G. *Opt. Lett.*, **21**, 324 (1996).
6. Jinsong L., Zhonghua H. *Phys. Lett. A*, **285**, 377 (2001).
7. Kristian M., Friedamann K., Carsten W., Denz C., McCarthyc G., Krolikowski W., Desyatnikov A., Kivshar Y. *Opt. Commun.*, **209**, 501 (2002).
8. Del Re E., Crosignani B., Tamburrini M., Segev M., Mitchell M., Refaeli E., Agranat A. *Opt. Lett.*, **23**, 421 (1998).
9. Sheu F., Shih M. *J. Opt. A.: Pure Appl. Opt.*, **9**, 271 (2007).
10. Zel'dovich B.Ya., Kataevskii N.G., Kundikova N.D., Naumova I.I. *Kvantovaya Elektron.*, **22**, 1161 (1995) [*Quantum Electron.*, **25**, 1125 (1995)].
11. Anikeev V.V., Bol'shakov M.V., Kundikova N.D., Lobachev A.V., Naumova I.I. *Trudy konferentsii 'Fundamental'nye problemy optiki'* (Proceedings of Conference on Funamental Problems of Optics) (St. Petersburg, 2000) p. 130.
12. Assel'born S.A., Kundikova N.D., Borodin M.V. *Pis'ma Zh. Tekh. Fiz.*, **34**, 50 (2008).
13. Frolova M.N., Shandarov S.M., Borodin M.V. *Kvantovaya Elektron.*, **32**, 45 (2002) [*Quantum Electron.*, **32**, 45 (2002)].
14. Gol'tser I.V., Zel'dovich B.Ya., Kundikova N.D., Naumova I.I. *Kvantovaya Elektron.*, **20**, 817 (1993) [*Quantum Electron.*, **23**, 708 (1993)].