Optik 126 (2015) 1621–1624

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Photorefractive spatial solitons supported by pyroelectric effects in strontium barium niobate crystals

Yanli Su*, Qichang Jiang, Xuanmang Ji

Department of Physics and Electronic Engineering, Yuncheng University, Yuncheng 044000, China

ARTICLE INFO

Article history:
Received 10 March 2014
Accepted 24 April 2015

Keywords:
Photorefractive spatial soliton
Pyroelectric effect
Divergenceless current

ABSTRACT

We show that pyroelectric spatial solitons can exist in non-photovoltaic photorefractive crystals under open-circuit conditions due to excellent pyroelectric effects. The space-charge field induced by pyroelectric fields is deduced by considering the boundary condition of divergenceless current. Moreover, the solution of bright, dark, and gray solitons is obtained by solving the solitary wave equation and the related numerical results are given.

1. Introduction

Recently, pyroelectric photovoltaic photorefractive spatial solitons (PPPSS) in lithium niobate crystals have been observed in experiment [1,2]. PPPSS is resulted from the combination of pyroelectric effects and photovoltaic effects and can be bright, dark, or gray [3]. To form PPPSS, there are two major conditions. Firstly, the pyroelectric field is large enough to support the soliton. Secondly, the pyroelectric field can persist for a remarkable long time, i.e. the relaxation time of pyroelectric fields is much larger than the formation time of the soliton. Considerable researches show that screening-photovoltaic photorefractive spatial solitons [4,5] can respectively degenerate into screening solitons [6,7] and photovoltaic solitons [8,9] under suitable conditions. Similarly, can the PPPSS be degenerated into pyroelectric solitons and photovoltaic solitons? Furthermore, we are more interested in the existence of the pure pyroelectric soliton in non-photovoltaic photorefractive crystals. In this paper, we will analyze the properties of pyroelectric fields in strontium barium niobate (SBN) crystals and point out that the pyroelectric field is large enough and can persist for a long time. Then, the space-charge field induced by pyroelectric fields is deduced from a set of electromagnetic equation. Finally, we give the solution of the bright, dark, and gray pyroelectric soliton and the related numerical results.

2. The properties of pyroelectric fields

The pyroelectric field E_{py} can be created in many photorefractive crystals, which originated from the change in spontaneous polarization P of the crystal resulting from a change in temperature. Assuming homogeneous heating, the pyroelectric field can be expressed as [10]

$$E_{py} = -\frac{1}{\varepsilon_0 \varepsilon_r} \frac{\partial P}{\partial T} \Delta T \qquad (1)$$

where ε_0 and ε_r are the permittivity of vacuum and relative permittivity, respectively. ΔT is the temperature change. It is very important that the homogeneous pyroelectric field can influence the photorefractive effect as does the externally applied electric field [11–13]. Refs. [11,12] have pointed out that large pyroelectric fields in SBN crystals can induce the space-charge field, which results in remarkable change of refractive index.

Moreover, the relaxation time of the pyroelectric field is given by [14]

$$\tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma_d} \qquad (2)$$

where σ_d is the dark conductivity of the crystal. For $LiNbO_3$, $\varepsilon_r = 28$, $\sigma_d = 10^{-16} - 10^{-18} (\Omega\,\mathrm{cm})^{-1}$, so the pyroelectric field can persist for several weeks in maximum. The PPPSS were observed in $LiNbO_3$ by virtue of those advantageous. However, the dark conductivity in SBN crystals, doped Ce concentration smaller than 0.1 wt %, is 4 to 5 orders of magnitude larger than that of $LiNbO_3$. This is disadvantageous for the observation of the soliton. Fortunately, the dark conductivity in SBN crystals will decrease dramatically when the dope concentration increases above 0.1 wt %, and the minimum of the dark conductivity is about $10^{-15} (\Omega\,\mathrm{cm})^{-1}$ [15]. Simultaneously,

* Corresponding author. Tel.: +86 359 8594374.
E-mail addresses: syli1979@163.com (Y. Su), jiangsir009@163.com (Q. Jiang), jixuanmang@126.com (X. Ji).

http://dx.doi.org/10.1016/j.ijleo.2015.04.053
0030-4026/

the relative permittivity ε_r in SBN crystals is 2 orders of magnitude larger than that of $LiNbO_3$. So, we can deduce that the pyroelectric field in SBN crystals also can persist for a long time compared with the formation time of the soliton. Next, we will discuss the solution of pyroelectric solitons in SBN crystals under open-circuit condition.

3. The solution of pyroelectric solitons

An optical beam propagates in an unbiased SBN crystal along the z-axis and is permitted to diffract only along the x-direction. The optical beam is linearly polarized along x-direction and the crystal is placed between an insulating plastic cover and a metallic plate whose temperature is accurately controlled by a Peltier cell [2]. As usual, the optical field is expressed in terms of slowly varying envelopes ϕ, i.e. $E_{opt} = \hat{x}\phi(x,z)\exp(ikz)$, where k is the wave number given by $k = k_0 n_e = (2\pi/\lambda_0)n_e$, n_e is the unperturbed index of refraction, and λ_0 is the free-space wavelength. Under these conditions, the evolution of the optical beam is governed by the equation [7]

$$i\frac{\partial \phi}{\partial z} + \frac{1}{2k}\frac{\partial^2 \phi}{\partial x^2} - \frac{k_0 n_e^3 r_{eff} E_{pysc}}{2}\phi = 0 \tag{3}$$

where r_{eff} is the effective ele ctro-optic coefficient, E_{pysc} is the space-charge field which is induced by the pyroelectric field. We will deduce the relation between the pyroelectric field E_{py} and space-charge field E_{pysc}. To obtain suitable expression of E_{pysc}, we consider the following equations.

The differential form of Ohm law is given by

$$j = \sigma E \tag{4}$$

The continuity equation for current is given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot j = 0 \tag{5}$$

The differential form of Gaussian theorem is expressed as

$$\nabla \cdot D = \rho \tag{6}$$

where j is the total current, $\sigma = \kappa I + \sigma_d$ is the total conductivity, E is the total electric field. ρ is the space-charge density, D is electric displacement vector, κ is the specific photoconductivity. Here, light intensity $I = (n_e/2\eta_0)\left|\phi\right|^2$ depends on x alone and is shown as $I(x) = I_0\bar{I}(x)$, $\bar{I}(x) = \exp(-2{s_1}^2)$, $s_1 = x/x_1$, x_1 is the characteristic size of the beam such as the beam radius, I_0 is the intensity of optical-beam center. Then, the total conductivity also can be expressed as $\sigma = \sigma_0[\bar{I}(x) + \eta]$, $\sigma_0 = \kappa I_0$, $\eta = I_d/I_0$.I_d is dark irradiation. Here, we consider SBN crystals under open-circuit conditions. Simultaneously, we assume that the illuminated region is small in extent compare to the thickness H of the crystal, i.e. $x_1 \ll H$. So, the total current j can be approximated by

$$j = j_d = \sigma_d \frac{V}{H} = \sigma_d E_{py} \tag{7}$$

where j_d is divergence-less current chosen to meet boundary condition, V is the voltage. Solving Eqs. (4)–(6), we have

$$\nabla \cdot \left[\varepsilon_0 \varepsilon_r \frac{\partial E}{\partial t} + \sigma E\right] = 0 \tag{8}$$

Considering the boundary condition and neglecting the diffusion and photovoltaic effects, we have [13]

$$\varepsilon_0 \varepsilon_r \frac{\partial E}{\partial t} + \sigma E = j_d \tag{9}$$

Solving the partial differential Eq. (9), we have

$$E\left(\bar{t}, s_1\right) = \frac{V}{H}\left\{\frac{\eta}{\bar{I}(s_1) + \eta} + \frac{\bar{I}(s_1)}{\bar{I}(s_1) + \eta}\exp\left[-\bar{t}\left(\bar{I} + \eta\right)\right]\right\} \tag{10}$$

where $\bar{t} = t/t_d$, $\tau_d = \varepsilon_0\varepsilon_r/\sigma_0$ is also known as the characteristic Maxwell time. The total electric field includes two components, i.e. $E = E_{py} + E_{pysc}$ [13,16]. The homogeneous heating causes a homogeneous pyroelectric field E_{py}, which causes a homogeneous refractive index change for the whole crystal. The formation of the soliton originates from an inhomogeneous refractive index change induced by the inhomogeneous space-charge field E_{pysc}. So we have

$$\begin{aligned} E_{pysc} &= E - E_{py} = E_{py}\frac{\bar{I}(s_1)}{\bar{I}(s_1) + \eta}\left\{\exp\left[-\bar{t}\left(\bar{I} + \eta\right)\right] - 1\right\} \\ &= E_{py}\frac{I}{I + I_d}\left\{\exp\left[-\bar{t}\left(\bar{I} + \eta\right)\right] - 1\right\} \end{aligned} \tag{11}$$

For $\bar{t} = 0$, it follows that $E_{pysc} = 0$, which means that the pyroelectric field has not been screened in the illuminated region yet and is fully present. For the steady-state case $\bar{t} \gg 1$, we have

$$E_{pysc} = -E_{py}\frac{I}{I + I_d} \tag{12}$$

This expression is similar to that of photovoltaic effects. However, the value and sign can be controlled flexibly by changing the temperature. Substituting Eq. (12) into (3), we obtain

$$i\frac{\partial U}{\partial \xi} + \frac{1}{2}\frac{\partial^2 U}{\partial s^2} + \alpha\frac{\left|U\right|^2}{1 + \left|U\right|^2}U = 0 \tag{13}$$

where $s = x/x_0$, $\xi = z/(kx_0^2)$, $\phi = (2\eta_0 I_d/n_e)^{1/2}U$, $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$ $\alpha = \delta E_{py}$, $\delta = (k_0x_0)^2(n_e^4 r_{eff}/2)$. x_0 is an arbitrary transverse scale. In what follows, we can deduce the solution of solitons based on the Eq. (13).

3.1. The solution of bright solitons

The bright solitary wave solutions can be obtained by expressing the beam envelope U in the usual fashion: $U = r^{1/2}y(s)\exp(i\nu\xi)$, where ν represents a nonlinear shift of the propagation constant and $y(s)$ is a normalized real function bounded between $0 \le y(s) \le 1$, and is required to satisfy the boundary conditions of $y(0) = 1$, $y'(0) = 0$ and $y(s \to \pm\infty) = 0$. The positive quantity r is defined as $r = I_0/I_d = 1/\eta$, which stands for the ratio of the maximum beam power density to that of the dark irradiance. Substitution of this form of U into Eq. (13) leads to the following equation:

$$\frac{d^2y}{ds^2} = 2\nu y - 2\alpha\frac{ry^3}{1 + ry^2} \tag{14}$$

Integrating Eq. (14), we can obtain

$$s = \pm\int_y^1 \left\{\frac{2\alpha}{r}\left[\ln\left(1 + r\tilde{y}^2\right) - \tilde{y}^2\ln(1 + r)\right]\right\}^{-1/2} d\tilde{y} \tag{15}$$

The normalized bright solitons profile $y(s)$ can be obtained from Eq. (15) by use of simple numerical integration procedures. We can show that expression of brackets is positive for $0 < y^2 < 1$, and thus we can know that the bright solitons require $\alpha > 0$, i.e. $E_{py} > 0$, which corresponds to $\Delta T > 0$. In this case, the crystal exhibits self-focusing effects. We take the following parameters [17,18]: $n_e = 2.35$, $\lambda_0 = 532$ nm, $x_0 = 20\,\mu$m, $r_{eff} = 237 \times 10^{-12}$ mV^{-1}, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, $\varepsilon_r = 3400$, $\partial P/\partial T = -3 \times 10^{-4}$, $r = 10$, $\Delta T = 10$, 15, 20. For this set of values, we have $\alpha = 20.1$, 30.2, 40.2, respectively. Fig. 1 depicts the normalized intensity profile of such bright