Physics Letters A 376 (2012) 3085–3087

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Pyroelectric photovoltaic spatial solitons in unbiased photorefractive crystals

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ARTICLE INFO

Article history:
Received 28 May 2012
Accepted 28 August 2012
Available online 30 August 2012
Communicated by A.R. Bishop

Keywords:
Nonlinear optics
Photorefractive spatial soliton
Pyroelectric effect

ABSTRACT

A new type of spatial solitons i.e. pyroelectric photovoltaic spatial solitons based on the combination of pyroelectric and photovoltaic effect is predicted theoretically. It shows that bright, dark and grey spatial solitons can exist in unbiased photovoltaic photorefractive crystals with appreciable pyroelectric effect. Especially, the bright soliton can form in self-defocusing photovoltaic crystals if it gives larger self-focusing pyroelectric effect.

1. Introduction

Photorefractive spatial solitons have been extensively investigated because of their possible applications for all-optical switching and routing. So far, there are three types steady-state photorefractive spatial solitons i.e. screening solitons [1,2], photovoltaic solitons [3,4] and screening–photovoltaic solitons [5,6] have been predicted theoretically and observed experimentally. In general, screening solitons require the application of an external bias field, whereas photovoltaic solitons exist in unbiased photorefractive crystals with appreciable photovoltaic effects. Screening–photovoltaic solitons result from the combination of the external bias field and photovoltaic effect. The physical source of these photorefractive solitons is all the photorefractive effect [7], that is to say, refractive index change driven by the space–charge field through the electro-optic effect. It is important to note that the pyroelectric field also is one of basic factors to induce space–charge field besides the external bias field and photovoltaic field [8–11].

However, the present investigation mainly focus on the external bias field, photovoltaic field and the combination of them, which resulted in screening solitons, photovoltaic solitons and screening–photovoltaic solitons, respectively. Very recently, the pyroliton i.e. pyroelectric spatial solitons originated from pyroelectric field in photorefractive crystals have been reported [12,13]. The forming process of the pyroliton can be expressed as follows: The change of temperature cause the spontaneous polarization of ferroelectric crystal and result in the pyroelectric field built up gradually. The ferroelectric field is not immediately compensated and induces a pyroelectric space–charge field and then the pyroliton form. They also pointed out that the pyroelectric field remains long enough to support a steady-state soliton form in their lithium niobate crystals and the sign of pyroelectric field can be transferred by increasing or decreasing temperature of the crystal. In this Letter, we will give bright, dark and grey soliton solutions based on pyroelectric effect and photovoltaic effect in unbiased photorefractive crystals. We can name them pyroelectric photovoltaic spatial solitons. The results show that the bright solitons can also exist in self-defocusing photovoltaic photorefractive crystals in virtue of the pyroelectric field induced by temperature change.

2. Theoretical model

An optical beam propagates in an unbiased photovoltaic photorefractive 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. Under these conditions, the evolution of the optical beam is governed by the equation:

$$\left(i\frac{\partial}{\partial z}+\frac{1}{2k}\frac{\partial^2}{\partial x^2}+\frac{k}{n_e}\Delta n\right)A(x,z)=0 \tag{1}$$

with

$$\Delta n=-\frac{1}{2}n_e^3 r_{eff}E_{sc} \tag{2}$$

where A is the slowly varying envelope of the optical beam, $k=k_0n_e=(2\pi/\lambda_0)n_e$, n_e is the unperturbed index of refraction, and λ_0 is the free-space wavelength. r_{eff} is the effective electro-optic coefficient, E_{sc} is the space–charge field. In unbiased photovoltaic photorefractive, the space–charge field E_{sc} consists of two parts as follows [9,10]:

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0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2012.08.043

$$E_{sc} = E_{phsc} + E_{pysc} \tag{3}$$

where E_{phsc} is the space–charge field originated from the photovoltaic field E_p and can be expressed as [3,4]:

$$E_{phsc} = -E_p \frac{I}{I + I_d} \tag{4}$$

where I is the intensity of optical beam and I_d is dark irradiation. The amplitude of E_p is related to the light polarization and its sign is determined by the photovoltaic coefficient. E_{pysc} is the space–charge field originated from the pyroelectric field E_{py} resulted from temperature change and can be expressed approximately as [10,11]:

$$E_{pysc} = -E_{py} \frac{t_p}{2} \frac{\sigma_{ph}}{\varepsilon_0 \varepsilon_r} \approx -E_{py} \frac{\sigma I}{I_d}, \tag{5}$$

σ_{ph} is the photoconductivity, t_p is pulse duration, σ is a parameter related to the character of crystal and satisfies conditions of $\sigma I/I_d < 1$. Note that the approximation can be obtained based on two points. The first one is that pyroelectric effect induced by the pulse light is similar to that of direct temperature change i.e. the results all are to produce pyroelectric field. The second one is to consider the values of these parameters [8–11]. Especially, Ref. [11] has reported that the amplitude of the pyroelectric space–charge field can reach about a third of the pyroelectric field under continuous wave laser beam.

Substituting Eqs. (2)–(5) into Eq. (1), and adopting the following dimensionless coordinates and variables: $s = x/x_0$, $\xi = z/(kx_0^2)$, $A = (2\eta_0 I_{2d}/n_e)^{1/2} U$, x_0 is an arbitrary spatial width, we can obtain the dynamical evolution equation of solitons as follows:

$$i\frac{\partial U}{\partial \xi} + \frac{1}{2}\frac{\partial^2 U}{\partial s^2} + \beta |U|^2 U + \alpha \frac{|U|^2}{1 + |U|^2} U = 0 \tag{6}$$

where $\beta = \sigma \tau E_{py}$, $\alpha = \tau E_p$, $\tau = (k_0 x_0)^2 (n_e^4 r_{eff}/2)$. For simplicity, any loss effects have been neglected. In what follows, we will discuss the spatial soliton solutions of Eq. (6).

3. Spatial soliton solutions

3.1. The bright soliton solution

We begin our analysis by considering first the bright soliton solution. In this case the bright solitary wave solutions of Eq. (6) 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 $0 \leqslant y(s) \leqslant 1$, 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 $r = I(0)/I_d$, 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. (6) yields

$$\frac{d^2 y}{ds^2} = 2\nu y - 2\beta r y^3 - 2\alpha \frac{r y^3}{1 + r y^2}. \tag{7}$$

Integrating Eq. (7), we find that

$$s = \pm \int_y^1 \left\{ \beta r \tilde{y}^2 \left(1 - y^2\right) + \frac{2\alpha}{r}\left[\ln\left(1 + r\tilde{y}^2\right) - \tilde{y}^2 \ln(1 + r)\right] \right\}^{-1/2} d\tilde{y}. \tag{8}$$

The normalized bright solitons profile $y(s)$ can be obtained from Eq. (8) by use of simple numerical integration procedures.

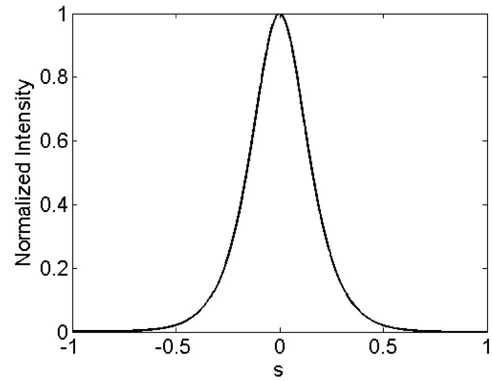

Fig. 1. The normalized intensity profile of bright spatial soliton for $a = -37.25$, $b = 46.07$, $r = 1$.

Bright spatial solitons require that the perturbation of crystal refractive index is positive i.e. the crystal exhibits self-focusing effect. However, Ref. [12] reported the bright pyroelectric photovoltaic soliton in an unbiased photovoltaic lithium niobate crystal where the perturbation of refractive index is generally negative because of the negative photovoltaic coefficients. The reason of bright soliton forming is that the self-focusing effect induced by the pyroelectric field is bigger than the self-defocusing effect induced by photovoltaic field. So we take the following parameters [12]: $\lambda_0 = 0.532$ μm, $x_0 = 20$ μm, $E_{ph} = -1.9 \times 10^6$ V/m, $E_{py} = 4.7 \times 10^6$ V/m, $r_{eff} = 30 \times 10^{-12}$ mV^{-1}, $n_e = 2.2$, $\sigma = 0.5$, $r = 1$. For this set of values, we have $a = -37.25$, $b = 46.07$. Fig. 1 depicts the normalized intensity profile of such bright pyroelectric photovoltaic soliton. The full width at half maximum (FWHM) of the soliton is approximately 7 μm which is consistent with the result of Ref. [12].

3.2. The dark soliton solution

Next we will prove that the dark pyroelectric photovoltaic soliton can also exist in this configuration. To obtain the soliton solution, we let $U = \rho^{1/2} y(s) \exp(i\mu\xi)$, where μ represents propagation constant and $y(s)$ is a normalized odd function of s, and is required to satisfy the boundary conditions of $y(0) = 0$, $y(s \to \pm\infty) = \pm 1$ and all the derivatives of y vanish at infinity. $\rho = I_\infty/I_d$, $I_\infty = I(s \to \pm\infty)$ indicates that the intensity of the dark soliton beam attains asymptotically a constant value at infinity. Taking the methods similar to bright soliton, we can obtain the numerical solution of normalized dark soliton:

$$s = \pm \int_y^0 \left\{ -\beta\rho\left(\tilde{y}^2 - 1\right)^2 - 2\alpha\left[\frac{\tilde{y}^2 - 1}{1 + \rho} - \frac{1}{\rho}\ln\left(\frac{1 + \rho\tilde{y}^2}{1 + \rho}\right)\right] \right\}^{-1/2} d\tilde{y}. \tag{9}$$

Dark spatial solitons require that the perturbation of crystal refractive index is negative i.e. the crystal exhibits self-defocusing effect. So we take $E_{py} = -2 \times 10^6$ V/m and the other parameters are same with the bright soliton. We have $a = -37.25$, $b = -19.61$. The normalized dark solitons profile $y(s)$ can be obtained by integrating Eq. (9) as shown in Fig. 2. The FWHM of the dark soliton is approximately 6 μm.

3.3. The grey soliton solution

Another interesting solitary wave solution is grey soliton. The grey soliton and dark soliton have the same conditions at infinite

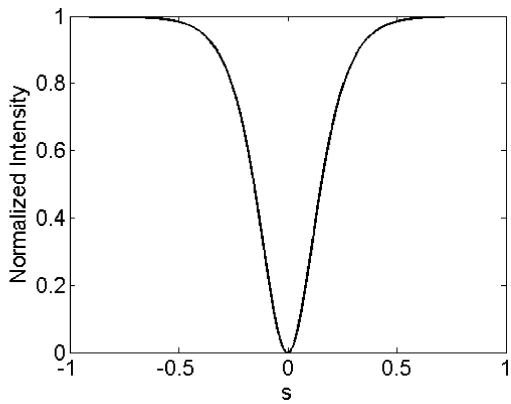

Fig. 2. The normalized intensity profile of dark spatial soliton for $a = -37.25$, $b = -19.61$, $\rho = 1$.

and their difference lies in the center of the beam. To obtain grey soliton solutions, we express U in the following fashion [1]:

$$U(s,\xi) = \rho^{1/2} y(s) \exp\left[i\left(\mu\xi + \int \frac{Q\,ds}{y^2(s)}\right)\right] \tag{10}$$

where Q is a real constant to be determined. $y(s)$ is a normalized even function and satisfies the boundary conditions: $y(s \to \pm\infty) = 1$, $y^2(0) = m$ $(0 < m < 1)$, m is the grayness of the solitons, $y'(0) = 0$, $y^{(n)}(\infty) = 0$ $(n \geqslant 1)$. Substituting Eq. (10) into Eq. (6), we find that

$$\frac{d^2 y}{ds^2} = 2\mu y + \frac{Q^2}{y^3} - 2\beta\rho y^3 - 2\alpha \frac{\rho y^3}{1 + \rho y^2}. \tag{11}$$

By further integrating Eq. (11), we can obtain

$$\left(\frac{dy}{ds}\right)^2 = 2\mu\left(y^2 - 1\right) - \beta\rho\left(y^4 - 1\right) - \left(\frac{1}{y^2} - 1\right)Q^2 - \frac{2\alpha}{\rho}\left[\rho\left(y^2 - 1\right) - \ln\left(\frac{1 + \rho y^2}{1 + \rho}\right)\right]. \tag{12}$$

Using the boundary conditions of y, we have

$$Q^2 = 2\beta\rho + 2\alpha \frac{\rho}{1 + \rho} - 2\mu, \tag{13}$$

$$\mu = \frac{1}{2(m-1)^2}\left\{m\left(m^2 - 1\right)\beta\rho + (1 - m)\left(2\beta\rho + \frac{2\alpha\rho}{1 + \rho}\right) + \frac{2m\alpha}{\rho}\left[\rho(m - 1) - \ln\left(\frac{1 + \rho m}{1 + \rho}\right)\right]\right\}. \tag{14}$$

The normalized grey soliton profile can be obtained by integrating Eq. (12). Fig. 3 depicts the grey soliton profile when $a = -37.25$, $b = -9.8$, $m = 0.3$, $\rho = 1$.

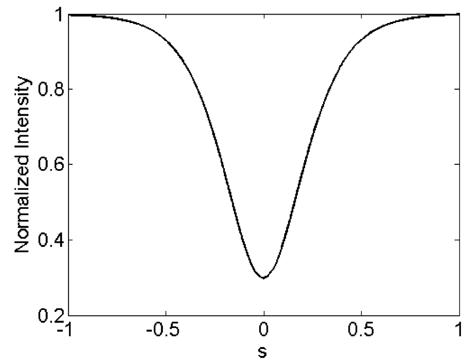

Fig. 3. The normalized intensity profile of grey spatial soliton for $a = -37.25$, $b = -9.8$, $m = 0.3$, $\rho = 1$.

4. Conclusions

In conclusion, we have proved that bright, dark and grey pyroelectric photovoltaic spatial solitons can exist in unbiased photovoltaic photorefractive crystals with appreciable pyroelectric effect. In self-defocusing photovoltaic photorefractive crystals, the bright soliton can also form in virtue of large self-focusing pyroelectric effect. The spatial soliton resulted from pyroelectric field also is possible in other pyroelectric photorefractive crystals.

Acknowledgements

This work was supported by the Natural Science Foundation of Shanxi Province, China (Grant No. 2011011003-2) and the Science and Technology Development Foundation of Higher Education of Shanxi Province, China (Grant No. 20111125).

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