Temperature Effects on the Self-Deflection of Bright Screening Solitons in Centrosymmetric Photorefractive Crystals

Yanli Su,* Qichang Jiang, and Xuanmang Ji

Department of Physics and Electronic Engineering, Yuncheng University, Yuncheng, 044000, China
(Received June 3, 2010)

The effects of temperature on the self-deflection of bright screening solitons in biased centrosymmetric photorefractive crystals were investigated numerically under steady-state conditions. The results show that the self-deflection of solitons is sensitive to temperature. The absolute value of the bending distance decreases monotonically with increasing temperature, which is different from the non-centrosymmetric photorefractive crystals. The crystal considered here is potassium lithium tantalite niobate (KLTN).

PACS numbers: 42.65.Tg, 42.65.Jx, 42.65.Hw

I. INTRODUCTION

Photorefractive (PR) spatial solitons are known to occur when the process of diffraction is exactly balanced by the PR effect. Such optical phenomenon have become a considered topic in PR nonlinear optics for their formation feature at low laser power and potential important applications. At present, three types of steady-state PR spatial solitons (screening solitons [1–3], photovoltaic solitons [4–6], and screening-photovoltaic solitons [7, 8]) have been predicted theoretically and found experimentally. All of the above mentioned solitons have been studied in non-centrosymmetric photorefractive (NCPR) crystals. A decade ago, screening spatial optical solitons in centrosymmetric photorefractive (CPR) crystals were firstly predicted theoretically by Segev and Agranat [9] and observed experimentally by DelRe et al. [10, 11]. Such solitons are governed by a change in the refractive index resulting from the quadratic electro-optic effect (dc Kerr effect) and are different from those in NCPR crystals, where the change in the refractive index is driven by the linear electro-optic effect (Pockels effect). In 2010, Zhan et al. [12] reported the self-deflection of bright screening solitons in CPR crystals. The results show that the solitons propagate along a parabolic trajectory due to the diffusion process, and the central spatial frequency component shifts linearly with the propagation distance.

As we know, the diffusion process and the dark irradiance of the crystal are dependent on the crystal temperature [13, 14]. It is important to note that the relative dielectric constant is also a function of temperature in a CPR crystal [10, 11]. As a result, the temperature effects on the self-deflection of PR solitons will be very obvious. In this paper, we have investigated the temperature effects on the self-deflection of bright screening spatial solitons in a biased CPR crystal. The results show that the self-deflection of such solitons is sensitive to temperature, and the properties of self-deflection are different from those in a non-centrosymmetric photorefractive crystal [15].
II. THEORETICAL MODEL

To analyze the self-deflection process of bright screening solitons, let us consider an optical beam that propagates in a biased CPR crystal along the \( z \)-axis and is permitted to diffract only along the \( x \)-direction. The crystal is taken here to be KLTN, which is put with its principal axes aligned with the \( x \), \( y \) and \( z \)-direction of the system. We assume that the optical beam is linearly polarized along the \( x \)-direction and an external bias electric field is applied to the crystal in the same direction. As usual, we express the optical field of the incident beam in terms of a slowly varying envelope, \( E = A(x, z) \exp(ikz) \), where \( k = k_0 n_e = (2\pi/\lambda_0)n_e \), \( n_e \) is the unperturbed index of refraction, and \( \lambda_0 \) is the free-space wavelength. Under these conditions, the optical beam satisfies the following envelope evolution equation [9, 12]:

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

with \( \Delta n = -\varepsilon_r g_{\text{eff}}\varepsilon_0^2(\varepsilon_r - 1)^2 E_{\text{sc}}^2/2 \), \( E_{\text{sc}} \) is the space charge field, \( g_{\text{eff}} \) is the effective quadratic electro-optic coefficient, \( \varepsilon_r \) is the relative dielectric constant at a certain temperature, which is monotonically decreasing with a temperature increase from \( T = 285 \) K. We can denote \( \varepsilon_r = 10000, 8000, 6000, 4800 \) corresponding to \( T = 292, 294, 299, 303 \) K [10].

We consider the optical beam that is a bright type. In the steady state, the space charge field can be obtained from the transport model of Kukhtarev et al. and can be expressed as

\[
E_{\text{sc}} = E_0 \frac{I_b + I_d}{I_b + I_d} - \frac{k_B T}{e} \frac{\partial I/\partial x}{I_b + I_d + I_d},
\]

where \( I = |A(x, z)|^2 \) is the intensity of the soliton beam, \( I_b \) and \( I_d \) are the intensity of background light and dark irradiance, respectively, \( k_B \) is Boltzmann’s constant, and \( E_0 \) is the biased electric field. The temperature dependence of \( I_d \) is described as follows [13, 14]:

\[
I_d = I_{d0} \left( \frac{T}{300} \right)^{3/2} \exp \left[ \frac{E_l}{k_B} \left( \frac{1}{300} - \frac{1}{T} \right) \right],
\]

where \( I_{d0} \) is the value of \( I_d \) at \( T = 300 \) K, and \( E_l = 10^{-19} \) J is the level location in the gap. Substitute Eqs. (2) and (3) into Eq. (1), and adopt the following dimensionless coordinates and variables: \( s = x/x_0, \xi = z/(kx_0)^2, A = [2\eta_0(I_b + I_d)/n_e]^{1/2} U \) where \( x_0 \) is an arbitrary spatial width. Under these conditions, the following dynamical evolution equation can be obtained:

\[
iU_{\xi} + \frac{1}{2} U_{ss} - \beta \frac{U}{(1 + |U|^2)^2} + \gamma_1 \left( \frac{|U|^2}{1 + |U|^2} \right) U + \gamma_2 \left[ \frac{|U|^2}{1 + |U|^2} \right]^2 U = 0,
\]
where $\beta = \delta E_0^2$, $\gamma_1 = 2\delta E_0 \tau$, $\gamma_2 = \delta \tau^2$, $\delta = (k_0 x_0)^2 (n_e^4 g_{\text{eff}} / 2) e_0^2 (\varepsilon_\tau - 1)^2$, and $\tau = k_B T / (x_0 e)$. $\gamma_1$ is the first-order diffusion term which produces odd effects such as beam-deflection, and $\gamma_2$ is the higher-order diffusion term which has even effects such as spatial broadening. For simplicity, any loss effects have been neglected.

By use of the results reported in Refs. [9, 12], the bright screening soliton solutions are rewritten as

$$s = \pm \int \left( \frac{2\beta}{r} \right)^{-1/2} \left( 1 - \frac{r \bar{y}^2}{1 + r} - \frac{1}{1 + r \bar{y}^2} \right)^{-1/2} d\bar{y}. \quad (6)$$

Let $r_0 = I(0) / I_{d0}$ denote the value of $r$ at $T = 300$ K, using Eq. (4), the quantity $r = I(0) / I_d$ can be expressed as

$$r = r(T) = \frac{I_0}{I_d} = r_0 \left( \frac{T}{300} \right)^{-3/2} \exp \left[ -\frac{E_0}{k_B} \left( \frac{1}{300} - \frac{1}{T} \right) \right]. \quad (7)$$

In this article, we pay attention to the temperature dependence of $\varepsilon_\tau$, $I_d$, and $\tau$. The bright soliton solutions of the form Eq. (6) are taken as the incident optical beam which is used to investigate the self-deflection of bright screening spatial solitons in biased CPR crystals.

### III. NUMERICAL SIMULATIONS AND DISCUSSIONS

To start, we take the following parameters [10]: $n_e = 2.2$, $g_{\text{eff}} = 0.12 \, \text{m}^4 \text{C}^{-2}$, $T = 300$ K, $E_0 = 2 \times 10^5 \, \text{V/m}$, $\lambda_0 = 0.5 \, \mu\text{m}$, and $x_0 = 40 \, \mu\text{m}$, thus we find that $\varepsilon_\tau = 5600$, $\beta = 34.88$, $\gamma_1 = 0.225$, and $\gamma_2 = 3.63 \times 10^{-4}$, and we let $r_0 = 5$. By numerically solving Eq. (5) we obtain the self-deflection of bright screening solitons as shown in Fig. 1. The
results show that the intensity profile remains approximately invariant during propagation and the center of the optical soliton moves on an approximately parabolic trajectory.

To investigate the effect of temperature on the self-deflection of bright solitons, we let the solitary wave in Fig. 1 be the incident beam, then numerically solve Eq. (5) under different temperatures. Figs. 2(a)–(d) give the evolution of the incident beam in the CPR crystal at $T = 292, 294, 299, \text{ and } 303 \text{ K}$, respectively. The spatial shift of the beam center in the crystal for the incident beam at the corresponding temperature is shown in Fig. 3. The results show that the temperature effects on self-deflection of the solitary beam are very obvious, i.e., the spatial shift of the beam center is strongly dependent on the temperature. The results also indicate that the incident beam, such as Fig. 2 (a) and (b), cannot involve a stable bright screening soliton when $T \neq 300 \text{ K}$, but tends to experience a cycle of compression and expansion, and its maximum amplitude oscillates with the propagation distance. When the temperature is slightly different from 300K, such as in Fig. 2 (c) and (d), the incident beam can reshape itself and tries to evolve into a solitary wave after a certain distance. In addition, the spatial shift of the beam center is monotonically decreasing with an increase of the temperature, which is different from the
IV. CONCLUSION

In conclusion, we investigated the effects of temperature on the self-deflection of bright screening solitons in a CPR crystal. Our results show that the bending distance of the beam center is strongly dependent on the temperature. The absolute value of the bending distance decreases monotonically with increasing temperature, which is different from the NCPR crystals. One can adjust the crystal temperature to change the bending angle of a bright screening soliton in a biased CPR crystal.

Acknowledgements

This work was Project supported by the Science and Technology Development Foundation of Higher Education of Shanxi Province, China (Grant No. 200611042) and The Basic Research Foundation of Yuncheng University, China (Grant No. JC-2009003)

References

* Electronic address: ysl1197981@163.com