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Effect of the dark soliton crystal temperature on the deflection of the bright soliton in a separate bright–dark screening soliton pair

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Abstract

We investigate theoretically the dark soliton crystal temperature effect on the deflection of the bright one in a bright–dark soliton pair which is formed in a serial non-photovoltaic photorefractive crystal circuit. Our numerical results show that the spatial shift of the bright soliton changes with the temperature of the dark one crystal and varying the temperature of the dark soliton crystal can influence the deflection strongly. The temperature dependence of the deflection process is further studied by perturbation technique and the results are found to be good agreement with that obtained by numerical method. Relevant examples are provided.

Keywords: Nonlinear optics; Spatial optical solitons; Soliton pair; Photorefractive effects; Screening

1. Introduction

Photorefractive (PR) spatial solitons have been a topic of research in nonlinear optics in the past few years because of their possible applications for optical switching and routing [1–22]. At present, three types of steady-state solitons (screening solitons [1–6], photovoltaic solitons [7–11] and screening-photovoltaic solitons [12]) have been predicted and already found experimentally [13–15]. At the same time, soliton pairs (coherent and incoherent) and soliton interaction have also been extensively investigated [16–24]. However, almost all the investigations on PR soliton, soliton pair and soliton interaction were concerned with only one piece of PR crystal [1–24]. Recently, Liu et al. [25–27] predicted a new type of soliton pair, named separate spatial soliton pair, which is formed in a crystal circuit in which two PR crystals are connected in a chain by electrode leads with or without a voltage source, and they investigated the parametric coupling effects between the two solitons in a separate soliton pair in detail on such biased [25] or unbiased [26,27] PR circuit. In the limit of the spatial extent of the optical wave being much less than the width of the crystal, the previous results indicated that the change of the intensity of the dark soliton can affect the other soliton whereas the bright one cannot, and the most distinct difference between separate soliton pair and the soliton pair formed in a single crystal is that the interaction of separate soliton pair is collisionless or contactless optically. These properties may provide a new way for the design of all optical devices.

As previously pointed out, the diffusion process introduces an asymmetric tilt in the light-induced PR waveguide, which results in the self-deflection of bright

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solitons during their propagation in the media [28,29]. Both the diffusion process and the dark irradiance of the crystal are dependent on the crystal temperature [30]. Therefore, temperature has an obvious effect on the self-deflection of bright solitons [31]. Since the two solitons in a separate soliton pair couple each other by parametric coupling, whether the temperature of one soliton can affect the deflection of the other soliton in such soliton pair? If it can, can we control the deflection of one soliton by adjusting the temperature of the other soliton?

In this paper, we pay our attention to the effect of the dark soliton crystal temperature on the deflection of bright one in a separate bright–dark screening soliton pair in one dimension. By using a numerical method, the dynamical evolution and the deflection of the bright soliton are discussed and then the analytical solution of the deflection of the bright soliton is also achieved by use of the perturbative procedure. Finally, comparison is made between the results obtained using the numerical and the analytical methods.

2. Theoretical model

We investigate steady-state PR solitons formed in a series PR crystal circuit in which two non-photovoltaic PR crystals denoted by P and $\hat{P}$, are connected electronically in a chain by electrode leads with an external voltage source V_A, as shown in Fig. 1. For each crystal, electrodes are made on the surfaces with their normal parallel to c-axis of the crystal; each crystal can support a spatial bright (dark) soliton, known as a separate screening spatial soliton pair. Considering two optical beams that propagate in the two crystals along the z and $\hat{z}$ axes and are permitted to diffract only along the x and $\hat{x}$ directions, respectively. The optical c axes of the two crystals P and $\hat{P}$ are oriented along the x and $\hat{x}$ coordinate, respectively. Moreover, let us assume that the polarizations of the two incident optical beams are both linearly polarized along x and $\hat{x}$ directions, respectively. Let $I = I(x,z)$ and $\hat{I} = \hat{I}(\hat{x},\hat{z})$ denote the intensities of the two incident beams, which can also be expressed as $I = I_d|U|^2$ and $\hat{I} = \hat{I}_d|\hat{U}|^2$, where I_d and $\hat{I}_d$ are the so-called dark irradiance, which are all depend on the crystal's temperature. U and $\hat{U}$ are the beam envelopes of the optical beams. By employing standard procedures and neglecting the loss in the material, we can obtain the following dynamical evolution equations of U and $\hat{U}$ [25]:

$$iU_\xi + \frac{1}{2}U_{ss} - \beta(\rho+1)\frac{U}{1+|U|^2} + \gamma\frac{(|U|^2)_s U}{1+|U|^2} = 0, \quad \text{(1a)}$$

$$i\hat{U}_{\hat{\xi}} + \frac{1}{2}\hat{U}_{\hat{s}\hat{s}} - \hat{\beta}(\hat{\rho}+1)\frac{\hat{U}}{1+|\hat{U}|^2} + \hat{\gamma}\frac{(|\hat{U}|^2)_{\hat{s}} U}{1+|\hat{U}|^2} = 0, \quad \text{(1b)}$$

where $U_\xi = \partial U/\partial\xi$, $U_{ss} = \partial^2 U/\partial s^2$, $\beta = \sigma E_0$, $\gamma = \sigma k_B T/(x_0 e)$, $\sigma = (k_0 x_0)^2(n_e^4 r_{33}/2)$, and $\rho = I_\infty/I_d$. $\xi = z/(kx_0^2)$, $s = x/x_0$, x_0 is an arbitrary spatial width, $k = n_e k_0 = (2\pi/\lambda_0)n_e$, λ_0 is the free-space wavelength of the lightwave employed, n_e is the unperturbed extraordinary index of refraction, r_{33} is the electro-optic coefficient of the PR crystal, $I_\infty = I(x \to \pm\infty, z)$, e is the electron charge, k_B is Boltzmann's constant, T is the absolute temperature of the crystal P. In this paper, the parameters with the symbol $\hat{}$ denoting the other optical beam have the same physical meaning.

We pay our attention to the bright–dark screening soliton pair. Let us assume that the bright soliton formed in crystal P and the dark one formed in crystal $\hat{P}$. The expressions for E_0 and $\hat{E}_0$ necessary for a bright–dark soliton pair are as follows [25]:

$$E_0 = gE_A, \quad \text{(2a)}$$

$$\hat{E}_0 = \hat{g}\hat{E}_A, \quad \text{(2b)}$$

where $g = \hat{\delta}(\hat{I}_\infty + \hat{I}_d)/[\delta(I_\infty + I_d) + \hat{\delta}(\hat{I}_\infty + \hat{I}_d)]$, $\hat{g} = \delta(I_\infty + I_d)/[\delta(I_\infty + I_d) + \hat{\delta}(\hat{I}_\infty + \hat{I}_d)]$, $E_A = V_A/W$, $\hat{E}_A = V_A/\hat{W}$, $\delta = S\mu s_i(N_D - N_A)/(\gamma_R N_A W)$ and $\hat{\delta} = \hat{S}\hat{\mu}\hat{s}_i(\hat{N}_D - \hat{N}_A)/(\hat{\gamma}_R \hat{N}_A \hat{W})$. S denotes the electrodes surfaces, μ the electron mobility, s_i the photoexcitation cross section, N_D denotes the donor density, N_A, the acceptor density and γ_R, the carrier recombination rate. The parameters g and $\hat{g}$ are known as coupling coefficients between the two solitons with $g + \hat{g} = 1$.

The bright (dark) soliton solution can be derived from Eq. (1a) (Eq. (1b)) by expressing the beam envelope U ($\hat{U}$) in the usual fashion: $U = r^{1/2}y(s)\exp(i v\xi)$($\hat{U} = \hat{\rho}^{1/2}\hat{y}(\hat{s})\exp(i\hat{v}\hat{\xi})$), where v ($\hat{v}$) represents a nonlinear shift of the propagation constant and $y(s)$ ($\hat{y}(\hat{s})$) is the normalized intensity profile, r ($\hat{\rho}$) is defined as $r = I(0)/I_d(\hat{\rho} = \hat{I}_\infty/\hat{I}_d)$. Using the boundary

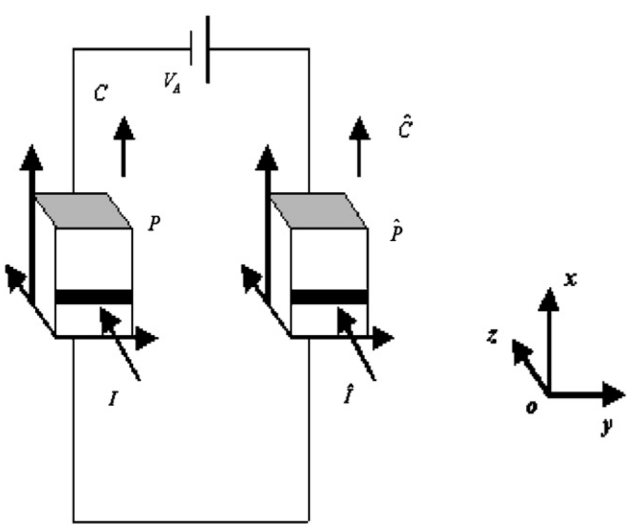

Fig. 1. Illustration of the serial PR crystal circuit. C and $\hat{C}$ denote the c axes. I and $\hat{I}$ denote the incident one-dimensional soliton-like laser beams.