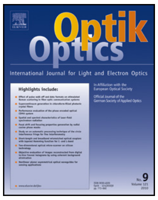
Optik 127 (2016) 5928–5934

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Coherently coupled bright-bright screening soliton pairs in biased centrosymmetric photorefractive crystals

Lili Hao[a,b,*], Chunfeng Hou[b], Xiaoxing Wang[b], Qiang Wang[a], Haiwei Mu[a]

[a] Department of Physics, Northeast Petroleum University, Daqing 163318, China
[b] Department of Physics, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 3 March 2016
Accepted 20 April 2016

Keywords:
Nonlinear optics
Photorefractive spatial soliton
Coherent coupling
Electro-optic effect

ABSTRACT

A comprehensively study of coherently coupled bright-bright spatial soliton pair co-propagating in biased centro-symmetric photorefractive crystals is investigated. It is shown that coherently coupled bright-bright spatial soliton pairs can be supported in steady-state regime under appropriate conditions. Moreover, the effects of three physical factors, i.e., the intensity ratio and the initial phase difference between two incident coherent beams, and various external bias field on the existence conditions, properties and self-deflection process of such bright-bright soliton pair have been discussed in detail. Finally, the evolution equations, analytic solutions, and the displacements of self-deflection of coherently coupled bright-bright soliton pair in the low-amplitude regime are also presented.

1. Introduction

Since their unique features of formation at low laser power and potential important applications [1], the researches on photorefractive (PR) spatial solitons have been spanned from the formation and properties of these PR spatial solitons to the interactions between spatial solitons. Among soliton interactions, soliton pairing has always been an appealing issue. When two incident beams propagate in the PR materials, the refractive-index modulation induced by beams will have influence on these beams and make these two beams trapped mutually, and then each of them propagates undistorted, i.e., coupled spatial soliton pairs form. During this process, every component of coupled spatial soliton pairs depend on each other and each beam alone cannot survive as a soliton if the other beam is absent. Incoherently coupled screening soliton pairs was firstly predicted by Christodoulides et al. [2] and experimentally observed by Chen et al. [3,4]. Soon later, Hou et al. [5–7] proved incoherently coupled bright, dark and dark-bright hybrid screening-photovoltaic soliton families in biased photovoltaic PR materials. Konar et al. investigated the photovoltaic soliton pairs in two-photon PR crystals under open circuit conditions [8–10]. All of the above mentioned soliton pair or families in noncentrosymmetric PR materials arise from the linear EO effect (Pockels effect). Moreover, Segev and Agranat [11] presented spatial solitons can occur in centrosymmetric PR crystals where PR effect result from the quadratic EO effect (dc Kerr effect) and incoherently coupled soliton pairs can also be found in centrosymmetric PR crystals [12,13]. In addition, the interactions between other types of PR solitons have also been widely studied [14–17]. The incoherent interactions of spatial solitons have already been widely concerned in recent two decades, whereas the researches regarding the coherent interactions are relatively few. Even in the research field of coherent interactions, much attention has been paid to the coherent coupling of beams that propagate non-collinearly and

---

* Corresponding author at: Department of Physics, Northeast Petroleum University, Daqing 163318, China.
E-mail address: haolili0820@126.com (L. Hao).

http://dx.doi.org/10.1016/j.ijleo.2016.04.116
0030-4026/

most works are based on the experimental methods. So far, the issue of coherent coupling of solitons co-propagating in PR materials has not been reported yet. In this paper, we investigate theoretically coherently coupled bright-bright spatial soliton pairs co-propagating in biased centrosymmetric PR crystals where the change of refractive index is governed by the quadratic electro-optic effect. The effects of the intensity ratio, the initial phase difference between two coherent incident beams, and various external bias field on the existence conditions and properties of coherently coupled bright-bright soliton pair will be discussed in detail. Moreover, the self-deflection of bright-bright soliton pair will be studied systematically by exploiting perturbation methods. Finally, the evolution equations, exact analytic solutions, the widths, both the deflections in the low-amplitude regime are also presented.

2. Theoretical model

We consider two mutually coherent incident optical beams that co-propagate along the z axis in biased centrosymmetric PR crystal which is put with its principal axes aligned with the x, y and z directions of the system. The polarization of coherent incident beams and an external bias electric field are both assumed to be parallel to the x-axis. For simplify, only the x-axis diffraction is taken into account. The optical fields of the incident beams are expressed as the slowly varying envelopes, i.e.,$\vec{E}_m(x,z)=\hat{x}\varphi_m(x,z)\exp[i(kz+\phi_m)]$, $m=1,\ 2$. ϕ_m represent the initial phase of two coherent incident beams, $k=k_0n_e=\left(2\pi/\lambda_0\right)n_e$ with n_e being the unperturbed index of refraction and λ_0 the free-space wavelength. Under these conditions, these two coherent incident beams satisfy the following equations [11]

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

with $\Delta n=-n_e^3g_{\mathrm{eff}}\varepsilon_0^2(\varepsilon_r-1)^2E_{sc}^2/2$. Here g_{eff} is the effective quadratic EO coefficient of PR crystal. ε_0 and $\varepsilon_r$are the vacuum and relative dielectric constants, respectively. $E_{sc}$is the space-charge field in the material. In the steady state, E_{sc} can be expressed as [18]

$$E_{sc}=E_0\frac{I_\infty+I_b+I_d}{I+I_b+I_d}-\frac{k_BT}{e}\frac{\partial I/\partial x}{I+I_b+I_d} \tag{2}$$

where I_d and I_b are the intensity of dark irradiance and background, respectively. I is the total intensity of two incident beams and can be expressed in the terms of the envelopes $\phi_m$by use of Poynting's theorem, i.e.,$I=I(x,z)=\left(n_e/2\eta_0\right)\left(|\varphi_1+\varphi_2|^2\right)$with $\eta_0=\left(\mu_0/\varepsilon_0\right)^{1/2}$. $E_0=E_{sc}(x\to\pm\infty,\quad z)$ and $I_\infty=I(x\to\pm\infty,z)$ represent the space charge field and the total intensity for $x\to\pm\infty$, respectively. In general, $E_0\approx\pm V/W$ where V is applied external voltage and W is the x-width of PR crystal.

The normalized envelope evolution equations can now be obtained by submitting Eq. (2) into (1). For convenience, we adopt following dimensionless parameters: $\xi=z/kx_0^2$, $s=x/x_0$, $\varphi_m=\left[2\eta_0(I_b+I_d)/n_e\right]^{1/2}U_m$, $m=1,\quad 2$ and x_0 is an arbitrary spatial width. Under these conditions, the envelopes of U_k are then found to obey

$$\mathrm{i}\frac{\partial U_m}{\partial\xi}+\frac{1}{2}\frac{\partial^2U_m}{\partial s^2}-\frac{\beta(1+\rho)^2U_m}{\left(1+|U_1+U_2|^2\right)^2}+\gamma_1\frac{\left(|U_1+U_2|^2\right)_s}{\left(1+|U_1+U_2|^2\right)^2}U_m-\gamma_2\frac{\left[\left(|U_1+U_2|^2\right)_s\right]^2}{\left(1+|U_1+U_2|^2\right)^2}U_m=0 \tag{3}$$

$\rho=I_\infty/(I_d+I_b)$, $\beta=(k_0x_0)^2n_e^4g_{eff}\varepsilon_0^2(\varepsilon_r-1)^2E_0^2/2$, $\gamma_1=k_0^2x_0n_e^4g_{eff}\varepsilon_0^2(\varepsilon_r-1)^2(k_BT)$
$\times E_0/e$, and $\gamma_2=k_0^2n_e^4\times g_{eff}\varepsilon_0^2(\varepsilon_r-1)^2(k_BT)^2/2e^2$. Here, γ_1 is the first-order diffusion term which is responsible for self-deflection and γ_2 is the high-order diffusion term which provides nonlinearity to counter diffract effect. For simplicity, any loss effects have been neglected in our analysis. In what follows, we will solve Eq. (3) and present bright-bright soliton pair solution in the steady-state regime. The existence condition, properties and self-deflection of bright-bright soliton pair will be discussed in detail.

Under a strong bias field condition and for broad incident beams, the drift effects will be dominant, thus diffusion effect can be neglected, i.e., $\gamma_1=\gamma_2=0$. Moreover, bright-bright soliton pair satisfies the following boundary conditions: $I(0)=I_{\max}$, $I_\infty=0$, and then $\rho=I_\infty/(I_b+I_d)=0$, thus Eq. (3) can be simplified to

$$\mathrm{i}\frac{\partial U_m}{\partial\xi}+\frac{1}{2}\frac{\partial^2U_m}{\partial s^2}-\beta\frac{U_m}{\left(1+|U_1+U_2|^2\right)^2}=0 \quad m=1,\ 2 \tag{4}$$

3. Results and discussions

3.1. Coherently coupled bright-bright soliton pair solution

To obtain the bright-bright soliton pair solution, we assume $U_m\left(s,\xi\right)=r_m^{1/2}y(s)\exp\left[\mathrm{i}\left(\nu\xi+\phi_m\right)\right]$. Here ν represents a nonlinear shift of the propagation constant. r_m denote the radio of the peak intensity of mth soliton component to the sum of background and dark irradiance, i.e.,$r_m=I_{m\max}/(I_b+I_d)=I_m(0)/(I_b+I_d)$. $y(s)$ is a normalized real function and satisfies