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Bright–dark self-coupled vector spatial solitons in biased two-photon photovoltaic photorefractive crystals

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ABSTRACT

This paper predicts that bright–dark self-coupled vector solitons are possible in biased two-photon photovoltaic photorefractive crystals under steady-state conditions. The solutions of these vector solitons can be determined by use of simple numerical integration procedures. When the photovoltaic effect is neglectable, these vector solitons are bright–dark vector screening solitons. When the external bias field is absent, these vector solitons degenerate the bright–dark vector photovoltaic solitons.

1. Introduction

Photorefractive spatial solitons (PRSS) were first observed experimentally by Duree et al. [1] just a year after their theoretical prediction by Segev et al. [2] in 1992 and have been the subject of active research both theoretically and experimentally since then [3–24]. To date, three different types of steady-state PRSS (screening solitons [3,4], photovoltaic (PV) solitons [5,6] and screening photovoltaic (SP) solitons [7,8]) have been predicted and have been observed experimentally. Moreover, PRSS can be denoted as scalar solitons (one component) and vector solitons (multi-components) according to the number of components of solitons [9]. The most important prerequisite for the generation of the vector solitons is the absence of any interference between the single components. In general, there exist three ways to achieve the requirements. The original suggestion of Manakov [10] is based on two beams with orthogonal states of polarization. A second approach can be realized by applying two beams of different wavelength as for the case of all quadratic solitons [11]. Finally, the vector solitons can be formed using mutually incoherent beams which have the same polarization, wavelength [12]. Vector screening solitons [13,14] and vector SP solitons [15] in a biased PR crystal have been predicted, which involve the two polarization components of an optical beam that are orthogonal to one another. Of particular interest are bright–dark self-coupled vector solitons. Bright–dark self-coupled vector screening solitons which occur in steady-state when the intensities of the two optical beams are approximately equal [14]. Bright–dark self-coupled vector SP solitons are possible in biased PR-PV crystals under steady-state conditions, its analytical solutions can be obtained when the intensities of the two optical beams are approximately equal and these vector solitons can also be determined by use of simple numerical integration procedures when the intensities of the two optical beams make a great difference [15].

All of the above-mentioned solitons result from the single-photon process. In 2003, a new model was introduced by Castro-Camus and Magana [16], which involves two-photon PR effect. This model includes a valance band (VB), a conduction band (CB) and an intermediate allowed level (IL). A gating beam is used to maintain a fixed quantity of excited electrons from the VB, which are then excited to the CB by signal beam. The single beam induces a charge distribution identical to its intensity distribution, which in turn gives rise to a nonlinear change of refractive index through space charge field. At one time, the two-photon process was observed experimentally by W Ramadan et al. [17]. Based on this model, screening solitons [18], PV solitons [19] and SP solitons [20] in two-photon PR crystals have been predicted. On the other hand, incoherently coupled bright–bright, dark–dark, bright–dark, and grey–grey soliton pairs whose carrier beams share the same polarization, wavelength, and are mutually incoherent have been predicted for screening solitons or PV solitons [21–25] that result from the two-photon PR effect. In this paper, we show that bright–dark self-coupled vector SP solitons are possible in biased PV-PR crystals with two-photon PR effect. Moreover, the stability of the bright–dark vector solitons is investigated numerically.

2. Theoretical model

As shown in Fig. 1, an envisaged experiment is arranged as follows. Two collimated CW laser beams produced by two separate lasers $L1$ and $L2$. The gating beam $L1$ is expanded and then sent to the crystal along the y direction. The signal beam $L2$ is focused on the crystal input face

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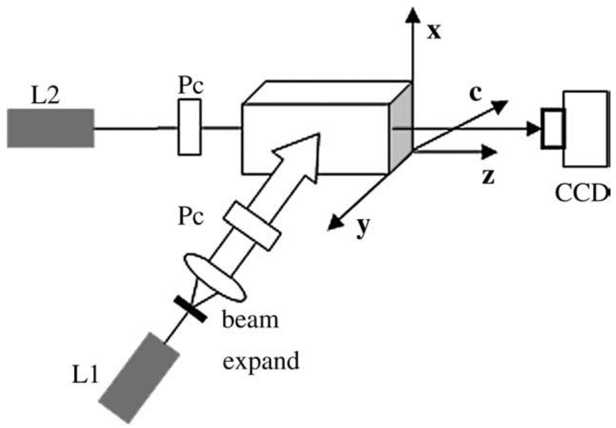

Fig. 1. An envisaged experiment arrangement, $L1$ and $L2$ are the lasers, Pc is the Pockels cell.

along the z axis. Two Pockels cells, one for the gating beam and one for the signal beam respectively, allow one to regulate the intensity and polarization of the two beams. The beam profiles can be detected by the charge coupled device (CCD). The signal beam propagates in a PV-PR crystal with two-photon PR effect and is allowed to diffract only along the x direction. Moreover, let us assume that the external bias electric field is also applied along x. For demonstration purposes, let the PV-PR crystal be $LiNbO_3$, which is illuminated by the gating beam. As previously pointed out, this crystal is a good candidate for the observation of the self-coupled or cross-coupled vector solitons [13–15]. More specifically, for the self-coupled case, the permittivity changes in $LiNbO_3$ along the extraordinary and ordinary components of the optical beam are equal, i.e., $\Delta\varepsilon_{ee}=\Delta\varepsilon_{oo}$, provided that the optical c axis of the crystal makes an angle $\theta\approx 11.9°$ with respect to the z axis in the xoz coordinate plane. $\Delta\varepsilon_{ee}$ and $\Delta\varepsilon_{oo}$ represent the diagonal perturbations on the relative permittivity tensor. Moreover, in this case the off-diagonal elements, i.e., $\Delta\varepsilon_{eo}$ and $\Delta\varepsilon_{oe}$, are zero. By associating slowly varying envelopes with the extraordinary and ordinary polarizations, $\varphi_e(x,z)$ and $\varphi_o(x,z)$, then one quickly finds the following set of self-coupled nonlinear evolution equations [14,15]:

$$2ik_e\frac{\partial\phi_e}{\partial z}+\frac{\partial^2\phi_e}{\partial x^2}+k^2\Delta\varepsilon\phi_e=0 \tag{1a}$$

$$2ik_o\frac{\partial\phi_o}{\partial z}+\frac{\partial^2\phi_o}{\partial x^2}+k^2\Delta\varepsilon\phi_o=0 \tag{1b}$$

where $k=2\pi/\lambda$ and λ is the free-space wavelength of the light wave used, and $\Delta\varepsilon=\Delta\varepsilon_{ee}=\Delta\varepsilon_{oo}$. The wave numbers k_e and k_o are defined as $k_e=k\hat{n}_e$ and $k_o=kn_o$, where $\hat{n}_e$ and n_o are the refractive indices seen by the extraordinary and ordinary components. The relative permittivity changes $\Delta\varepsilon_{ee}$ and $\Delta\varepsilon_{oo}$ can be expressed as $\Delta\varepsilon_{ee}=-r_{eff,e}\hat{n}_e^4E_{SC}$ and $\Delta\varepsilon_{oo}=-r_{eff,o}\hat{n}_o^4E_{SC}$, where $r_{eff,e}$ and $r_{eff,o}$ are the effective electro-optic coefficients for the extraordinary and ordinary polarizations, respectively. When the optical beam propagates in $LiNbO_3$ along the z axis at an angle $\theta=11.9°$ with respect to the c axis, $\Delta\varepsilon_{ee}=\Delta\varepsilon_{oo}=235.85\times10^{-12}E_{SC}$ and E_{SC} represents the space-charge field [14]. Under strong electro-field, the drift component will be dominant. In this case, we can neglect the diffusion effect, thus E_{SC} can be approximately given by [20]

$$E_{SC}=gE_A\frac{(I_{2\infty}+I_{2d})(I_2+I_{2d}+\gamma_1N_A/s_2)}{(I_{2\infty}+I_{2d}+\gamma_1N_A/s_2)(I_2+I_{2d})} + E_p(gI_{2\infty}-I_2)\frac{s_2(I_2+I_{2d}+\gamma_1N_A/s_2)}{(s_1I_1+\beta_1)(I_2+I_{2d})} \tag{2}$$

where $I_1$is the intensity of the gating beam; $I_2=I_2(x,z)$ is total power density of the extraordinary and ordinary components, can be obtained by summing the two Poynting fluxes, i.e., $I_2=(\hat{n}_e/2\eta_0)|\phi_e|^2+(n_o/2\eta_0)|\phi_o|^2$; $g=\frac{1}{1+pSR(I_{2\infty}+I_{2d})}$, $p=\frac{e\omega(s_1I_1+\beta_1)(N-N_A)}{W\gamma N_A(I_{2\infty}+I_{2d}+\gamma_1N_A/s_2)}$, where S is the surface area of the crystal's electrodes, R is resistance, W is the distance between the crystal's electrodes; In general,$0<g<1$, which implies that only part of the bias field E_A can be applied to the crystal. For example, the short-circuit condition, $R=0$ and $g=1$, which implies that E_A can be totally applied to the crystal. For the open-circuit condition, $R\to\infty$ then $g=0$, this implies that no bias field is applied to the crystal. $I_{2d}=\beta_2/s_2$ is the so-called dark irradiance, N_A is the acceptor or trap density; γ,γ_1 are the recombination factor of the CB-VB, IL-VB transition, respectively; β_1 and β_2 are the thermoionization probability constant for transitions of VB-IL and IL-CB; s_1 and s_2 are photoexcitation crosses; $E_p=\kappa\gamma N_A/e\omega$ is the PV field, κ, ω, and e are, respectively, the PV constant, the electron mobility, and the charge. For the sake of convenience, let us adopt the following dimensionless coordinates and variables: $s=x/x_0$, $\xi=z/(k_0x_0^2)$, $U=(2\eta_0I_{2d}/\hat{n}_e)^{-1/2}\phi_e$ and $V=(2\eta_0I_{2d}/n_o)^{-1/2}\varphi_o$. x_0 is an arbitrary spatial width, and the power densities of the optical beams have been scaled with respect to the dark irradianceI_{2d}. By employing these latter transformations and by substituting expressing Eq. (2) into Eqs. (1a) and (1b), and after appropriate normalization, we find that the normalized planar envelopes U and V satisfy

$$i\left(\frac{\hat{n}_e}{n_o}\right)\frac{\partial U}{\partial\xi}+\frac{1}{2}\frac{\partial^2U}{\partial s^2}-\frac{g\beta(1+\rho)}{(1+\rho+\sigma)}\left(1+\frac{\sigma}{1+|U|^2+|V|^2}\right)U - \alpha\eta\frac{\left(g\rho-|U|^2-|V|^2\right)\left(1+|U|^2+|V|^2+\sigma\right)}{1+|U|^2+|V|^2}U=0 \tag{3a}$$

$$i\frac{\partial V}{\partial\xi}+\frac{1}{2}\frac{\partial^2V}{\partial s^2}-\frac{g\beta(1+\rho)}{(1+\rho+\sigma)}\left(1+\frac{\sigma}{1+|U|^2+|V|^2}\right)V - \alpha\eta\frac{\left(g\rho-|U|^2-|V|^2\right)\left(1+|U|^2+|V|^2+\sigma\right)}{1+|U|^2+|V|^2}V=0 \tag{3b}$$

where $\alpha=-(235.85\times10^{-12}/2)(kx_0)^2E_p$, $\beta=-(235.85\times10^{-12}/2)(kx_0)^2E_A$, $\eta=\frac{\beta_2}{s_1I_1+\beta_1}$, $\sigma=\gamma_1N_A/\beta_2$, $\rho=I_{2\infty}/I_{2d}$. In what follows, we will discuss the possible bright–dark vector SP soliton solutions of Eq. (3a).

3. Bright–dark self-coupled vector solitons

To find the bright–dark self-coupled vector solitons solutions of Eq. (3a) let us express the normalized envelopes U and V in the following way: $U=r^{-1/2}f(s)\exp[i(n_0/\hat{n}_e)\mu\xi]$, $V=\rho^{1/2}q(s)\exp(i\nu\xi)$, where $f(s)$ corresponds to a bright beam envelope and $q(s)$to a dark one. Here we have assumed, without and loss effects, that the extraordinary envelope U is bright, whereas the ordinary envelope V is dark. Hence, one requires that $f(0)=1$,$f'(0)=0$,$f(s\to\pm\infty)=0$,$q(0)=0$, and $q(s\to\pm\infty)=\pm1$, and that all the derivatives of $f(s)$ and $q(s)$ vanish at infinity $(s\to\pm\infty)$. The positive variables r and ρ represent the ratios of their maximum power density with respect to the dark irradiance I_{2d}. Substitution of these forms of U and V into Eq. (3a), we get

$$f''=2\left\{\begin{array}{l}\mu+\frac{g\beta(1+\rho)}{1+\sigma+\rho}+\frac{g\beta\sigma}{1+\sigma+\rho}\left(\frac{1+\rho}{1+rf^2+\rho q^2}\right)\\ +\alpha\eta\left[(1+g\rho)+\frac{(1+g\rho)\sigma}{1+rf^2+\rho q^2}-\left(1+rf^2+\rho q^2\right)-\sigma\right]\end{array}\right\}f \tag{4a}$$