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Gray spatial solitons in biased two-photon photovoltaic photorefractive crystals

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ABSTRACT

This paper predicts that gray spatial solitons can exist in biased two-photon photovoltaic photorefractive crystals. Under appropriate conditions and in the steady state, the gray spatial solitons solution of the optical evolution equation is obtained. The properties associated with these solitons, such as their intensity profile, intensity full width at half-maximum, width, transverse velocity and phase distribution, are discussed as functions of their normalized intensity and degree of "grayness". Relevant examples are provided.

1. Introduction

Since their theoretical prediction and first experimental observation [1,2], photorefractive (PR) spatial optical solitons have attracted much special interest, for these solitons can be formed at low light intensity and in two dimensions, and are potentially useful for all-optical switching, beam steering, and optical interconnects [3,4]. Most often, the photorefractive nonlinearity responsible for the self-trapping of solitary beams relies on the application of the external electric field, the photovoltaic field of the photorefractive materials, or both of them. Thus, screening solitons have been investigated in biased PR crystals due to the non-uniform screening of the bias field [5–9], photovoltaic solitons have been investigated in PR crystals resulting from the photovoltaic effect of the crystals [10–12], and screening-photovoltaic solitons have also been proved in biased photovoltaic PR crystals owning their existence to both photovoltaic effect and spatially non-uniform screening of the applied field [13,14]. Moreover, it has been proved that holographic solitons [15,16], counter-propagating solitons [17], elliptical solitons [18], discrete solitons in waveguide arrays [19], and solitons in anisotropic media [20] could also form in biased or unbiased PR crystals.

In 2003, for the first time, Ramadan et al. observed the self-confinement of light beams at 633 nm via two-step absorption processes [21]. Castro-Camus and Magana provided a theoretical model to describe the two-photon PR effect [22]. Castro-Camus model includes a valence band (VB), a conduction band (CB), and an intermediate allowed level (IL). The intermediate allowed level is used to maintain a quantity of excited electrons from the valence band by the gating beam. These electrons are then excited again to the conduction band by the signal beam. The pattern of the signal beam can induce a spatial dependent charge distribution that gives rise to nonlinear changes of refractive index in the medium. Based on this model, several groups have investigated spatial solitons due to two-photon PR effect in biased or unbiased crystal [23–26]. Their results not only show the existence of dark and bright spatial solitons, but gray solitons and soliton pair as well. Very recently, we had just predicted that spatial solitons are possible in biased two-photon photovoltaic PR crystals [27]. Inasmuch as these spatial optical solitons result from both the spatially non-uniform screening of the bias electric field and the photovoltaic effect, we termed these solitons two-photon screening-photovoltaic (TPSP) solitons.

In this paper, we demonstrate the existence of gray TPSP solitons in biased two-photon photovoltaic PR crystal. In the steady state and under appropriate conditions, the gray solitons solution of the optical wave evolution equation is obtained. The properties associated with these solitons, such as their intensity profile, inten-

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sity full width at half-maximum (FWHM), transverse velocity and phase distribution are discussed in detail.

2. Dynamical evolution equation of TPSP solitons

We start our analysis by considering an optical beam propagating in a biased two-photon photovoltaic PR crystal along the z axis. The crystal, an external electric field with voltage bias V_a, and a resistor are connected in a chain by electrode leads. The beam is permitted to diffract only along the x direction. The crystal is put with its optical axis along the x coordinate and is illuminated by the gating beam. Moreover, let us assume that the incident optical beam is linearly polarized along the x direction, and the external bias field is applied in the same direction. As usual, we express the optical field of the incident beam in terms of the slowly varying envelope ϕ, i.e. $E = \hat{x}\phi(x,z)\exp(ikz)$, where $k = k_0 n_e$, $k_0 = 2\pi/\lambda_0$, n_e is the unperturbed extraordinary index of refraction and λ_0 is the free-space wavelength of the light wave employed. Under these conditions the optical beam satisfies the following envelope evolution equation [6,27].

$$i\phi_z + \frac{1}{2k}\phi_{xx} - \frac{k_0}{2}(n_e^3 r_{33} E_{sc})\phi = 0, \tag{1}$$

where $\phi_z = \partial\phi/\partial z$, $\phi_{xx} = \partial^2\phi/\partial x^2$, r_{33} is the electro-optic coefficient of the TPPR crystal, and E_{sc} is the induced space-charge field.

The space-charge field in Eq. (1) can be obtained from the set of rate, current, and Poisson's equations proposed by Castro-Camus and Magana [22], which describes the two-photon PR effect in a medium in which the photovoltaic current is nonzero. In steady state, by neglecting the diffusion and losses effects, the space-charge field E_{sc} can be obtained as follows [27].

$$E_{sc} = gE_a\frac{(I_{2\infty}+I_{2d})(I_2+I_{2d}+\gamma_1 N_A/s_2)}{(I_2+I_{2d})(I_{2\infty}+I_{2d}+\gamma_1 N_A/s_2)} + E_P \times \frac{s_2(gI_{2\infty}-I_2)(I_2+I_{2d}+\gamma_1 N_A/s_2)}{(s_1 I_1+\beta_1)(I_2+I_{2d})}, \tag{2}$$

where $g = 1/(1+p)$, $p = e\mu n_\infty \frac{SD}{W}$, μ and e are the electron mobility and the charge, $n_\infty = n(x \to \pm\infty)$ is the electron density in the regions $x \to \pm\infty$; D is the resistance, W is the x width of the PR crystal and S is the surface area of the crystal's electrodes. From the expression of g we can see that it is a positive parameter associated with the resistance and is bounded between $0 \leqslant g \leqslant 1$. For the case of $g = 1$, which corresponding to the case of $D = 0$, which implies that E_a can be totally applied to the crystal. For the case of $g = 0$, which corresponding to the open-circuit condition with $D \to \infty$, and no bias field is applied to the crystal in this case; $E_a = V_a/W$, V_a is the external bias voltage, when the spatial extent of the soliton beam is much narrower than the width W of the PR crystal, this expression can hold [6]; $E_P = \kappa\gamma N_A/e\mu$ is the photovoltaic field, N_A is the acceptor or trap density, κ is the photovoltaic constant; γ and γ_1 are the recombination factors of the CB–VB and IL–VB transitions, respectively; s_1 and s_2 are photoexcitation crosses; $I_{2d} = \beta_2/s_2$ is the dark irradiance intensity; β_1 and β_2 are the thermoionization probability constants for the transitions of VB–IL and IL–CB; I_1 denotes the intensity of the gating beam, which can be considered as a constant; $I_{2\infty} = I_2(x \to \pm\infty, z)$, I_2 denotes the intensity of the soliton beam. According to Poynting's theorem, I_2 can be expressed as $I_2 = (n_e/2\eta_0)|\phi|^2$, where $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$.

By substituting Eq. (2) into Eq. (1), we can establish the envelope evolution equation of TPSP solitons. For convenience, we adopt the following dimensionless coordinates and variables, i.e. $\xi = z/(kx_0^2)$, $s = x/x_0$ and $\phi = (2\eta_0 I_{2d}/n_e)^{1/2}U$. Where x_0 is an arbitrary spatial width. Under these conditions, the normalized envelope U satisfies the following dynamical evolution equation [27]:

$$iU_\xi + \frac{1}{2}U_{ss} - g\beta\frac{(\rho+1)(|U|^2+1+\sigma)}{(|U|^2+1)(\rho+1+\sigma)}U - \alpha\tau\frac{(g\rho-|U|^2)(|U|^2+1+\sigma)}{|U|^2+1}U = 0. \tag{3}$$

Where $U_\xi = \partial U/\partial\xi$, $U_{ss} = \partial^2 U/\partial s^2$, $\rho = I_{2\infty}/I_{2d}$ is the intensity ratio of the soliton beam at $\eta \to \pm\infty$ with respect to I_{2d}, $\alpha = (k_0 x_0)^2 (n_e^4 r_{33}/2)E_p$, $\beta = (k_0 x_0)^2 (n_e^4 r_{33}/2)E_a$, $\tau = \beta_2/(s_1 I_1 + \beta_1)$ and $\sigma = \gamma_1 N_A/s_2 I_{2d} = \gamma_1 N_A/\beta_2$. Eq. (3) represents the normalized dynamical evolution equation of TPSP solitons. As we can see, TPSP solitons result from both the spatially non-uniform screening of the applied field (E_a or β) and the photovoltaic effect (E_p or α), they differ from both screening solitons in a biased non-photovoltaic two-photon PR crystal [23] and photovoltaic solitons in a two-photon PR photovoltaic crystal without an external bias field [26]. In fact, Eq. (3) can be used to describe the evolution of two-photon screening solitons or two-photon photovoltaic solitons under appropriate conditions.

3. Solution of the gray TPSP solitons

Now we look for the gray spatial solitons solution of Eq. (3), in doing so, we introduce the moving coordinates $\eta = s - \upsilon\xi$, $\zeta = \xi$, and substitute the transformation $U(s, \xi) = A(\eta, \zeta)\exp(i\upsilon\eta)\exp(i\upsilon^2\zeta/2)$ into Eq. (3), we can find that the new envelope $A(\eta, \zeta)$ satisfies the same evolution equation of Eq. (3), i.e.

$$iA_\zeta + \frac{1}{2}A_{\eta\eta} - \frac{g\beta(\rho+1)(|A|^2+1+\sigma)}{(|A|^2+1)(\rho+1+\sigma)}A - \frac{\alpha\tau(g\rho-|A|^2)(|A|^2+1+\sigma)}{|A|^2+1}A = 0. \tag{4}$$

Where $A_\zeta = \partial A/\partial\zeta$, $A_{\eta\eta} = \partial^2 A/\partial\eta^2$. In the new moving-coordinate system υ represents the normalized transverse velocity of the gray TPSP solitons. Eq. (4) is just the Galilean invariance of Eq. (3), and the solution of Eq. (4) automatically satisfies Eq. (3) and vice versa. According to [8,9], the gray TPSP spatial solitons solution of Eq. (4) can be expressed as

$$A = \rho^{1/2}y(\eta)\exp\left[i\mu\zeta - iJ\int_0^\eta \frac{d\hat{\eta}}{y^2(\hat{\eta})} + i\Phi_0\right], \tag{5}$$

where J is a real constant to be determined, Φ_0 is an arbitrary phase, $y(\eta)$ is a normalized real function bounded between $|y(\eta)| \leqslant 1$, $y(\eta)$ satisfies the boundary conditions: $y^2(0) = m$, $y'(0) = 0$, $y(\eta \to \pm\infty) = 1$ and all the derivatives of $y(\eta)$ are also zero at infinity. Note that the parameter m $(0 < m < 1)$ describes the soliton grayness, i.e., the intensity at the beam centre is $I_2(0) = mI_{2\infty}$, and also that $m = 0$ corresponds to a dark soliton. By employing the condition $J = \upsilon$, we obtain

$$U(s,\xi) = \rho^{1/2}y(\eta)\exp\left[i\left(\mu + \frac{\upsilon^2}{2}\right)\xi + i\upsilon\left(\eta - \int_0^\eta \frac{d\tilde{\eta}}{y^2(\tilde{\eta})}\right) + i\Phi_0\right]. \tag{6}$$

We put the condition $J = \upsilon$ so that the phase of the gray spatial solitons is constant when η or $s \to \pm\infty$, which is consistent with the excitation conditions right at the origin [8].

By substituting Eq. (6) into Eq. (3) we find that the normalized intensity profile $y(\eta)$ satisfies the following ordinary differential equation:

$$\frac{d^2y}{d\eta^2} - 2\mu y - \frac{\upsilon^2}{y^3} - 2\frac{g\beta(1+\rho)}{1+\rho+\sigma}\left(1 + \frac{\sigma}{1+\rho y^2}\right)y - 2\alpha\tau\rho(g - y^2) \times (1 + \frac{\sigma}{1+\rho y^2})y = 0. \tag{7}$$

According to the boundary conditions of $y(\eta)$ at infinity, we arrive at

$$\upsilon^2 = -2\mu - 2g\beta - 2\alpha\tau[g\rho - \rho - \sigma + \sigma(g\rho+1)/(1+\rho)]. \tag{8}$$