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Photovoltaic solitons in two-photon photorefractive materials under open-circuit conditions

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Abstract

We present the evolution equation of one-dimensional spatial soliton in two-photon photorefractive media under open-circuit conditions. In the steady state regime, our solutions show that the dark and bright photovoltaic spatial solitons can be supported in two-photon photorefractive media under open-circuit conditions.

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Illuminated by light, photorefractive materials can set up space charge field in their interior, which will induce non-linear changes in the refractive index of the materials by means of the electro-optic (Pockels) effect. The latter process is then capable of counteracting the effects of diffraction, and thus the non-diffracting optical beam or photorefractive soliton forms [1,2]. So far, several different types of photorefractive spatial solitons have been investigated, namely, quasi-steady-state solitons [3–5], screening solitons [6–9], photovoltaic solitons [10–13], and screening-photovoltaic solitons [14–17]. The quasi-steady-state solitons can occur in biased photorefractive crystal during the finite time in which the externally applied field is slowly being screened by the space charge field. The screening solitons can exist in steady-state in biased non-photovoltaic photorefractive crystal. They result from non-uniform screening of the bias field. The photovoltaic solitons can be formed in steady-state in photovoltaic photorefractive materials. These photovoltaic solitons rely on the photovoltaic effect to create the space charge field. The screening-photovoltaic solitons are possible in steady-state in biased photovoltaic photorefractive materials, they stem from both photovoltaic effect and non-uniform screening of the bias field. Moreover, several years ago Vlad et al. [18–22] studied the self-confinement and breathing soliton-like propagation in BSO crystal with strong optical activity.

All of the above mentioned photorefractive solitons are result from single-photon photorefractive effect. In 2003, Ramadan et al. [23] demonstrated that it was possible to realize bright spatial solitons at not directly absorbed wavelengths by using two-step excitation in BSO crystal applied with bias field. Later on, in 2006 Vlad et al. [24] created soliton waveguides in lithium niobate crystals with low-power cw green laser and with high-repetition-rate femtosecond laser pulses, at 800 nm, assisted by a green background and an external bias electrical field. Recently, Castro-Camus and Magana [25] provided a new model of the two-photon photorefractive effect. 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 give rise to non-linear changes of refractive index in the medium.

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Based on Castro-Camus model, we have just shown that screening solitons can be formed in two-photon photorefractive media [26].

In this letter, the evolution equation of one-dimensional spatial solitons in the photovoltaic photorefractive media with two-photon photorefractive effect is presented by using Castro-Camus model, the solutions predict that dark and bright photovoltaic spatial solitons can also be supported in two-photon photorefractive media in the steady state and under open-circuit conditions. Compared to screening solitons, the external bias field is not required to realize photovoltaic solitons in two-photon photorefractive media, which is convenient for practical applications. The establishment of the photovoltaic solitons in two-photon photorefractive media requires two laser beams, without the gating beam, the signal beam can not evolve into spatial soliton. This aspect of the photovoltaic solitons in two-photon photorefractive media may be useful for all-optical switching and beam steering. Moreover, these two-photon photovoltaic solitons have the advantage of creating permanent waveguides with no erasure problem as a result of re-excitation of the electrons by the signal beam, though the producing process of these two-photon photovoltaic solitons is a bit more complicated than the single-photon photovoltaic solitons.

To study the photovoltaic spatial solitons in two-photon photorefractive materials, we consider an optical beam that propagates in a photorefractive medium with two-photon photorefractive effect along the z axis and is permitted to diffract only along the x direction. The photorefractive medium is put with its optical c axis oriented along x coordinate and is illuminated by the gating beam. Moreover, let us assume that the polarization of the incident optical beam is parallel to the c axis. As usual, we express the optical field of the incident beam in terms of slowly varying envelope ϕ, i.e., $E = \hat{x}\phi(x,z)\exp(\mathrm{i}kz)$, where $k = k_0 n_e = (2\pi/\lambda_0)n_e$, n_e is the unperturbed extraordinary index of refraction, and λ_0 is the free-space wavelength. Under these conditions the optical beam satisfies the following envelope evolution equation [8,26]:

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

where $\phi_z = \partial\phi/\partial z$, $\phi_{xx} = \partial^2\phi/\partial x^2$, r_{33} is the electro-optic coefficient, and $\vec{E}_{sc} = E_{sc}\hat{x}$ is the space charge field in the medium.

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 to describe the two-photon photorefractive effect. In the steady-state and under open-circuit conditions these equations are [25]

$$(s_1 I_1 + \beta_1)(N - N^+) - \gamma_1 n_1 N^+ - \gamma n N^+ = 0, \tag{2}$$

$$(s_1 I_1 + \beta_1)(N - N^+) + \gamma_2 n(n_{01} - n_1) - \gamma_1 n_1 N^+ - (s_2 I_2 + \beta_2)n_1 = 0, \tag{3}$$

$$(s_2 I_2 + \beta_2)n_1 + \frac{1}{e}\frac{\partial J}{\partial x} - \gamma n N^+ - \gamma_2 n(n_{01} - n_1) = 0, \tag{4}$$

$$\varepsilon_0\varepsilon\frac{\partial E_{sc}}{\partial x} = e(N^+ - n - n_1 - N_A), \tag{5}$$

$$J = e\mu n E_{sc} + eD\frac{\partial n}{\partial x} + \kappa s_2(N - N^+)I_2 = 0, \tag{6}$$

where N is the donor density, N^+ is the ionized donor density, N_A is the acceptor or trap density, and n is the density of the electrons in the CB; n_1 is the density of the electron in the intermediate; n_{01} is the density of traps in the intermediate state; s_1 and s_2 are photoexcitation crosses; β_1 and β_2 are the thermoionization probability constants for the transitions of VB–IL and IL–CB; γ, γ_1, and γ_2 are the recombination factors of the CB–VB, IL–VB, and CB–IL transitions, respectively; D is the diffusion coefficient; κ is the photovoltaic constant; μ and e are, respectively, the electron mobility and the charge; ε_0 and ε are the vacuum and relative dielectric constants, respectively; J is the current density; I_1 is the intensity of the gating beam, which can be considered as a constant; I_2 is the intensity of the soliton beam; and E_{sc} is the space charge field in the medium. According to Poynting's theorem, I_2 can be expressed in terms of the envelope ϕ, that is, $I_2 = (n_e/2\eta_0)|\phi|^2$, where $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$. One can adopt the approximation $N^+ \sim N_A$ and neglect the term $(n_{01} - n_n) \ll N_A$ with respect to the other terms. In this case, from Eqs. (2) and (3) we obtain

$$n_1 = \frac{\gamma N_A n}{s_2 I_2 + \beta_2}. \tag{7}$$

Substituting Eq. (7) into Eq. (2), we get

$$n = \frac{(s_1 I_1 + \beta_1)(s_2 I_2 + \beta_2)(N - N_A)}{\gamma N_A (s_2 I_2 + \beta_2 + \gamma_1 N_A)}. \tag{8}$$

From Eq. (6) we have

$$E_{sc} = -\frac{\kappa s_2 (N - N_A) I_2}{e\mu n} - \frac{D}{\mu n}\frac{\partial n}{\partial x}. \tag{9}$$

The insertion of Eq. (8) into Eq. (9) yields

$$E_{sc} = -E_p\frac{s_2 I_2 (I_2 + I_{2d} + \gamma_1 N_A/s_2)}{(s_1 I_1 + \beta_1)(I_2 + I_{2d})} - \frac{D\gamma_1 N_A}{\mu s_2 (I_2 + I_{2d} + \gamma_1 N_A/s_2)(I_2 + I_{2d})}\frac{\partial I_2}{\partial x}, \tag{10}$$

where $E_p = \frac{\kappa\gamma N_A}{e\mu}$ is the photovoltaic field, and $I_{2d} = \beta_2/s_2$ is the so-called dark irradiance. In photovoltaic materials, the photovoltaic field will be dominant. In this case, the diffusion effect (D term) can be considered small and can be dropped out. Thus, the expression for the space charge field can be simplified as

$$E_{sc} = -E_p\frac{s_2 I_2 (I_2 + I_{2d} + \gamma_1 N_A/s_2)}{(s_1 I_1 + \beta_1)(I_2 + I_{2d})}. \tag{11}$$

By substituting expression (11) into Eq. (1), we can establish the envelope evolution equation of the soliton. For convenience, the following dimensionless coordinates and