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Self-deflection suppression of bright spatial solitons in absorbing photovoltaic photorefractive crystals by periodic diffusion management

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ABSTRACT

The propagation behavior of bright spatial solitons under the diffusion effect in photovoltaic (PV) photorefractive (PR) crystals poled periodically is investigated by considering the optical absorption of the crystals. The numerical simulations show that, soliton beams follow a wiggling trajectory under the combined influence of the crystal absorption and the diffusion effect which is properly managed by designing the periodic domain inversion structure of periodically poled PV PR crystals. Moreover, the oscillation amplitude of the wiggling trajectory of a low-intensity soliton decreases gradually with the propagation distance, but the situation for a high-intensity soliton is contrary. Furthermore, the recursive equations describing the propagation trajectory are formulated and the analytical result of the propagation trajectory is in good agreement with the numerical one. The research results contribute to enriching the dynamics of PR spatial solitons and provide a method to suppress the self-deflection of soliton beams arising from the diffusion effect.

1. Introduction

Optical spatial solitons are self-trapped optical beams and can propagate without diffractive broadening by virtue of various nonlinear optical effects in optical materials. They have potential applications in the field of optical communication, such as all-optical switching [1,2], all-optical logic gate [3], and all-optical network [4]. In recent decades, photorefractive (PR) spatial solitons have became one of the hot topics in the field of optical spatial solitons, because they take advantage of weak-light nonlinear optical effects in PR materials and can be observed with elementary experimental apparatuses at very low optical power levels. So far, many types of PR spatial solitons have been predicted theoretically and observed experimentally, including quasi-steady-state solitons [5–7], screening solitons [8–10], photovoltaic (PV) solitons [11–14], screening-photovoltaic solitons [15–18], holographic solitons [19,20], and surface solitons [21–26]. Among PR spatial solitons, PV solitons are the best candidates for all-optical communication because they can be formed under the photovoltaic effect in PV PR materials without external electric field.

As is well-known, the diffusion effect in PR materials can greatly affect the propagation process of optical beams, especially for relatively narrow beams [27,28]. Carvalho et al. [8] reported the effects of diffusion on the evolution behavior of steady-state dark and grey solitons in biased PR materials and predicted theoretically that, the center of soliton beams moves along a parabolic trajectory and the minimum intensity of soliton beams varies linearly with the propagation distance. Kang et al. [29] investigated the propagation of a type of (2+1)D surface solitons in virtue of the cooperation of diffusion and drift nonlinearities. Yang et al. [13] theoretically and experimentally demonstrated the surface dark solitons and their behaviors near surface in $LiNbO_3$ crystal by taking advantage of diffusion and PV nonlinearities. Zhan et al. [30] investigated theoretically the effect of diffusion on self-deflection of steady-state bright spatial solitons in biased centrosymmetric PR crystals, and found that the soliton beam propagates along a parabolic trajectory and the deflection effects vary cubically with applied external bias field. Moreover, Zhan et al. [31] investigated theoretically the self-deflection of one-dimensional bright spatial solitons in two-photon centrosymmetric PR media under the diffusion effect. Ciattoni et al. [32] predicted strictly bending-free miniaturized soliton propagation in centrosymmetric PR crystal which is biased by a periodically modulated external voltage. Cui et al. [33] reported that, under the diffusion effect in periodically poled PV PR crystals without biased electric field, bright spatial solitons follow a wiggling propagation trajectory whose oscillation amplitude remains constant, and the self-deflection of soliton beams arising from the diffusion effect can be effectively suppressed by the diffusion manage-

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ment (DM) technology based on designing the periodic domain inversion structure (PDIS) of periodically poled PV PR crystals. As mentioned above, lots of researches have shown that soliton beams exhibit numerous fascinating properties under the diffusion effect in PR materials, and moreover, some reports have proposed effective methods for the suppression of adverse influences (especially the self-deflection of soliton beams) arising from the diffusion effect [32,33].

However, all of the previous researches on the self-deflection suppression of spatial solitons under the diffusion effect in PR materials, to our knowledge, did not consider the optical absorption of PR materials. In this paper, we investigate the propagation behavior of bright spatial solitons under the diffusion effect in periodically poled PV PR crystals by considering the crystal absorption. The research results show that, under the linear crystal absorption and the diffusion effect managed properly by designing the PDIS of periodically poled PV PR crystals, soliton beams follow a wiggling trajectory whose oscillation amplitude gradually decreases or increases with the propagation distance, and the self-deflection of soliton beams arising from the diffusion effect can be effectively suppressed. We find that, under the combined influence of the crystal absorption and the diffusion effect, soliton beams exhibit some novel dynamic evolution characteristics which have never been observed in the situation that the crystal absorption is neglected. Because the theoretical model containing the optical absorption of crystals is more in accordance with the real circumstance, our finding would not only contribute to enriching the dynamics of PR spatial solitons under the diffusion effect, but also have more practical value in suppressing the self-deflection of soliton beams arising from the diffusion effect.

2. Theoretical model

We consider a signal beam which propagates in a PV PR crystal along the x axis and is allowed to diffract only along the z direction. Under appropriate initial conditions, the signal beam can form a (1+1)-dimensional soliton beam. In order to promote the formation of the soliton beam, two background beams with equal initial intensity are set to propagate along the x axis and their propagation directions are opposite. It should be noted that the total intensity of the two background beams remains constant along the x axis under the circumstance that the crystal has slight linear absorption loss. A copper-doped $K_{0.25}Na_{0.75}Sr_{1.5}Ba_{0.5}Nb_{0.5}O_{15}$ (Cu:KNSBN) crystal, which is a non-centrosymmetric material, is selected as the propagation medium and its crystalline c-axis is oriented along the z direction. In addition, the signal beam is an e ray and the two background beams are o rays. When the crystal has linear absorption loss, the propagation equation of the signal beam takes the following form [11,34]:

$$i\frac{\partial u}{\partial \xi} = -\frac{1}{2}\frac{\partial^2 u}{\partial \zeta^2} - \beta\frac{1+r|u|^2}{1+|u|^2}u - \gamma(\xi)\frac{\partial \ln(1+|u|^2)}{\partial \zeta}u - i\Gamma u. \quad (1)$$

In this equation, $\zeta = z/z_0$ is the normalized transverse coordinate, where z_0 is an arbitrary spatial scale; $\xi = x/x_0$ is the normalized propagation distance; $x_0 = k_e z_0^2$; $k_e = 2\pi n_e/\lambda_e$ is the wave number of the e ray, where n_e is the unperturbed extraordinary index of refraction and λ_e is the free-space wavelength of the e ray; $r = \kappa^e/\kappa^o$, where κ^e and κ^o are the glass constants of the e ray and the o ray, respectively; $\beta = (1/2)n_e^2 k_e^2 z_0^2 r_{eff} E_{pv}$ is associated with the drift effect; r_{eff} is the effective electro-optic coefficient; $E_{pv} = \kappa^o \gamma_R N_A/(q\mu_m)$ is the PV field, where γ_R is the carrier recombination rate, N_A is the acceptor density, q is the carrier charge and μ_m is the mobility of the charge carrier; $\gamma(\xi) = (1/2)n_e^2 k_e^2 z_0^2 r_{eff} K_B T/q$ is associated with the diffusion effect, where K_B is Boltzmann's constant and T is the absolute temperature; $\Gamma = (1/2)x_0\Gamma_0$; Γ_0 is the absorption coefficient of the crystal; u is the normalized slowly varying envelope of the e ray; $|u|^2 = s_e I_e/(s_o I_o)$; s_e and s_o are the photoionization cross sections of the e ray and the o ray, respectively; I_e and I_o are the intensities of the e ray and the o ray, respectively.

We now present a brief qualitative analysis to illustrate the physical mechanism of the DM technology of periodically poled PV PR crystals. When the domain inversion period of periodically poled PV PR crystals is much larger than the width of incident beams, the absolute value of E_{pv} remains practically constant [35,36]. Moreover, both E_{pv} and r_{eff} depend on the polarized directions of domains and have an opposite sign for antiparallel domains. Because $\gamma(\xi)$ contains only r_{eff} but β contains both r_{eff} and E_{pv}, $\gamma(\xi)$ depends on the polarized directions of domains while β does not. Consequently, the diffusion effect in periodically poled PV PR crystals can be managed by designing the PDIS of the crystals.

3. Numerical simulations and discussion

In numerical simulations, we choose the following parameters: the wavelengths of the e ray and the o ray are both 488 nm; $n_e = 2.27$; $n_o = 2.35$; $z_0 = 10$ μm; $r = 2.5$; $E_{pv} = 28F(\xi)$ kV/cm and $r_{eff} = 200F(\xi)$ pm/V, where $F(\xi)$ is the structure function which is equal to +1 or −1 for the positive or the negative domains, respectively [7,37]. When $\gamma(\xi) = \Gamma = 0$, Eq. (1) takes the form of a nonlinear Schrödinger equation with a higher-order nonlinearity and its bright solitary wave solutions can be obtained by expressing the beam envelope in the following form:

$$u(\zeta, \xi) = \rho^{1/2} y(\zeta)\exp(i\mu\xi). \quad (2)$$

The positive quantity ρ is defined as $\rho = |u|^2_{\max} = s_e I_{\max}/(s_o I_o)$, where $I_{\max}$ represents the maximum power density of the e ray; $y(\zeta)$ is a normalized real function varying between $0 \le y(\zeta) \le 1$; μ is a nonlinear shift of the propagation constant. By substituting Eq. (2) into Eq. (1) with $\gamma(\xi) = \Gamma = 0$ and employing the boundary conditions of bright solitons (i.e., $y(0) = 1$, $y'(0) = 0$ and $y(\zeta \to \pm\infty) = 0$), the functional form $y(\zeta)$ of bright solitons can be obtained [33]. The existence curve of bright spatial solitons at the input face of the crystal is depicted by the solid curve which exhibits a valley in Fig. 1. It can be seen that, with the increase of ρ, the full width at half maximum (FWHM) of the intensity of soliton beams decreases or increases when $\rho < 2.43$ or $\rho > 2.43$, respectively. Based on the above characteristics, in our study, a soliton with $\rho < 2.43$ ($\rho > 2.43$) is regarded as a low-intensity (high-intensity) soliton.

Soliton beams will have a transverse acceleration arising from the diffusion effect as soon as they are inputted into a PV PR crystal. At the input face of the crystal, because the propagation distance $\xi = 0$, the energy loss of soliton beams equals to zero and thus Γ can be neglected (i.e., $\Gamma = 0$). When choosing $T = 300$ K, $\gamma(\xi)$ is equal to $0.114F(\xi)$. By

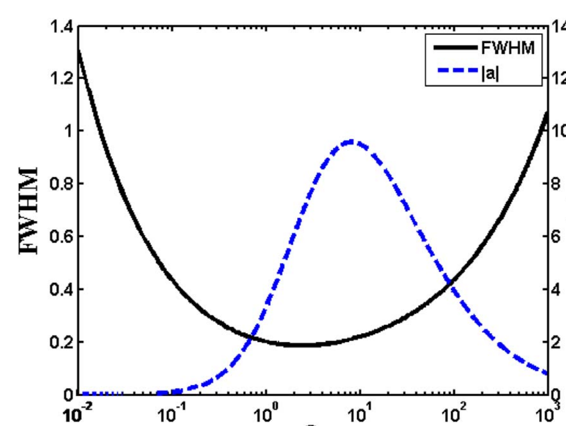

Fig. 1. Intensity FWHM of bright spatial solitons and absolute value of solitons' transverse acceleration versus ρ at the input face of the crystal. The solid line depicts the relation between the intensity FWHM and ρ when $\gamma(\xi) = \Gamma = 0$. The dash line depicts the relation between the absolute value of solitons' transverse acceleration and ρ when $\gamma(\xi) = 0.114$ and $a_E^L = -7.087$.