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Dynamical behavior of the bright incoherent spatial solitons in self-defocusing nonlinear media

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ABSTRACT

We present a theory of bright incoherent photovoltaic (PV) solitons in self-defocusing nonlinear media by using a coherent density approach. It is shown that this theory model is effectively governed by an infinite set of coupled nonlinear Schrödinger equations, which are initially weighted with respect to the incoherent angular power spectrum of source. We then numerically study the particular case of spatially incoherent beam propagating in $LiNbO_3$:Fe crystal with split-step Fourier method. Numerical simulations indicate that the ratio of PV constant κ is a key parameter to spatial compression as well as the possible dark and bright PV solitons. Besides, the formation of bright incoherent PV solitons is affected by intensity ratios r_T and width of the source angular power spectrum θ_0. Better coherent property is found at margins of bright incoherent soliton through the associated coherence length calculation. These results are in good agreement with recent experimental observations.

1. Introduction

Spatially partially incoherent solitons have attracted considerable attention in the past few years. Thus far, it has been demonstrated in the forms of bright incoherent solitons, dark incoherent solitons, and white light incoherent solitons experimentally and theoretically [1–12]. As to experimental studies, photovoltaic (PV) solitons, screening solitons and dipole soliton have been observed and induced their waveguides [5,10–12]. For theoretical researches on incoherent solitons, there are mainly three approaches, namely the coherent density approach [1], the self-consistent multimode approach [2], and the geometric optics approach (in the diffractionless limit) [3]. In fact, the three approaches are demonstrated to be equivalent to each other in nonlinear media in Ref. [4]. The incoherent PV solitons come into being due to bulk PV effect without external bias voltage. It is prospective in all-optical devices. In PV crystals with opening circuit, the change of refraction index is $\Delta n = -0.5n_b^3 r_{eff} E_p I/(I + I_d)$ [13], where I, I_d, n_b, r_{eff} and E_p are the beam intensity, the natural dark irradiance, the unperturbed refractive index, the effective linear electro-optic coefficient and PV field, respectively. In self-focusing PV crystals, the Δn is positive and bright PV solitons are obtained [14]; while in self-defocusing PV crystals, the Δn is negative and dark PV solitons are observed [15]. Only very recently has the experimental observation of bright incoherent solitons been reported in self-defocusing $LiNbO_3$:Fe crystal [16,17]. It is different from the traditional PV solitons. In these experiments, a monochromatic partially spatially incoherent background beam was used to self-trap in PV photorefractive (PR) crystal, with a larger PV constant than that of soliton beam. During the formation of bright PV solitons, we found a unique transition of self-defocusing to self-focusing. This

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phenomenon is first reported by Anastassiou et al. in self-defocusing material [18]. Following it, this new type of bright incoherent solitons is studied experimentally for its formation mechanism and modulation instability [16,17,19]. However, relatively little work is done on its propagation and incoherent properties. Since Christodoulides et al. first investigated the propagation properties of incoherent screening solitons in SBN crystal with coherent density approach [1], there have been many works about incoherent solitons [2–10]. Nevertheless, the incoherent properties of bright PV solitons in self-defocusing crystal have not been contacted before. Owing to the transition of self-defocusing to self-focusing in PV media, it is worth studying for its potential applications in optical switches.

In this paper, the bright incoherent PV solitons in self-defocusing material are discussed carefully by using a coherent density approach. The coherent density approach here is described by a set of coupled nonlinear Schrödinger-like equations provided that they are appropriately weighted with respect to the source incoherent angular power spectrum. We discuss the theory model and numerically simulate it with split-step Fourier method. Our simulations demonstrate that spatial compression as well as dark and bright solitons is possible under appropriate conditions. We also present the influencing factors of bright incoherent solitons and the associated coherence length. In these cases, self-trapping can be intuitively understood as fusion of multi-particles [20], and the response time of nonlinear media is longer than the phase fluctuation time across the optical beam.

2. Theoretical model

In a noninstantaneous self-defocusing PV medium, the refractive index change varies with space-charge field E, i.e. $\Delta n(E) = -0.5 n_b^3 r_{eff} E$ [13], where n_b is the unperturbed refractive index, and r_{eff} is the effective electro-optic coefficient of crystal. We assume that the incoherent soliton beam propagates along z axis, diffracting only in x direction with intensity I_s. The crystal is illuminated uniformly by a background beam with intensity I_b. Moreover, we consider the standard set of rate, continuity, and Gauss's law in PR medium in which electrons are the sole charge carriers. In one-dimension steady states, theses equations are [13,15,17,21]

$$(S_s I_s + S_b I_b + \beta) \cdot (N_d - N_d^i) - \gamma n N_d^i = 0, \tag{1a}$$

$$J = q\mu n E + k_B T \mu \frac{\partial n}{\partial x} + (\kappa_s S_s I_s + \kappa_b S_b I_b) \cdot (N_d - N_d^i) \tag{1b}$$

$$\frac{\partial E}{\partial x} + (q/\varepsilon_s) \cdot (n + N_A - N_d^i) = 0, \tag{1c}$$

where β is the dark generation rate, ${N_d}^i$ is the density of ionized donors, n is the electron density, J is the current density, and E is the space-charge field. Relevant crystal parameters are the total donor density N_d, the density of negatively charged acceptors N_A, the electron charge q, the electron mobility μ, the recombination coefficient γ, the low-frequency dielectric constant ε_s, the Boltzmann's constant k_B, and the temperature T. S_s, S_b are the photoionization cross-section of soliton beam and background beam. $\kappa = \kappa_b/\kappa_s$ is the ratio between the PV constant that can attain different values by changing material or varying the wavelength.

From Eqs. (1a)–(1c), neglecting diffusion term in Eq. (1b), $\partial E/\partial x$ term in Eq. (1c), and the electron density n for $n << N_d^i$, $N_A < <N_d$, we obtain the space-charge field [18]

$$E \approx \frac{J - \kappa_s N_d \cdot (I_s S_s + \kappa I_b S_b)}{q\mu \frac{N_d}{N_A \gamma} \cdot (I_s S_s + I_b S_b + \beta)}. \tag{2}$$

Under the condition of open-circuit without external bias voltage, the space-charge field E becomes

$$E = -E_p \cdot \frac{I_s S_s + \kappa I_b S_b}{I_s S_s + I_b S_b}, \tag{3}$$

where $E_p = \kappa_s \gamma N_A/(q\mu)$. Substituting Eq. (3) into $\Delta n = -0.5 n_b^3 r_{eff} E$, we have

$$\Delta n(x) = C \cdot \frac{\kappa + I_s/{I'}_b}{1 + I_s/{I'}_b} = C \cdot \frac{\kappa + I_N}{1 + I_N}, \tag{4}$$

where $C = 0.5 n_b^3 r_{eff} E_p$, $I'_b = (I_b S_b)/S_s$, and $I_N = I_s/{I'}_b$ is the normalized intensity of incoherent soliton which is compose of discrete index.

When the incoherent optical beam with normalized intensity I_N propagates in a slowly responding nonlinear medium, each of these coherent components will be influenced by nonlinearity. The nonlinearity here is intensity-dependent expressed in Eq. (4). Under steady-state conditions, the incoherent beam evolves according to the following infinite set of coupled nonlinear Schrödinger-like equations [1,5,8]:

$$i\left\{\frac{\partial U_j}{\partial z} + (j\Delta\theta)\frac{\partial U_j}{\partial x}\right\} + \frac{1}{2k}\frac{\partial^2 U_j}{\partial x^2} + \frac{k_0}{2} n_e^3 r_{eff} E_p \frac{\kappa + I_N(x,z)}{1 + I_N(x,z)} U_j = 0, \tag{5}$$

where

$$I_N(x,z) = \sum_{-\infty}^{\infty} \left|U_j(x,z)\right|^2, \tag{6}$$

the discrete index $j = 0, \pm 1, \pm 2, \ldots,$ and $k = k_0 n = 2\pi n/\lambda_0$ in which λ_0 is the free-space wavelength. Eqs. (5) and (6) describe the process of incoherent beam propagating in self-defocusing PV PR crystal in the limit $\Delta\theta \to 0$. At $z=0$, the so-called coherent density is

$$U_j(x,0) = (r,\rho)^{1/2} G_N^{1/2}(j\Delta\theta)\phi_0(x), \tag{7}$$

where θ is the angle with respect to z-axis, $G_N(\theta)$ is the normalized angular power spectrum of incoherent source, and $\phi_0(x)$ is the input spatial modulation function. Moreover, r is the maximum intensity of a bright incoherent beam at $x = 0$, whereas ρ is the normalized intensity of a dark beam at $x \to \pm\infty$. The normalized angular power spectrum of incoherent source is assumed as Gaussian form, i.e. $G_N(\theta) = \exp(-\theta^2/\theta_0^2)/(\sqrt{\pi}\theta_0)$, where θ_0 is associated with its angular width.

The coherence properties of these evolving partially incoherent beams can be described by coherent factor μ_{12}