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Propagation dynamic of a Gaussian in the inverted nonlinear photonic crystals

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ABSTRACT

In this work, we study the evolution of a Gaussian beam inside a one-dimensional inverted nonlinear photonic crystals (INPC) with a Kerr nonlinearity. The INPC is a kind of virtual crystals which is generated by the optical induction via the electromagnetically induced transparency (EIT). The propagation dynamics of the Gaussian with different total power are identified. Four types of propagation behavior are found. They are collapse beam, breather beam, soliton and symmetry-breaking beam, respectively. The border between these four behavior types are given. For symmetry-breaking beam, an asymmetric profile of the beam is evolving from the symmetry Gaussian, which can be termed as a kind of dynamical symmetry breaking (DSB). The influences on the appearance of the symmetry breaking point are studied by varying input parameters of the Gaussian. The results of this work are both suitable in nonlinear optics and Bose-Einstein condensate (BEC).

1. Introduction

The periodical modulations of linear refractive index and the nonlinear refractive index can form a nonlinear photonic crystal, where the former modulation forms the linear lattice (LL), and the latter forms the nonlinear lattice (NL). Combined actions of LL and NL to the propagating waves is an interesting topic and attracts many concerns [1,2]. The evolution of wave inside these crystals can be described by the nonlinear schrödinger equation under the paraxial approximation. The LL plays the role of linear potential in the equation, while the NL plays the role of a pseudopotential [3,4].

In optics, an optical denser medium (alias larger linear refractive index) always own a larger nonlinear refractive index, while an optical thicker medium always own a smaller nonlinear refractive index. Under this circumstance, the modulations of LL and NL are in-phase coincidence. Recently, another kind of medium, in which LL and NL are π-out-phase juxtaposed, is reported existence theoretically and experimentally in some special types of optical media [5–12]. Because the maximums of the linear refractive index are coincided with the minimums of the nonlinear refractive index, these media, which is named as inverted nonlinear photonic crystals (INPC), will exhibit competition between the LL and NL. As a result, the interplay between the LL and NL in the INPC shows abundant power-dependent features. In the low-power region, the LL plays an essential role in dynamics of the wave propagation. With the power increasing, the influence from the NL gradually becomes more and more important. Finally, if the power of the wave is large enough (beyond some thresholds), the NL takes the place of the LL to play the dominating role. For the INPC with cubic nonlinearity, it is reported that solitons undergo double symmetry breaking as the power is increasing [7,38], while for the saturable nonlinearity, the soliton can switch between the linear and nonlinear channel with the power's increasing [12].

In this work, we study the propagation of a Gaussian beam in one-dimensional INPC with a Kerr self-focusing nonlinearity (see Fig. 1). The INPC is assumed to be fabricated by means of periodically doping of Pr^{3+} ions (active material) into YSO crystals (passive background) [13,14,16], which is shown in Fig. 1. We consider the dopants have an N-type near-resonant four-level energy level

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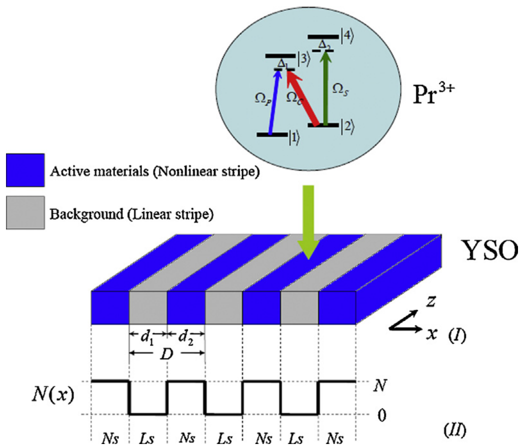

Fig. 1. The INPC is fabricated by means of periodically doping of Pr^{3+} ions into YSO crystals, the energy structure of the active ions are N-type energy system. D is the period of the lattice, d_1 and d_2 are the width of the linear and nonlinear stripe, respectively. $N(x)$ is the density distribution of the active ions.

structure and are activated by electromagnetically induced transparency (EIT) [14]. By appropriately selecting the detuning of the optical fields, the system can feature π-out-of phase modulation between LL and NL, which is a kind of virtual lattice to the probe wave. The evolution of the probe wave in this virtual crystal can be described by the one-dimensional nonlinear schrödinger equation. Formation of symmetry and asymmetry solitons in such kind of medium were studied in literatures, but the dynamical evolution of Gaussian beams inside such a system is still absent. In the following, we will present our study to the propagation behavior of the Gaussian in this system. And our paper is organized as follows. A brief presentation of INPC by means of EIT is introduced in Section 2. The propagation dynamic of the Gaussian is studied in detail in Section 3. And a conclusion is given in Section 4.

2. The model

We consider the N-type near-resonant four-level ions as the active dopant. The scheme of the energy levels is shown in Fig. 1, in which $|1\rangle$ and $|2\rangle$ are the ground and metastable state, respectively. These two states' wave functions have the same parity, which is opposite to that of states $|3\rangle$ and $|4\rangle$. A weak probe wave E_p with Rabi frequency $\Omega_p = \wp_{31} E_p/\hbar$ is assumed to act on transition $|1\rangle \to |3\rangle$,with single-photon detuning Δ_1. Here $\wp_{31}$ (which is assumed to be real) is the matrix element of the dipole transition between $|1\rangle$ and $|3\rangle$. Further, the atomic transition $|2\rangle \to |3\rangle$ with detuning $\Delta_c = \Delta_1$ is driven by a traveling-wave field with Rabi frequency Ω_c, hence the two-photon detuning is given by $\delta = \Delta_1 - \Delta_c \equiv 0$. As another ingredient of the EIT scheme, the atomic transition $|2\rangle \to |4\rangle$ with detuning Δ_2 is induced by another traveling-wave with Rabi frequency Ω_s. The decay rate for level $|n\rangle$ is γ_n. For convenience, we neglect γ_1 and γ_2, and set $\gamma_3 \approx \gamma_4 \equiv \gamma$. Assuming that the sample is under a very low temperature and all the ions are populated in the ground state, we can let Δ_1, $\Delta_2 \gg \gamma$, Ω_C, so the absorption from the atoms can be safely neglected. At the same time, because of the low temperature environment, the inhomogeneous broadening contributed by the crystal-field effect can be neglected as well. Under these conditions, the steady-state solutions of the related matrix elements between $|1\rangle$ and $|3\rangle$ can be obtained as [15–18]

$$\rho_{31} \approx \frac{|\Omega_s|^2}{2\Delta_2|\Omega_c|^2}\Omega_p - \frac{|\Omega_p|^2}{2\Delta_1|\Omega_c|^2}\Omega_p. \tag{1}$$

The first term in the right side of Eq. (1) comes from the giant Kerr effect of EIT [19], while the second term comes from the self-enhanced Kerr effect of EIT [20]. The polarization of the ions is given as $\mathcal{P}(x) = 2N(x)\wp_{31}\rho_{31}$ [21]. The (1 + 1)-dimensional paraxial steady-state propagation equation of E_P in the slowly varying envelopes then reads as

$$2ik_P \frac{\partial}{\partial z} E_P = -\frac{\partial^2}{\partial x^2} E_P - \frac{k_P^2}{\epsilon_0}\mathcal{P}(x), \tag{2}$$

where $k_P = 2\pi/\lambda_p$ is the wave number of E_P. After selecting $\Delta_2 = \Delta_1 = -\Delta < 0$, substitutes ρ_{31} with Eq. (1) into Eq. (2), we get a scaled nonlinear schrödinger equation (NLSE):

$$i\frac{\partial}{\partial z'}U = -\frac{1}{2}\frac{\partial^2}{\partial x'^2}U + V(x')(1 - |U|^2)U, \tag{3}$$

where $z' = zk_P$, $x' = xk_P$, $U = \Omega_P/\Omega_S$ and

$$V(x') = \frac{N(x')|\wp_{31}|^2}{2\epsilon_0\hbar\Delta}\frac{|\Omega_S|^2}{|\Omega_C|^2}. \tag{4}$$

From Eq. (3), the virtual LL and NL potential, which are created by Ω_C, are π out-of-phase, and the medium can be termed as an INPC. In the following, coefficients are chosen as follows: the density of active atoms inside the waveguides is $N_0 = 1.0 \times 10^{18}\,\text{cm}^3$ (which corresponds to the dopant concentration 0.1%), $\wp_{31} = 1.18 \times 10^{-32}\,\text{C m}$, and $\gamma = 30\,\text{kHz}$, the probe wavelength being 605 nm [21], and the detuning $\delta = 100\gamma$, which results in $N_0|\wp_{31}|^2/2\epsilon_0\hbar\Delta \approx 1/4$ [cf. Eq. (4)].

3. Propagation behavior of a Gaussian

As discussed above, we can rewrite the scaled 1D NLSE Eq. (3) into

$$iu_z = -\frac{1}{2}u_{xx} + V(x)(1 - |u|^2)u, \tag{5}$$

where $V(x) = V_0 R(x)$. Here $R(x)$ is a normalized Kronig-Penney potential which has the height fixed at 1 [22–24]. V_0 is the modulation depth of the potential. The width of potential well and potential barrier are set to be d_1 and d_2, respectively. The total power of the field is

$$P = \int_{-\infty}^{\infty} |u|^2 dx. \tag{6}$$

We choose the input of the field (alias the initial condition) as a Gaussian with $u_0(x) = A\exp(-x^2/W^2)$, which is centered at the linear channel (or stripe) and can be identified by its total power P and the width W.

The study of the evolution of the Gaussian is carried out by means of the split-step Fourier transform algorithm. In the simulation, we fix $d_1 = d_2 = 4$ and $V_0 = 0.04$, which corresponds to $|\Omega_S|^2/|\Omega_C|^2 = 0.16$ [cf. Eq. (4)]. The numerical results show that there are four types of propagation behavior by given different values of P and W. They are collapse beam, breather beam, soliton and symmetry breaking beam, which are displayed in panel (a)–(d) of Fig. 2, respectively. In Fig. 2(a), a small total power leads to a low light intensity so that the self-defocusing nonlinearity is not enough to compensate the diffraction, and the beam collapses. When the power increases, the effect of nonlinearity becomes stronger. But before this nonlinearity can completely support a self-localization of the beam, a breather beam is generated [see in Fig. 2(b)], which is formed by incompletely self-localization. By further increasing the power, a soliton is created [see in Fig. 2(c)] as a complete self-localized mode. For these three types, even with a increase nonlinearity, the LL still dominates in the interplay of LL and NL so that the beam still locates at the center of the linear channel. However, if the power keeps increasing to a threshold value, the NL will