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Impact of loss on the light propagation in 1D optical waveguide array in the presence of Kerr-type nonlinearity

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ABSTRACT

The interplay between radiation loss (diagonal and off-diagonal) and Kerr-type nonlinearity on the light propagation in 1D array of nonlinear dissipative optical waveguides are investigated numerically. Our results show that, at low nonlinear parameters, the diagonal loss only reduces the light intensity in the guides and does not affect the ballistic regime of light spreading. However, for nonlinear parameters above a critical value, the transition from the localized to the ballistic regime can be observed, after certain propagation distance. The study of the interplay between off-diagonal loss term and Kerr type nonlinearity, demonstrates that the results depend mainly to the nonlinear parameter strength. In this case, and for low strength of nonlinearity, the transition from ballistic to diffusive regime is observed after a critical propagation distance, while, spreading from localized to diffusive regime occurs at high nonlinear parameters (above the critical one). In addition, we have examined the impact of the both diagonal and off-diagonal losses in highly nonlinear optical lattices. In this case, by increasing the propagation distance, three different regimes of light spreading (from localized to the ballistic, and then, from ballistic to the diffusive) can be observed. Both critical propagation distances in which these transitions occur increase by the magnitude of the nonlinear parameter, while, decrease by the enhancement of the loss coefficients.

1. Introduction

In recent years, by appropriate design of guides for light propagation, the optical waveguide arrays provide experimental tools to simulating and testing certain fundamental theories and phenomena in some branches of physics, such as condensed matter and quantum optics [1–4]. In design, there are some basic effects such as disorder, loss and gain, surface and nonlinear effects, which affects the light propagation in optical waveguide arrays [1–3,5–8]. The presence of loss leads to a non-Hermitian system with imaginary eigenvalues, and violates the energy conservation, because of the energy transfer from the guides to the environment. The co-existence of loss and gain in double lattices open a new research about the non-Hermitian parity-time reversal ($\mathcal{PT}$) symmetric lattices with real eigenvalues and conserved energy [9–16].

The $\mathcal{PT}$-symmetric lattices can be created by importing the gain and loss to the double-lattices and appropriate design of the coupling coefficients between guides [9–14]. Moreover, the symmetric treatment can be observed in the passive systems contain the diagonal loss term without the gain [9,14].

In the previous work [17], we investigated the impact of loss on the light propagation in linear optical waveguide arrays. As shown in [17], loss introduces an extra imaginary term to the coupling coefficients between neighbor guides, beside an imaginary term to the propagation constant of each guide, which are called off-diagonal and diagonal loss terms, respectively. In a linear system, the off-diagonal loss term results on the transition of the light spreading from the ballistic to the diffusive regime, after a critical propagation distance.

In propagation of high-power light in optical waveguide arrays, the nonlinear effects must be considered. The most important nonlinear effect on light propagation in the coupled waveguide array is the third-order Kerr-type nonlinearity. In the absence of loss, and for a nonlinear parameter above the critical one, the Kerr-type nonlinearity hindered the ballistic expansion of light, through the self-trapping mechanism [18–21].

In this paper, we investigate the interplay between the loss (diagonal and off-diagonal terms) and Kerr-type nonlinearity. Both effects exist in 1D optical waveguide array, and in the case of high-power input light and striking loss of guides, should be considered together.

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We have obtained different regimes of light spreading (from the transverse localization to diffusive and ballistic regimes) based on interplay between diagonal/off-diagonal loss term and Kerr-type nonlinearity. The transition between different regimes occurs after some critical propagation distances that depend to the loss coefficients and nonlinear parameter.

We believe that our findings are significant for the study of discrete-optical solitons in waveguide arrays and optical fibers. Furthermore, these results can be useful for high-intensity light propagation in non-Hermitian and $\mathcal{PT}$-symmetric waveguide lattices [1,3,15,16].

This paper is organized in four sections. Section 2 is devoted to the theoretical model. Numerical results and discussion are presented in Section 3. Finally, we conclude and summarize our results in Section 4.

2. Theoretical model

There are two sources of loss in waveguide lattices: material absorption and geometrical loss. The first source play a role when the frequency of incident light is near the one of absorption frequencies of waveguide material [22]. The later loss is related to the geometry of the waveguide's boundary. At the boundary, tail of the electric field, in the nearby environment, move with different velocity respect to the electric field profile in the guide, and causes the transfer of energy from the middle of guide to its surrounding medium, to compensate the velocity mismatch. This type of loss is known as a radiation loss and can be controlled by the appropriate design of guide's boundaries [22]. The radiation loss introduces inherently in the light propagation along the 1D array of optical waveguides, while the material loss needs tuning of the incident light frequency.

In our previous work [17], the radiation loss is introduced by considering the electric permittivity of guides and surrounding medium as two different complex numbers. In the presence of radiation loss and by employing the slowly varying envelope approximation (SVEA), the light propagation in 1D array of optical waveguides (see Fig. 1) can be described by the following tight-binding (TB) equations [17]:

$$-i\frac{dE_n(z)}{dz} = (K_n + i\kappa_n)E_n(z) + (C_{n-1} + iC'_{n-1})E_{n-1} + (C_n + iC'_n)E_{n+1}, \quad n = 1, 2, \dots, N, \tag{1}$$

where, $E_n(z)$ is the electric field amplitude of light wave in the nth guide, which propagate along the z direction (see Fig. 1), K_n is the propagation constant of nth guide, C_n is the coupling coefficient between nth and $(n+1)$th guides, and N is the number of waveguides. Imaginary parts κ_n and C'_n indicate the radiation loss. Diagonal loss term κ_n depends on the imaginary parts of the dielectric constants of the system, while off-diagonal term C'_n is proportional to the mismatch between the imaginary parts of the dielectric constants of guides and their surrounding medium(absorption discrepancy). C'_n is also proportional to the coupling coefficient C_n between guides. This imaginary off-diagonal term strongly affects the dispersion relation of the system and, in the linear case, after a critical propagation distance, changes the transverse spreading of light from the ballistic to diffusive regime [17].

In the presence of third-order Kerr-type nonlinearity, the system of Eq. (1) are modified as follow:

$$-i\frac{dE_n(z)}{dz} = (K_n + i\kappa_n)E_n(z) + (C_{n-1} + iC'_{n-1})E_{n-1} + (C_n + iC'_n)E_{n+1} + \gamma \mid E_n(z)|^2 E_n(z), \tag{2}$$

where $\gamma = \frac{n_2\omega}{cA_{eff}}$ is the nonlinear parameter. Moreover, n_2, ω, c and A_{eff} are the nonlinear refractive index, frequency of incident light, speed of light in vacuum and the effective area of single-mode guide, respectively.

Here, we consider a periodic 1D array of identical guides surrounded by the same medium. Therefore, $K_n = K, \kappa_n = \kappa_0, C_n = C, C'_n = C' = \alpha C$, and we have:

$$-i\frac{dE_n(z)}{dz} = (K + i\kappa_0)E_n(z) + C(1 + i\alpha)(E_{n-1} + E_{n+1}) + \gamma \mid E_n(z)|^2 E_n(z). \tag{3}$$

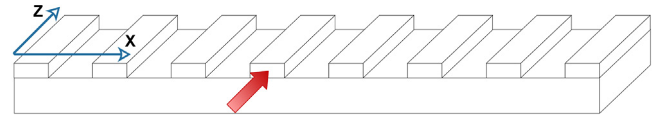

Fig. 1. (Color online) Array of optical waveguides.

By applying $\varphi_n(z) = \frac{E_n(z)}{\sqrt{P}} e^{-i(K+i\kappa_0)z}$, $Z = Cz$, $\kappa = \frac{\kappa_0}{C}$ and $\chi = \frac{\gamma P}{C}$, we obtain the following set of the dimensionless nonlinear coupled equations:

$$-i\frac{d\varphi_n(Z)}{dZ} = (1 + i\alpha)(\varphi_{n-1}(Z) + \varphi_{n+1}(Z)) + \chi e^{-2\kappa Z} \mid \varphi_n(Z)|^2 \varphi_n(Z), \quad n = 1, 2, \dots, N. \tag{4}$$

Here χ is normalized nonlinear parameter, $P = \sum_{n=1}^{N} \mid E_n(Z=0)|^2$ is the total power of light at the entrance plane, and κ and α are the dimensionless diagonal and off-diagonal loss terms, which are normalized to the coupling coefficient C between neighbor guides. It is important to note that, in these equations, the exponential decay of light intensity is factored out in $\varphi_n(Z)$, and instead of it, dimensionless nonlinear parameter $\chi e^{-2\kappa Z}$ decreases along the propagation distance. This clearly shows the reduction of nonlinear effects by loss, during propagation. We use the Runge–Kutta Fehlberg method to solve numerically these equations for $N = 200$ waveguides, with zero boundary conditions, when the middle guide ($n_0 = 100$) is excited at the entrance plane ($\varphi_n(Z=0) = \delta_{n,n_0}$).

3. Numerical results and discussion

We define the participation rate ($PR(Z)$) in (1 + 1)D optical waveguide arrays as a measure to study the different regimes of light spreading along the transverse direction:

$$PR(Z) = \frac{\left(\int_{-\infty}^{\infty} \mid \varphi(X,Z)|^2 dX\right)^2}{\int_{-\infty}^{\infty} \mid \varphi(X,Z)|^4 dX} = \frac{\left(\sum_{n=-\infty}^{\infty} \mid \varphi_n(Z)|^2\right)^2}{\sum_{n=-\infty}^{\infty} \mid \varphi_n(Z)|^4}. \tag{5}$$

The last term comes from the discretization of the middle term along the transverse direction. This measure counts the number of guides contain nonzero light amplitude. In completely extended finite system with $\varphi_n(Z) = \frac{1}{\sqrt{N}}$, the participation rate equals to the total number of guides, i.e. $PR(Z) = N$, while in exactly localized regime where $\varphi_n(Z) = \delta_{n,n_0}$, the participation rate equals one.

In (1 + 1)D optical system, the participation rate has the length dimension and can be interpreted as a beamwidth of light ($\omega(Z) = PR(Z)$), while in (2 + 1)D systems the participation rate has the length square dimension and the beam width can be defined as the square root of the participation rate ($\omega(Z) = \sqrt{PR(Z)}$). The participation rate (beamwidth) in 1D array of optical guides can change with the propagation distance as $PR(Z) \propto Z^{\beta}$, where $\beta = 1, 0.5, 0$ referring to the light spreading in ballistic, diffusive and localized regimes, respectively.

Fig. 2 shows the light intensity distribution ($I_n(Z) = \mid \varphi_n(Z)|^2$) and their corresponding beamwidth along the propagation distance in linear ($\chi = 0$) dissipative system for different off-diagonal loss terms (α) [17]. In this case, according to Eqs. (4), the value of diagonal loss κ does not affect the intensity distribution of the system. As shown in this figure, in the presence of off-diagonal imaginary term (α), the mechanism of light spreading in transverse direction changes from ballistic to diffusive regime after a critical propagation distance ($Z_c \simeq 10, 5$ in Fig. 2(b) and (c), respectively). The critical propagation distance decreases by enhancement of α. This result is in agreement with previous results in [17] .

In Fig. 3, we investigated the impact of Kerr-type nonlinearity on light propagation in the absence of any loss ($\kappa = 0, \alpha = 0$). Kerr-type