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One- and two-dimensional bright solitons in inhomogeneous defocusing nonlinearities with an antisymmetric periodic gain and loss

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Abstract

We address that various branches of bright solitons exist in a spatially inhomogeneous defocusing nonlinearity with an imprinted antisymmetric periodic gain-loss profile. The spectra of such systems with a purely imaginary potential never become complex and thus the parity-time symmetry is unbreakable. The mergence between pairs of soliton branches occurs at a critical gain-loss strength, above which no soliton solutions can be found. Intriguingly, which pair of soliton branches will merge together can be changed by varying the modulation frequency of gain and loss. Most branches of one-dimensional solitons are stable in wide parameter regions. We also provide the first example of two-dimensional bright solitons with unbreakable parity-time symmetry.

Keywords: Bright solitons; Inhomogeneous nonlinearity; Parity-time symmetry

1. Introduction

In 1998, Bender *et al.* put forwards the concept of parity-time ($\mathbb{PT}$) symmetry in quantum mechanics [1]. Even non-Hermitian Hamiltonians can exhibit entirely real spectra provided that they respect $\mathbb{PT}$ symmetry [1, 2]. This important finding has been generalized into many fields in physics, due to its fundamental physics and potential applications [3–6]. The necessary condition for a non-Hermitian Hamiltonian to be $\mathbb{PT}$-symmetric is that $V(x) = V^*(-x)$ [1–6]. The spectrum of $\mathbb{PT}$ systems is purely real below a phase-transition point.

Evolution of beams was also reported in both linear and nonlinear media modulated by a $\mathbb{PT}$ potential [3, 4]. Afterwards, dynamics of nonlinear modes in $\mathbb{PT}$ symmetric systems have attracted considerable interest, since that optics can provide a fertile ground where $\mathbb{PT}$ related concepts can be experimentally tested [4]. Various types of spatial solitons were explored theoretically and observed experimentally in nonlinear configurations with a $\mathbb{PT}$ symmetry [7–14]. For a review of early works, see [15] and references therein.

Another area drawing major interest is the dynamics of beams in inhomogeneous nonlinear media [16]. One- and two-dimensional (1D and 2D) solitons were predicted in inhomogeneous focusing media [17–21]. Within this broader theme, attentions were also drawn on the possibility of the bright coherent structures in defocusing nonlinearities. A fundamental proposal, put forth a few years ago, was that, if the growth rate of the nonlinearity toward the periphery of the medium is faster than r^D, localized solitary waves and vortical structures with a limited spatial size can self-trap [22–28].

Thus far, properties of bright solitons in inhomogeneous defocusing media modulated by an antisymmetric gain and loss are still poorly understood. Main efforts were devoted to the variation of nonlinearity geometries [22–28]. On the other hand, almost all solitons in $\mathbb{PT}$ systems inevitably undergo a symmetry breaking above the phase-transition point. The only exception is that, an inhomogeneous defocusing medium combined with a localized antisymmetric gain and loss can support solitons with unbreakable $\mathbb{PT}$ symmetry [25]. Dynamics of 2D unbreakable bright solitons in inhomogeneous defocusing media with a $\mathbb{PT}$ symmetry is not yet reported.

Recalling the fact that a periodic gain and loss usually leads to new features of solitary waves [4], we here explore the properties of solitons in inhomogeneous defocusing media with a periodic gain and loss. We show that diverse branches of multipole solitons can exist in such schemes and pairs of soliton branches merge at critical values of gain-loss strength. The variation of frequency of gain and loss results in the change of the mergence components of soliton pairs. The nonlinear system never undergo a symmetry breaking. Detailed stability analysis and propagation simulations prove that such solitons can propagate stably in wide parameter windows. We also reveal the properties of 2D bright solitons.

2. Theoretical model

We consider a beam propagation along the z axis in transverse inhomogeneous defocusing media modulated by a antisymmetric periodic gain and loss. Evolution of nonlinear waves is governed by the scaled nonlinear Schrödinger equation for the field amplitude q:

$$i\frac{\partial q}{\partial z} = -\frac{1}{2}\frac{\partial^2 q}{\partial x^2} + \sigma(x)|q|^2 q + i\gamma R(x)q, \tag{1}$$

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