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Spatial solitons in a nonlocal fused coupler

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ABSTRACT

We study soliton-modes of optical pulses and their stabilities in a nonlocal nonlinear fused dual-core planar waveguide. Taking the different parameters, we find the symmetric, antisymmetric and asymmetric bright soliton pairs and dipole soliton pairs. During the long-distance propagation, the amplitudes of some solitons adding the white noise exhibit periodic oscillations and the solitons except asymmetric soliton can propagate steadily. We also find that the phases and profiles of solitons in the nonlocal coupler are determined by the propagation constant, the amplitude of the optical field and the region of the fused segment.

1. Introduction

The dual-core couplers, in which parallel guiding cores interact via evanescent fields [1], is one of the basic types of optical waveguides. An optical coupler is an optical passive device used to achieve optical signal splitting or routing. If the intrinsic nonlinearity in the cores is strong enough, the powers of energy exchange between them is affected by the intensity of the guided signals, which is the basis for designing the all-optical switch [2], nonlinear amplifiers [3], stabilization of wavelength division multiplexed transmission schemes [4] and logic gates [5]. In the early years, the coupling structure was simple, functional single and is mostly used to obtain part of the energy from the transmission line to monitor and so on. Until now, there have obtained some major breakthroughs in structure and performance. And they have been used to the optical fiber communications, the fiber optic sensors, fiber test technology and signal processing systems. In addition to the simplest dual-core system, realizations of nonlinear couplers have been proposed in semiconductor waveguides [6], in twin-core Bragg gratings [7–9], in which there is quadratic [10] and cubic–quintic (CQ) [11] nonlinearities, in dual-core traps for matter waves in Bose–Einstein condensates (BEC) [12], in parallel arrays of discrete waveguides [13,14], in which there is the nonlocal nonlinearity [15].

In 1976, Barnoski and Friedrich used a focused CO_2 laser as a local heat source to heat and fuse two multimode fibers, and made the first fiber-optic directional coupler [16]. In this system, the coupling ratio can be controlled by adjusting the distance between the fiber core and the interaction length of the fusion segment. The heating and fusing methods provide considerable technical support for the large-scale production of fiber couplers. To further understand the performance of the coupler, researching on solitons in fused couplers is attracting more and more attention. Malomed proposed an exactly solvable model for soliton pulse that describes the important situation in which the soliton period is much longer than the length of the coupling region in the nonlinear fiber coupler. And the controlling, switching, and splitting of soliton are discussed [15]. Mandal analyzed its motion and found that launching a pulse in one arm of the coupler could generate pulses in both arms [17]. The fused fiber coupler has been used as a spectral filter in femtosecond fiber soliton lasers to eliminate the spectral sideband structure associated with the generated pulse characteristic period soliton [18]. Afanasjev et al. proposed a simple scheme of dark soliton generation in a fused coupler resulting from the interaction of a bright soliton in one arm with a long pulse in another arm. They also proposed an analytical method for calculating the parameters of the dark soliton [19].

Another possibility is to study the propagation of optical signals in the dual-core planar waveguides with short fused segments [20]. Such structures can be molded using polymer materials or built into photonic crystals by means of techniques proposed in Ref. [21]. An alternative way is to write the virtual dual-core waveguide pattern into the photorefractive medium by a strong pump beam [22]. For this narrow fused coupler [23], one of the simplest approximations is to approximate the coupling strength on the x axis as the δ function. In such a model, the collisions of an incident soliton with single and double locally fused couplers have been studied by means of systematic simulations and several analytical methods [24]. So far, some scholars have studied different types of solitons in nonlocal nonlinear couplers [15,25]. The study in Ref. [26] focuses on the existence of soliton pairs in a nonlocal nonlinear coupler and the effects of nonlocal nonlinearity on the stability and types of soliton pairs. The mechanisms that produce nonlocal nonlinear

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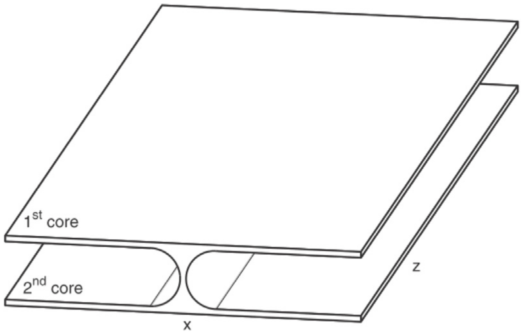

Fig. 1. Schematic diagram of a fused planar coupler [24].

effects are as follows: thermal diffusion [27], atomic diffusion [28], and surface plasmas [29]. The introduction of nonlocality increases the space to a new degree of freedom. Therefore, the interaction of nonlocalities will change the nonlinear excitation of the optical material and results in the generation of new phenomena, such as a self-gravity attracting photon beam [30] and the generation of new solitons [31]. In addition, some analytical solutions in nonlocal nonlinear media have also been studied [32,33], but reports on nonlocal nonlinear narrow fused couplers are lacking. The main task of this paper is to study different types of solitons and the characteristics of solitons in nonlocal nonlinear narrow fused couplers.

The paper is organized as follows. The model is formulated in Section 2, where we built a coupled Schrödinger equation in which the coupling coefficient is approximated as a Gaussian function in a nonlocal nonlinear fused dual-core planar waveguide. In Section 3, by the means of Newton iteration, when different parameters are selected, we find out the different types of bright soliton pairs and dipole soliton pair and discuss the stabilities of these soliton propagations. Section 4 is a conclusion.

2. Model

The propagation of the optical beams along axis z in the nonlocal fused coupler (see the schematic shape of the fused coupler in Fig. 1 [24]) can be described by the coupled nonlinear Schrödinger equation as follows [26]

$$iu_z + \frac{1}{2}u_{xx} + mu + p(x)v = 0, \tag{1a}$$

$$iv_z + \frac{1}{2}v_{xx} + nv + p(x)u = 0, \tag{1b}$$

$$m - dm_{xx} - \beta|u|^2 = 0, \tag{1c}$$

$$n - dn_{xx} - \beta|v|^2 = 0, \tag{1d}$$

where u and v are the amplitudes of the optical beams, x is the transverse direction, the coefficient of the Kerr nonlinear term is given by a constant β, m and n denote the refractive indices respectively, d is the squared correlation radius of the nonlocality which controls the competition between the length scales determined by the nonlocal and local interactions in the system. The coupling strength $p(x)$ is a function of the transverse coordinate x.

Stationary solutions of the system (1) with propagation constant b are sought as

$$u(z,x) = U(x)\exp(ibz), v(z,x) = V(x)\exp(ibz), \tag{2a}$$

$$m = m(x),\ n = n(x) \tag{2b}$$

with real functions $U(x)$ and $V(x)$ obeying the ordinary differential equations:

$$-bU + \frac{1}{2}U_{xx} + mU + p(x)V = 0, \tag{3a}$$

$$-bV + \frac{1}{2}V_{xx} + nV + p(x)U = 0, \tag{3b}$$

$$m - dm_{xx} - \beta U^2 = 0, \tag{3c}$$

$$n - dn_{xx} - \beta V^2 = 0. \tag{3d}$$

In Ref. [24], the authors investigated the interactions of spatial solitons in fused couplers. Excitation dynamics of a soliton trapped by a local coupler was studied by means of the variational approximation and the simulation. If the coupling effect of the dual-core planar waveguides is generally nonlocal, the coupling function $p(x)$ to the transverse coordinate x is approximately a Gaussian function, that is, $p(x) = p_0\exp(-x^2/w)$, where the coupling constant p_0 denotes the coupling length of the waveguide's dual-core and w represents the region of the fused segment that is much smaller than the width of the solitons.

3. Numerical solution

We try to search for some kinds of spatial solitons and their propagation stabilities of the system (3) with $p(x) = p_0\exp(-x^2/w)$ by the simulation method.

3.1. Spatial bright soliton solution and propagation stability

We assume that the system (3) has the following form of the initial solution:

$$U(x) = A_1\exp(-x^2/w_1), V(x) = A_2\exp(-x^2/w_2), \tag{4a}$$

$$m(x) = B_1\exp(-x^2/w_3), n(x) = B_2\exp(-x^2/w_4), \tag{4b}$$

where $A_i(i = 1,2)$ are the amplitudes of the complex fields, $B_i(i = 1,2)$ are the amplitudes of the refractive indices, and $w_i(i = 1,2,3,4)$ are the widths of solitons. Selecting the parameters $b = 1.3$, $d = 0.5$, $\beta = 1$, $A_1 = 3$, $A_2 = 1$, $B_1 = 1$, $B_2 = 1$, $w_i = 2$, $w = 0.01$, and $p_0 = 1$, we find the symmetrical bright soliton solution as shown in Fig. 2(a) . The blue line and red dotted line are the profiles of u and v, and the green and black dotted lines are the refractive indices m and n. To observe the stability of the solitary wave solutions, we take the solution with white noise as the initial perturbed solution and simulate the evolution of this perturbed solution along the propagating direction by the split-step Fourier method. Taking the propagation constant as $b = 1.3$, the power value as $P = P_u + P_v = \int_{-\infty}^{\infty} u^2 + v^2 dx = 9.325$ and the nonlocal degree as $d = 0.5$, we find that the amplitudes of the symmetric bright solitons ($u = v$) are periodically changed along the propagation direction z under white noise perturbation and this soliton can be transmitted steadily (see Fig. 2(b) and (c)). Changing the propagation constant b in the range $0.7 \le b \le 1.3$ and the corresponding total power in the range $5.79 \le P \le 9.33$, we find that the solutions are all symmetric soliton pairs and that the total power P linearly increases when the propagation constant b increases in this interval, as shown in Fig. 2(d). There is no soliton solution when $1.3 < b < 1.7$. When the propagation constant b increases to 1.7 and the other parameters do not change, we get an antisymmetric soliton pairs ($u = -v$), and the light field u is broken into a double-peak soliton, when the light field v becomes a reverse soliton which phase has π difference with that of the light field u as shown in Fig. 3(a). We find that the propagation of the light field v with white noise is almost stable but its amplitude changes periodically as shown in Fig. 3(c). While, the double-peaks soliton with white noise becomes a one-peak one whose amplitude is quasi-periodically changed along the propagating direction as shown in Fig. 3(b). When the propagation constant b is increased to 2 and the other parameters are unchanged, asymmetric soliton pairs ($u \ne v$ and $u \ne -v$) are obtained. The power value of u is calculated to be 6.9707, but the power value of v, $P_v = \int_{-\infty}^{\infty} v^2 dx$, is only 0.0186, as can be seen