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Dark soliton control in inhomogeneous optical fibers

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ABSTRACT

Analytic two-dark soliton solutions for a variable–coefficient nonlinear Schrödinger equation are obtained via modified Hirota method. Parallel solitons are observed and soliton control such as the soliton compression is realized with different group velocity dispersion profiles. Besides, soliton interactions are investigated with the interaction distance being adjusted. In addition, soliton repulsive structures as well as attractive ones are obtained with exponential dispersion profile. Results in our research may be useful for the soliton control in inhomogeneous optical fibers, which will be a benefit to the realistic optical communication systems.

1. Introduction

Since the optical soliton was theoretically proposed [1] and experimentally realized [2] in fiber systems, the fundamental properties of the optical solitons and their practical applications in such fields as long-distance communication systems [3–6], all-optical ultrafast switching devices and coupler [7–9] have been extensively investigated. Due to the balance between the group-velocity-dispersion (GVD) and self-phase modulation, optical soliton can propagate over a long distance in monomode fibers without either attenuation or change of temporal waveform, which can be applied as an ideal subject to transmit optical signals [5,10].

Though the optical soliton has the particle like property, the existing problems caused by the variable dispersion, nonlinearity, fiber gain/loss in real optical soliton application systems could not be ignored [5,11,12]. To be specific, on one hand, the balance between the GVD and nonlinearity cannot be kept constant during soliton propagation and on the other hand, the fiber loss can influence that balance inevitably [10]. When it comes to the high-speed signal transmission over long distance, the interaction of adjacent solitons will restrict the transmission quality [13]. Taking the above problems into consideration, a new concept of

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soliton control, which is significant for the soliton communications, has been proposed and developed in recent years [11,14,15].

In the previous studies of soliton control, the limitation of soliton transmission distance was firstly overcome [16]. Subsequently, several kinds of modulators were invented to realize soliton control [17–20]. In addition, the authors of Ref. [21] studied the linear stability analysis of the dispersion management solitons controlled by the inline narrow-band filters. And in the next year, the spectral filtering technique was employed for soliton control [22]. The results of Ref. [23] revealed that the soliton control system may relax the limitations to parametric conditions. The phenomenon of symmetry breaking and controlled soliton emission during the light propagation through a nonlinear defect has been studied with a novel approach being used to achieve complete nonlinear control of the process [24]. The stable control of the pulse time delay has been achieved by means of the resonance soliton solutions [25]. The optical soliton transmission in fibers can be exactly controlled by proper dispersion and nonlinearity managements and the Raman gain, which can be well confirmed by the existing experiments [10]. The dispersion-decreasing fibers with different profiles are found to be able to control the soliton velocity and a new approach to control the soliton interactions using the dispersion-decreasing fiber with the Gaussian profile is suggested [26]. In addition, multiple soliton control in fiber lasers by active intensity modulation has been investigated [27]. Recently, a novel way of soliton control, based on the modulated electromagnetically induced transparency effect, has been offered by three-level atomic system [28].

Due to the inevitable fiber loss, the propagation of the optical solitons in the inhomogeneous optical fibers can be described by the following variable–coefficient nonlinear Schrödinger (vc-NLS) equation [29,30]:

$$i\frac{\partial u}{\partial z} - i\frac{g(z)}{2}u - \frac{D(z)}{2}\frac{\partial^2 u}{\partial \tau^2} + \rho(z)\left|u\right|^2 u = 0 \tag{1}$$

where $u(z,\tau)$ represents the slowly varying envelope of electric field, τ is the normalized delay time, and z refers to the normalized propagation distance. The functions $D(z)$, $\rho(z)$ and $g(z)$ are related to the varying GVD, Kerr nonlinearity and fiber amplification (or absorption), respectively. Various investigations on Eq. (1) have been done over the last few years [31–35]. Appropriate solitary wave solutions of the vc-NLS equation applying to propagation in optical fibers and optical fiber amplifiers as well as the soliton interactions have been studied [31,32]. Exact self-similar solutions (called the similaritons) to the equation have been obtained, and the similariton interactions can under certain conditions lead to the formation of molecule-like bound states of two similaritons [29]. In addition, formation and amplification of frequency-modulated soliton-like pulses have been studied [33,34]. In our recent work, interactions of dromion-like structures governed by the equation have been studied for the first time [35].

However, to the best of our knowledge, the analytic two-dark soliton of Eq. (1) has not been studied in detail yet, and the dark soliton control in the inhomogeneous optical fibers considering the fiber loss has not been discussed. In this paper, analytic two-dark soliton solutions will be obtained via modified Hirota method. According to the solutions obtained, different types of dark solitons such as the parallel dark solitons and dumbbell-shaped dark solitons under different kinds of dispersion and gain (or absorption) profiles have been studied and methods to control the interval between the two dark solitons are proposed. This paper will be structured as follows. In Section 2, the analytic two-dark soliton solutions for Eq. (1) will be derived with the modified Hirota method [30,36,37]. In Section 3, the soliton control will be studied by choosing different GVD and gain (or absorption) profiles. Finally, conclusions are drawn in Section 4.

2. Analytic two-dark soliton solutions for Eq. (1)

With the dependent variable transformation being introduced [30,36,37]

$$u(z,\tau) = A(z)\frac{h(z,\tau)}{f(z,\tau)} \tag{2}$$