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Interactions between butterfly-shaped pulses in the inhomogeneous media

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HIGHLIGHTS

- Interactions between butterfly-shaped pulses are investigated.
- Methods to control the pulse interactions are suggested.
- Analytic two-soliton solutions for butterfly-shaped pulses are derived.

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ABSTRACT

Pulse interactions affect pulse qualities during the propagation. Interactions between butterfly-shaped pulses are investigated to improve pulse qualities in the inhomogeneous media. In order to describe the interactions between butterfly-shaped pulses, analytic two-soliton solutions are derived. Based on those solutions, influences of corresponding parameters on pulse interactions are discussed. Methods to control the pulse interactions are suggested.

1. Introduction

Solitons, first proposed by Zabusky and Kruskal in 1965, have been investigated in a variety of nonlinear media [1,2]. Due to the balance between the nonlinearity and other effects, solitons are stable, localized, and particle-like objects [3]. Subsequently, many methods, such as the Painlevé

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analysis, inverse scattering transformation, the Hirota method, Darboux transformation, similarity transformation method, improved (G'/G)-expansion method, mapping method, have been developed to derive soliton solutions for nonlinear evolution equations [4–14]. Applications of solitons have been involved in such fields as nonlinear optics, fluid dynamics, plasma physics, condensed matter physics, solids, particle physics and astrophysics [15–25]. As representative ones, optical solitons have been studied and perfected by researchers in nonlinear optics [26–29]. Being nonlinear objects, optical solitons can interact with each other either elastically or inelastically [30].

As to elastic interactions, optical solitons are mechanical particles, whose number is conserved, without any changes in physical quantities such as their amplitudes, velocities, and shapes after interactions [31]. Alternatively, inelastic interactions show different phenomena: some solitons merge together or give birth to new solitons [32]. As a result, co-propagating solitons do interact and share energy [32]. In fact, when two or more solitons propagate in the inhomogeneous media at the same time, they interact with each other, and the propagation quality of systems are affected. Hence, investigations on soliton interactions are necessary before implementing them in nonlinear systems, and some researches have been carried out [33,34].

By solving the coupled nonlinear Schrödinger (CNLS) equations, bright and bright–dark type multi-soliton solutions for CNLS equations with focusing, defocusing and mixed type nonlinearities have been obtained with suitable coefficient constraints, and interaction dynamics of solitons has been investigated [35–39]. Elastic and inelastic interactions between optical solitons in nonlinear systems have been studied [32]. Influences of polarization mode dispersion on soliton propagation in birefringent fibers have been analyzed, and nonlinear gain devices with perturbation terms have been introduced to reduce soliton interactions [40]. Another research area involved in soliton interactions is the passive mode-locked fiber lasers [41]. In that field, soliton interactions play a crucial role in the stable multi-pulse generation mode [41]. States of bound solitons or soliton crystals can occur in the case of the soliton attraction, while the soliton repulsive accounts for the harmonic passive mode locking [42–48]. Recently, the mechanism of soliton–soliton repulsion and the occurrence of harmonic passive mode locking have been demonstrated [41].

However, as a type of solitonics, interactions of butterfly-shaped pulses are not reported in the inhomogeneous media. In this paper, analytic soliton solutions to describe butterfly-shaped pulse interactions will be derived with the Hirota method. Parameters for the obtained solutions will be analyzed to discuss the influences on interactions between butterfly-shaped pulses. Suggestions will be made to weaken the pulse interactions, and pulse qualities will be improved during the propagation in the inhomogeneous media.

This paper will be structured as follows. In Section 2, analytic two-soliton solutions to describe butterfly-shaped pulse interactions will be obtained. In Section 3, influences of corresponding parameters on butterfly-shaped pulse interactions will be analyzed. Finally, our conclusions will be made in Section 4.

2. Analytic two-soliton solutions

The soliton propagation in the inhomogeneous media can be described by the following variable coefficients nonlinear Schrödinger (vcNLS) equation [16,32,49]:

$$\frac{\partial u}{\partial z} - i\frac{D(z)}{2}\frac{\partial^2 u}{\partial t^2} + i\rho(z)|u|^2 u = g(z)u, \tag{1}$$

where $u(z,t)$ is the temporal envelope of the pulse. z is the longitudinal coordinate along the inhomogeneous media, and t is the time in the moving coordinate system. $D(z)$ represents the group-velocity dispersion (GVD) coefficient, $\rho(z)$ is the coefficient of Kerr nonlinearity, and $g(z)$ is related to the material amplification coefficient.

To construct the soliton solutions, we perform the dependent variable transformation [50]

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