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Original research article

Chirped and dipole soliton in nonlinear negative-index materials

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ABSTRACT

In this article, we find chirped and dipole soliton for nonlinear negative-index materials with quadratic-cubic nonlinearity. We will use sub-ODE method [32] to find chirped soliton and ansatz method of Choudhuri and Porsezian [41] to get dipole soliton.

1. Introduction

The soliton propagation in nonlinear optical fiber is a topic of current research because of the vital applications of short light pulses to telecommunication and ultrafast signal routing systems [1–37]. Chirped soliton is a type of signal emerges when frequency changes with time [38,39]. Chirped pulses are used in solitary wave-base communications, design of fiber optic amplifier and optical pulse compressors due to their applications in amplification or pulse compression [30]. Bouzida et al. [39] used dual power law in nano optical fibers to find chirped soliton. Dipole soliton or dark in the bright soliton were first observed by Choudhuri and Porsezian [41]. Dipole soliton are composed of product of bright and dark soliton. Chettouh et al. [42] studied extended nonlinear Schrödinger for dipole soliton. In this paper, we find the chirped soliton with sub-ODEs method and dipole soliton under the ansatz method for nonlinear negative index materials under quadratic-cubic nonlinearity [41].

2. Mathematical model

The model studies the dynamics of soliton propagation through optical metamaterials is given as [23]:

$$\begin{aligned} iq_t + aq_{xx} + (b_1|q| + b_2|q|^2)q = i\{\alpha q_x + \beta(|q|^2q)_x + \nu(|q|^2)_x q\} \\ + \theta_1(|q|^2q)_{xx} + \theta_2|q|^2q_{xx} + \theta_3 q^2 q^*{}_{xx} \end{aligned} \tag{1}$$

where wave profile is represented by $q(x, t)$, group velocity dispersion is represented by the coefficient of a. While quadratic-cubic nonlinearity is shown by b_1 and b_2. On other side of mathematical model, inter modal dispersion, self-steepening and nonlinear dispersion are represented by α, β and ν respectively.

In the following subsection, we find the chirped soliton for Eq. (1)

2.1. Chirped soliton

We start with the hypothesis [38]:

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$$q(x,t) = \rho(\xi)e^{i(X(\xi)-\Omega t)}, \tag{2}$$

where

$$\xi = x - \mathrm{ut}$$

where $\rho(\xi)$ represents amplitude function, $X(\xi)$ is the phase function, u is the wave velocity and Ω shows the frequency of wave oscillation. Now by using Eq. (2) and its derivatives into Eq. (1), we get the following real and imaginary part;

$$\begin{aligned}&\rho X'u + \rho\Omega + a\rho'' - a\rho(X')^2 + (b_1\rho^2 + b_2\rho^3) + \alpha\rho X' + \rho^3X'\beta\\&\quad + \theta_1(-3\rho''\rho^2 - 6\rho(\rho')^2 + \rho^3(X')^2) + \theta_2(\rho^3(x')^2 - \rho^2\rho'')\\&\quad\quad + \theta_3(\rho^3(X')^2 - \rho^2\rho'') = 0\end{aligned} \tag{3}$$

and

$$\begin{aligned}&-\rho'u + a\rho X'' + 2\alpha\rho'X'' + 2\alpha\rho'X' - \alpha\rho' - 3\beta\rho^2\rho' - 2\nu\rho^2\rho'\\&\quad + \theta_1(-6\rho^2\rho'X' - \rho^3X'') + \theta_2(\rho^3X'' - 2\rho^2\rho'X')\\&\quad\quad + \theta_3(2\rho^2\rho'X' + \rho^3X'') = 0\end{aligned} \tag{4}$$

We can solve the above equations by considering the chirp as [38]:

$$X' = \delta\rho^2 + \eta \tag{5}$$

where δ and η are the nonlinear and constant chirp parameters. We get two algebraic equations by using Eq. (5) into Eq. (4)

$$\delta = \frac{3\beta + 2\nu}{4a} \tag{6}$$

$$\eta = \frac{u + \alpha}{2a} \tag{7}$$

Now using Eqs. (5)–(7) in to Eq. (3) we get,

$$A\rho^7 + B\rho^5 + C\rho^3 + (b_1 + \rho''D)\rho^2 + (E - 6\theta_1(\rho')^2)\rho + a\rho'' \tag{8}$$

$$A = \delta^2(\theta_2 + \theta_1 + \theta_3), \quad B = 2\delta\eta(\theta_1 + \theta_2 + \theta_3) - a\delta^2 + \beta\delta$$

$$C = b_2 + \delta(u + \alpha) + \eta(-2a\delta + \beta) + \eta^2(\theta_1 + \theta_2 + \theta_3)$$

$$D = -(3\theta_1 + \theta_2 + \theta_3), \quad E = \Omega + \eta(\alpha - a\eta + u)$$

Multiplying Eq. (8) with ρ' and integrating we get

$$(\rho')^2 = a_1\rho^8 + a_2\rho^6 + a_3\rho^4 + a_4\rho^2 \tag{9}$$

$$a_1 = \frac{-A}{4a}, \quad a_2 = \frac{-B}{3a}, \quad a_3 = \frac{-C}{2a}, \quad a_4 = \frac{-E}{a}$$

$$a_1 = \frac{-\delta^2(\theta_2 + \theta_1 + \theta_3)}{4a}$$

$$a_2 = \frac{-2\delta\eta(\theta_1 + \theta_2 + \theta_3) - a\delta^2 + \beta\delta}{3a}$$

$$a_3 = \frac{-b_2 + \delta(u + \alpha) + \eta(-2a\delta + \beta) + \eta^2(\theta_1 + \theta_2 + \theta_3)}{2a}$$

$$a_4 = \frac{-\Omega + \eta(\alpha - a\eta + u)}{a}$$

By using the sub-ODE [32], we get the following solutions for Eq. (9);

Bell type solitary wave solutions: $a_1 > 0$, $a_2 < 2a_1$, $a_3 = \frac{a_2^2}{4a_1} - a_1$

$$\rho(\xi) = \frac{1}{\cosh\sqrt{a_1}\xi - \frac{a_2}{2a_1}} \tag{10}$$

By considering $a_2 = 0$, we obtain bright soliton solution.

$$\beta = -\frac{2\nu}{3} \tag{11}$$

$$\rho(\xi) = \sqrt{\mathrm{sech}(2\sqrt{a_1}\xi)} \tag{12}$$