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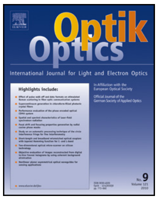

Original research article

Solitons in optical metamaterials with anti-cubic law of nonlinearity by generalized G'/G-expansion method

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ABSTRACT

This paper studies soliton perturbation in optical metamaterials, with anti-cubic nonlinearity, by implementing an integration approach, namely, the generalized G'/G-expansion method (GGEM). Bright, dark and singular soliton solutions are retrieved. The existence criteria of these solitons in metamaterials are also demonstrated. All solutions have been verified back into its corresponding equation with the aid of maple package program. Finally, we believe that the executed method is robust and efficient than other methods and the obtained solutions in this paper can help us to understand the variation of solitary waves in optical metamaterials.

1. Introduction

The nonlinear dynamics that describes the propagation of pulses in optical metamaterials (MMs) is given by the nonlinear Schrödinger equation (NLSE). In the presence of parabolic law nonlinearity, with an additional anti-cubic nonlinear term and perturbation terms that include inter-modal dispersion (IMD), self-steepening (SS) as well as nonlinear dispersion (ND), the governing equation reads [1–3]

$$iq_t + aq_{xx} + \left(b_1|q|^{-4} + b_2|q|^2 + b_3|q|^4\right) q = i\left[\alpha q_x + \beta\left(|q|^2 q\right)_x + \nu\left(|q|^2\right)_x q\right] + \theta_1\left(|q|^2 q\right)_{xx} + \theta_2|q|^2 q_{xx} + \theta_3 q^2 q^*_{xx}. \tag{1.1}$$

In Eq. (1.1), the unknown or dependent variable $q(x, t)$ represents the wave profile, while x and t are the spatial and temporal variables respectively. The first and second terms are the linear temporal evolution term and group velocity dispersion (GVD), while third term introduces the anti-cubic nonlinear term, fourth and fifth terms account for the parabolic law nonlinearity, and sixth, seventh and eighth terms represent the IMD, SS and ND respectively. Finally, the last three terms with θ_k for $k = 1, 2, 3$ appear in the context of metamaterials [4,5].

Metamaterials are basically artificially structured materials which are made from assemblies of multiple elements fashioned from composite materials such as metals or plastics. In just a few years, the field of optical metamaterials has emerged as one of the most exciting topics in the science of light, with stunning and unexpected outcomes that have fascinated scientists and the general public alike. Its applications' include super lenses, super-resolution devices, and negative-indexed materials. Such applications necessitate the presence of unnatural materials with properties that can fit into these applica-

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tions and others. The study of solitons in optical metameterials is trending as a hotspot in the field of optical materials. There has been a significant amount of results that are reported in this field. However, there is still a long way to go. There are many unanswered questions than answers. This paper will quell the thirst partially. In the past, solitons in optical metamaterials have been studied with various forms of non-Kerr laws of nonlinearity where several integration schemes have been implemented [6–28]. Interested reader also read herein references [29–45]. This paper is going to revisit the study of solitons in optical metamaterials for a specific form of nonlinear medium. This is of anti-cubic (AC) type. There are three forms of integration algorithms that will be applied to extract soliton solutions to metamaterials with AC nonlinearity. These schemes will retrieve bright, dark and singular soliton solutions that will be very important in the study of optical materials. These solitons will appear with constraint conditions that are otherwise referred to as existence criteria of the soliton parameters. After a quick introduction to the model, the integration techniques will be applied and the details are enumerated in the subsequent sections.

In order to solve Eq. (1.1), the starting hypothesis is [4,5]

$$q(x,t)=u(\xi(x,t))\exp(i\phi(x,t)), \tag{1.2}$$

where

$$\xi(x,t)=k(x-vt), \tag{1.3}$$

and the phase component ϕ is given by

$$\phi(x,t)=-\kappa x+\omega t+\theta, \tag{1.4}$$

In (1.2) and (1.3), $u(x, t)$ represents the amplitude portion of the soliton, and k and v are inverse width and velocity of soliton. From (1.4), κ is the frequency of the soliton, ω is the wave number of the soliton and finally θ is the phase constant. Inserting (1.2) into (1.1) and then decomposing into real and imaginary parts yield a pair of relations. Imaginary part gives

$$v=-\alpha-2a\kappa, \tag{1.5}$$

and

$$3\beta+2v-2\kappa(3\theta_1+\theta_2-\theta_3)=0, \tag{1.6}$$

while real part leads to

$$\begin{aligned} &ak^2u''-(\omega+a\kappa^2+\alpha\kappa)u+b_1u^{-3}+(b_2-\beta\kappa+\kappa^2\theta_1+\kappa^2\theta_2+\kappa^2\theta_3)u^3\\ &\quad+b_3u^5-(3k^2\theta_1+k^2\theta_2+k^2\theta_3)u^2u''-6k^2\theta_1u(u')^2=0. \end{aligned} \tag{1.7}$$

To acquire an analytic solution, the transformations $\theta_1=0$ and $\theta_2=-\theta_3$ are applied in Eq. (1.7), and gives

$$ak^2u''-(\omega+a\kappa^2+\alpha\kappa)u+b_1u^{-3}+(b_2-\beta\kappa)u^3+b_3u^5=0, \tag{1.8}$$

where

$$3\beta+2v+4\kappa\theta_3=0. \tag{1.9}$$

In order to obtain closed-form solutions, we employ the transformation given by

$$u=v^{1/2}, \tag{1.10}$$

that will reduce Eq. (1.8) into the ODE

$$ak^2(2vv''-v'^2)+4b_1-4(\omega+a\kappa^2+\alpha\kappa)v^2+4(b_2-\beta\kappa)v^3+4b_3v^4=0, \tag{1.11}$$

The generalized (G'/G)-expansion approach [26–28] will now be applied, in the subsequent section, to Eq. (1.11) to retrieve bright, dark and singular soliton solutions to the NLSE with AC nonlinearity (1.1). Biswas and coworkers investigated the extended nonlinear Schrödinger equation [46], the nonlinear Schrödinger's equation with parabolic law nonlinearity [47], the perturbed nonlinear Schrödinger's equation with five different forms of nonlinearity [48], the Schrödinger–Hirota equation in birefringent fiber [49], the Gerdjikov–Ivanov equation [50], the complex Ginzburg–Landau equation [51] and obtained new exact solutions including different forms of optical solitons. Also, authors of [52–54] studied the nonlinear Schrödinger's equation and obtained optical solitons with help of the trial and extended trial equation methods. Finally, bright optical soliton solutions from resonant nonlinear Schrödinger's equation have been gained by the aid of semi-inverse variational principle by Biswas et al. [55].

This paper is organized as follows: Section 2 presented a brief discussion about generalized (G'/G)-expansion method and its application for solving the aforementioned equation. Besides, the results and discussion are given in Section 3. Finally, we draw a conclusion about executed method and the generated results in Section 4.