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Solitons in optical metamaterials having parabolic law nonlinearity with detuning effect and Raman scattering

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ABSTRACT

The dynamics of pulse propagation through nonlinear optical metamaterials, maintaining parabolic law nonlinearity, is investigated. The model includes spatio-temporal dispersion, detuning effect, inter-modal dispersion, self-steepening effect, Raman scattering, nonlinear dispersion and third-order dispersion. Bright, dark and singular soliton solutions are derived by the implementation of coupled phase-amplitude formulation. The conditions on the material parameters for the existence of these solitons are also enumerated.

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1. Introduction

Optical soliton propagation is possible through a variety of waveguides. These include optical fibers, PCF, couplers, crystals and many others. This paper will address soliton propagation through optical metamaterials (MMs) that first came into existence a few years ago [1–5]. These MM have several advantages over regular form of optical fibers. One aspect of performance enhancement is that these MMs prevent the effect of differential group delay and thus pulse splitting is avoided during its transmission across long distances. Many results with MM have been reported. However, perturbative effects have not been considered in almost any of the papers.

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In this paper we retrieve bright, dark and singular soliton solutions for a perturbed nonlinear Schrödinger's equation (NLSE) that includes spatio-temporal dispersion term (STD) in addition to group-velocity dispersion (GVD), parabolic law nonlinearity, Raman effect, nonlinear dispersion (ND), self-steepening (SS), third-order dispersion (3OD), competing cubic–quintic nonlinearity, and second-order nonlinear dispersion. The model describes ultrashort optical pulse propagation through nonlinear MMs. The constraint conditions on material parameters for the existence of these structures are also presented.

2. Theoretical background

The dynamics of pulses in nonlinear MMs with STD, parabolic law nonlinearity, detuning, intermodal dispersion (IMD), SS, Raman effect, ND and 3OD, is given by the following perturbed NLSE [2–5]

$$\begin{aligned} &iq_t + aq_{xx} + bq_{xt} + c|q|^2q + d|q|^4q + eq + i\lambda q_x + is\left(|q|^2q\right)_x + i\mu\left(|q|^2\right)_x q \\ &+i\theta|q|^2q_x + i\gamma q_{xxx} + \theta_1\left(|q|^2q\right)_{xx} + \theta_2|q|^2q_{xx} + \theta_3 q^2 q^*_{xx} = 0, \end{aligned} \tag{1}$$

where $q(x, t)$ is the complex-valued function that represents soliton profile. x and t are the independent variables that represent the spatial and temporal variables respectively. Then, a and b are the coefficients of GVD and STD terms respectively. Next, c and d are the coefficients of cubic and quintic nonlinear terms, respectively. The cubic and quintic nonlinearities constitute parabolic law nonlinearity. The coefficients of detuning, IMD and Raman effect terms are e, λ, μ and θ, while s is the coefficient of SS term in order to avoid formation of shock waves and λ is the coefficient of 3OD term that appears whenever the GVD is negligibly small. Finally, the last three terms with θ_i for $i = 1, 2, 3$ appear in the context of nonlinear MMs [2–5].

Obviously, when b, d, λ, s, μ, θ, γ, e and θ_i are all equal to zero, then Eq. (1) reduces to basic NLSE with GVD and cubic nonlinearity, which admits bright and dark soliton solutions [3]. The latter describes the propagation of picosecond pulses in optical fibers, applicable in optical communications.

In order to solve Eq. (1) by the traveling wave hypothesis, an initial solution hypothesis is considered as [4]:

$$q(x, t) = g(s)e^{i\phi(x,t)}, \tag{2}$$

where $g(s)$ is real and represents amplitude of the wave, and

$$s = x - vt, \tag{3}$$

is often referred to as the traveling coordinate, with v being the speed of the wave. The phase component $\phi(x, t)$ is defined as

$$\phi(x, t) = -\kappa x + \omega t + \varphi. \tag{4}$$

where κ gives the soliton frequency, and ω accounts for the wave number while φ stands for the phase constant.

Now, substituting (2) into (1) and then decomposing into real and imaginary parts yields a pair of relations. The real part implies

$$\begin{aligned} &(a - bv + 3\gamma\kappa)g'' + 6\theta_1 g(g')^2 + \left(3\theta_1 + \theta_2 + \theta_3\right)g^2g'' \\ &+ \left(b\omega\kappa + \lambda\kappa + e - \omega - a\kappa^2 - \gamma\kappa^3\right)g \\ &+ \left(c + s\kappa + \theta\kappa - \theta_1\kappa^2 - \theta_2\kappa^2 - \theta_3\kappa^2\right)g^3 + dg^5 = 0, \end{aligned} \tag{5}$$

while the imaginary part indicates

$$\begin{aligned} &\left(b\omega + \kappa vb - v - 2a\kappa + \lambda - 3\gamma\kappa^2\right)g' \\ &+ \left(2\mu + \theta + 3s - 6\theta_1\kappa - 2\theta_2\kappa + 2\theta_3\kappa\right)g^2g' + \gamma g''' = 0, \end{aligned} \tag{6}$$

where the notations $g' = dg/ds$, $g'' = d^2g/ds^2$ and so on, are adopted in (5) and (6) for convenience.

Eq. (6) only contains third-order and first-order derivatives. We can, therefore, integrate it to obtain

$$g'' = \sigma g + \delta g^3 + c_1, \tag{7}$$

where c_1 is an integration constant, and

$$\sigma = \frac{v + 2a\kappa - b\omega - \kappa vb - \lambda + 3\gamma\kappa^2}{\gamma}, \tag{8}$$

$$\delta = \frac{2\kappa\left(3\theta_1 + \theta_2 - \theta_3\right) - 2\mu - \theta - 3s}{3\gamma}. \tag{9}$$

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