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Bright optical solitons for Lakshmanan-Porsezian-Daniel model by semi-inverse variational principle

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ABSTRACT

This paper secures bright soliton solution to the Lakshmanan-Porsezian-Daniel equation that serves as an alternate model for describing soliton propagation dynamics along optical fibers. The two types of nonlinear media are studied. They are Kerr law and power law. The semi-inverse variational principle is adopted in this paper. The solitons appear with a number of constraint relations that must remain valid for their existence.

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1. Introduction

The dynamics of optical solitons propelling through various forms of waveguides has been a constant topic of investigation in the field of nonlinear optics. A plethora of research results are visible across a variety of journals all over the globe [1–10]. The include research in optical fibers, PCF, DWDM systems, optical couplers, metamaterials and metasurfaces, magneto-optic waveguides and several others. There also exists a wide range of models that are studied in the context of soliton propagation. A few of the models studied are Manakov model, nonlinear Schrödinger's equation, Gerdjikov-Ivanov equation and many more. This paper studies the dynamics of soliton propagation by the aid of a Lakshmanan-Porsezian-Daniel (LPD) model that appeared a couple of decades ago. Very recently, bright, dark and singular soliton solutions for this model have been reported [3]. The difference is that it was recently studied with the inclusion of spatio-temporal dispersion (STD) whose necessity was pointed out during 2012 [2,4]. This paper considers LPD model from a totally different perspective. It utilizes the method of semi-inverse variational principle (SVP) which enables the recovery of bright solitons. The two nonlinear

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forms studied here are Kerr law and power law. The results are listed with a few constraints on the parameters that must hold for solitons to exist. The details are all enumerated in the upcoming sections.

2. Governing equation

The LPD model in its dimensionless structure to be studied in this paper reads as follows [3,6]:

$$iq_t + aq_{xx} + bq_{xt} + cF\left(|q|^2\right)q = \sigma q_{xxxx} + \alpha(q_x)^2 q^* + \beta|q_x|^2 q + \gamma|q|^2 q_{xx} + \lambda q^2 q^*_{xx} + \delta|q|^4 q. \tag{1}$$

In (1), $q(x, t)$ is the complex-valued dependent variable that represents the wave profile. The two independent variables are spatial co-ordinate x and temporal co-ordinate t. The nonlinear functional F is the dependence on the refractive index of the optical fiber that dictaes the nonlinearity structure and thus it represents the self-phase modulation of the optical pulse. The coefficients of a and b are group-velocity dispersion and STD respectively. On the right hand side of (1), σ is the coefficient of fourth order dispersion and δ represents two-photon absorption. Other perturbation terms with nonlinear forms of dispersion are indicated by the coefficients of α, β, γ ad λ. There are two forms of the functional F that will be addressed in this paper.

For (1), the traveling wave hypothesis is the start-up scheme and is given by [1,8,9]:

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

where $g(s)$ gives wave structure with

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

while the phase factor $\phi(x, t)$ is as below:

$$\phi(x, t) = -\kappa x + \omega t + \theta_0. \tag{4}$$

Here, κ refers to soliton frequency, and ω stands for the wave number with θ_0 being the phase constant. Upon substituting this assumption (2) into (1) and splitting into real and imaginary parts leads to a pair of relations. The real part reads as follows:

$$\begin{aligned} &\sigma g^{(iv)} - (a - bv + 6\sigma\kappa^2)g'' - (b\kappa\omega - \omega - a\kappa^2 - \sigma\kappa^4)g - (\alpha + \beta + \gamma + \lambda)\kappa^2 g^3 \\ &+\delta g^5 - cF\left(g^2\right)g + (\alpha + \beta)g(g')^2 + (\lambda + \gamma)g^2 g'' = 0, \end{aligned} \tag{5}$$

while the imaginary part is structured as:

$$\left\{(1 - b\kappa)v + \left(2a\kappa + 4\sigma\kappa^3 - b\omega\right)\right\}g' - 2(\alpha + \beta + \gamma + \lambda)\kappa g^2 g' - 4\sigma\kappa g''' = 0. \tag{6}$$

In (5) and (6), the notations $g' = dg/ds$, $g'' = d^2g/ds^2$ and so on have been adopted. Next, upon setting the coefficients of the linearly independent functions to zero in (5) and (6), one recovers:

$$\alpha + \beta = 0 \tag{7}$$

$$\gamma + \lambda = 0 \tag{8}$$

$$\sigma = 0 \tag{9}$$

Implementing these constraints the soliton speed, irrespective of the nonlinearity structure, falls out to be

$$v = \frac{b\omega - 2a\kappa}{1 - b\kappa} \tag{10}$$

whenever

$$b\kappa \neq 1. \tag{11}$$

The constraints (7)–(10) solves the perturbation coefficients in terms of two free parameters γ and δ by the aid of Gaussian elimination as given by

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \lambda \\ \sigma \end{bmatrix} = \alpha \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \gamma \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \\ 0 \end{bmatrix} \tag{12}$$

Eq. (1) therefore condenses to

$$iq_t + aq_{xx} + bq_{xt} + cF\left(|q|^2\right)q = \alpha(q_x)^2 q^* + \beta|q_x|^2 q + \gamma|q|^2 q_{xx} + \lambda q^2 q^*_{xx} + \delta|q|^4 q. \tag{13}$$

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