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Optical solitons in birefringent fibers with weak non-local nonlinearity and four-wave mixing by extended trial equation method

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ABSTRACT

This paper studies optical solitons in birefringent fibers with parabolic law nonlinearity coupled with waekly non-local nonlinear medium. The four-wave mixing effect is taken into consideration and thus retrieval of soliton solutions would require phase-matching condition.

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1. Introduction

Optical soliton dynamics in birefringent fibers is a growing area of interest in the field of telecommunications engineering. When pulses split into two, with the non–uniformities of fiber diameter and its rough handling, it results in differential group delay. The cumulative effect of these delays amount to birefringence. This paper will study birefringence in optical fibers with two forms of nonlinearities taken into account. They stem from parabolic law and weakly non–local nonlinear form. There are several mathematical approaches to address these problems from mathematical photonics arena [1–20]. This paper will successfully implement the extended trial equation method to the current project in birefringent fibers when four-wave mixing (4WM) effect is accounted for. This compels the choice of phase-matching condition in the two components of the wave to permit its integrability. It must be noted that the results of birefringence without 4WM has been already reported with this form of integration scheme. The rest of the paper details the soliton solution extraction from the model.

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1.1. Governing model

The dimensionless form of the NLSE with parabolic law of nonlinearity in presence of nonlinear dispersion that is going to be studied in this paper is given by [1,16,17]

$$iu_t + au_{xx} + \left(b_1|u|^2 + b_2|u|^4\right)u + b_3(|u|^2)_{xx}u = 0, \tag{1}$$

where the unknown function $u(x, t)$ is the normalized slowly varying amplitude, and x and t represent the distance and time variables, respectively. For the model described by (1), the first term is the linear temporal evolution of the pulse while the coefficient of a is the group velocity dispersion (GVD). The two nonlinear terms are the coefficients of b_1 and b_2 which together represents parabolic form of nonlinearity. Finally, b_3 is due to weak nonlocal nonlinearity [1,16,17].

For birefringent fibers the corresponding governing coupled system derived from (1), with 4WM effect taken into account, is given by:

$$\begin{aligned} iq_t &+ a_1q_{xx} + \left(c_1|q|^2 + d_1|r|^2\right)q + \left(\xi_1|q|^4 + \eta_1|q|^2|r|^2 + \zeta_1|r|^4\right)q \\ &+ \left\{\lambda_1(|q|^2)_{xx} + \theta_1(|r|^2)_{xx}\right\}q + \left\{\gamma_1(qr^*)_{xx} + \nu_1(q^*r)_{xx}\right\}q = 0, \end{aligned} \tag{2}$$

$$\begin{aligned} ir_t &+ a_2r_{xx} + \left(c_2|r|^2 + d_2|q|^2\right)r + \left(\xi_2|r|^4 + \eta_2|q|^2|r|^2 + \zeta_2|q|^4\right)r \\ &+ \left\{\lambda_2(|r|^2)_{xx} + \theta_2(|q|^2)_{xx}\right\}r + \left\{\gamma_2(rq^*)_{xx} + \nu_2(r^*q)_{xx}\right\}r = 0. \end{aligned} \tag{3}$$

From (2) and (3), the coefficients of a_j for $j = 1, 2$ represents GVD for the two components. Then, the coefficients of self-phase modulation (SPM) are c_j, ξ_j and λ_j for $j = 1, 2$. Finally, the coefficients of cross-phase modulation (XPM) are d_j, η_j, ζ_j and θ_j for $j = 1, 2$. Finally, γ_j and ν_j stem from 4WM effect.

1.2. Mathematical analysis

In order to handle the governing coupled system, the following is our starting hypothesis:

$$q(x, t) = P_1[\eta(x, t)]\exp[i\phi(x, t)], \tag{4}$$

$$r(x, t) = P_2[\eta(x, t)]\exp[i\phi(x, t)], \tag{5}$$

where $P_l(\eta)$ for $l = 1, 2$ are the amplitude component of the soliton and

$$\eta = x - vt, \tag{6}$$

and the phase component ϕ is defined as

$$\phi = -\kappa x + \omega t + \theta, \tag{7}$$

for $l = 1, 2$. Here, v is the velocity of the soliton, κ is the frequency of the solitons in each of the two components while ω is the soliton wave number and θ is the phase constant. Inserting (4) and (5) into (2) and (3) and splitting into real and imaginary parts yield a pair of relations.

Real part gives

$$\begin{aligned} &-\left(\omega + a_l\kappa^2\right)P_l + c_lP_l^3 + d_lP_lP_{\bar{l}}^2 + \xi_lP_l^5 + \eta_lP_l^3P_{\bar{l}}^2 + \zeta_lP_lP_{\bar{l}}^4 + 2\lambda_lP_l\left(P_l'\right)^2 + 2(\gamma_l + \nu_l)P_lP_l'P_{\bar{l}}' \\ &+2\theta_lP_l\left(P_{\bar{l}}'\right)^2 + a_lP_l'' + 2\lambda_lP_l^2P_l'' + (\gamma_l + \nu_l)P_lP_{\bar{l}}P_l'' + (\gamma_l + \nu_l)P_l^2P_{\bar{l}}'' + 2\theta_lP_lP_{\bar{l}}P_{\bar{l}}'' = 0, \end{aligned} \tag{8}$$

while imaginary part equation causes

$$(v + 2a_l\kappa)P_l' = 0, \tag{9}$$

for $l = 1, 2$ and $\bar{l} = 3 - l$. It is possible to get the speed of the soliton from Eq. (9) as

$$v = -2a_l\kappa. \tag{10}$$

Equating the two values of the soliton velocity (10) implies

$$a_1 = a_2. \tag{11}$$

Therefore, it makes sense to define

$$a_1 = a_2 = a, \tag{12}$$

and then speed of the solitons for both components reduce to

$$v = -2a\kappa. \tag{13}$$

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