Optik 165 (2018) 341–344

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Periodic oscillations of dark solitons in nonlinear optics

Weitian Yu [a], Mehmet Ekici [b], Mohammad Mirzazadeh [c], Qin Zhou [d,*], Wenjun Liu [a,*]

[a] State Key Laboratory of Information Photonics and Optical Communications, and School of Science, P.O. Box 122, Beijing University of Posts and Telecommunications, Beijing 100876, China
[b] Department of Mathematics, Faculty of Science and Arts, Bozok University, 66100 Yozgat, Turkey
[c] Department of Engineering Sciences, Faculty of Technology and Engineering, East of Guilan, University of Guilan, P.C. 44891-63157, Rudsar-Vajargah, Iran
[d] School of Electronics and Information Engineering, Wuhan Donghu University, Wuhan 430212, China

ARTICLE INFO

Article history:
Received 25 March 2018
Accepted 30 March 2018

Keywords:
Dark soliton
Variable coefficient nonlinear Schrödinger equation
Hirota method
Periodic oscillation

ABSTRACT

Dark solitons draw much attention due to their stable transmission property in nonlinear optics. In this paper, the variable coefficient nonlinear Schrödinger equation is solved by the Hirota method, and a new type of dark solitons with periodic oscillations is presented. Oscillations can be achieved without any external influence on them. The frequency and amplitude of dark soliton oscillations can be controlled by adjusting corresponding parameters. We hope those results are helpful for the dark soliton investigation.

1. Introduction

Optical solitons were demonstrated theoretically and experimentally in 1973 and 1980 [1,2]. Shortly afterwards, dark solitons were observed in 1987 [3]. Generally, the stable optical soliton is generated when the group velocity dispersion is balanced with the Kerr nonlinearity in single mode fibers [4–10]. In the anomalous dispersion region, solitons are transmitted as bright solitons, while solitons are transmitted as dark solitons in the normal dispersion region, and some theoretical and experimental work have been carried out based on bright and dark optical solitons [11–17]. Dark solitons appear as inverted bell-shaped local depressions on a non-zero plane, and no energy field exists within the depressions [18]. Compared with bright solitons, dark solitons have the advantages of slower pulse broadening, slower amplitude attenuation and less influence of various disturbances with the same loss and transmission distance [19–22]. Under the same noise influence, dark solitons are also less affected by noise than bright solitons, and interactions between dark solitons are weaker than bright solitons. Because of those advantages, dark solitons are more suitable than bright solitons for the transmission of optical communications. Dark solitons are also used in optical waveguides and optical switches [23–25]. Moreover, dark solitons have drawn much attention from researchers for their potential applications in long-distance optical communications and ultra-fast optics [23–28].

Dark solitons described by nonlinear Schrödinger (NLS) equations have been discussed by some researchers [29–35]. The dark soliton with oscillatory background density, solved by two-coupled NLS equation, has been first reported [29]. The interaction and dynamics of periodic solitons derived from two-coupled NLS equation have been investigated [30]. The nonlinear tunneling of dark solitons worked out from the variable coefficient NLS equation has been explored [31,32]. The stability analysis of dark solitons have been discussed [33–35].

* Corresponding authors.
E-mail addresses: qinzhou@whu.edu.cn (Q. Zhou), jungliu@bupt.edu.cn (W. Liu).

https://doi.org/10.1016/j.ijleo.2018.03.137

In this paper, dark solitons with periodic oscillations will be obtained by solving the following variable coefficient NLS equation with the Hirota's method,

$$\frac{\partial A}{\partial z} - i\frac{D(z)}{2}\frac{\partial^2 A}{\partial t^2} + i\rho(z)|A|^2 A = g(z)A. \tag{1}$$

z is the ordinate representing the propagation distance, and t is the propagation time. $A(z, t)$ indicates the temporal envelope. $\rho(z)$, $D(z)$ and $g(z)$ respectively represents a Kerr nonlinear coefficient, the group-velocity dispersion(GVD) coefficient and the loss or gain coefficient.

In this paper, we obtain two groups of dark solitons according to one soliton solution of Eq. (1). Moreover, dark solitons in those two groups oscillate periodically. The realization of those oscillations do not require external influence on it. And we study them by changing the corresponding parameters. The dark soliton with periodic oscillation has not been reported before. We hope our research will be helpful for the development of dark solitons and optical communications.

We organize the paper as shown below. In Section 2, we will use the Hirota method to obtain one soliton solution of Eq. (1). In Section 3, new dark soliton structures with periodic oscillations will be derived and discussed. In Section 4, we will get the conclusion.

2. Analytic one soliton solution

We firstly introduce the independent variable transformation so as to get the one soliton solution of Eq. (1),

$$A(z, t) = \frac{h(z, t)}{f(z, t)}, \tag{2}$$

where the function $h(z, t)$ is complex, and the function $f(z, t)$ is real. Then, the bilinear form of Eq. (1) can be obtained with symbolic computation,

$$[iD_z + \frac{1}{2}D(z)D_t^2 - ig(z) + \lambda(z)]h\cdot f = 0, \tag{3}$$

$$[D(z)D_t^2 + 2\lambda(z)]f\cdot f + 2\rho(z)|h|^2 = 0, \tag{4}$$

where $\lambda(z)$ is a function to be determined. Moreover, the bilinear operators D_z and D_t can be defined by

$$D_z^m D_t^n(G\cdot F) = (\frac{\partial}{\partial z} - \frac{\partial}{\partial z'})^m (\frac{\partial}{\partial t} - \frac{\partial}{\partial t'})^n G(z, t)F(z', t')|_{z'=z, t'=t}.$$

By introducing the power series expansion of functions $h(z, t)$ and $f(z, t)$ as following, Eq. (3) can be solved,

$$h(z, t) = h_0(z, t)[1 + \varepsilon h_1(z, t) + \varepsilon^2 h_2(z, t) + \varepsilon^3 h_3(z, t) + \cdots], \; f(z, t) = 1 + \varepsilon$$
$$f_1(z, t) + \varepsilon^2 f_2(z, t) + \varepsilon^3 f_3(z, t) + \cdots,$$

where ε is a expansion parameter. And in order to derive one soliton solution, we can hypothesis that

$$h(z, t) = h_0(z, t)[1 + \varepsilon h_1(z, t)], \tag{5}$$

$$f(z, t) = 1 + \varepsilon f_1(z, t), \tag{6}$$

where

$$h_0(z, t) = de^{Q_0(z,t)}, \quad h_1(z, t) = -e^{Q_1(z,t)}, \quad ; f_1(z, t) = me^{Q_1(z,t)},$$
$$Q_0(z, t) = ia(z) + ibz, \quad ; Q_1(z, t) = k(z) + wt + \delta.$$

Substituting expressions (5) and (6) into the bilinear form, we have

$$m = 1, \quad ; \lambda(z) = -\frac{1}{4}w^2 D(z), \quad ; \rho(z) = \frac{w^2 D(z)}{4d^2},$$
$$k(z) = -bw\int D(z)dz, \quad ; a(z) = -\frac{1}{4}\int [(2b^2 + w^2)D(z) + 2ig(z)]dz,$$

where d, b, w, δ are arbitrary parameters. Finally, one soliton solution of Eq. (1) can be solved as

$$A(z, t) = \frac{h_0(z, t)[1 + \varepsilon h_1(z, t)]}{1 + \varepsilon f_1(z, t)} = \frac{e^{ibt - \frac{1}{4}i\int [(2b^2 + w^2)D(z) + 2ig(z)]dz}(1 - e^{tw + \delta - bw\int D(z)dz})}{1 + e^{tw + \delta - bw\int D(z)dz}}.$$