Abstract: The paper derives stationary optical solitons with nonlinear chromatic dispersion. A nonlocal form of nonlinearity and quintuple power–law of nonlinearity are considered. The Kudryashov’s integration scheme enables to retrieve such solitons. A plethora of solitons come with this algorithm.

Keywords: nonlinear chromatic dispersion; Kudryashov; stationary solitons

1. Introduction

There is a growing interest in quiescent optical solitons modeled by various forms of the nonlinear Schrödinger’s equation (NLSE) with its nonlinear form of chromatic dispersion (CD). A wide variety of results in this context have been recovered in the past with various structural forms of self-phase modulation (SPM) [1–22]. A wide range of results have also been recovered with direct software application to address the reduced ordinary differential equations. These results were for a variety of models, such as the Sasa–Satsuma model and Lakshmanan–Porsezian–Daniel model. The current study will apply the enhanced Kudryashov’s scheme to recover such stationary solitons for the NLSE that includes Kudryashov’s proposed form of SPM. It contains the quintuple power law of nonlinearity and a nonlocal form of nonlinearity. The algorithm recovers singular, dark and bright solitons that are all listed in the present study. The parametric restrictions that enable us such solitons are also extracted. The results are recovered, and the details of the derivation are drafted after quick recapitulation of the integration algorithm. The governing model that will be addressed in the paper reads as

\[ iq_t + a(q^r q)_{xx} + \left[ b_1 |q|^{2m} + b_2 |q|^{2m+n} + b_3 |q|^{2m+2n} + b_4 |q|^{2m+n+p} + b_5 |q|^{2m+2n+p} + (|q|^r q)_{xx} \right] q = 0. \] (1)

here, the last term stands for nonlocal nonlinearity, whereas \( b_j (1 \leq j \leq 5) \) comes from the SPM structure as introduced by Kudryashov [1]. The first term stems from linear temporal...
evolution, whilst \( q(x, t) \) implies the wave profile. Next, \( a \) arises from CD, while \( t \) and \( x \) are temporal and spatial coordinates in sequence. Finally, the exponents \( m, n, \) and \( p \) are positive quantities while \( r \geq 0 \). For the special case when \( r = 0 \), it collapses to the case of linear chromatic dispersion. However, the range of values that these parameters can pick up are not yet known. That is an open problem that can presumably be answered by the aid of Benjamin–Feir stability analysis. This is a separate project that will be taken up in future. The current paper only retrieves the quiescent soliton solutions for non-negative values of these parameters. After preliminary hand-computed algebraic expressions, the form of quiescent soliton solution structures are recovered by the aid of Mathematica.

The study of quiescent optical solitons has gained popularity in the field of fiber optics during the past decade, primarily because the emergence of such solitons, during intercontinental distance transmission, is an unwanted feature since it would stall the pulse transmission [15–20]. Thus, the pre-existing and current works are means and measures for various models to study the emergence and existence of quiescent solitons and must be avoided at all costs. In particular, the model given by (1) was studied earlier this year by the application of the \( \mathcal{G}'/\mathcal{G} \) expansion algorithm [19]. The current work revisits the model with a richer approach that will provide a fresh and novel perspective to it.

The adopted enhanced Kudryashov’s algorithm would reveal stationary optical soliton solutions which are bright and singular types. It is not out of place to mention that kink solitons are special cases of topological solitons [23–25]. This has also been indicated in additional works [26,27]. Additionally, dark solitons, that are also known as topological solitons, will be revealed in this work [28].

2. Enhanced Kudryashov’s Algorithm

Consider a governing model [2–5]

\[ F(u, u_x, u_t, u_{xt}, u_{xx}, \ldots) = 0. \] (2)

here, \( F \) implies to a polynomial and \( u = u(x, t) \) signifies a function, where \( t \) and \( x \) are temporal and spatial coordinates in sequence.

**Step 1:** By the aid of the restriction

\[ \xi = k(x - vt), u(x, t) = U(\xi), \] (3)

Equation (2) sticks out as

\[ P \left( U, -kvU', kU', k^2U'', \ldots \right) = 0, \] (4)

where \( k \) and \( v \) denote constants.

**Step 2:** Equation (4) satisfies the solution form

\[ U(\xi) = A_0 + \sum_{i=1}^{N} \sum_{i+j=l} A_{ij} Q^i(\xi) R^j(\xi), \] (5)

with the aid of the auxiliary equations

\[ Q'(\xi) = Q(\xi)(\eta Q(\xi) - 1), \] (6)

and

\[ R'(\xi)^2 = R(\xi)^2(1 - \chi R(\xi)^2), \] (7)

where the newly introduced functions \( Q(\xi) \) and \( R(\xi) \) admit the analytical solutions

\[ R(\xi) = \frac{4a}{4a^2e^\xi + \chi e^{-\xi}}, \] (8)
and

\[ Q(\xi) = \frac{1}{\eta + be^\xi}. \]  

(9)

here, \( \chi, \eta, b, A_0, a, \) and \( A_{ij}(i, j = 0, 1, \ldots, N) \) stand for constants.

Step 3: With the aid of the balancing technique in Equation (4), we arrive at the parameter \( N \) in Equation (5).

Step 4: Inserting Equation (5) together with Equations (6) and (7) into Equation (4) provides us a system of equations that yields the constant parameters in (3)–(9).

3. Application to the Model

Equation (1) satisfies the solution hypothesis

\[ q(x, t) = U(kx)e^{i(\omega t + \theta_0)}. \]  

(10)

here, \( \theta_0 \) depicts the phase constant, whilst \( \omega \) denotes the wave number. Substituting (10) into (1) enables

\[ ak^2(r + 1)U'^{r+1}U^r + ak^2(r + 1)U'U'^2 + b_4U'^{2m+n+p+2} + b_3U'^{2m+2n+p+2} + b_2U'^{2m+n+1} + b_1U'^{2m+2} + k^2pU'^{r+1}U^r + k^2(p - 1)pU'U'^2 - \omega U^2 = 0. \]  

(11)

Taking \( r = 2m + p \), Equation (1) shapes up as

\[ iq_t + a(|q|^{2m+p}q)_{xx} + \left[ b_1|q|^{2m} + b_2|q|^{2m+n} + b_3|q|^{2m+2n} + b_4|q|^{2m+n+p} + b_5|q|^{2m+2n+p} + (|q|^p)_{xx} \right] q = 0, \]  

(12)

and Equation (11) stands as

\[ ak^2(2m + p + 1)U'U'^{2m+n+p+1} + ak^2(2m + p)(2m + p + 1)U'^2U'^{2m+p} + b_4U'^{2m+2n+p+2} - \omega U'^2 + b_3U'^{2m+2n+p+2} + b_2U'^{2m+n+1} + b_1U'^{2m+2} + k^2pU'^{r+1}U^r + k^2(p - 1)pU'^2U'^2 = 0. \]  

(13)

Using the transformation

\[ U = V^\frac{4}{2}, \]  

(14)

Equation (13) reads as

\[ n^2V^2(-\omega + b_1V^{2m} + b_3V^{2m+2n} + b_2V^{2m+2n+p} + b_4V^{2m+n+p} + b_5V^{2m+2n+p}) + k^2(p - 1)pV'^2V^\frac{4}{2} + ak^2(2m + p)(2m + p + 1)V'^2V^{2m+n} + k^2pV^\frac{4}{2}(nVU'^r - (n - 1)V'^2) + ak^2(2m + p + 1)V^{2m+n}(nVU'^r - (n - 1)V'^2) = 0. \]  

(15)

Setting \( p = n = 2m \), Equation (12) turns into

\[ iq_t + a(|q|^{4m}q)_{xx} + \left[ b_1|q|^{2m} + b_2|q|^{4m} + (b_3 + b_4)|q|^{6m} + b_5|q|^{6m} + (|q|^{2m})_{xx} \right] q = 0, \]  

(16)

and Equation (15) shapes up as

\[ 2ak^2(m + 1)V'^r + ak^2(2m + 1)(4m + 1)V'^2 + 4b_5m^2V^4 + 4(b_3 + b_4)m^2V^2 + 4b_2m^2V^2 + 4b_1m^2V + 4k^2m^2V'^r - 4m^2\omega = 0. \]  

(17)

Balancing \( V'^r \) with \( V^4 \) in (17) collapses Equation (5) to

\[ V(\xi) = \lambda_0 + \lambda_{01}R(\xi) + \lambda_{10}Q(\xi). \]  

(18)
Substituting (18) along with (6) and (7) into (17), we arrive at the results:

**Result 1:**

\[
\lambda_0 = \frac{8b_5m^2 - (b_3 + b_4)(6m + 1)(4m + 1)}{4b_5(5m + 1)(4m + 1)} - \frac{\lambda_{10}}{25},
\]

\[
\lambda_{01} = 0, \quad \lambda_{10} = -\frac{9\sqrt{3}}{2b_5(4m + 1)(5m + 1)},
\]

\[
k = \sqrt{\frac{m\varphi_1}{\varphi_1}},
\]

\[
b_1 = \frac{8b_5^2(4m + 1)(5m + 1)}{\varphi_1},
\]

\[
b_2 = \frac{8b_5(6m + 1)(5m + 1)}{\varphi_1},
\]

\[
\omega = -\frac{\varphi_4}{4b_5^2(4m + 1)(5m + 1)^2}.
\]

where

\[
\varphi_1 = (6m + 1)(4m + 1)(3a^2(b_3 + b_4)^2(4m + 1)^3(6m + 1) - 8ab_5(4m + 1))
\]

\[
(ab_4(4m + 1)(5m + 1)^2 - 6(b_3 + b_4)m^3) - 192b_5^2m^4),
\]

which introduces the constraint condition

\[
\varphi_2 = 48ab_5m^2(5m + 1)(4m + 1)\left(\frac{b_3(6m + 1)(4m + 1)}{b_4(4m + 1)(6m + 1) - 8m^2}\right)
\]

\[
+3a^2(4m + 1)^2(b_3(4m + 1)(6m + 1) + b_4(4m + 1)(6m + 1) - 8m^2)^2,
\]

\[
\varphi_3 = a^2(b_3 + b_4)^3(3m + 1)(4m + 1)^4(6m + 1)^2
\]

\[
-4a^2(b_3 + b_4)b_5(4m + 1)^2(6m + 1)(3m + 1)
\]

\[
(ab_2(5m + 1)^2(4m + 1) - 6(b_3 + b_4)m^3)
\]

\[
-64ab_5^3m^3(4m + 1)\left(ab_2(4m + 1)(5m + 1)^2 - 3(b_3 + b_4)m^2(7m + 1)\right) - 512b_5^4m^6(7m + 1),
\]

\[
\varphi_4 = a^4b_4^4(6m + 1)^3(4m + 1)^6(2m + 1)
\]

\[
+4a^3b_5^3(4m + 1)^4(6m + 1)^2(ab_4(6m + 1)(4m + 1)^2(2m + 1) - 24b_5m^4)
\]

\[
+(a^2b_5^2(6m + 1)(4m + 1)^3(2m + 1) - 4a^4m
\]

\[
+1(ab_2(5m + 1)^2(8m^2 + 6m + 1) + 2b_4m^2(m(26m + 9) + 1)b_5 + 192b_5^2m^5)
\]

\[
(ab_2(5m + 1)^2(4m + 1)^3(6m + 1)^2 - 4ab_3(4m + 1)(6m + 1)
\]

\[
(ab_4(4m + 1)(5m + 1)^2 - 2b_4m^2(7m + 1))
\]

\[
-64b_5^2m^4(11m + 2) + 2a^2b_5^2(6m + 1)^2(4m + 1)^2
\]

\[
(3a^2b_5^2(6m + 1)(4m + 1)^4(2m + 1)
\]

\[
-4ab_3(4m + 1)^2(b_2(5m + 1)^2(8m^2 + 6m + 1) + 36b_4m^4)
\]

\[
-96b_5^2m^4(m(11m + 6) + 1)) + 4ab_3(4m + 1)(a^2b_5^2(2m + 1)(4m + 1)^5
\]

\[
(6m + 1)^3 - 4(4m + 1)^3(6m + a)^2b_4(a(5m + 1)^2)
\]

\[
18b_4m^4 + b_2(8m^2 + 6m + 1)b_5 + 96am^4m + 16m
\]

\[
+1(ab_2(4m + 1)(5m + 1)^2 - (6m + 1))
\]

\[
(b_4(m(11m + 6) + 1)b_5^2 + 256b_5^6m^6(m(206m + 95) + 16) + 1).
\]

Inserting (19) along with (9) into (18) paves the way to the solitary wave

\[
q(x, t) = \left\{ \frac{8b_5m^2 - (b_3 + b_4)(6m + 1)(4m + 1)}{4b_5(5m + 1)(4m + 1)} \right\} \frac{\lambda_{10}}{25} \frac{1}{m^\varphi_1 - \rho^\varphi_1}
\]

\[
\times e^{i(\frac{\lambda_1}{4b_5}(6m + 1)(5m + 1)^2)\frac{1}{m^\varphi_1 - \rho^\varphi_1}}.
\]
Taking $ab\delta \zeta_{1}<0$ and $\eta = \pm b$ transforms the soliton (24) to the dark and singular solitons

$$q(x,t) = \left\{ \frac{8b_{3}m^{2}-(b_{3}+b_{4})(6m+1)(4m+1)}{4b_{3}(5m+1)(4m+1)} + \frac{\sqrt{\eta}}{4ab_{3}(4m+1)^{5}(5m+1)} \times \tan h \left\{ \frac{m^{2}\delta_{1}}{4ab_{3}(4m+1)^{5}(5m+1)} \right\} x \right\}^{\frac{1}{2m}}$$

and

$$q(x,t) = \left\{ \frac{8b_{3}m^{2}-(b_{3}+b_{4})(6m+1)(4m+1)}{4b_{3}(5m+1)(4m+1)} + \frac{\sqrt{\eta}}{4ab_{3}(4m+1)^{5}(5m+1)} \times \cot h \left\{ \frac{m^{2}\delta_{1}}{4ab_{3}(4m+1)^{5}(5m+1)} \right\} x \right\}^{\frac{1}{2m}}$$

Figure 1 depicts the plot of a stationary dark soliton (25). The parameter values chosen are $b_{3} = 1$, $b_{4} = 1$, $b_{5} = 1$, $a = 1$ and $m = \frac{1}{10}, \frac{1}{4}, \frac{1}{6}, \frac{1}{8}, \frac{1}{10}$, respectively.

![Figure 1. Profile of a stationary dark soliton.](image)

**Result 2:**

$$\begin{align*}
\lambda_{0} &= \frac{8b_{3}m^{2}-(b_{3}+b_{4})(6m+1)(4m+1)}{4ab_{3}(4m+1)^{5}(5m+1)}, \\
\lambda_{10} &= \sqrt{\frac{m^{2}\delta_{1}}{8a^{2}b_{3}(4m+1)^{5}(5m+1)^{5}}}, \\
k &= \sqrt{\frac{m^{2}\delta_{1}}{2a^{2}b_{3}(4m+1)^{7}(5m+1)^{5}}}, \\
b_{1} &= \frac{\delta_{1}}{8ab_{3}^{2}(4m+1)^{4}(5m+1)^{5}}, \\
\omega &= \frac{\delta_{1}}{256a^{4}b_{3}^{2}(4m+1)^{5}(5m+1)^{5}},
\end{align*}$$

where $\delta_{1}$, $\delta_{2}$ and $\delta_{3}$ are given by (20)–(22) and

$$\begin{align*}
\delta_{5} &= (a(b_{3}+b_{4})(4m+1)(6m+1)-8b_{3}m^{2})(5a^{3}(b_{3}+b_{4})^{3} \\
&\quad + 2m+1)(4m+1)^{6}(6m+1)^{2} - 64ab_{3}^{2}(4m+1) \\
m^{2}(2ab_{2}(4m+1)(5m+1)^{2}(8m+1) - (b_{3}+b_{4})m^{2}(2m(80m+9) - 1)) \\
&\quad - 8(b_{3}+b_{4})b_{5}(6m+1)(4am+a)^{2} \\
&\quad + (2ab_{2}(5m+1)^{2}(8m^{2}+6m+1) - (b_{3}+b_{4})m^{2}(10m+1)(16m+5)) \\
&\quad - 1536b_{5}^{2}(20m+3)m^{6}).
\end{align*}$$
Inserting (27) along with (8) into (18) gives the solitary wave

\[
q(x, t) = \left\{ \frac{8b_5m^2 - a(b_3 + b_4)}{4ab_5(4m+1)(5m+1)} \right\} \frac{\chi_0}{\sqrt{8a^2\beta_5^2(5m+1)^2(4m+1)^2}}
\]

\[
\times \left[ 4a^2 \exp\left( \frac{m^2 \chi_0}{2a^2\beta_5(4m+1)(5m+1)^2(4m+1)^2} x \right) \right]
\]

\[
- \chi \exp\left(- \frac{m^2 \chi_0}{2a^2\beta_5(4m+1)(5m+1)^2(4m+1)^2} x \right)
\]

\[
\times e^{i\left( \frac{\chi_0}{2a^2\beta_5(4m+1)(5m+1)^2(4m+1)^2} x \right)^{1/2} + \theta_0}.
\]

Setting \(ab_5\chi_0 > 0\) and \(\chi = \pm 4a^2\) reduces the soliton (29) to the bright and singular solitons

\[
q(x, t) = \left\{ \frac{8b_5m^2 - a(b_3 + b_4)}{4ab_5(4m+1)(5m+1)} \right\} \frac{\chi_0}{\sqrt{8a^2\beta_5^2(5m+1)^2(4m+1)^2}}
\]

\[
\times \text{sech}\left( \frac{m^2 \chi_0}{2a^2\beta_5(4m+1)^2(5m+1)^2} x \right) \right\}^{1/2}
\]

\[
\times e^{i\left( \frac{\chi_0}{2a^2\beta_5(4m+1)^2(5m+1)^2} x \right)^{1/2} + \theta_0},
\]

and

\[
q(x, t) = \left\{ \frac{8b_5m^2 - a(b_3 + b_4)}{4ab_5(4m+1)(5m+1)} \right\} \frac{\chi_0}{\sqrt{8a^2\beta_5^2(5m+1)^2(4m+1)^2}}
\]

\[
\times \text{csch}\left( \frac{m^2 \chi_0}{2a^2\beta_5(4m+1)(5m+1)^2(4m+1)^2} x \right) \right\}^{1/2}
\]

\[
\times e^{i\left( \frac{\chi_0}{2a^2\beta_5(4m+1)(5m+1)^2(4m+1)^2} x \right)^{1/2} + \theta_0}.
\]

Figure 2 depicts the plot of a stationary bright soliton (30). The parameter values chosen are \(b_3 = 1, b_4 = 1, b_5 = 1, a = 1\) and \(m = \frac{1}{2}, \frac{1}{3}, \frac{1}{5}, \frac{1}{10}, \frac{1}{10}\), respectively.
4. Conclusions

The present paper secures stationary optical solitons with the NLSE having nonlinear CD and a nonlocal form of a nonlinear medium as well as Kudryashov’s quintuple form of the power law of nonlinearity. The results are recovered by the implementation of the enhanced Kudryashov’s algorithm. Thus, an abundance of optical solitons has emerged. The takeaway from this paper is that optoelectronics engineers must exercise extreme caution before laying fiber optic cables underground or under the sea. They must make absolutely sure that the chromatic dispersion stays linear throughout the transmission of solitons for intercontinental distances. The solitons would otherwise become stalled as the analysis indicated.

The results of the paper are thus novel and therefore indicate profound promise to venture further along in this direction. The nonlinear CD will be later replaced by the nonlinear cubic–quartic (CQ) dispersive terms that will lead to additional results which will be later disseminated. Furthermore, additional forms of SPM will be taken up with nonlinear CD and nonlinear CQ dispersive effects. The findings of these studies will be later made visible. The proposed results should be along the lines of the recently reported results [16–25].

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