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RESEARCH ARTICLE

Bright and Dark Soliton Pulse in Solid Core Photonic Crystal Fibers

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Abstract: The nonlinear Schrodinger (NLS) equation was utilized to conduct an analytical study on the soliton control in homogeneous photonic crystal fibers (PCFs) within both the normal and anomalous dispersion regimes. The split step Fourier method and MATLAB computation were used to generate the analytical soliton solutions for the NLS problem. The bright and dark soliton can be controlled by the group-velocity distribution (GVD). It is capable of demonstrating the fabrication of a fully coherent PCF. Moreover, dark soliton pulses have been seen in PCF in the typical dispersion domain. Here, we present the bound states of bright–dark soliton pairs that are mutually confined in a PCF. Solitons are produced when two modes with opposing dispersions are replanted. One laser operating in the anomalous dispersion domain produces the bright soliton, while the second laser running in the normal dispersion phase produces the dark soliton by normal dispersion cross-phase modulation with the light soliton. The results unequivocally point to a novel method of generating dark soliton pulses. Capturing both bright and dark solitons can produce light states that, interestingly, have a consistent power output and spectrally resemble a frequency comb. These results may have use in soliton states in atomic physics, ultrafast optics, frequency comb technologies, and telecommunications systems. A radically new approach to the stabilization of powerful wave packages in the negative and positive GVD regions of interacting waves is illustrated.

Keywords: photonic crystal fibers, nonlinear Schrodinger equation, group-velocity dispersion, bright soliton, dark soliton

1. Introduction

Both temporal and spatial solitons, as well as brilliant and dark solitons, have been the subject of in-depth theoretical and empirical research in recent years (Abdou et al., 2020; Altaie, 2022; Biswas, 2020; Ekici et al., 2016; González-Gaxiola et al., 2020; Green & Biswas, 2010; Gao et al., 2020; Moubissi et al., 2019; Wazwaz, 2021; Wimmer et al., 2015; Yang et al., 2011; Zhou et al., 2015). A nonlinear change in a structure's index of refraction brought on by the intensity of light dispersion gives rise to soliton, which are restricted self-guided beams throughout space or constrained pulses in time (Nie, 1993). When the combinations of refract nonlinear dynamics and pulse dispersion (for temporal solitons) or beam diffraction (for spatial solitons) perfectly balance each other, the pulse or beam keeps spreading without changing shape (Chen et al., 2012). The nonlinear processes in photonic crystal fibers (PCFs) that generate soliton production are typically weak and Kerr effect, resulting in a local index change that is exactly proportional to the amplitude (Kartashov et al., 2011). The primary nonlinear equation controlling the pulse progression in this instance is the widely recognized nonlinear Schroeder (NLS) equation for the challenging and intricate electric field magnitude packet (Wattis & James, 2014). This equation features two different types of localized options: bright and dark solitons, which vary based on the group-velocity dispersion's (GVD) magnitude (Talla Mbé et al., 2017). Haelterman & Sheppard's illustration (1994) shows that these two wave shapes seem to be a component of a wider family of localized solutions. These two single wave forms are actually rather diverse; they have wholly different natures and are the result of extremely differing physics (Fenton & Rienecker, 1982), as shown in Figure 1. Despite appearing to belong to the same wide family of localized solutions, prior research has indicated that the GVD of temporal solitons in PCFs vanishes at a wavelength and is positive at longer wavelengths and negative at shorter wavelengths (Zhao & Sun, 2020). The two different signs of GVD (Longhi, 2003) enable two different types of solitons, brilliant in the second instance and dark in the first because silica optical fibers always have a positive Kerr coefficient. Similar conditions apply to self-guided beams or spatial optical solitons found in bulk media or planar waveguides (Kivshar & Luther-Davies, 1998). Here, diffraction serves a purpose akin to dispersion in the temporal domain, but the nonlinearity may be positive or negative contingent upon the self-focusing or self-defocusing nature of the medium (Kivshar & Pelinovsky, 2000). As a result, there are two distinct kinds of solitons – bright and dark. When there is typical GVD in PCFs (or self-defocusing nonlinearity in waveguides), bright solitons do not emerge; instead, the first pulses (or spatially limited beams) experience enhanced dispersion, which causes broadening and chirping (Pedri & Santos, 2005). In this case, a constant amplitude wave is modulationally stable, and localized pulses might only show up as dark solitons or "holes" on a continuous wave (CW) background (Hoyos et al., 2015). My research paper is organized as follows:

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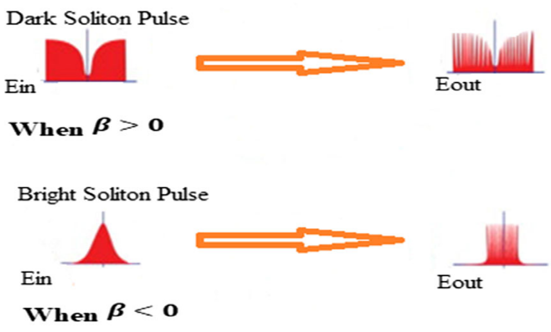
Figure 1
A strategy for forming dark–bright soliton pairs



1. An explanation of the basic equations governing the physics of dark and brilliant solitons in PCFs is given in one. This includes self-guided optical beams that need the use of generalized phenomenological models for non-Kerr nonlinearity and nonlinear pulse propagation in PCFs, where weak nonlinearity may be described using the Kerr effect.
2. A distinct set of mathematical tools for studying these two types of solitons, as well as a special role for the integrals of motion, are produced by analyzing the results of modulational instability of CWs, which allows one to comprehend the physical origins of dark and bright solitons and investigate their differences.
3. In more realistic physical models specified by the NLS equation, solitary waves will be examined and provide an overview of the perturbation theory's findings for dark and bright solitons.
4. The usual conditions of the instability-induced dynamics of dark and bright solitons are also explored. One specifically looks at a number of significant effects for optical applications.
5. A quick explanation of the role of a finite-width background in dark and dazzling solitons, as well as the impact of dispersion on these types of solitons inWQ232/wfo. Regarding systems that depict the parametric and incoherent interplay of optical polarization modes or harmonics, many significant multi-component generalizations of dark and bright solitons are described.

An overview of theoretical research for both bright and dark solitons on PCFs in dark spatial solitons. Two things are proposed: theoretical evidence of optical vortex solitons and higher-dimensional expansions of the dark soliton idea. In conclusion, the research provides references to a number of outstanding topics.

Figure 1 illustrates a broad method that may be used to display the bright and dark solitons.

2. Materials and Methods

Abnormal waves, such as soliton and rogue waves, have garnered significant attention in several branches of physics in recent times. Research on fiber lasers and fiber transmission in various systems is still ongoing (Song et al., 2020). A key component of fiber optic laser technology is the soliton. Soliton-connected configurations, often referred to as soliton molecules, are those in which direct soliton interaction forms a strong bond between two or more basic solitons in the temporal or spatial domain. In the complex Ginzburg–Landau equation system, Akhmediev et al. (2001) studied the formation of solitons localized states. The solitons in the system have prescribed separations and continuous phase differences. Research has demonstrated that the dissipative feature gives the solitons novel and distinctive communication highlights, which can organize stable-constrained conditions of dissipative solitons (Wang et al., 2020; Wang et al., 2021). Its nonlinear optical characteristic has not yet been investigated, nor has the related photonics device. Another method for creating soliton is to use bismuthene nanosheets and phosphorus, which are produced by sonochemical exfoliation and deposited onto the taper region of a microfiber by optical deposit. The broad range, high liveliness, and customizable dissipative solitons of frequency division multiplexing applications make it appealing. Using synthetic polymethyl methacrylate PMMA-TIPMMA as a saturable barrier that would withstand long-distance mechanical loadings into the fiber laser hole, a steady dissipative soliton mode-locking with a 3-dB frightening transmission capacity up to 51.62 nm and controllable wavelength range of 22 nm was produced (Wang et al., 2015). We shall examine here some of the most important solitons, including generic nonlinear equations.

1. Sine-Gordon formula

Frenkel and Kontorova introduced a solid-state physics analysis kind of issue in 1939 to preserve the relationship between crystal disorder and plastic deformation. Deformation motion in substances may be expressed as:

$$\frac{\partial^2 E}{\partial t^2} + \frac{\partial^2 E}{\partial x^2} + sinE = 0 \tag{1}$$

where $E(x, t)$ is a progressively moving envelop and x and t are space and time coordinates, respectively.

2. Lattice equation of Toda

Morikazu Toda, who discovered the lattice in 1967, is named for him. It begins for a one array of homogeneous mass merged with exponentially nonlinear forces, as described in

$$\frac{\partial^2 E_n}{\partial t^2} = \exp[-(E_n - E_{n-1})] - \exp[-(E_{n+1} - E_n)] \tag{2}$$

The lengthwise movement of the n atom from its equilibrium position is given by $E_n(t)$.

3. The equations of Korteweg and De Vries

Korteweg and De Vries theoretically investigated the wave train detected by Scott Russell, afterwards known as KVD, for the first time in 1985. The KVD equation is a simple type nonlinear equation (Tariq & Seadawy, 2017).

$$\frac{\partial E}{\partial t} + \frac{\partial^3 E}{\partial t^3} + 6E\frac{\partial E}{\partial x} = 0 \tag{3}$$

where $E(x, t)$ is a progressively moving envelop and x and t are space and time coordinates, respectively.

4. NLS equation

The NLS equations explain the high-speed light transmission in optical fibers.

$$i\frac{\partial E}{\partial t} \pm \frac{\partial^2 E}{\partial x^2} + 2\,|E|^2 E = 0 \tag{4}$$

where $E(x,t)$ is a progressively moving envelop and x and t are space and time coordinates, respectively. The + and − signs denote anomalous and normal dispersion, respectively, whereas the second and third terms denote the system's GVD and self-phase modulation (SPM) (Bagri & Kumar, 2020).

The NLS equation, which is derived from Maxwell's equations (Bowen et al., 2018), is the basic equation guiding the deployment of fiber optic pulses in our current investigation. The general equation of soliton is obtained by combining the Maxwell equation with the response of linear and nonlinear semiconducting. Picosecond pulse transmission in optical fiber is better described using NSE (Gredeskul & Kivshar, 1989).

2.1. General solve of NLS equations

Nonlinear Schrödinger equation in the normalized form is (Jasim et al., 2019; Yan et al., 2015; Yang et al., 2022; Zhang et al., 2022):

$$iE_z + DE_\alpha + \beta|E|^2E = 0 \tag{5}$$

where E is a complicated function that characterizes the normalization of electric field, z is the transmission distance, t is the delay of time, and E is the component of temporally dispersion with $D = +1$ for the anomalous dispersion portion ($GVD < 0$) and $D = -1$ for the normal dispersion region ($GVD > 0$). The magnitude of β is the self-phase modulation coefficient (Yan et al., 2015).

The Kerr effect describes how the refractive index of n_o evolves over time.

$(n_\circ + n_2|E|^2)$ as a result of which the change is achieved as $(n_2|E|^2)$ (Hasegawa, 2000; Raza & Zubair, 2018). Factors that impact the wave change include:

$$n_2|E|^2\frac{\omega}{c} = \frac{2\pi n_2}{\lambda|E|^2} \tag{6}$$

When the refractive index n is divided by ω, the wave modulation frequency deviates somewhat from the center frequency due to the rise in wave numbers, ($K = {}^{n\omega}/_{c}$) (Hoyos et al., 2015; Moubissi et al., 2019). Thus, the wave vector equation is as follows:

$$K - K_\circ = K^`(\omega - \omega_\circ) + \frac{K^{``}}{2}(\omega - \omega_\circ) \tag{7}$$

Depending on the Kerr effect [4], Equation (7) is as follows:

$$K - K_\circ = K^`(\omega - \omega_\circ) + \frac{K^{``}}{2}\,g\,E^2 \tag{8}$$

Then, by modifying the value of $(\omega - \omega_\circ)$ and $(K - K_\circ)$ by $\Delta\omega$ and Δk with $\Delta\omega \approx \frac{i\partial}{\partial t}$, $\Delta k \approx \frac{i\partial}{\partial z}$ (Amiri et al., 2011; Yang et al., 2022), the formula becomes:

$$\left(i\frac{\partial}{\partial z} + K^`\frac{\partial}{\partial t}\right) - \frac{K^{``}}{2}\frac{\partial^2}{\partial t^2} + g|E|^2 = 0 \tag{9}$$

Equation (9) is solved using the electric field E (z, t) (Jasim et al., 2019; Yang et al., 2022).

$$i\frac{\partial E}{\partial \xi} + \frac{K^{``}}{2}\frac{\partial^2 E}{\partial \tau^2}\,g\,\frac{|E|^2E}{\varepsilon^2} = 0 \tag{10}$$

Equation (10) becomes a generalized nonlinear Schrödinger equation (Hasegawa, 2000; Yan et al., 2015; Yang et al., 2022) by substituting z and g with λ:

$$i\frac{\partial E_\omega}{\partial z} + \frac{1}{2}\,\sigma\mu\frac{\partial^2 E_\omega}{\partial \tau^2} + \lambda|E_\omega|^2E_\omega \tag{11}$$

If $\lambda > 0$, the solution for soliton is known as bright soliton, and if $\lambda < 0$, the solution is known as dark soliton (Chen et al., 2012; Wattis & James, 2014).

2.2. Bright soliton

A bright soliton forms when there is a negative GVD [29]. This shows the transmission of a rising pulse in femtoseconds (Raza & Zubair, 2018; Wang et al., 2020; Wang et al., 2021; Zhang et al., 2022).

$$iE_z + E_\mu + \beta|E|^2 + i\gamma E_{\mu z} = i[\alpha_1(|E|^2)_t E + \alpha_2(|E|^2E)_t] \tag{12}$$

where t is the significant delay, E is the membrane electric field, and z is the transmission distance. The coefficients of stimulated Raman scattering, self-steepening, SPM, and third-order dispersion (TOD) $(\gamma, \beta, \alpha_1, \alpha_2)$ (Chen et al., 2012; Pedri & Santos, 2005). Because the value of $\gamma\ \alpha\ k_{\omega\omega\omega}$ in TOD is considered to be very small, thus it can be ignored. By calculating the value of $\alpha_1 = 5\delta, \alpha_2 = -4\delta$, then (Hasegawa, 2000; Wang et al., 2020; Wang et al., 2021; Yang et al., 2022):

$$E = A\mathrm{sech}\left[A\sqrt{\frac{\beta - 2\delta V}{2}}\,(t - 2V_t)\right]\exp\left[iV_t - i\left(V^2\,\frac{A^2(\beta - 2\delta V)}{2}\right)z\right] \tag{13}$$

According to the above, the bright soliton appears in Figures 2 and 3.

Figure 2
Bright soliton in two dimensions

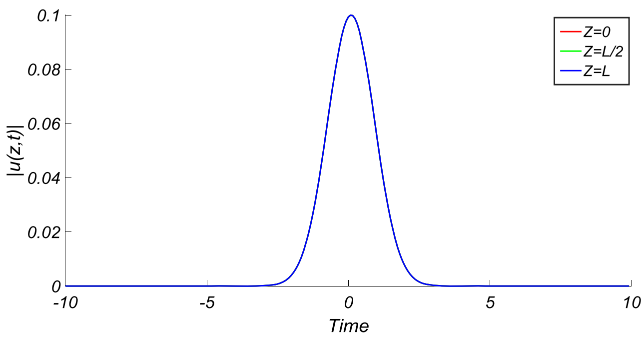


Figure 3
Bright soliton in three dimensions

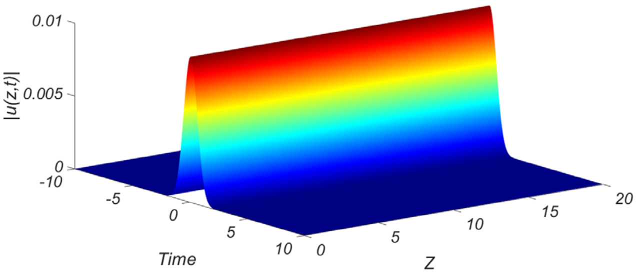
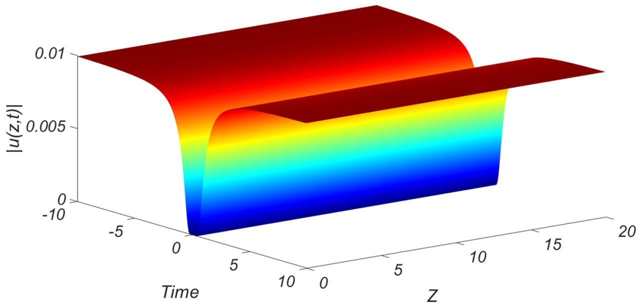


Figure 5
Dark soliton in three dimensions



2.3. Dark soliton

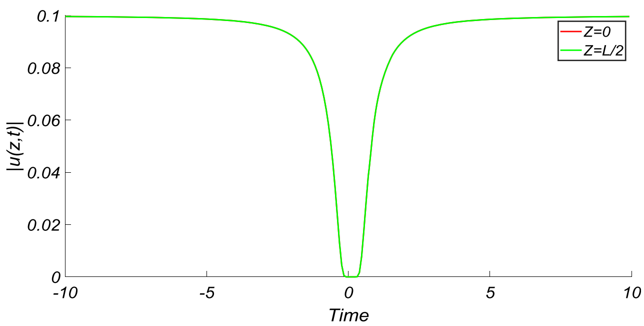
To solve NSE, one can employ the inverse dispersion in the normal dispersion (Song et al., 2020). Dark soliton is the term used to describe the hole soliton solution in the positive dispersion location ($\lambda < 0$). This position prevents the dark soliton pulse from spreading because the resolution is equal to the gaps in the continuous light carrier wave. Dark soliton will propagate more slowly and restrict more quickly than other solid-state particles (Parra-Rivas et al., 2017; Scott et al., 1973). The dark soliton solution is

$$\mathrm{E}(0,\mathrm{t}) = A\left[1-{}^{2}sech^{2}\left(Am\sqrt{\frac{2\delta V-\beta}{2}}\,(t-2V_z)\right)\right]^{1/2}\exp(i,\varphi) \tag{14}$$

$$\begin{aligned}\varphi = {} & tan^{-1}\left[\frac{m}{\sqrt{1-m^2}}\tan h\left(Am\sqrt{\frac{2\delta V-\beta}{2}}\,(t-2V_z)\right]\right. \\ & + A\sqrt{\frac{(1-m^2)(2\delta V-\beta)}{2}}\,(t-2V_z)+V(t-V_z) \\ & + \left[A^2\left(\frac{2\delta V-\beta}{2}\right)(m^2-3)-2\delta A^3\sqrt{\frac{(1-m^3)(2\delta V-\beta)}{2}}\right]z\end{aligned} \tag{15}$$

see Figures 4 and 5. Using the previously mentioned dark soliton formulation, the pulse profile may be communicated in the normal dispersion region.

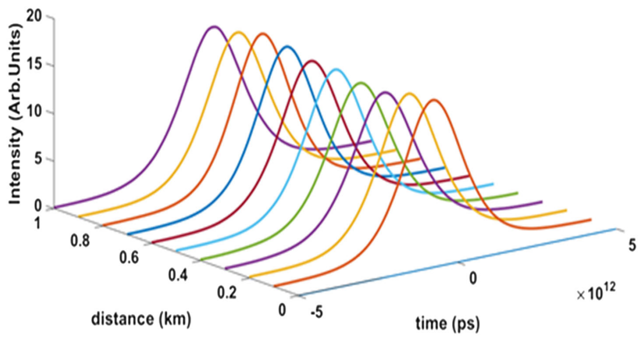
Figure 4
Dark soliton in two dimensions



2.4. Visualization and analysis

The computations were carried out by using MATLAB software. Assuming the initial circumstances provided, the pulse was in the a Gaussian in the form $E(0,t)| = Aexp^{-t^2}$. The photon propagation curve of Gaussian pulses is shown in Figure 6 to be center-focused and constant.

Figure 6
Illustrates Gaussian pulse propagation in photonic crystal fiber



An optical soliton is a pulse that propagates without distortion from dispersion or other sources. SPM, which happens when the wave's electric field alters the refractive index as seen by the Kerr effect, reduces them to a nonlinear process. SPM produces a crimson shift near the pulse's abrupt termination. When the blue shift at the sharp end of a pulse cancels, this shifts at an anomalous dispersion region, a pulse that maintains its frequency and duration forms.

3. Results and Discussion

Novel wave forms of solitons were graphically represented by assigning suitable values to the properties that allow us to comprehend the physical processes of these models. Data from the literature were utilized to evaluate the generated solutions. This approach may be used successfully to other equations in theoretical physics.

3.1. Effect dispersion on bright solitons

The value of β, which defines the dispersion effect, affects the pulse width in bright soliton and is steady and concentrated toward the middle. Figure 7 demonstrates how the value of the β parameter affects the width and amplitude of bright soliton pulses in two dimensions, while Figure 8 demonstrates how the value of parameter β influences the amplitude and width of a bright soliton pulse in three dimensions. The simulation is run with $A = 1$, $\delta = 0.1$, and $z = 0.02$ km, and by employing the value of $\beta = (-0.0005, -0.05)$ (ps^2)/km.

According to formula (13), the NLS solitons propagate in the medium at $\beta = (-0.0005, -0.05)$ (ps^2)/km at the duration of a weak (linear) pulse as shown in part a of Figures 7 and 8 in two and three dimensions. However, because of the initial phase modulation, their mobility might diverge from the linear pulse duration, and $\beta = -0.05$ (ps^2)/km. Similar to multisoliton pulses transform into several different solitons when a threshold of the original pulse's phase modulation depth is crossed, as portion b of Figures 7 and 8 illustrates. When a pulse's dispersion effect increases, the soliton's spatial development structure becomes more complicated. However, at a specific route length, the solitons combine into a single peak whose breadth is t times smaller than the original signal. The duration of an optical picosecond pulse was shortened to femtoseconds by using this information. The splitting of a luminous star is shown in Figures 7 and 8.

3.2. Effect dispersion on dark solitons

Equation (14) now reveals the existence of a different kind of soliton called the dark soliton. Figure 9 depicts the behavior of the dark soliton in two and three dimensions when the dispersion value $\beta = 0.0005)$ $(ps^2)/km$. As Figure 9 illustrates, the dark soliton profiles are inverse. It may be understood that the bifurcation scenario is essentially flipped in the case of anomalous dispersion that produces dazzling soliton. As the dispersion parameter is increased, the localized states show oscillatory instability; a period-doubling cascade toward chaos is initiated by a period-doubling bifurcation. This finding has been applied to pinpoint the places in parameter space where different dynamical and stable states interact. That there is a notable rise in the value of β for the solitons that organize the spatial dynamics. A typical dispersion regime is shown in Figure 10, when $\beta = 0.05$ $(ps^2)/km$.

Actually, because the discontinuous spectrum points' degeneracy is eliminated by even a slight alteration in the initial condition, Figure 6's conclusions are hard to understand. As a result, only a few unique circumstances allow the conversion of the initial optical pulse into a multipole soliton. Dispersion solitons' many aspects are covered in a number of studies and reviews, such as Maimistov (2010), Hasegawa (2002), Liu et al. (2020), and notable books (Boiti et al., 1988; Kang & Schneider, 2020; Kodama & Hasegawa, 1987; MacPherson et al., 1987; Rubino et al., 2012) whose authors made important contributions to the advancement of the soliton theory. The factor has a major effect on the propagation of a femtosecond pulse. It was determined that the stability (type of splitting) of the interwave high-energy bound state of the brilliant and dark solitons in the

Figure 7
Demonstrates bright soliton in two dimensions, when (a) $\beta = -0.0005)$ $(ps^2)/km$, (b) $\beta = -0.05$ $(ps^2)/km$

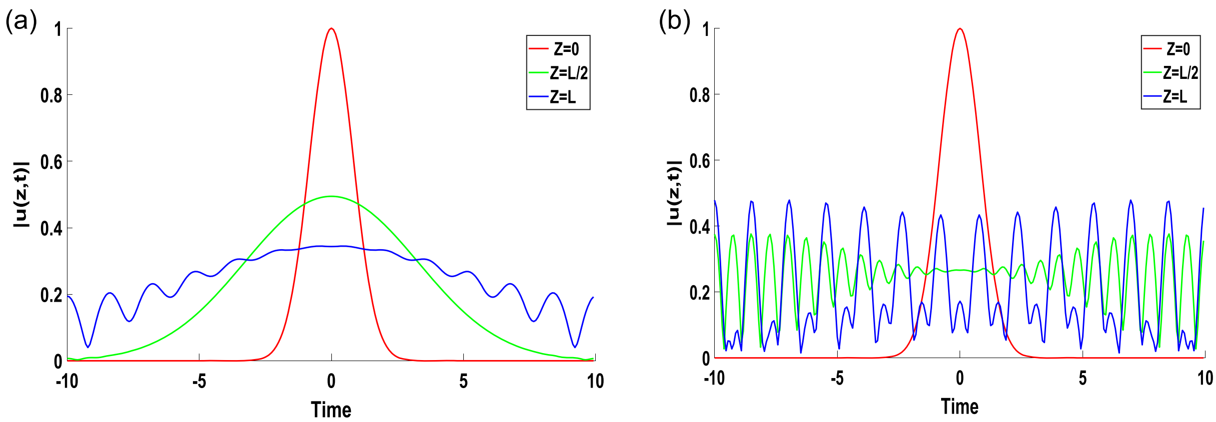
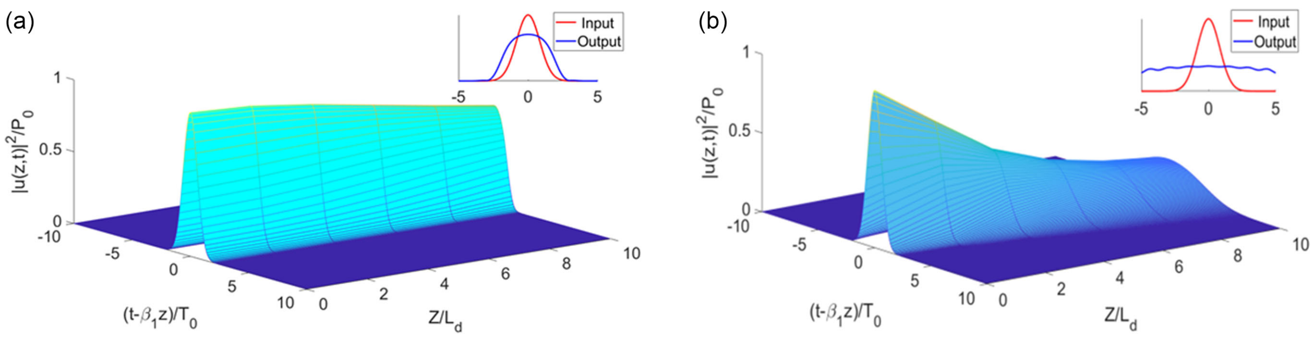


Figure 8
Demonstrates bright soliton in three dimensions, when (a) $\beta = 0.0005$ ps^2/km, (b) $\beta = 0.05$ ps^2/km



presence of such disruptive factors as dispersion of the third order was significant. The conveying pulse of the dark soliton in the imagined instance can break into a sequence of isolated pulses since it lies in the modulational instability area. As a result of the theoretical research, it was discovered that the modulation instability effect can be used to excite both bright and dark solitons in an efficient manner by increasing dispersive, and that the physical manifestation of modulation instability is the creation of new spectral harmonics as a result of dispersion processes (Figures 9 and 10). In this pulse waveform and chirping characteristic, the phase of a dazzling and dark soliton shifts from high to low amplitude point.

3.3. Collision bright and dark soliton

The collision of two identically wavelength solitons (λ = 1.55 nm) traveling in a single direction through a PCF with a variable GVD β = (0.0005 and 0.05) $(\mathrm{ps}^2)/\mathrm{km}$ has been studied in model frames. By closely investigating the collision dynamics of these connected bright and dark solitons, it is demonstrated that significant effects such as commencement of intensity redistribution, signal phase shift, and changes in relative separation distance occur in the bright solitons during collision. In contrast, dark solitons experience elastic collisions but share the same signal phase shift as light solitons. Thus, the collision system consists of a shape-changing collision of light solitons and an elasticity collision of dark solitons with signal phase shift, which influence each other in a complicated way. Figures 11 and 12 confirm this.

Simulations have demonstrated how different group-velocity values and the beginning interval between pulses can cause collisions. Soliton pulses pass each other, changing shape or speed, as GVD increases. The proportion of energy at the reflected pulse rises as the relative velocity of collision solitons decreases. One example is seen in Figures 11 and 12, where nearly all of the energy is contained in the reflected pulse. Temporal misalignment does not exist at the locations of dazzling and dark solitons. Thus, stable bound states of light and dark solitons might be expected.

Figure 9
Demonstrates dark soliton in (a) Two dimensions, (b) three dimensions, when $\beta = 0.0005\ \mathrm{ps}^2/\mathrm{km}$

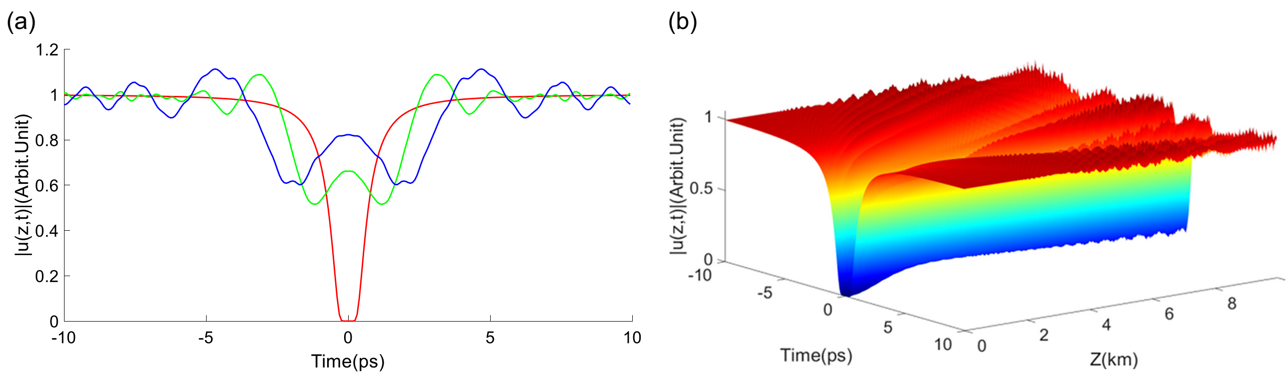


Figure 10
Illustrates dark soliton in (a) two dimensions and (b) three dimensions, when $\beta = 0.05)\ (\mathrm{ps}^2)/\mathrm{km}$

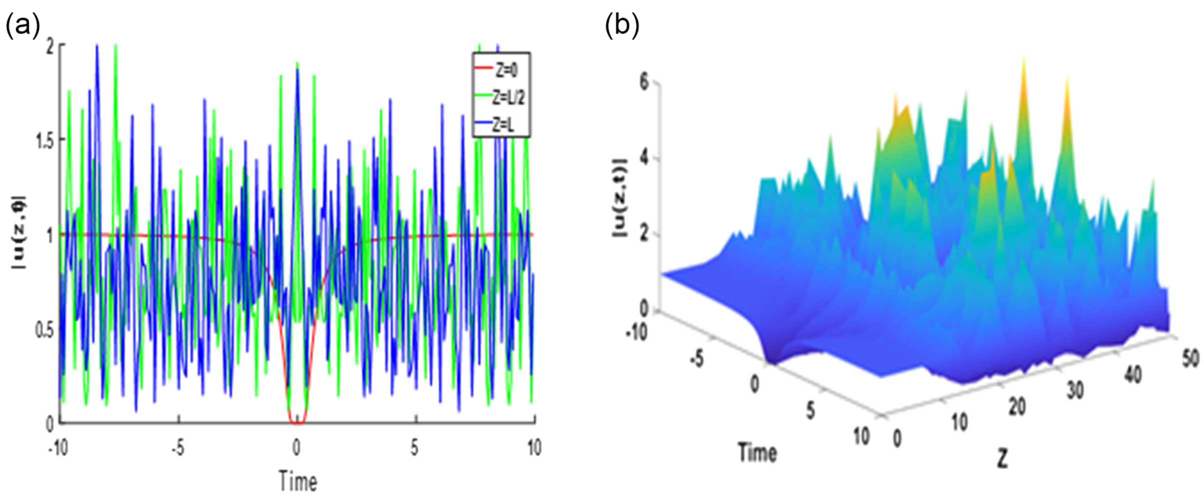


Figure 11
Intensity profiles of bright and dark solitons, when $\beta = \mp 0.0005)$ $(ps^2)/km$

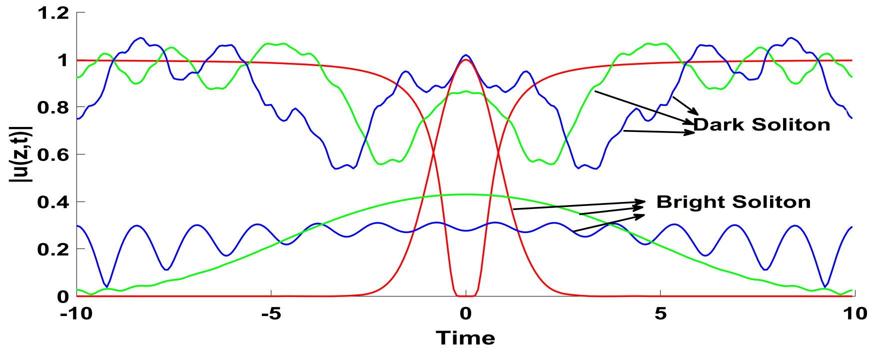
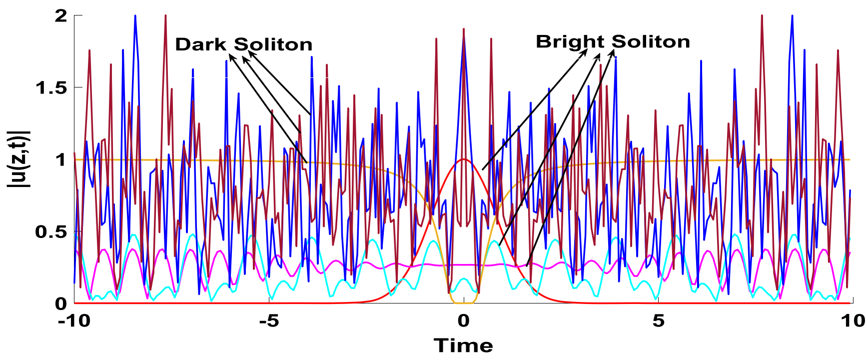


Figure 12
Bright and dark soliton collision intensity profiles, when $\beta = \mp 0.05)$ $(ps^2)/km$



4. Conclusions

When a PCF's dispersion and nonlinear effects are balanced, a soliton is created. When there is steady wave propagation in a soliton that can convey huge amounts of data quickly, it is appropriate for use in optical communication. Gaussian pulses with transmission directed at the center are how soliton pulses propagate. The pulse type of bright soliton is influenced by the parameter β, suggesting that the group velocity effects the soliton pulse width. In contrast to dazzling soliton, dark soliton exhibits a hole-shaped pulse and a shorter pulse width, suggesting that it is less appropriate for optical transmission. The technology of signal generators might benefit from this research. It was shown to analyze and validate the results that the soliton control method affects mutual collision and that the brilliant and dark solitons in multisoliton communications networks may also be managed. Our results suggest that creating a novel soliton control mechanism may be possible.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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