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A Review of Dark and Bright Solitons

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Abstract: ***In the realm of optics, the terms "bright" and "dark" are used to characterize the black shadows and luminous spots that develop in optical fibers. Nonetheless, soliton observations in water were made in the 1830s. When dazzling solitons were found on the surface of deep ocean waters in the 1960s and 1970s, oceanographers were first shocked by the finding. But since then, a lot of studies have been carried out to look into and confirm the phenomenon; some of these have shown that bright solitons are the reason of rogue waves at sea. It has now become possible to witness both dark and light solitons in a variety of settings, including plasmas, fiber optics, and Bose-Einstein condensates. [30]***
Keywords: Dark Soliton, Bright Soliton, Nonlinear Optics, Self Reinforcing, Nonlinear Schrodinger Equation, Dispersion, Self Phase Modulation.

I. INTRODUCTION

A generally agreed definition of soliton is difficult to come up with. Solitons are provided with three features by Drazin & Johnson (1989, p. 15). [1]. They are confined to a certain area, possess a permanent shape, and have the ability to communicate with other solitons. They also avoid phase transitions, but they are unaffected by collisions otherwise.Although there are more formal formulations available, they involve a lot of arithmetic. In addition, some scientists label events that don't meet these three requirements as soliton phenomena (for example, even though "light bullets" in nonlinear optics lose energy during interaction, they are sometimes referred to as solitons).[2]The combination of dispersion and nonlinearity can result in either permanent or localized wave patterns. Imagine a dazzling pulse traveling through glass. This pulse could consist of a combination of multiple distinct light frequencies. The dispersion of glass causes these distinct frequencies to travel through it at different speeds, which over time modifies the pulse's structure. Additionally, there is the nonlinear Kerr effect, which states that a material's refractive index at a given frequency is determined by the brightness or amplitude of the light. A correctly generated pulse keeps its shape over time because the Kerr effect precisely cancels out the dispersion effect. As such, the pulse is a soliton [3]. Numerous fully solvable models are solved by solitons, such as the sine-Gordon equation, the Korteweg–de Vries equation, the coupled nonlinear Schrödinger equation, and various nonlinear Schrödinger equations. The integrability of the field equations, which is typically accomplished using the inverse scattering transform, is what makes the soliton solutions stable. The mathematical theory of these equations is one dynamic and broad field of mathematics.[3] In certain "undular" tidal bore events that happen in a few rivers, such as the River Severn, a wavefront and a train of solitons travel simultaneously. More solitons are produced as internal waves, driven by the topography of the seafloor, move along the oceanic pseudocline. There are more atmospheric solitons. As an example, think of the morning glory cloud in the Gulf of Carpentaria. Massive linear roll clouds brought on by pressure solitons passing through a layer of temperature inversion are what produce it. The soliton model of neuroscience, which was proposed recently but is not widely accepted, uses pressure solitons to explain how signals are transmitted within neurons [3].Topological soliton, sometimes called topological defect, is any solution of a system of partial differential equations that is persistent against decay to the "trivial solution". Topological restrictions, not the integrability of the field equations, are the source of soliton stability. Constraints are almost always present because the differential equations must maintain the nontrivial homotopy group of the boundary and meet a set of boundary conditions. As a result, homotopy classes can be used to organize differential equation solutions [3]. More specifically, by reducing two primary types of pulse degradation, soliton transmission in optical fibers improves the quality of data transmission.One type of deterioration is the dispersion that happens when pulses travel over long fiber lengths.The other is the nonlinear effects brought about by signals interacting power-dependently with the fiber and with each other.However, for particular types and powers of optical pulses, the effects can cancel each other out, at least to first-order approximation. Generally speaking, the two effects compound each other to aggravate the condition. Solitons are the name given to these types of pulses.Solitons' built-in longevity is one of the main advantages for high-speed, long-distance gearboxes.Over extended fiber lengths, soliton can be rendered inherently stable in spite of soliton attenuation. This offers a way to lessen the signal quality loss brought on by dispersion and nonlinear effects, which is a serious problem at 10 Gbit/s and gets worse at higher transmission speeds. Due to these features, scientists are developing soliton systems for long-haul 10-Gbit/s and future 40-Gbit/s networks [4].

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II. LITERATURE REVIEW

The soliton phenomena was first documented by John Scott Russell (1808–1882), who saw a single wave on Scotland's Union Canal in 1834. When he managed to duplicate the occurrence in a wave tank, he dubbed the phenomena the "Wave of Translation".Solutions to the Korteweg–de Vries equation that propagate locally confined and strongly stable can characterize waves similar to the ones Russell saw. Names for these solutions were originally assigned by Zabusky and Kruskal as "soliton." The term was meant to highlight the solitary nature of the waves, with the suffix "on" recalling its original usage to designate particles such as hadrons, baryons, and electrons and indicating their observed particle-like activity.[3].

The earliest documented observation of a lone wave was made by a young engineer called John Scott Russell, who was hired for a summer project in 1834 to investigate methods to improve the designs for barges designed to travel canals—specifically, the Union Canal in Edinburgh, Scotland. One August day, the tow rope connecting the mules to the barge broke, bringing the vessel to a sudden halt. Nevertheless, the mass of water in front of the barge's blunt prow rolled forward quickly, creating a sizable, isolated elevation and a smooth, rounded mound of water that continued down the canal without changing in direction or velocity. Russell (1844). Russell followed up on this accidental discovery by riding up to and past the Wave of Translation. The Wave of Translation maintained its original dimensions of around thirty feet by one foot to one and a half, rolling at a speed of about eight or nine miles per hour. Then, he used a wave tank in closely watched laboratory experiments; he reported the findings in 1844 (Russell, 1844). He mentioned the following four examples: He observed hyperbolic secant structure in single waves. A sufficiently big initial volume of water can produce two or more waves that gradually separate and become nearly isolated. When separated, waves can pass one another "without change of any kind". In a shallow water channel of height h, a single wave with amplitude A travels at the speed of [g(A+h)]1/2, where g is the gravitational acceleration. Greater amplitude waves travel faster than lower amplitude waves in this nonlinear phenomenon.

It was Diederick Korteweg, a Dutch scientist, and his student Gustav de Vries (KdV) (de Vries, 1895) (Scott, 2005) who developed the nonlinear partial differential equation (PDE) that is now named for them. Korteweg and de Vries suggest that the KdV equation (1) could account for Russell's experiments. The rate of change of the wave's height over time is determined by the combination of the amplitude effect, a nonlinear component, and the dispersive term, which allows waves of different wavelengths to travel at different velocities, as shown in Equation (1). Together with a solitary-wave solution, Korteweg and de Vries also found a periodic solution that matched Russell's wave. These solutions resulted from a trade-off between dispersion and nonlinearity. Russell's results and the work of Norman Zabusky and Martin Kruskal, who published their numerical solutions to the KdV equation (and invented the name "soliton"), were ignored until 1965 by mathematicians, physicists, and engineers studying water waves (Zabusky, 1965). According to (1) (Fermi, 1955; Porter, 2009b; Weissert, 1997), Kruskal produced a continuous description of the oscillations of unidirectional waves propagating on the cubic, Fermi–Pasta–Ulam (FPU) nonlinear lattice. At the same time, Morikazu Toda created history when he became the first person to recognize a soliton in the discrete, integrable system that is today called the Toda lattice (Toda, 1967).[5] Gary Deem, Zabusky, and Kruskal (1965) made films of interacting solitary waves in an FPU lattice, the KdV equation, and a modified KdV equation; see the discussion in the review study (Zabusky, 1984). Using the KdV equation, we demonstrate the dynamics of solitons in the space-time diagram presented in Figure 1. When Robert Miura realized the significance of this discovery, he found a precise transition between this modified KdV equation and equation (1) (Miura, 1976). After Clifford Gardner, John Greene, Martin Kruskal, and Robert Miura solved the initial-value problem of the KdV equation in 1967 (Miura, 1968; Gardner, 1967; Gardner, 1974), there was a surge in interest in the mathematical study of solitons.

Consequently, a notion of integrability appropriate for continuum frameworks was developed. In 1972, Vladimir Zakharov and Alexei Borisovich Shabat extended the inverse scattering technique by proving the availability of soliton solutions and the integrability of the nonlinear Schrödinger (NLS) problem. The sine-Gordon equation was one of the several nonlinear PDEs for which Mark Ablowitz, David Kaup, Alan Newell, and Harvey Segur proved that they had soliton solutions in 1973. This equation's integrability was previously established by Albert Backlünd's 19th-century research on surfaces with continuous negative Gaussian curvature. Since then, other scholars have investigated similar soliton solutions and derived alternate integrable PDEs (in one and several spatial dimensions). The Kadomtsev-Petviashvili (KP) equation demonstrates the need for a more complex definition of a "soliton" over several spatial dimensions.Asymptotic analysis, variational approximations, and/or perturbative techniques are typically employed in analytical methods for investigating solitary waves in nonintegrable equations (Kivshar, 1989). (Scott, 2005) One well-known example of a nonintegrable system with exact solutions for isolated solitary waves in optics is the coupled mode equations of the fiber Bragg grating.

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The study of solitons and solitary waves is currently one of the most active areas in mathematics and physics (Scott, 2005).Numerous academic fields have been impacted, including pure mathematics and experimental science.This has led to important discoveries in many areas, such as supersymmetry, nonlinear dynamics, biology, optics, and integrable systems.

III. MATHEMATICAL EQUATIONS OF SOLITON

Nonlinear Schrodinger equation (NLS)[6],[7]:

$$i\frac{\partial A}{\partial z}-\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2}+\gamma\mid A\mid^2 A=0 \quad (8)$$

B_2 is the GVD of the optical fiber

ϒ is the nonlinear coefficient of the fiber,

$$\gamma=\frac{n_2\omega_0}{cA_{\text{eff}}}$$

The effects of dispersion & assuming Gaussian pulse shape, [6],[7]:

$$i\frac{\partial A}{\partial z}-\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2}=0$$

(without the nonlinear term) (8a)

$$\tau_{out}=\tau_{in}\,(1+(\beta_2.L/\tau^2)^2)^{1/2} \quad (9)$$

$$\tau_{out}=\tau_{in}\,(1+(L/L_D)^2)^{1/2} \quad (10)$$

Where , $L_D=\tau^2//\beta_2$ is the dispersion length.

The effects of nonlinearity, [6],[7]:

$$i\frac{\partial A}{\partial z}+\gamma\mid A\mid^2 A=0$$

(without the dispersion term) (8b)

The maximum nonlinear phase shift, [6],[7]:

$$\varphi_{max}=\gamma P_0 L=L/L_{NL}$$

And the nonlinear length, [6],[7]:

$$L_{NL}=(\gamma P_0)^{-1}$$

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For the Self-Phase Modulation, I(t) gives the intensity of an ultrashort pulse with a Gaussian form and constant phase at time t ,[6][7]:

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau^2}\right) \tag{11}$$

From the Optical Kerr Effect [6][7]:

$$n(I) = n_0 + n_2 \cdot I \tag{12}$$

This change in refractive index causes a displacement in the pulse's immediate phase [6][7]:

$$\phi(t) = \omega_0 t - kx = \omega_0 t - \frac{2\pi}{\lambda_0} \cdot n(I) L \tag{13}$$

The pulse shifts in frequency as a result of the phase shift. The frequency ω(t) at any given instant is provided by ,[6][7]:

$$\omega(t) = \frac{d\phi(t)}{dt} = \omega_0 - \frac{2\pi L}{\lambda_0} \frac{dn(I)}{dt} \tag{14}$$

$$\omega(t) = \omega_0 + \frac{4\pi L n_2 I_0}{\lambda_0 \tau^2} \cdot t \cdot \exp\left(\frac{-t^2}{\tau^2}\right) \tag{15}$$

A. The Bright Soliton

The localised intensity peak of a bright soliton is located above a continuous wave (CW) backdrop, whereas the localised intensity dip of a dark soliton is located below a CW background. A "vector dark bright soliton" is a polarisation condition in which one polarisation is bright and the other is dark.[33]

The following is the form of Eq. (16) bright solitary solutions[27][28]:

$$u_b(\zeta) = \frac{A_b}{\sqrt{1 + N_b \cosh(\alpha_b \zeta)}} \tag{16}$$

where A_b, N_b, and α_b are real constants which represent wave parameters (A_b and α_b related to the amplitude and pulse width of the bright wave profiles, respectively) to be determined by the physical coefficients of the model.

The following parameters: energy ξ, N_b, α_b, and a_b[27][28]:

$$A_b = \sqrt{\frac{2a_1}{a_3}}$$
$$\alpha_b = \sqrt[4]{a_1}$$
$$N_b = \sqrt{\frac{a_3^2 + 4a_1 a_5}{a_3^2}}$$
$$\xi = \frac{a_1 a_2}{2a_3} \tag{17}$$

under parametric circumstances [27][28]:,

$$a_2a_3 + 4a_1a_4 = 0, a_1 > 0, a_3 > 0, {a_3}^2 + 4a_1a_5 > 0 \quad (18)$$

B. The Dark Soliton

The formation of dark solitons[31] is typified by a localised decrease in intensity in contrast to a continuous wave background that is more intense. All normal dispersion fibre lasers mode-locked using the nonlinear polarisation rotation method can create scalar dark solitons (also known as linearly polarised dark solitons), which can be rather stable. Because of the two polarisation components' cross-interaction, vector dark solitons[32] are far less stable. Consequently, it is intriguing to look at the evolution of these two polarisation components polarisation states. Specific medium conditions have been considered in the investigation of both forms of solitons, In temporal solitons, $\beta 2 < 0$ or $D > 0$, anomalous dispersion, and this indicates that the self-phase modulation produces self-focusing in spatial solitons, $n 2 > 0$. [29]:

$$\frac{-1}{2}\frac{\partial^2 a}{\partial \tau^2} + i\frac{\partial a}{\partial \zeta} + N^2|a|^2 a = 0. \quad (19)$$

Solitons-like solutions exist for this problem. Regarding N = 1, the first order [29]:

$$a(\tau, \zeta) = \tanh(\tau)e^{i\zeta} \quad (20)$$

For higher order solitons (N>1) we can use the following closed form expression [29]:

$$a(\tau, \zeta = 0) = N\tanh(\tau) \quad (21)$$

The solutions for dark solitary adopt the following form[27][28]:

$$u_d(\zeta) = \frac{A_d \sinh(\alpha_d \zeta)}{\sqrt{1 + N_d \sinh^2(\alpha_d \zeta)}} \quad (22)$$

In this case, the real constant Nd is assumed to be positive. The dark wave profiles' amplitude and pulse width are correlated with the real parameters A_d and α_d, respectively[27][28].

The following parameters A_d, α_d, and energy ξ can be obtained [27][28] :

$$A_d = \sqrt{\frac{2a_1 N_d}{a_3}}$$
$$\alpha_d = \sqrt[2]{a_1}$$
$$\xi = \frac{a_1}{2a_3} \quad (23)$$

based on the parametric conditions [27][28]:

$$2(a_2a_3 + 2a_1a_4) - a_3 = 0, a_1 > 0, a_3 > 0, {a_3}^2 + 4a_1a_5 > 0. \quad (24)$$

The precise single-wave dark solutions [27][28]:

$$E_d(z,t) = \left\{ \frac{2a_1 N_d}{a_3} \frac{\sinh^2\left[\sqrt[2]{a_1}(t + \beta z)\right]}{1 + N_d \sinh^2\left[\sqrt[2]{a_1}(t + 2\alpha_1 \omega z)\right]} \right\}^{\frac{1}{4}} \times e^{i(kz - \omega t)} \quad (25)$$

IV. CONCLUSION

In a non-linear dispersive medium, soliton light pulses propagate across very long distances without broadening. That's why the communications industry is quite interested in them. In optical fibers, soliton operation is caused by two effects that can cancel each other out under certain conditions. Chromatic dispersion is a phenomenon that arises when pulses of different wavelengths scatter during their passage through an optical fiber. The alternative that operates over a larger range of pulse spectrum wavelengths is self-phase modulation, or SPM. Once the pulse achieves equilibrium in the fiber, dispersion and SPM balance each other out, allowing the pulse to keep its shape or dispersion. SPM may cause the pulse to either expand or compress more strongly. On the other hand, attenuation weakens the pulse and increases the difficulty of the pulse holding its shape along the fiber span. In order to maintain pulse forms and balance attenuation, optical amplifiers have been built. [24][25]. The non-linear wave equations that describe how waves propagate in certain physical systems can be solved to get soliton solutions. These waves appear as solutions in mathematical models of many different systems, such as optical waveguides, crystal lattice vibrations, and water waves. Dark solitons show local dips on a modulationally stable continuous-wave background. Compared to dazzling solitons, dark solitons in fiber lasers are more stable and less prone to loss in noisy situations.

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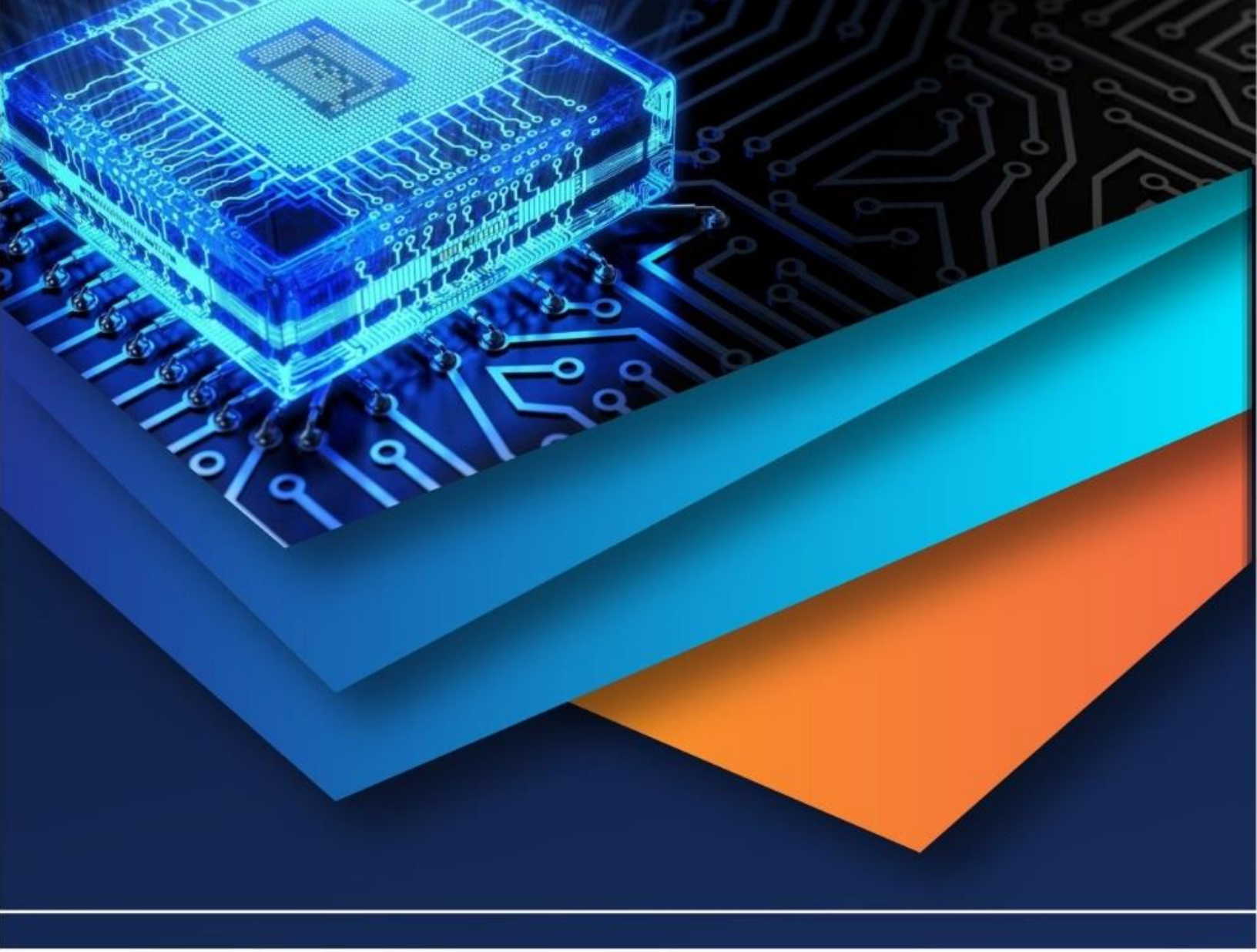

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