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The Study of Soliton Propagation in Optical Fibers

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Abstract: In optical fibres, soliton formation results from a balance between the chirps produced by GVD and SPM, which, when functioning separately, both restrict the system's performance. We will analyse the dispersion-induced pulse broadening and the nonlinear optical effects to understand how such a balance is feasible. During an optical pulse's propagation inside an optical fibre, the GVD broadens it, unless the pulse is first chirped correctly. More precisely, whenever β2 and the chirp parameter C have opposing signs, resulting in β2C being negative, a chirped pulse is compressed at early phases of transmission. SPM causes the optical pulse to chirp so that C > 0. The criterion β2C < 0 can be easily met if β2 < 0. Furthermore, since the SPM-induced chirp is power-dependent, it is conceivable that, under some circumstances, SPM and GVD might work together to the point where the SPM-induced chirp is just the proper amount to cancel out the GVD-induced pulse broadening. In this case, an optical pulse propagates as a soliton with no distortion.[27]

Keywords: Soliton, Optical Fiber, 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. Though they need a lot of mathematics, there are more formal formulations accessible. Moreover, certain scientific events that do not meet these three requirements are categorised as soliton phenomena (e.g., solitons are occasionally used to describe "light bullets" in nonlinear optics, even though they lose energy during interaction).[2] Depending on how dispersion and nonlinearity interact, wave patterns can be both confined and permanent. Imagine a dazzling pulse travelling through glass. This pulse could consist of multiple distinct light frequencies. Glass has a dispersion that causes these distinct frequencies to travel through it at different speeds, changing the pulse's structure over time. 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 properly generated pulse holds its shape over time because the dispersion effect is precisely cancelled by the Kerr effect. As such, the pulse is a soliton [3]. Several nonlinear Schrödinger equations, the coupled nonlinear Schrödinger equation, the sine-Gordon equation, the Korteweg–de Vries equation, and other models are all completely solvable by solitons. Because the field equations are integrable, which is typically accomplished via the inverse scattering transform, the soliton solutions are 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, go along the oceanic pycnocline. 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. In the recently proposed, but not widely accepted, neuroscience soliton model, pressure solitons are used to describe the signal conduction within neurons [3].A topological soliton, often called a 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 satisfy a set of boundary conditions. As a result, homotopy classes can be used to organise differential equation solutions [3].

More specifically, by reducing two primary types of pulse degradation, soliton transmission in optical fibres improves the quality of data transmission. One type of deterioration is the dispersion that happens when pulses travel over long fibre lengths. The other is the nonlinear effects that arise from signals interacting in a power-dependent way with the fibre and with each other. However, for some forms 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 fibre lengths, soliton can be made 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].

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 characterise waves similar to the ones Russell observed. 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 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 recognise a soliton in the discrete, integrable system that is today called the Toda lattice and 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 realised 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. 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 fibre Bragg grating.

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.

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III. MATHEMATICAL EQUATIONS OF SOLITON

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

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

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]:

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

(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]:

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

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]:

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

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]:

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

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

IV. PROPAGATION OF SOLITONS IN OPTICAL FIBERS

We pick s = -1 in the following equation, assuming that pulses are propagating in the region of anomalous GVD, in order to determine the conditions under which solitons can form[27]:

$$iL_D \frac{\partial U}{\partial z} - \frac{s}{2}\frac{\partial^2 U}{\partial \tau^2} + \frac{L_D}{L_{NL}} p(z)|U|^2 U = 0$$

The equation above assumes the form ξ = z/LD, where ξ is a normalised distance[27].

$$i\frac{\partial U}{\partial \xi} + \frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} + N^2 |U|^2 U = 0$$

wherein the definition of parameter N is[27]:

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

It is an arbitrary combination of the fiber's characteristics and the pulse. It is possible to eliminate the single parameter N entirely by adding u = NU as a renormalized amplitude. This modification gives the NLS equation its canonical form[27].

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0$$

This NLS equation is a member of a unique class of nonlinear partial differential equations that may be precisely solved using the inverse scattering method, a mathematical methodology. Using this approach, it was first resolved in 1971. The primary outcome can be summed up as follows. When an initial amplitude pulse in the input[27]:

$$u(0,\tau) = N\operatorname{sech}(\tau)$$

is launched into the fibre; for N = 1, its shape stays constant during propagation; however, for integer values of N > 1, it exhibits a periodic pattern that recovers the input shape at $\xi = m\pi/2$, where m is an integer[27]

Without using the inverse scattering method, the following equation can be solved directly to find the solution corresponding to the fundamental soliton[27].

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0$$

The method is presuming that a formative solution[27]:

$$u(\xi,\tau) = V(\tau)\exp[i\phi(\xi)]$$

The nonlinear differential equation is then found to be satisfied by the function V(τ)[27]:

$$\frac{d^2V}{d\tau^2} = 2V(K - V^2)$$

Thus the Sech Equation gives us[27]:

$$u(\xi,\tau) = \operatorname{sech}(\tau)\exp(i\xi/2)$$

for the fundamental soliton using direct integration of the NLS equation.

The fibre nonlinearity essentially compensates for the effects of fibre dispersion when the input pulse has a "sech" form and its peak power and width are related by[27]:

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

V. CONCLUSION

The ability of an optical fibre to drive any input pulse towards a soliton is astonishing. An easy way to conceptualise this behaviour is to consider optical solitons as the nonlinear waveguide's temporal modes. By raising the refractive index solely in the pulse's centre, higher intensities in the pulse's centre produce a temporal waveguide. Similar to how the core-cladding index difference causes optical fibres to have spatial modes, such a waveguide can support temporal modes. Most of the pulse energy can still be coupled to a temporal mode even when the input pulse is not exactly matching it, but it is close to it. Dispersive waves are how the remaining energy disperses. In order to reduce the impact of such dispersive waves on system performance, the input conditions should be as near to the ideal values as feasible. Particle-specific perturbation theory can be used to examine the soliton amplitude, width, frequency, speed, and phase evolution along the fibre when the solitons respond to perturbations adiabatically[27].

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