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Soliton and Its Underlying Principle

KEYWORDS: soliton, Self phase modulation, Group velocity dispersion

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ABSTRACT *In general a wave cannot travel very long distances and gets affected after collision with another wave with regard to its amplitude, velocity, etc.*

But a new kind of waves called as soliton waves could travel rapidly and unattenuated over very long distance even thousands of kilometers. In soliton kerr effect cancel the dispersion effect and thus pulse shape is maintained.

Soliton are narrow and high intensity pulses which can retain their shape by compensating the effects of SPM and GVD Mechanisms.

INTRODUCTION:
The soliton wave concept was suggested by John Scott-Russell [7] which can travel rapidly and unattenuated over very long distance even thousands of kilometers maintaining its shape and size. They interact with other soliton as normal waves but unlike normal waves after interaction emerge out by retaining their shape and amplitude with phase change (or) splits into two solitary waves with the same shape and velocity as before collision as shown in figure 1.

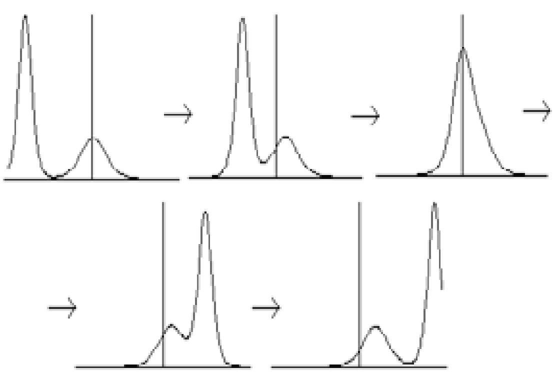

Fig: 1: Solitons before and after collision.
Sources: Wikipedia

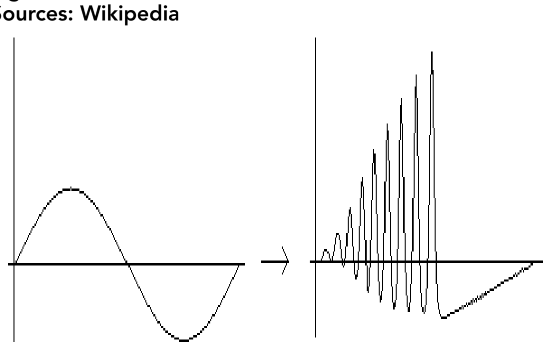

Fig: 2: Solitons break into a train of solitons.
Sources: Report on wave

1.1.2 Properties associated with soliton:
In general a wave cannot travel very long distances and gets affected after collision with another wave with regard to its amplitude, velocity, etc.

But a new kind of waves called as soliton waves could travel rapidly and unattenuated over very long distance even thousands of kilometer [1] and also a soliton of large height and greater velocity when merge with soliton with slower waves of less height, the large height soliton emerges out undistorted with their shape and identity uncharged but there would be change in phase only.

Following are the properties associated with solitons [4-6]
- They interact with other soliton as normal waves.
- After interaction emerge out by retaining their shape and amplitude but there is phase change
- They can travel long distances.
- They are permanent and localized waves.
- In soliton kerr effect cancel the dispersion effect and thus pulse shape is maintained.

1.1.3 Few more important properties of solitons are:
- Speed of wave is directly proportional to the size of the wave and width depends on the depth of water in water channel or water tank.
- Normal wave merge or combine but in case of soliton waves of two different size, small wave is overtaken by large wave and soon splits in to two separate wave again of small and big size waves.
- These waves can travel large distances and are stable retaining their shape and size.
- They do not steepen out or flatten out by decreasing their amplitude and maintain their shape of well defined water heap.
- If the water tank depth is (h) and η is the amplitude of the wav the expression for the velocity of soliton wave is given by $v=\sqrt{g(h+\varsigma)}$
- Small size wave travels with less velocity.

Results and Discussion:
1.2.1: Effect of Self Phase Modulation mechanism in soliton:

Self phase modulation (SPM) [8] solitons are narrow and high intensity pulses that maintains its shape by balancing the pulse compression occurring by SPM and pulse broadening occurring by GVD (group velocity dispersion).

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The root cause of SPM(self phase modulation)[2] is the change in frequency which is in turn changes by the phase difference introduced (or) developed by the refractive index of fiber which in turn depends on the intensity.

Different parts of travelling pulse have different intensity suffer different phase shift and this results in frequency change (or) also called as frequency chirping. The phase introduced by the fiber after travelling a fiber length L is given by equation

$$\ddot{O} = \frac{2\eth}{\ddot{e}}(n\acute{e} + n_{n\acute{e}} I)\, L_{eff} \quad (1.1)$$

The first term of above expression gives the linear portion of phase and second term gives the non linear phase constant [3, 12].

As phase is varying with time it leads to frequency variation also called as chirping frequency due to SPM.

As phase is varying it leads to change in frequency spectrum or broadening of a pulse due to self phase modulation [10, 11] as shown in figure below.

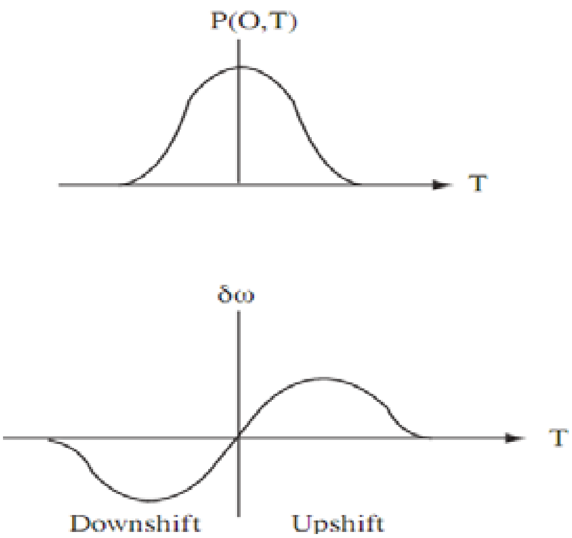

Figure 3: changes in frequency spectrum or broadening of a pulse due to self phase modulation.

1.2.2 Effect of GVD mechanism in soliton:
The effect of GVD is the overlapping of neighboring pulses which is caused by the group velocity of the signal. Due to overlapping error occurs at the receiver.

The group velocity is given by

$$u_g = c\left(\frac{d\beta}{dk}\right)^{-1}$$

And the delay difference over a length L is given by

$$\delta\tau = \frac{d\tau_g}{d\omega}\delta\omega = \frac{d}{d\omega}\left(\frac{L}{u_g}\right)\delta\omega = L\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega$$

Where $\hat{a}_2 = \frac{d^2\hat{a}}{d\dot{u}^2}$ is called the GVD parameter.

1.2.3 Wave equation (NLSE) of soliton:
A wave is represented by a wave equation mathematically. For example, matter wave is represented by Schrodinger wave equation which may be time dependent (or) time independent. Similarly, non linear Schrodinger equation (NLSE) is used to describe the propagation of solitons in optical fiber [9]

It is given by

$$i\left(\frac{\partial u}{\partial z}\right) - \frac{s}{2}\left(\frac{\partial^2 u}{\partial t^2}\right) + N^2|u|^2 u + i\left(\frac{\acute{a}}{2}\right)u = 0$$

The solution can be written as

$$u(z,t) = \sec h(t)\exp(\dot{z}\ /2) \quad (1.10)$$

Here sech (t) represents the hyperbolic secant function. This is a bell-shaped pulse used for soliton pulses. The first term of NLSE equation gives the GVD effects in which dispersion tends to broaden pulse. The second term gives nonlinear factor which shows the relationship between refractive index of the fiber and intensity of light [5, 6].

This leads to broadening of frequency spectrum of pulse through self phase modulation (SPM).

The third term gives the alternation or amplification in other words the loss or gain of energy respectively.

Also, from NLS equation, it is derived that the dispersive and nonlinear terms are complementary phase shifts and upon integration leads to phase shift but maintains its shape and size.

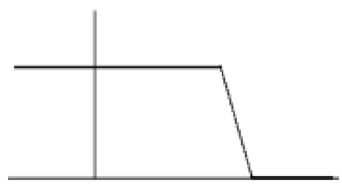

Figure 4: Nonlinear term (steepen).

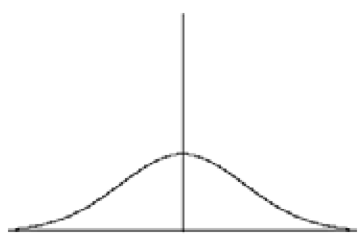

Figure 5: Dispersion term (flatten).

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CONCLUSIONS:
If a wave is in motion, the compression of pulses occurs by SPM (Self phase modulation) and broadening of pulse occurs by GVD (Group velocity dispersion).
If these two mechanisms compensate each other the pulse do not change shape (called fundamental solitons).
If Pulses undergo periodic change in shape then they are called higher order soliton.

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