International Journal on Emerging Technologies **2**(2): 141-145(2011) **ISSN No. (Print) : 0975-8364**
ISSN No. (Online) : 2249-3255

Solitons, its Evolution and Applications in High Speed Optical Communication

R. L. Sharma*and Dr. Ranjit Singh*

**Department of Electronics and Communication Engineering, Ajay Kumar Garg Engineering College, Ghaziabad (U.P.)*

ABSTRACT : In this paper, evolution of soliton pulses has been discussed. It is based on pulse spreading due to linear effects i.e. Group Velocity Dispersion (GVD) and non-linear effects which are dependent on refractive index variation due to the intensity of light, called self phase modulation (SPM). The dispersion due to GVD is balanced by the dispersion due to SPM and the resultant waves are called solitons. The solitons maintain their shapes over long distances and are found to be very suitable for long-range communication. Schrödinger equation that describes the light propagation in optical fibres, has been discussed. The applications of solitons in long-range optical communication have been dealt with. The problems and difficulties associated with solitons and their remedies have been outlined.

Keywords: Solitons, Kerr Effect, Transparency, Self Phase Modulation, Chirping, Group Velocity Dispersion, Intersymbol Interference, Full Width at half Maximum, Amplifier Spontaneous Effect (ASE)

I. INTRODUCTION

Dispersion has been a problem in optical fibre communication, particularly at high bit-rates and for long haul communication. Solitons based optical pulses, which maintain their shapes over long distances of several thousands of kilometres, find their application in optical networks carrying huge information.

Optical solitons are localized electromagnetic waves that propagate steadily in non-linear media from a robust balance between non-linearity and linear broadening due to dispersion and/or diffraction [1]. The solitons are classified on being either temporal or spatial, depending upon whether the confinement of light occurs in time or space during propagation. Both types of solitons evolve from a non-linear change in refractive index of a material caused by the variation in the intensity of light, a phenomenon called Kerr effect.

A spatial soliton is formed when the self-focussing of an optical beam balances its natural diffraction induced spreading. Self Phase Modulation (SPM) counter acts the natural dispersion broadening of an optical pulse and leads to formation of temporal solitons. The earliest example of temporal solitons is related to the discovery of the self induced transparency (SIT) in 1967 [2]. Optical soliton in a fibre forms a solitary wave as the envelope satisfies non-linear Schrödinger equation and was shown theoretically for the first time in 1973 [2]. It has been established that the optical pulses could propagate in an optical fibre without changing their shapes, if they experience anomalous dispersion [1]. In this paper, we discuss the concepts of temporal solitons and their applications in fibre optic communications.

II. TEMPORAL SOLITONS AND THEIR EVOLUTION

It is necessary to understand how optical pulses propagate inside a single mode fibre in the presence of dispersion (chromatic) and non-linearity (intensity dependence of refractive index).

These are best understood by the phenomenon called Self Phase Modulation (SPM) and the Group Velocity Dispersion (GVD). We discuss these two phenomena one by one and thereafter Schrödinger's equation.

(*a*) *Self Phase Modulation*

SPM is the change in the frequency of an optical pulse caused by a phase shift induced by the pulse itself. SPM arises because the refractive index of the fibre has intensity dependent component. When the optical pulse propagates through the fibre, the higher intensity portions of an optical pulse encounter high refractive index of the fibre compared with the lower intensity portions. The leading edge of the pulse, thus experiences a positive refractive index gradient $\left(\frac{dn}{dt}\right)$ and the trailing edge, a negative refractive index gradient $\left(-\frac{dn}{dt}\right)$. This temporally varying refractive index change results in a temporally varying phase change. The optical phase changes with time in exactly the same way as the optical signal [5, 6]. Different parts of the pulse undergo different phase shift because of the intensity dependence of phase fluctuations. This is called frequency chirping [7]. The rising edge of the pulse finds frequency shift in upper side, while the trailing edge experiences shift in lower side as shown in Fig. 1 [2, 7].

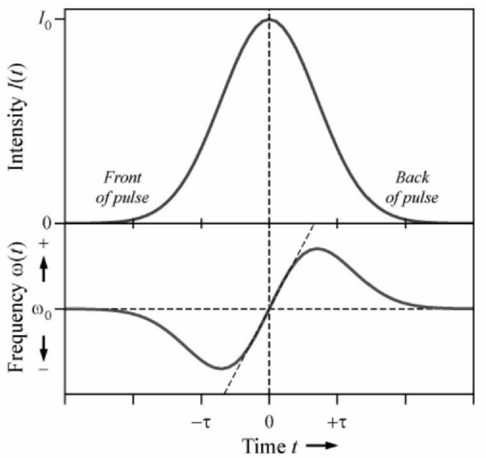

Fig. 1: Spectral Broadening of a pulse due to SPM.

Hence, primary effect of SPM is to broaden the spectrum of the pulse keeping the temporal shape unaltered.

For an optical fibre which contains high transmitted power of intensity I, the phase [ϕ] induced by a field $E = E_o \cos(\omega t - kz)$ over a fibre length L is given by [6, 7, 8].

$$\phi - \frac{2\pi}{\lambda}(n_1 - n_{nl} I).L_{eff}$$

Where L_{eff} is the effective length $\frac{1-\exp(-\alpha l)}{\alpha}$, n_1 is linear refractive index, n_{nl} is non-linear refractive index and α is attenuation constant.

In equation (1) above, the first term, *i.e.* $\frac{2\pi}{\pi}.n_1.L_{eff}$ refers to linear portion of the phase constant $(\varnothing_l)$, while the second term *i.e.*, $\frac{2\pi}{\lambda}.n_{nl}.I.L_{eff}$ denotes non-linear phase constant (ϕ_{nl}). This variation in phase with time is responsible for change in frequency spectrum.

For a Gaussian Pulse, the optical carrier frequency ù is modulated and the new instantaneous frequency becomes,

$$\omega' = w_0 + \frac{d\varnothing}{dt} \quad ...(2)$$

The sign of phase shift due to SPM is negative because of the minus sign in the expression for phase *i.e.* ($\omega t - kz$). From equations (1) and (2), we get

$$\frac{d\phi}{dt} = \frac{2n}{\lambda} L_{eff}.n_{nl}\cdot\frac{dt}{dt} \quad ...(3)$$

Therefore,

$$\omega' = w_0 - \frac{2\pi}{\lambda} L_{eff}.n_{nl}\cdot\frac{dI}{dt} \quad ...(4)$$

At the leading edge of the pulse, $\frac{dI}{dt} > 0$,

Therefore,

$$\omega' = \omega_0 - \omega(t) \quad ...(5)$$

and at the trailing edge $\frac{dI}{dt} > 0$

Therefore,

$$\omega' = \omega_0 + \omega(t) \quad ...(6)$$

Where

$$\omega(t) = \frac{2\pi}{\lambda}\cdot L_{eff}.n_{nl}\cdot\frac{dI}{dt}$$

Thus the chirping (frequency variation) takes place due to SPM. The chirping leads to spectral broadening of the pulse without any change in temporal distribution.

(b) Group Velocity Dispersion

Any optical signal contains a number of wavelengths depending upon the number of channels/information carried by it. The group velocity of a signal is the function of wavelength and each spectral component, by and large, travels independently, and undergoes a group delay and the pulse broadening [Ref. 8]. The pulse broadening leads to overlapping with neighbouring pulses which further leads to Inter symbol interference (ISI) and the receiver is not able to identify the exact pulses. The group delay, $I_{g,}$ per unit length in the direction of propagation is given by:

$$\frac{I_g}{L} = \frac{1}{v_g} = \frac{1}{c}\cdot\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\cdot\frac{d\beta}{d\lambda} \quad ...(8)$$

where, L is the distance traveled by the pulse, β is the propagation constant along fiber axis, k is the wave propagation constant $= \frac{2\pi}{\lambda}$ and v_g = group velocity = $c\left(\frac{d\beta}{db}\right)^{-1}$ (9) [9]. The delay difference per unit wavelength can be approximated as, $\frac{dI_g}{d\lambda}$ assuming the optical source not to be too wide in spectral width. For spectral width $\delta\lambda$, the total delay difference δT over distance L, can be written as

$$\delta T = \frac{\delta I_g}{d\omega} \cdot \delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\delta\omega = L\left(\frac{d\beta}{d\omega^2}\right)\delta\omega \quad ...(10)$$

where ω is the angular frequency

The factor is $\beta_2 = \frac{d^2\beta}{d\omega^2}$ a GVD parameter, which determines the quantum of pulse dispersion in time.

(*c*) Schrödinger Equation

The non-linear Schrodinger Equation [8, 9] best describes the light propagation in optical fibers [8, 9]. The Schrödinger Equation can be expressed in terms of the normalized coordinates as:

$$i\left(\frac{du}{dz}\right) - \frac{s}{2}\left(\frac{\delta^2 u}{\delta t^2}\right) + N^2 |u|^2 . u + i\left(\frac{\alpha}{2}\right)u = 0 \quad ...(11)$$

where u (z, t) is the pulse envelope function, Z is the propagation distance along the fiber, N is an integer designating the order of soliton and, α is the coefficient of energy gain per unit length. α if negative, represents the energy loss.

Hence $s = -1$ for negative β_2 (anomalous GVD – Bright Soliton) and is + 1 for positive β_2 (normal GVD – Dark Soliton) as shown in Fig. 2 and 3.

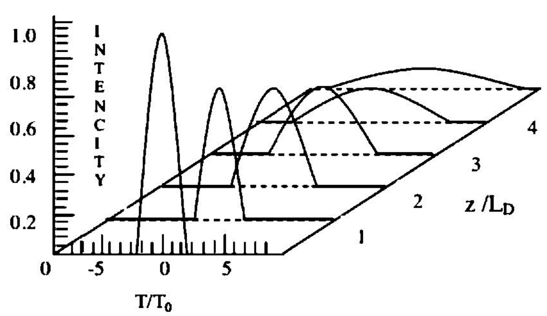

Fig. 2: Evolution of Soliton in normal dispersion regime.

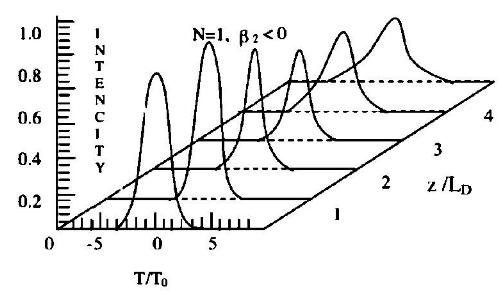

Fig. 3: Evolution of Soliton in anomalous dispersion regime.

$N^2 = \frac{L_D}{L_{NL}} = \frac{yP_0T_0}{|l\beta_z|}$ with non linear parameter γ and non linear length L_{NL}.

P_0 is peak power of the pulse,

T_0 is the normalized time

L_D is the dispersion length

There are three conditions for three different values of N, as under

(*i*) If $N > 1$, the SPM dominates

(*ii*) If $N < 1$, the dispersion effects dominate.

I.For $N \approx 1$, both GVD and the SPM act against each other in such a way that frequency chirping induced by the SPM is just right to cancel the GVD induced broadening of the pulse. The optical pulse would then propagate undistorted in the form of a soliton [12, 13]. These are called fundamental solitons.

By integrating eqn (1), the Schrödinger equation, solution for the fundamental soliton ($N \approx 1$) can be written as:

$$u(z, t) = \text{sech}(t)\exp\left(\frac{tz}{2}\right) \quad ...(12)$$

where sech (t) is the hyperbolic secant function.

A special role is played by those solitons whose initial amplitude at $z = 0$ is given by putting $z = 0$ in eqn (12), as:

$$u(0, t) = \text{sech}(t) \quad ...(13)$$

During the analysis for input pulse having an initial amplitude given by eqn (13), it is found that its shape remains unchanged during the propagation in the fiber when $N \approx 1$ (it is called fundamental solitons), but follow a periodic pattern for integer values of $N > 1$ (called higher order temporal solitons).

In eqn (13), we see that the phase term $\exp\left(\frac{tz}{2}\right)$ has no influence on the shape of the pulse, the soliton is independent of Z and hence it is non-dispersive in the time domain [14, 15]

It is this property of a fundamental soliton that it is an ideal solution for optical communication. The optical solitons are very stable against perturbations. Thus they can be created even when the pulse shape and peak power deviates from ideal condition (i.e. value corresponding to N = 1).

III. APPLICATIONS AND CONSTRAINTS

An important application of the solitons is the transmission of information through optical fibers. Here we will discuss the concept of solitons as carriers in the optical communication system. We will also discuss various problems related to the soliton based communication systems and measures to tackle them.

(*a*) *Information Transmission*

The soliton is used in each bit slot representing 1 in a bit stream as shown in Fig. 4. The neighboring solitons in this scheme should be well separated and thus the spacing between two solitons exceeds a few times their FWHM (Full Width at Half Maximum). [12, 16]. This can be ensured by keeping soliton width a small fraction of the bit slot. For this we use RZ format as shown in Fig. 4.

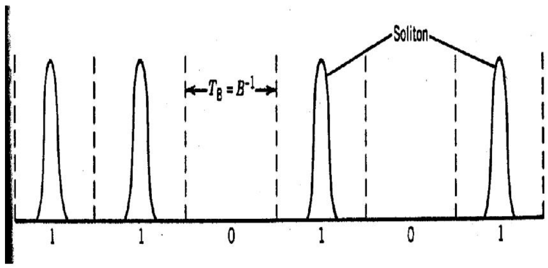

Fig. 4: Soliton bit stream in RZ format.

The bit rate and the soliton width is related as [Ref 2]

$$B = \frac{1}{T_B} = 1/2q_0T_0 \qquad ...(14)$$

where T_B is the duration of the bit slot and is $2q_0 = \frac{T_B}{T_0}$ the normalized separation between neighboring solitons. The soliton communication systems require an optical source capable of producing chirp free Pico-second pulses at a high repetition rate with a shape closest to the "Sech Shape". The source should operate in the wavelength region ~ 1.55 μ m.

(*b*) *Interaction Problems*

The existence of solitons in the neighboring bit perturbs a soliton because the combined optical field is not a solution to the NLSE. The neighboring solitons either come closer or move apart because of the non linear interaction between them. This introduces error in the data. This phenomenon has been studied in detail [17, 18]. It has been found that this interaction can be reduced by using unequal amplitude for neighboring solitons. This interaction can also be modified by factors such as initial frequency chirp imposed on input pulse. A relatively large soliton spacing, necessary to avoid soliton interaction, limits the bit rate of soliton based optical fiber communication.

(*c*) *Loss Managed Solitons*

At long distances, the effect Self Phase Modulation (SPM), which is dependent on the intensity of the optical signal, weakens due to losses in the optical fiber. Due to this, the SPM effect is not strong enough to counter the dispersion due to GVD. Therefore, to overcome the effect of fiber losses, soliton must be amplified periodically using either of the two kinds of amplification techniques [12, 19] dumped and distributed techniques. If the spacing between amplifiers L_A is less than the dispersion length L_D ($L_A << L_D$), the dumped amplification is useful. The systems with bit rates greater than 10 Gb/s, the condition of $L_A << L_D$ cannot be satisfied. In such circumstances, the other technique, distributed amplification technique is better suited. This scheme is superior to the dumped amplification because it compensates losses locally at every point along the optical fiber link.

(*d*) *Dispersion Managed Solitons*

For WDM systems, it is necessary to employ dispersion management. It has been found that if the GVD parameter β_2 varies along the fiber length, the soliton systems benefit considerably. A scheme proposed in 1987 [20] relaxes the condition of $L_A << L_D$ imposed on loss managed solitons, by decreasing the GVD along the fiber length. Such fibers, called Dispersion-Decreasing Fibers (DDFs) are designed in such a way that the decreasing GVD counteracts the reduced SPM experienced by solitons which have weakened from fiber losses. The soliton would then remain unperturbed. Such systems are called Dispersion Managed Solitons.

Qualitatively, since the soliton peak power decreases exponentially in a lossy fiber, the GVD parameter also has to decrease exponentially with the same loss coefficient to counteract the reduced SPM. The fundamental soliton then maintains its shape and width even in a lossy fiber.

(*e*) *Noise and Jitter*

Optical amplifiers are used in the soliton systems to take care of fiber losses. But these amplifiers add noise to the systems. This noise is originated from amplified spontaneous emission effect (ASE effect). The cumulative effect of ASE is that the variances of both the amplitude and frequency fluctuations increase linearly along the fiber link.

Amplitude fluctuations degrade the SNR of the soliton bit stream. The SNR degradation, although undesirable, is not the most limiting factor. Infact, the frequency fluctuations affect the system performance much more severely by inducing the timing jitter. Thus as the soliton frequency fluctuates randomly, its transmit time through the fiber link becomes random. This puts an upper limit on the bit rate length product.

IV. CONCLUSION

Soliton has shown a lot of potential for optical fiber communication systems.Solitons with EDFAs are more suitable for long-range communication, because of their high information carrying capacity and repeater less transmission. Soliton based such systems are yet to be deployed in field .With the development of technology and increase in demand by the customers, these systems will find their way for the better bit rate and longer distance.

V. REFERENCES

1. Rakesh Kumar and Mukesh Tiwari "Solitons in optical communication" dated May, 05, 2005.
2. R.Gangwar, S. P. Singh, and N.Singh, Soliton Based Optical Communication" *Progress in Electromagnetic Research,* PIER74,157-166,2007.
3. S.L.McCall and E.L.Hahn, *Phys. Rev. Lett.* **18**,908 (1967).
4. A.Hasegawa and F.D.Tappert, Appl. Phys. Lett. **23**, 142 (1973).
5. Stolen, R. H. and C. Lin, "Self-phase modulation in silica optical fibers," *Physical Review A*, Vol. **17**, No. 4, 1448–1453, 1978.
6. Singh, S. P. and N. Singh, "Nonlinear effects in optical fibers: Origin, management and applications," *Progress In Electromagnetic Research,* PIER 73, 249–275, 2007.
7. Agrawal, G. P., *Fiber Optic Communication Systems*, 2nd edition, Wiley, New York, 1997.
8. John M . Senior, 'Optical FiberCommunication – principles and practice ; second edition, Prentice hall of India ,New Delhi, 2003.
9. Rajiv Ram swami and Kumar N. Sivarajan ',Optical networks–A practical perspective', second edition ,Morgan Kaufman publishers, 2004.
10. Hasegawa, A. and Y. Kodma, *Soliton in Optical Communication*, Clarendon Press, Oxford, 1995.
11. Haus, H. and W. S. Wong, "Soliton in optical communications,"*Rev. Mod. Phys.*,Vol. **68**, 432–444, 1996.
12. Haus, H. A., "Optical fiber solitons: Their properties & uses,"*Proc. IEEE*, Vol. **81**, 970–983, 1993.
13. Biswas, A. and S. Konar, "Soliton-solitons interaction with kerr law non-linearity," *Journal of Electromagnetic Waves and Applications*, Vol. **19**, No. **11**, 1443–1453, 2005.
14. Biswas, A., S. Konar, and E. Zerrad, "Soliton-soliton interaction with parabolic law nonlinearity," *Journal of Electromagnetic Waves and Applications*, Vol. **20**, No. 7, 927–939, 2006.
15. Biswas, A., Shwetanshumala, and S. Konar, "Dynamically stable dispersion- managed optical solitons with parabolic law nonlinearity, "*Journal of Electromagnetic Waves and Applications*, Vol. **20**, No. 9, 1249–1258, 2006.
16. Chraplyvy, A. R. and R. W. Tkach, "Terabit/ second transmission experiments," *IEEE J. Quantum Electron.*, Vol. **34**, 2103–2108, 1998.
17. F.M.Mitschke and L.F.Mollenauer,*Opt.Lett* **12**, 355(1987)
18. Y.Kodama and .Nozaki, *Opt.Lett.* **12**,1038(1987)
19. Tauser, F., F. Adler, and A. Leitenstorfer, "Widely tunable sub-20 fs pulses from acompact erbium-doped fiber source," *Opt. Lett.*, Vol. **29**, 516, 2004.
20. K.Tajima, *Opt. Lett.* **12**, 54(1987)