Solitons: A Promising Technology in Optical Communication

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Abstract: ***Optical solitons are stable optical pulses formed by the perfect balancing of Group Velocity Dispersion (GVD) and Self Phase Modulation (SPM) in a fiber. These pulses carrying information would travel trans-oceanic distances without changing shapes and hence assures a high speed optical communication. Here, we present a review of optical solitons, focusing on its formation and underlying principles, mathematical model, challenges faced, and applications.***

Keywords: Optical solitons, group velocity dispersion, self phase modulation, optical non-linearities

1. Introduction

The birth of fiber optic communication has revolutionized the area of information technology around the globe enabling fast and reliable data exchange at the speed of light. But there are certain practical limitations that prevent from achieving this high speed data transfer. This is the temporal pulse spreading caused by GVD leading to inter symbol interference (ISI).

Another important phenomenon that occurs at high intensity is SPM, which results in frequency chirping causing broadening in frequency domain. Thus by perfectly balancing GVD and SPM, stable optical pulses that maintain their shape and width as they propagate through the fiber, can be formed. These are the '*Optical Solitons'*.

The propagation of solitons in optical fiber was predicted by A. Hasegawa and F.D. Tappert, in 1973 [1]. Experimentally soliton propagation in fiber was confirmed by L.F. Mollenauer, R. H. Stolen and J.P. Gorden in 1980 [2]. In 1988 L.F. Mollenauer and K. Smith successfully demonstrated the first all optical soliton transmission over 4000 Km using Raman amplification [3].

In this paper we present a review on various aspects dealing with soliton propagation in a fiber.

2. Formation of optical Solitons

Solitons are formed by the perfect balancing of GVD and SPM in a fiber. The principles behind the formation of solitons are given below.

2.1 Group Velocity Dispersion

Optical pulses have a Gaussian shape with photons concentrated towards the center of the pulse. Practically no source can be perfectly monochromatic. This is because of small thermal fluctuations and quantum uncertainties [4]. Hence an optical pulse constitutes a range of wavelengths.

A frequency component 'ω' (ω=2πc/λ) introduced into a fiber of length 'L' would arrive at fiber output after a time 'T' given by

$$T = \frac{L}{v_g} \qquad (1)$$

where 'v_g' is the group velocity defined as

$$v_g = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1} \qquad (2)$$

where 'β' is the propagation constant (β=nω/c).

The refractive index of the fiber is frequency dependent and hence light of different frequencies travel along the fiber at different velocities. Thus they arrive at the receiver at different times resulting in pulse spreading and lower peak intensity. This is 'G*roup Velocity Dispersion or Chromatic Dispersion*'. This would cause the pulses to overlap over few kilometers and they would no longer carry any information. Thus even though optical communication offers high speed data transfer, practically it is been limited by GVD.

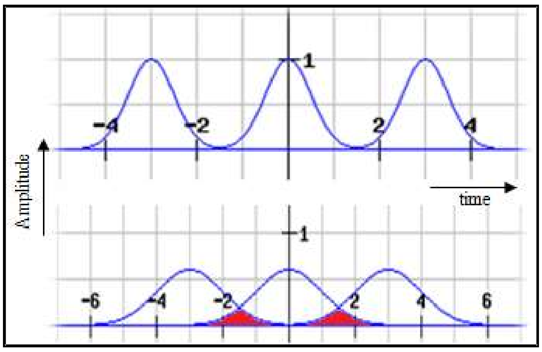

Figure 1: Inter symbol interference

If 'Δω' is the spectral width of the pulse, the pulse spread due to GVD can be written as,

$$\Delta T = \frac{dT}{d\omega}\Delta\omega = \frac{d\left(\frac{L}{v_g}\right)}{d\omega}\Delta\omega = L\left(\frac{d^2\beta}{d\omega^2}\right)\Delta\omega = L\beta_2\Delta\omega \qquad (3)$$

where β_2 is the GVD parameter.

$$\Delta T = L\beta_2\left(-\frac{2\pi c}{\lambda^2}\right)\Delta\lambda = DL\Delta\lambda \qquad (4)$$

where $D = \beta_2\left(-\frac{2\pi c}{\lambda^2}\right)$ is the Dispersion parameter.

For silica fiber, 1310 nm is the zero dispersion wavelength, D = 0. Below this wavelength dispersion is negative and above, it is positive.

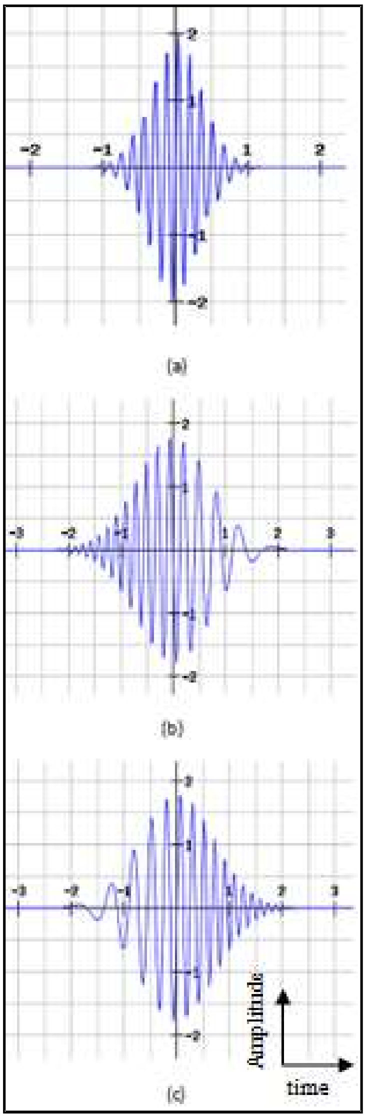

Figure 2: The effect of GVD on a Gaussian pulse
a) Gaussian pulse, b) Effect of anomalous dispersion,
c) Effect of normal dispersion

Depending on the wavelength of operation, the fiber can be normally dispersive (D < 0) or anomalously dispersive (D > 0). In case of normal dispersion, the refractive index decreases with increasing wavelength and in case of anomalous dispersion, refractive index increases with increasing wavelength. This would cause low frequency (high λ) components to travel faster than high frequency (low λ) components. Vice versa is true for anomalous dispersion.

2.2 Self Phase Modulation

When optical pulses are highly intense, fiber tends to exhibit non-linearities and refractive index becomes dependent on intensity and becomes non-linear.

Modified refractive index is given by

$$n' = n_0 + n_2 I \quad (5)$$

where n_0 is linear refractive index, n_2 is non-linear refractive index and I is the intensity of Gaussian optical pulse given by $I = I_0 \exp(-t^2/\tau_0^2) = P/A_{eff}$, I_0 is the peak intensity, τ_0 is the half width of the pulse, P is the peak optical power and A_{eff} is the effective core area. Since propagation constant β is a function of refractive index, it becomes non-linear too.

$$\beta = \frac{(n_0 + n_2 I)\omega}{c} = \frac{n_0\,\omega}{c} + n_2 \frac{P}{A_{eff}}\frac{\omega}{c} = \beta_0 + \gamma P \quad (6)$$

where β_0 is the free space propagation constant, γ is a non-linear parameter, value ranging between 1-5 W^{-1}/Km depending on A_{eff} and λ [5].
An optical pulse initially expressed as $\tilde{A}(0,\omega_0)$, propagate through a fiber and become $\tilde{A}(z,\omega_0)$ at the output.

$$\tilde{A}(z,\omega_0) = \tilde{A}(0,\omega_0) exp(-i\beta z) \quad (7)$$

The phase of the pulse is given by

$$\varphi = \omega_0 t - \beta z \quad (8)$$

Thus optical phase is dependent on β and hence there is a self induced non-linear variation of φ with respect to time. This process is *'Self Phase Modulation'*. The instantaneous frequency is given by

$$\frac{d\varphi}{dt} = \omega_0 - \frac{d\beta}{dt} L \quad (9)$$

where L is the distance propagated by the pulse. Thus SPM leads to frequency chirping of the pulse. That is a time dependent frequency shift Δω = -(dβ/dt)L. Hence according to equation (6), the frequency chirp Δω is proportional to -(dP/dt) and depends on the pulse shape.

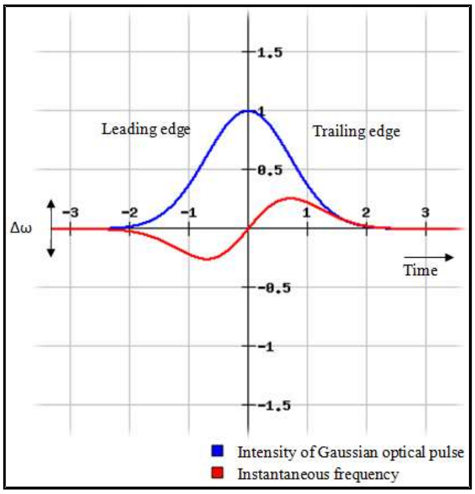

Figure 3: Effect of SPM on a Gaussian pulse

Thus the leading edge shifts to a lower frequency and trailing edge to a higher frequency and hence instantaneous frequency increases linearly from leading edge to trailing edge-'*upchirp*'. The center portion of the pulse has a linear variation of frequency.

Now depending on whether the medium is normally dispersive or anomalously dispersive SPM has different effects on the pulse. When the medium is normally dispersive, high frequencies are slower than low frequencies. Hence if SPM happens in normally dispersive medium, pulse will be broadened further to the effect of GVD. But if the medium is anomalously dispersive, high frequencies will be faster than low frequencies. Thus SPM results in pulse compression reducing the broadening effect of GVD in anomalously dispersive medium. Thus in anomalously dispersive medium, with high intensity input pulse, SPM counteracts GVD and cancels out pulse broadening from pulses that are capable of retaining the shape along the fiber-*The optical solitons'*.

2.3 Optical Solitons

The non-linear length of optical fiber is the effective propagation distance at which maximum non-linear phase shift occurs, $L_{NL} = (\gamma P)^{-1}$. The dispersion length of optical fiber is the effective propagation distance at which dispersion becomes significant, $L_D = \tau_0^2/|\beta_2|$. These lengths are not physically measurable. They come into effect only when pulse propagate through the fiber. If the physical length of the fiber L is much less than L_{NL} and L_D, neither dispersion nor linear effects becomes significant. When L_D is comparable to L_{NL}, dispersion and non-linearity acts together. This is an important condition for the formaton of solitons as expressed below

$$\frac{\tau_0{}^2}{|\beta_2|} = \frac{1}{\gamma P} \qquad (10)$$

$$P = \frac{\beta_2}{\gamma \tau_0{}^2}, \beta_2 < 0 \qquad (11)$$

Thus peak power of the pulse transmitted through the fiber should satisfy equation (11), for the formation of solitons. That $\frac{L_D}{L_{NL}} = 1$ (12)

Generally,

$$\frac{L_D}{L_{NL}} = N^2 \qquad (13)$$

Here N is an integer. When N=1, there is perfect balance between SPM and GVD. This is the fundamental soliton. For other values of N, higher order solitons are formed.

3. Mathematical Model of Optical Solitons

The optical pulse envelope A(z,t) propagating in the fiber is given by non-linear Schrödinger (NLS) equation [5]

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A = 0 \qquad (14)$$

This is considered in absence of fiber losses and higher order dispersion terms. Here, SPM and GVD are taken into account.

Equation (14) is re-written in a normalized form as

$$i\frac{\partial U}{\partial \varepsilon} - \frac{s}{2}\frac{\partial^2 U}{\partial \tau^2} + N^2|U|^2 U = 0 \qquad (15)$$

where, $U = A/\sqrt{P}$, $\varepsilon = z/L_D$, $s = \mathrm{sgn}(\beta_2)$ and $\tau = t/\tau_0^2$.

From equations (11) and (13), $N^2 = \gamma P\ \tau_0^2/|\beta_2|$, it is dimensionless and a combination of pulse-fiber parameters. Now when s = -1, the medium exhibits anomalous GVD, and hence equation (15) is written as

$$i\frac{\partial u}{\partial \varepsilon} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0 \qquad (16)$$

with u = NU as normalized amplitude. This equation is solved by using inverse scattering method proposed by Zakharov and Shabat [6]. Accordingly, when an input pulse with initial amplitude

$$u(0,\tau) = N\mathrm{sech}(\tau) \qquad (17)$$

is launched into the fiber, its shape remains unchanged during propagation, when N = 1. But it follows a periodic pattern for N > 1, such that input shape is recovered at $\varepsilon = m\pi/2$, where m is an integer.

Thus the effect of GVD exactly compensates with SPM, when input has a '*sech*' shape and when its width and peak power is related by equation (11). These are *Bright solitons*.

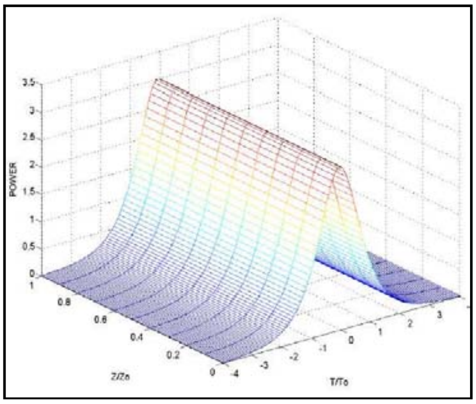

Figure 4: Bright solitons

When NLS equation is solved with inverse scattering method for normal dispersive medium, the resulting intensity profile of the solution exhibits a dip in uniform background and this dip remain unchanged during propagation inside the fiber. These are the *Dark solitons*.

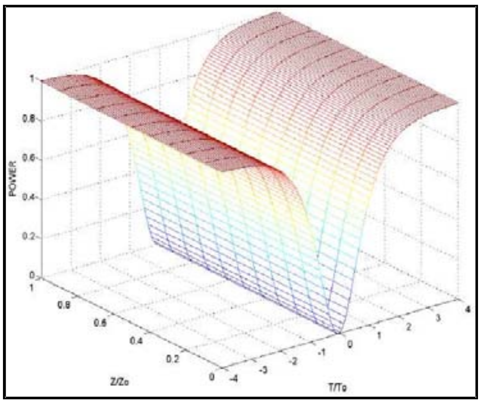

Figure 5: Dark solitons

4. Challenges faced in Soliton Propagation

For soliton propagation, the exact peak power and shape parameters as specified in equation (11) and (17) respectively, must be satisfied. Otherwise the action between SPM and GVD will not mould soliton pulses. Precisely meeting these criteria are difficult in practice. Losses in fiber is a great issue in retaining the peak power. When input parameters vary substantially from ideal soliton values, '*dispersive waves*' will be formed. This will cause the pulse to loose some of its energy as it evolves into a soliton. This energy loss can cause interference with neighboring pulses and would adversely affect the system performance. Fiber losses would reduce the peak power of the pulse weakening SPM required to balance GVD, causing soliton broadening. This will in turn affect the capacity of the system. By placing optical amplifiers periodically, fiber losses can be compensated. Erbium Doped Fiber Amplifier (EDFA) is the most commonly used optical amplifier. But it would add noise known as '*Amplified Spontaneous Emission*' (ASE) [7]. This would result in random fluctuations of soliton parameters both amplitude and frequency, degrading the system performance. Amplitude fluctuations reduces the SNR of the system. With frequency fluctuations, soliton frequency would vary randomly and hence its transit time through fiber becomes random. This causes fluctuation in the arrival time of solitons known as '*Gordon-Haus timing jitter*' (GH jitter). One possible way of removing noise outside the bandwidth of optical signal is using an appropriate filter [8].

Usually, sources generate chirped initial pulses. Since soliton formation are sensitive to chirp, it would affect the system. Even with small amount of initial chirp, solitons are formed, but with loss of large percentage of energy. Hence generation of unchirped pulses are important.

If solitons are so closely spaced, neighboring solitons would interact. This is '*Soliton-Soliton Interaction*'. This would cause pulse overlap that results in the attraction of the two pulses [9]. Due to this attractive force neighboring solitons merge into a single pulse having twice the magnitude of the initial one. This leads to error in detection. A stipulated gap between solitons is mandatory to avoid the interaction. But this would limit the bit rate of the system. The bit rate is also limited by the modulation speed of the laser used as source of generating solitons and also the bandwith of EDFA.

'*Dispersion managed solitons*' (DMS) [10] can be used to increase the transmission capacity of the soliton based communication. DMS transmission has a low path averaged chromatic dispersion, but a high local one, there by suppressing the GH jitter as well as four-wave mixing simultaneously. The DMS has enhanced energy increasing the SNR and improving the system performance.

As soliton width decreases '*Intra Pulse Raman Scattering*' down shifts the solitons mean frequency. Large drifts of the soliton mean frequency can change the conditions of propogation by changing GVD locally. The frequency shifts due to Intra Pulse Raman Scattering can be compensated by Parametric Amplification [11].

For high bit rate system, at a given point in the fiber, the GVD is varying considerably over the soliton spectral width (because of Third-Order Dispersion(TOD)), resulting in a perturbation of the soliton. Insertion of fast saturable absorbers after the amplifiers would likely permit stable propagation over trans-oceanic distances. Dispersion-Flattened fibers can also prevent generation of dispersive waves by lowering TOD.

5. Applications

The key application of optical solitons are ultra long haul, all optical and high data rate networks. Other potential applications of optical solitons are in optical switches and volatile optical memories [12], both required for realizing an optical computer. Volatile optical memory is obtained by trapping the soliton pulse forming a loop due to internal reflection in a precisely designed flat sheet of fiber optic material with variable refractive index. Here the presence of soliton is interpreted as '1' and absence as '0'.

6. Conclusion

Soliton based optical communication is a promising technology of very high potential capability for high bit-rate transmission. However its practical implementation have been a real challenge. Studies are going on for the improvement of the soliton based systems due to the ever increasing demand for long distance multi-Terabit transmission.

References

[1] A. Hasegawa and F. D. Tappert, Appl.Phys.Lett.23, 142 (1973)
[2] L. F. Mollenauer, R. H. Stolen and J. P. Gordon, Phys.Rev.Lett.45, 1095 (1980)
[3] L.F.Mollenauer and K.Smith, Opt.Lett.13,675(1988)
[4] A Primer in Optical Soliton Theory by John Mauro
[5] Fiber-Optic Communication Systems, Third Edition, Govind P. Agrawal, John Wiley and sons publication 2002
[6] V. E. Zakharov and A. B. Shabat, *Sov. Phys. JETP* **34**, 62 (1972)
[7] Solitons in Optical Communication by Rakesh Kumar and Mukesh Tiwari, May 5, 2005
[8] Performance Estimation of Soliton Propagation in EDFA and DCF Based Optical Network by D. Esther Nesa Malar and Dr. D. Mohana Geetha, Bonfring International Journal of Research in Communication Engineering, Vol. 2, Special Issue 1, Part 1, February 2012
[9] Solitons interaction and their stability based on Nonlinear Schrödinger equation by Asim Shahzad and M. Zafrullah, International Journal of Engineering & Technology IJET Vol: 9 No: 9
[10] Physics and mathematics of dispersion-managed optical solitons by Sergei K. Turitsyn, Elena G. Shapiro, Sergei B. Medvedev, Mikhail P. Fedoruk, Vladimir K. Mezentsev, C. R. Physique 4 (2003) 145–161
[11] Ultrahigh-bit-rate soliton communication systems using dispersion-decreasing fibers and parametric amplifiers by René-Jean Essiambre and Govind P. Agrawal, OPTICS LETTERS / Vol. 21, No. 2 / January 15, 1996
[12] Novel Technique for Volatile Optical Memory Using Solitons by Mohd Abubakr and R. M. Vinay

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