INTERNATIONAL JOURNAL OF SCIENTIFIC PROGRESS AND RESEARCH (IJSPR) ISSN: 2349-4689
Volume-13, Number - 03, 2015

Optical Solitons in Communications

Rini Jain[1], Zohaib Hasan[2]
[1]*M.Tech Student, Gyan Ganga Institute of Technology and Sciences*
[2]*Assistant Lecturer, Gyan Ganga Institute of Technology and Sciences*

Abstract: Nowadays, wired optical communication is growing fast. Over long distance, the losses in conventional pulses goes on increasing. Thus for long distance communication, the need of pulses with minimum loss is required. The new type of transmission pulse for optical fibers called optical soliton is discussed in this paper. In this paper, the generation and advantages of soliton over conventional pulse is described.

Keywords: Solitons, NRZ.

I. INTRODUCTION

The Scottish scientist John Scott Russell made the first observation of the solitary wave in 1834. While observing the movement of a canal barge, Russell noticed a water wave preserved its original shape over a very long distance. The word “Solitons” was first introduced by Zahusky and Kruskal when they were solving the wave motion of one dimensional non-linear lattice vibration known as the Korteweg de Vries (KdV)[1] equation. They found that the shape of the non linear wave remains unchanged even when solitary wave collide with each other, and the wave behave like a particle. They introduced the word Solitons by combining “Solitary” with the suffix “on” which is generally used for the particle like proton, electron, etc. The optical solitons is different from KDV solitons. In contrast to the KDV solitons, which describes the solitary nature of a wave, the optical soliton in fiber is an envelope of a light wave. In 1971 Zakharov and Shahat showed analytically that a solitons can also be generated in a non linear dispersive medium, the non linear effect due to SPM-Chirp and the group velocity dispersion (GVD), these two effects counter balance each other and lead to the formation of a Solitons The effect can be described by the non-linear Schrödinger equation (NLS) [2-5]. In 1973 Hasegawa and Tappert [2] showed that theoretically optical solitons could be formed in a dielectric fiber. However at that time good quality fiber was not available so he was not successful in demonstrating it experimentally. In 1980 Mellenuer was the first to demonstrate the propagation of solitons in optical fiber. [3]

II. GENERATION OF OPTICAL SOLITONS IN FIBER

We generally treat optical fiber as a linear medium, which is the intensity associated with optical pulse is very small. But in actual practice, all the media are nonlinear. In silica optical fiber one of the effects of non linearity is the intensity dependent refractive index, according to following equation

$$n = n_0 + n_2 I \qquad (1)$$

Where n_0 is the linear refractive index of the silica (for low intensity levels) n_2 is the nonlinear refractive index coefficient and $I = \frac{P}{A_{eff}}$ is the intensity within the medium with P being the optical power of the mode and A_{eff} is the effective area of the fiber. The intensity dependent refractive index leads to the phenomenon known as SPM. SPM lead to a chirping with lower frequency in the leading edge and higher frequency in the trailing edge, which is just opposite the chirp cast by linear dispersion in the wavelength in the region above zero dispersion wavelengths. By a proper choice of the pulse shape (a hyperbolic secant shape) and the power carried by the pulse, we can compensate one effect with the other. In such a case the pulse would propagate undistorted in the fiber such a pulse would broaden neither in the time domain (as in the linear dispersion) nor in frequency domain (as in SPM) and is a solitons.

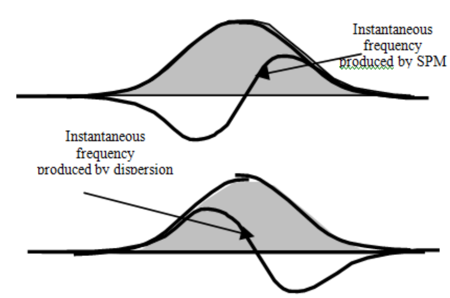

Figure 1 Frequency variation in the solitons pulse

III. SHAPE AND THE POWER OF THE SOLITON PULSE

The shape of the solitons pulse can be found out by solving non linear Schrodinger equation. The envelope of an optical pulse propagating through a non-linear dispersive medium is approximately governed by the following equation

$$\frac{\partial A}{\partial Z} + \beta_1 \frac{\partial A}{\partial t} + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} = i\gamma |A|^2 A \qquad (2)$$

Where $\beta_1 = \frac{1}{v_g} = \left|\frac{dK}{d\omega}\right|_{\omega=\omega_0}$ is the first order dispersion parameter, which is inversely related to the group velocity v_g, β_2 is the second order group velocity dispersion parameter, $\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$ and $A(Z,t)$ represents the envelope term of the pulse.

If we define new variables

$$\tau = \frac{t - \frac{z}{v_g}}{T_0}, \quad z = \frac{Z}{L_D}, \quad u = \sqrt{|\gamma| L_D} A \quad \text{and} \quad L_D = \frac{T_0^2}{|\beta_2|}$$

The interpretation of the following variables is as such since the pulse propagates with velocity β_1(in the absence of dispersion), $t - \beta_1 z$ is the time axis in a reference moving with the pulse. The variable τ is the time in this reference frame in the unit of T_0(pulse width of the soliton pulse).The variable z measures in the unit of dispersion length L_D, P_0 is the peak power of the pulse and u is the envelope of the pulse.

The equation (2) can be written as

$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0 \qquad (3)$$

We will take the solution of the form

$$u(z,\tau) = N_0 \psi(\tau)\exp[i\phi(z)] \qquad (4)$$

Where N_0 is the term related to the peak electric field and the envelope function $\psi(\tau)$ is a real function of τ. Substituting (3) in (2) and using the boundary conditions

$$\lim_{\tau\to\infty}\psi(\tau) = 0 \quad \text{and} \quad \lim_{\tau\to\infty}\frac{d\psi}{d\tau} = 0$$

We get the following solution

$$u(z,\tau) = N_0 \sec h(\tau)\exp\left(i\frac{z}{2}\right) \qquad (5)$$

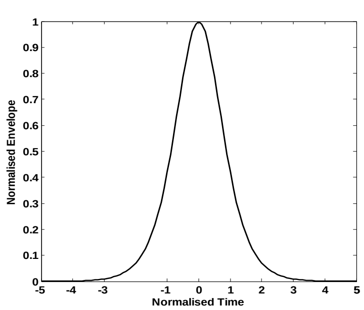

Figure2 Schematic of secant hyperbolic pulse

The optical power associated with the solitons pulse is

$$p(t) = p_0 \sec h^2(\tau)$$

The FWHM of the pulse is T_f and is obtained from the condition:

$$\sec h^2(t_0) = \frac{1}{2}$$
$$T_f = 2t_0 = 2T_0 \ln\left(1 + \sqrt{2}\right)$$

The peak solitons power P_o can be calculated as

$$P_0 = \frac{1}{2}\varepsilon_0 n_0 c |N_0|^2 A_{eff}$$
$$P_0 = \frac{0.776\lambda_0^3 |D| A_{eff}}{\pi^2 c n_2 T_f^2} \qquad (6)$$

Where D is the dispersion parameter and is given as

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = \frac{-2\pi c\beta_2}{\lambda^2}$$

The power of the optical solitons pulse varies directly with dispersion and inversely with pulse width. When an input pulse having an initial amplitude $u(0,\tau) = N_0 \sec h(\tau)$ is launched into the fiber, its shape remains unchanged during propagation when $N_0 = 1$, but follows a periodic pattern for integer value $N_0 > 1$ such that the input pulse is recovered at $z = \frac{m\pi}{2}$ where is a m integer, and N_0 is related to input pulse parameter as $N_0^2 = \gamma P_0 L_D = \frac{\gamma P_0 T_0^2}{|\beta_2|}$ where $\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$.An optical pulse with $N_0 = 1$ is called fundamental solitons and for higher values of N the pulse is called higher order solitons. Equation (5) shows that inside the fiber only phase of the pulse get modified by factor $\frac{iz}{2}$, but amplitude remains constant. This property makes a solitons a very good candidate for optical communication. The important property of optical solitons is that they are stable against any perturbation. Thus even though the fundamental solitons required a specific shape and a certain peak power corresponding to $N_0 = 1$, it can be created even when the pulse peak power deviate from the ideal condition. It was find out that the pulse width and the peak power oscillate initially but eventually becomes constant after the input pulse has adjusted itself to satisfy to condition $N_0 = 1$ [4-6].

IV. THE ADVANTAGE OF SOLITONS OVER LINEAR PULSE

1) Solitons can be generated in the loss minimum region at around 1550 nm.

2). Solitons pulse transmission is possible over long distance. Solitons can be both time and polarized multiplexed.

3). There is no waveform distortion over long distances which are useful for long distance communication.

4). Solitons are dispersion free, and the collision of the solitons are elastic in nature, after collision their amplitude and frequency remain unchanged, only position and phase changes.

5). Two counter propagating solitons pass each other without affecting each others' motion.

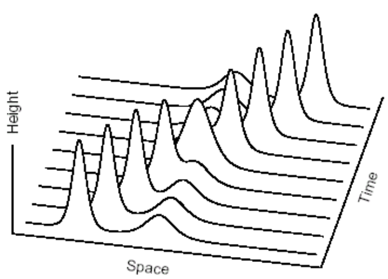

Figure 3 Movement of two orthogonal solitons in fiber

V. NRZ VS. SOLITONS

The main difference between encoded digital signals with solitons and with NRZ is that in NRZ if two ones are close together then the signal intensity does not falls to zero between individual bits but it does fall in solitons. For NRZ the nonlinearity in optical fiber is a problem that can distort the signal.

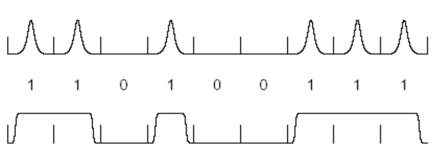

Figure 4 Comparison of NRZ versus Solitons

VI. EFFECT OF FIBER LOSS

Solitons result from a balance between the non linear and dispersive effect, the pulse must maintain its peak power if it has to preserve its character. The fiber loss is detrimental because the peak power of the pulse decreases exponentially with the fiber length. As a result the pulse width of the fundamental solitons increases as it propagates through the fiber.

If we incorporate the loss of the fiber then equation (3) will be modified as

$$i\frac{\partial u}{\partial z}+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+|u|^2 u=-i\frac{\eta}{2}u \qquad (7)$$

The term on the right hand side represent losses due to fiber. For the input pulse of the form $u(0,\tau)=N_0 \sec h(\tau)$ the pulse shape after a distance z in a lossy fiber is given by [7]

$$u(z,\tau)=u_1 N_0 \sec h(\tau)\exp\left(i\frac{z'}{2}\right) \qquad (8)$$

Where

$$u_1=\exp(-\eta z),\ z'=\frac{1}{4\eta}[1-\exp(-2\eta z)] \qquad (9)$$

The pulse width of the solitons pulse T_1 along the fiber changes as

$$T_1=T_0\exp(\eta z) \qquad (10)$$

It is evident from the last expression that due to the fiber loss the peak pulse power decreases exponentially and associated pulse width increases with propagation distance. This broadening arise due to mismatch between SPM effect and GVD, as SPM weaken due to loss of fiber [7-11]. If the relation between dispersion and non-linearity is modified accordingly to the average power of the propagating solitons, this type of soliton is known as average solitons.

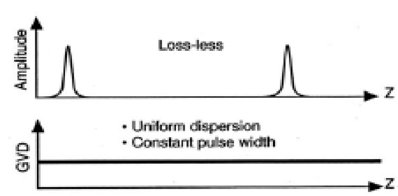

Figure 5 Nature of the solitons in lossless fiber

VII. CONCLUSION

In this paper, a new type of optical transmission pulse known as optical solitons is discussed. This pulse have many advantages over the conventional pulses. Howvere, the genertion of optical solitons in fiber is not straight forward, and once they are generated, then their survival in optical fiber is more critical. As these pulses behave like an ideal pulse in optical systems, therefore can be considered as next generation optical pulses in infromation transfer.

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