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Evolution of Solitons in Optical Communication

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Abstract- This paper presents a review on optical solitons, focusing on its evolution and applications in long range communication. In an optical communication system, solitons are very narrow, high intensity stable optical pulses that are outcome of balancing group velocity dispersion, GVD by self phase modulation, SPM. If the relative effects of SPM and GVD are controlled just right, and the appropriate pulse shape is chosen, The pulse compression resulting from SPM can exactly offset the pulse broadening effect of GVD.

Index Terms- Solitons, SPM, GVD, Kerr Effect, Chirping, Optical non-linearities

1. INTRODUCTION

Modern high capacity telecommunication networks based on optical fiber technology now have become an integral and indispensable part of society. Due to the importance of these networks to everyday life users expect constant availability of communication services. There are evolving international telecommunications standards that were predicting very high data rate requirements, and transmission capacity. Fiber optic transmission systems have provided enormous capacity required to overcome short falls due the various catastrophic effects like noise, attenuation, dispersion and nonlinear effects. Fiber optic transmission systems have many advantages over most conventional transmission systems. They are less affected by noise, do not conduct electricity and therefore provide electrical isolation, carry extremely high data transmission rates and carry data over very long distances.

Because of optical fiber technology fast and reliable data exchange at the speed of light became possible. But there are certain practical limitations that prevent from achieving this high speed data transfer. Dispersion is one of the most important distortion effects in the optical fibers. Pulse spreading caused by Group Velocity dispersion (GVD) leads to inter symbol interference (ISI). Another phenomenon called as self phase modulation (SPM) gives rise to frequency chirping. However a particular pulse shape known as a soliton takes advantage of nonlinear effects in silica, particularly SPM resulting from Kerr nonlinearity, to overcome pulse broadening effect of GVD [5].

Solitons are narrow pulses with high peak powers and special shapes. Depending upon the particular shape chosen, the pulse either do not undergo change in its shape during propagation, or undergoes periodic changes in its shape [5]. Fundamental solitons are those who do not change their shape during propagation, and those who undergo periodic change in shape are called higher order solitons.

Soliton pulses balance effect of GVD and SPM. In order for this balance to occur, the soliton pulses must not only have a specific shape but also a specific energy. Due to inevitable fiber attenuation, the pulse energies are reduced, this weakens the nonlinear interaction needed to balance GVD. Hence periodically spaced optical amplifiers are required in a soliton link to restore the pulse energy[5,7].

2. FORMATION OF SOLITONS

To understand the formation of soliton pulses it is necessary to understand the propagation of optical pulses inside the optical fiber in presence of It is necessary to understand how optical pulses propagate inside a single mode fiber in the presence of dispersion (chromatic) and non-linearity (intensity dependence of refractive index). Hence first we need to understand the phenomenon Self Phase Modulation (SPM) and the Group Velocity Dispersion (GVD).

Dispersion mechanism within the fiber causes broadening of transmitted light pulses as they travel along the channel.

Fig.1. Chromatic dispersion causes pulse broadening and bit error

3. DISPERSION TYPES

- Mode Dispersion
- Chromatic dispersion
    a. Waveguide dispersion
    b. Material dispersion
    c. Polarization dispersion

3.1. *Chromatic dispersion*

It is caused by two reasons,

1. The refractive index of the material used to manufacture optical fiber is frequency dependent, thus different frequency components are travelling at different speeds which gives rise to material dispersion.
2. If wavelength changes, the power distribution associated with core and cladding changes which in tern changes the effective index and thus gives rise to waveguide dispersion.

Due to presence of chromatic dispersion the shape of pulses propagating in optical fiber are not preserved [7]. The parameter which governs the change in shape of the light pulse as it travels along the optical fiber is GVD parameter and is denoted as

$\beta_2 = d^2\beta / d\omega^2 = 1/c\ (2dn/d\omega + \omega d^2n/d\omega^2$

Where β is propagation constant

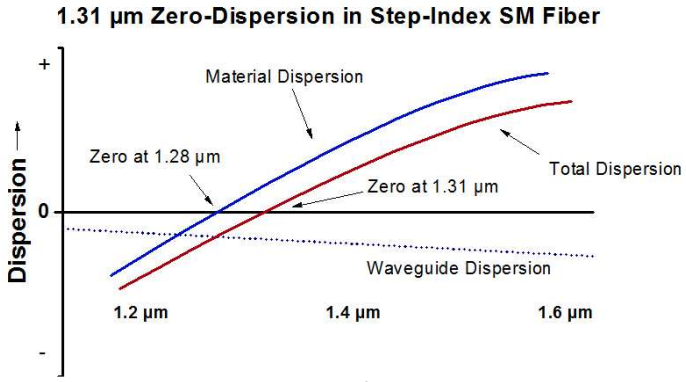

Fig.2. Total Chromatic dispersion for standard single mode fiber

Dispersion D is defined as

$D = dt_g / d\lambda$

Where $t_g = 1/v_g = d\beta/d\omega = \beta_1$

$D = d\beta_1/d\lambda = -2\pi c/\lambda^2\ \beta_2 = \beta_1$

Where,

$\beta_1 = d\beta/d\omega = 1/v_g = t_g = n/c(1+\omega/n\ dn/d\omega)$

4. NONLINEAR EFFECTS

The material properties of a given medium change when high intensity light is transmitted through it are called nonlinear effects. The refractive index of many optical materials has a weak dependence on optical intensity I given by

$$n(I) = n_0 + n_2 I$$

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Where n0 is ordinary refractive index and n2 is nonlinear index coefficient[10].

Time varying refractive index is given by

$dn(I)/dt = n2dI/dt = n_2.I_0.\ -2t/\tau^2.\ exp\ (-t^2/\tau^2)$

The phase of modulation is defined by

$\Phi(t) = \omega_0 t - kx = \omega_0 t - 2\pi/\lambda_0.\ n(I).L$

ω_0 and λ_0 are carrier frequency and wavelength of the pulse and L is the distance in which wave

propagates[10]. Due to change in refractive index phase shift of the pulse occurs, therefore [10]

$\omega(t) = d\,\Phi(t)/dt = \omega_0 - 2\pi L/\lambda_0 \,.\, dn(I)/dt$

$\omega(t) = \omega_0 + 4\pi L n_2 I_0/\lambda_0\, \tau^2 .t.\, exp\,(-t^2/\tau^2)$

Thus leading edge shifts to lower frequencies (red shift) and trailing edge shifts to higher frequencies (blue shift). Linear frequency shift (chirp) at the center of the pulse is given by[10]

$\omega(t) = \omega_0 + \alpha.t$

$\alpha = d\omega/dt = 4\pi L n_2 I_0/\lambda_0\, \tau^2$

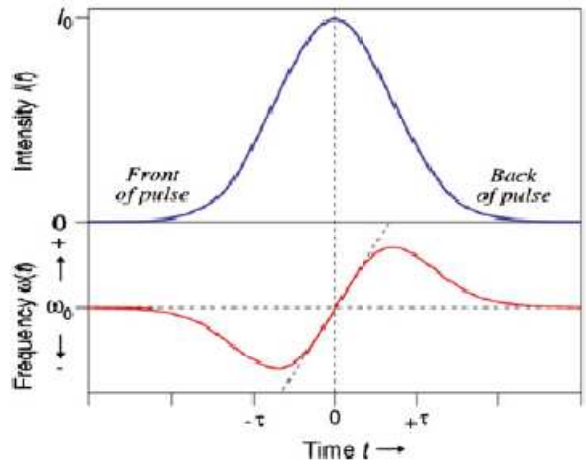

Fig.3. Spectral broadening of the pulse due to self phase modulation.

5. SOLITON PULSES

When a high intensity optical pulse couples to a fiber self phase modulation takes place which causes phase fluctuations thereby producing a chirping effect in the pulse. The result is that the front of the pulse has lower frequencies and back of the pulse has higher frequencies than the carrier frequencies [5].

When such a pulse travels in a medium with positive GVD parameter leading part of the pulse shifted towards longer wavelength so that speed in that portion increases and in trailing part frequency rises hence speed decreases. This causes trailing part to be further delayed. Thus the energy at the center on the pulse is dispersed on either side and pulse eventually takes rectangular wave shape [5].

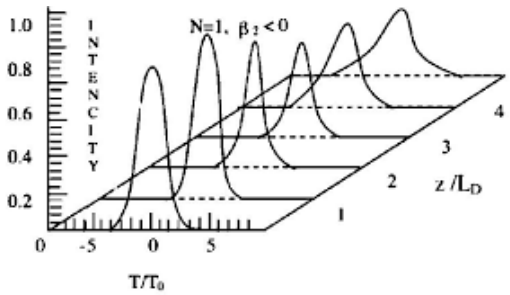

Fig.4. A narrow high intensity pulse that is subjected to kerr effect as it travels through a nonlinear dispersive fiber that has a positive GVD parameter

When a narrow high intensity pulse traverses a medium with a negative GVD parameter , GVD counteracts the chirp produced by SPM. Now GVD retards the low frequencies in the front end of the pulse and advances high frequencies at the back. The result is that The high intensity sharply peaked soliton pulse changes neither its shape nor its spectrum as it travels along the fiber[5].

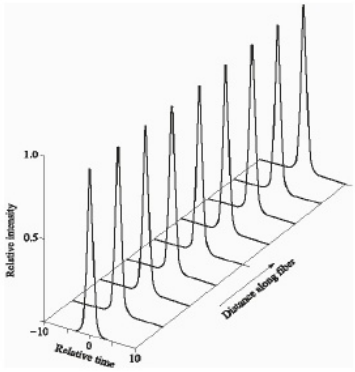

Fig.5. A narrow high intensity sharply peaked soliton pulse that is subjected to kerr effect as it travels through a nonlinear dispersive fiber that has a negative GVD parameter

To derive the evolution of the pulse shape required for soliton transmission we need to consider nonlinear Schrodinger equation (NLS).

$-i\partial u/\partial z = \frac{1}{2}\frac{\partial 2u}{\partial t2} + |u|^2 u - i\ 1/2\alpha u$

The first term of above equation represents GVD effect. The second term denotes the fact that the refractive index of fiber depends on light intensity and the third term represents effect of energy loss or gain.

The solution to above equation for the fundamental soliton is given by

$U(z,t) = sech(t)exp(iz/2)$

6. CONCLUSION

The important advantage of soliton pulses in optical communication is that they reduce the effect of attenuation caused by chromatic dispersion completely.
They are highly immune to fiber dispersion and thus allow transmission at high speed of a few tens of Giga bits per second.

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