SOLITONS: NOVEL APPROACH FOR DISPERSION MANAGEMENT

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Abstract

Soliton is a special kind of wave packet that travels distortion less over long distances. It is a pulse able to maintain its shape and width due to compensation of Self Phase Modulation (SPM) process which is a non-linear effect based on refractive index variation and Group Velocity Dispersion (GVD) process which is a linear effect. For long range communication, soliton pulses are very suitable as the pulse width remain constant over the entire transmission distance. It eliminates the need to cope with any type of dispersion. The transmission of light in optical fiber given by Nonlinear Schrödinger equation has been discussed in the paper. The performance of fiber with soliton parameters is compared to that with fiber without soliton parameters using OptiSystem Software.

Keywords: *Dispersion, GVD, Soliton pulses, SPM*

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1. INTRODUCTION

A solitary wave is a confined wave that ascends from stability between various linear and nonlinear effects. When the optical pulse propagates along the fiber, it experiences GVD and SPM. These effects put limitation on increase in demand of capacity. So, soliton is come into existence.

GVD is a linear effect where refractive index varies with frequency components. When different frequency components travel with different velocity, differential transit time takes place and the pulse gets distorted. Whereas when the nonlinear phase shift of optical signal changes with respect to time, it results in varying frequency called chirping and the phenomena is known as SPM. Positive SPM is caused when refractive index increases with increase in pulse intensity. This alteration in refractive index leads to a phase shift in time domain. The pulse spectrum due to SPM changes, as frequency is the derivative of phase shift in time domain. As a result of combination of the positive GVD and the positive SPM, broadening of the pulse takes place. A pulse with the exact compensation between the negative GVD and the positive SPM, a pulse propagates with no distortion as shown in Fig 1.1.

This astonished, at first, since a change in the time domain and the frequency domain is caused by GVD and SPM respectively. However, a spectrum will retain its shape if any shift in phase is added to a Fourier transform limited pulse in time domain [1]. The pulse propagates with same shape and remains undispersed after travelling long distance, if GVD will cancel this phase shift in the same fiber. Solitons are therefore a remarkable breakthrough in the field of optical fiber communications.

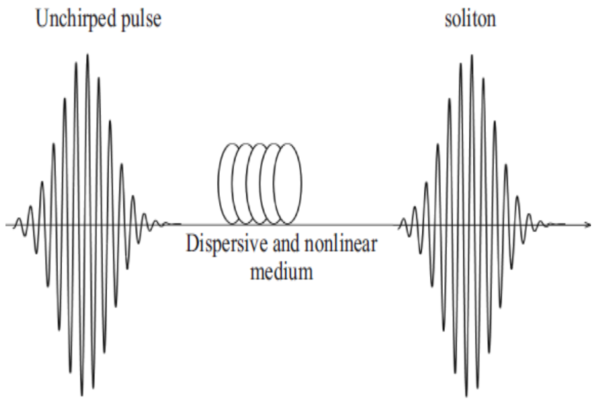

Fig-1.1: Soliton pulse

Solitons are the localized solitary waves that have very distinctive properties: (i) They propagate through the optical fiber at a constant speed by maintaining their shape. (ii) They are enormously stable to the changes produced during propagation especially when collided with small amplitude linear waves. (iii) They remain stable when collision occurs between two soliton pulses. When two soliton pulses collide, they just pass through each other and emerge out by holding their original shape [5].

2. EVOLUTION OF TEMPORAL SOLITONS

In order to understand dispersion properties of optical pulses for a single mode fiber, it is important to know how it propagates under influence of dispersive conditions. This has been briefly discussed by the dispersion broadening processes and self-phase-modulated narrowing processes further.

2.1 Self Phase Modulation

When the pulse itself induces the phase shift, it results in the variation in frequency of a pulse known as SPM. SPM arises as intensity component of the fiber is linked to the refractive index. High refractive index is experienced by the pulse when it propagates along the fiber with high pulse intensity, causes the leading side of pulse to attain a positive refractive index gradient $\left(\frac{dn}{dt}\right)$ and experiences lower refractive index, when it travels with lower pulse intensity, causes the trailing side to attain a negative refractive index gradient$\left(-\frac{dn}{dt}\right)$. Phase shift is induced in the different parts of the pulse due to refractive index variations. This is called frequency edge of the pulse is shown in Fig-2.1. Therefore, main effect of SPM is to spread the pulse by maintaining its temporal shape [6],[7].

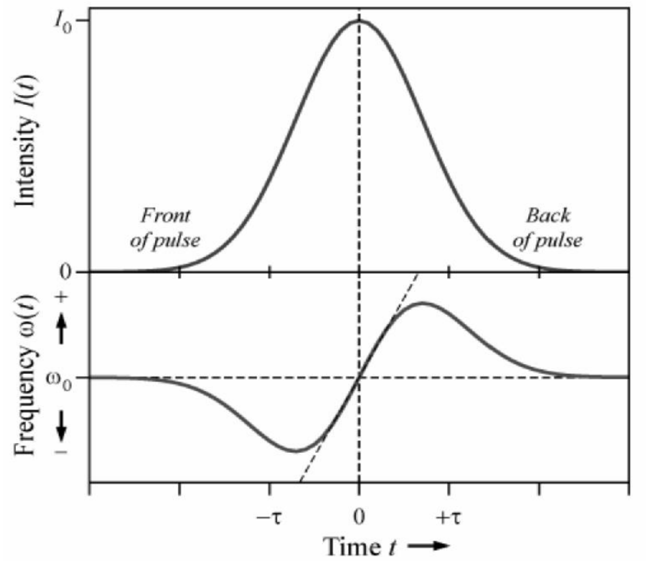

Fig-2.1: Pulse spread due to SPM

For a pulse propagating through the optical fiber of length L with high pulse intensity I, the phase shift [□]isgiven by

$$\phi = \frac{2\pi}{\lambda}(n_1\text{-}n_2 \mathrm{I})L_{eff} \qquad \text{….(1)}$$

where L_{eff} is the effective length and is given by

$$L_{eff} = \frac{1-\exp(-\alpha l)}{\alpha}$$

n_1 is linear R.I, n_2 is non-linear R.I and α is attenuation constant.

In equation (1), $\frac{2\pi}{\lambda}\, n_1 L_{eff}$ is linear phase constant and $\frac{2\pi}{\lambda}\, n_2 \mathrm{I} L_{eff}$ is non-linear phase constant. This phase change in time domain results in different frequency components. When the frequency of optical carrier is modulated then new frequency component becomes

$$\omega' = \omega_0 + \frac{d\phi}{dt} \qquad \text{….(2)}$$

From equation (1) & (2)

$$\frac{d\phi}{dt} = -\frac{2\pi}{\lambda} L_{eff} n_2 \frac{dI}{dt} \qquad \text{….(3)}$$

Therefore

$$\omega' = \omega_0 - \frac{2\pi}{\lambda} L_{eff} n_2 \frac{dI}{dt} \qquad \text{….(4)}$$

At rising edge of pulse $\frac{dI}{dt} > 0$

Then

$$\omega' = \omega_0 - \omega(t) \qquad \text{….(5)}$$

At trailing edge of pulse $\frac{dI}{dt} < 0$

Then

$$\omega' = \omega_0 + \omega(t) \qquad \text{….(6)}$$

where $\omega(t) = \frac{2\pi}{\lambda} L_{eff} n_2 \frac{dI}{dt}$

Thus the variations in frequency components occur due to SPM. This variation further leads to spreading of the pulse.

2.2 Group Velocity Dispersion

When the optical pulse propagates along the fiber, it experiences a group delay, as pulse consists of different wavelengths, each travelling at a different velocity. This group delay leads to the broadening of the pulse. The pulse spreading causes the adjacent pulses to overlap which further leads to Inter Symbol Interference (ISI) [6],[7]. GVD is also referred as group delay dispersion parameter. The group delay, *Ig* per unit length is given by

$$\frac{I_g}{L} = \frac{1}{V_g} = \frac{1}{c}\frac{d\beta}{dk} = \frac{-\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \qquad \text{….(7)}$$

where, L is the distance traveled by the pulse, □ □ is the propagation constant along fiber axis, k is the wave propagation constant , k = $\frac{2\pi}{\lambda}$ and *vg* is the group velocity, $v_g = c\left(\frac{d\beta}{db}\right)^{-1}$. 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 □ □ ,the total delay difference □T over distance L, can be written as

$$\delta T = \frac{\delta I_g}{d\omega}\delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\delta\omega = L(d^2\beta/d\omega^2)\delta\omega \qquad \text{….(8)}$$

where ω is angular frequency.

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

The Group Velocity dispersion puts severe limitation on high bit rate information carrying capacity for long distance optical communication systems. A simple solution to this problem is the use of optical soliton pulses that maintain their width over entire transmission distances. Soliton based optical communication systems can be utilized over long distances with immeasurable data carrying capacity by using optical enhancers and a speed of the order of T bit/s can be accomplished if WDM system with optical amplifiers is consolidated in soliton based communication systems.

3. SOLITON BASED TRANSMISSION

Soliton is a pulse able to keep its shape and width constant and hence propagate undistorted over long distances and stay unaffected after colliding with other soliton pulses.

•RZ (Return to Zero) refers to digital data transmission in which binary low and high states are represented by 0, 1

• NRZ (Not Return to Zero) is a binary code in which 1s are represented by positive voltage.

• Soliton format principally utilizes one soliton to represent '1' bit.

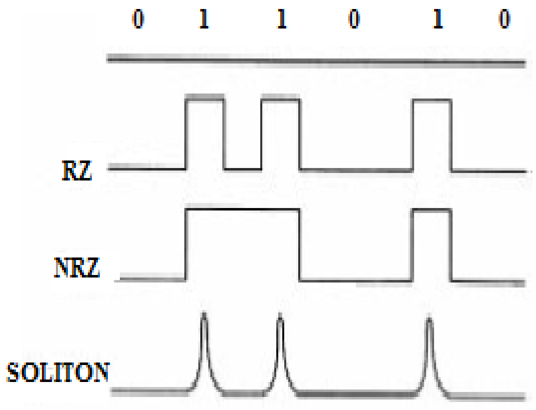

Fig-3.1: RZ, NRZ and SOLITON format

3.1 Transmission of information

While utilizing solitons for dispersion management the conventional approach is to represent the entire bit slot with high pulse, but this is possible only in cases where neighboring bit sequence are isolated and the separation is more than FWHM. The same cannot be used for consecutive similar bits hence in order to use soliton RZ format is used for isolation for every slot shown in Fig-3.2.

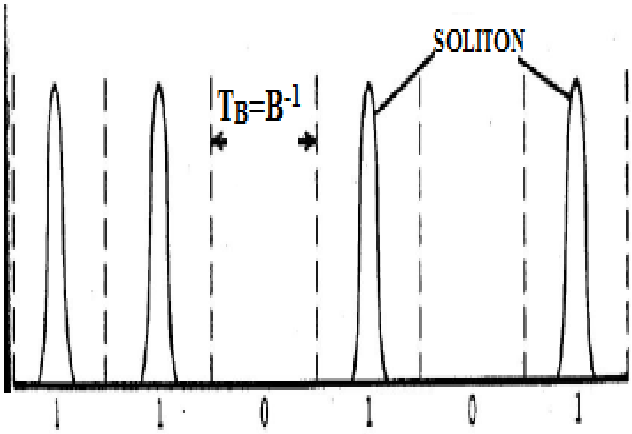

Fig-3.2: Transmitting Soliton pulse using RZ format

The soliton width and Bit rate is related as

$$B= 1/T_B = 1/2q_0T_0$$

where TB is the Bit duration and between the adjacent solitons, the partition is given by $q_0= T_B/T_0$. The optical communication system using soliton pulses requires an optical source that generates Pico-second pulses without any frequency chirping. The wavelength region ~ 1550 nm is used by the optical source.

3.2 Soliton in Optical Fiber

The soliton pulses in optical fibre are present as the result of compensation between the variations induced by fiber dispersion characterized by GVD coefficient β_2 and fiber nonlinearity characterized by SPM coefficient ω. Analytically soliton is a answer of nonlinear Schrodinger equation depicting pulse spreading in optical fiber [5].

The transmission of light in optical fiber is given by nonlinear Schrödinger equation (NLSE). Using standardization parameters for example, the normalized time T_0, the dispersion length L_D and pulse peak power P_0, the nonlinear Schrödinger equation is given by

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

where $u(z, t)$ is pulse envelope function, z is transmission distance along the fiber, soliton order is given by integer N and α is the coefficient of energy where loss in energy is represented by negative values. The value of s is -1 for negative β_2 and +1 for positive β_2 as shown in figure 3.3 and 3.4.

The fundamental soliton is the pulse with order 1and if order is greater than 1then it is known as higher-order solitons [8]. Order of soliton pulses (N) depends on the balance between dispersion and nonlinearity characteristics and is defined as

$$N^2=\frac{\gamma P_0}{|\beta_2|}T_0^2$$

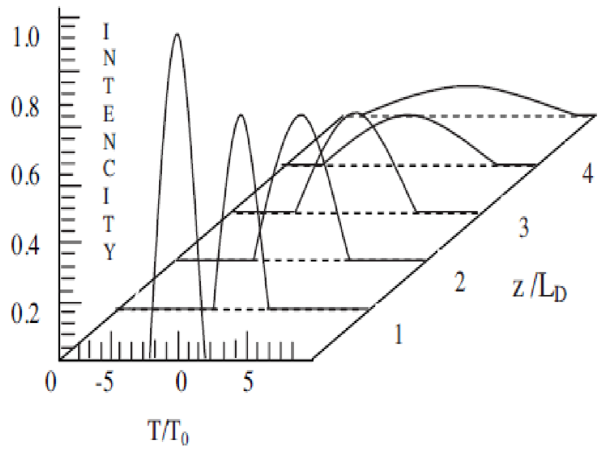

Fig-3.3: Soliton evolution in regime of normal dispersion

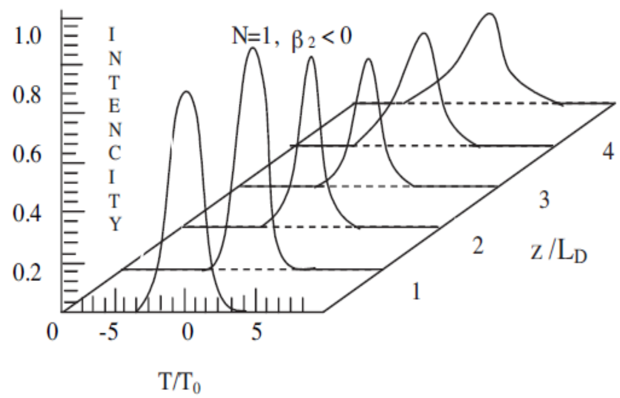

Fig-3.4: Soliton evolution in regime of anomalous dispersion

It is observed that if order of soliton is more than 1 then SPM is high and if order of soliton is less than 1 then GVD increases. At the fundamental order both SPM and GVD cancel each other. So it is efficient to use the fundamental soliton with order 1 as soliton travels undistorted over the entire transmission distance. [5].

The solution for fundamental soliton (N = 1) is given by integrating the NLSE and can be written as

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

where sech (t) is capacity of hyperbolic secant. Since the shape of the pulse is not changed by the phase term exp (iz/2), therefore soliton pulses are independent of z and hence remain distortion less in time domain. As a result fundamental soliton pulses are used in optical communication system. Even if the intensity of pulse changes from the stable conditions, no change is noticed in the optical solitons as they are very stable against perturbations.

4. SIMULATION AND RESULTS

Experimental setup is shown in Fig-4.1 and Fig-4.6 for the comparative study of using fiber for transmitting information up to 1000km with using soliton parameters and without using soliton parameters.

4.1 Without using Soliton Parameters

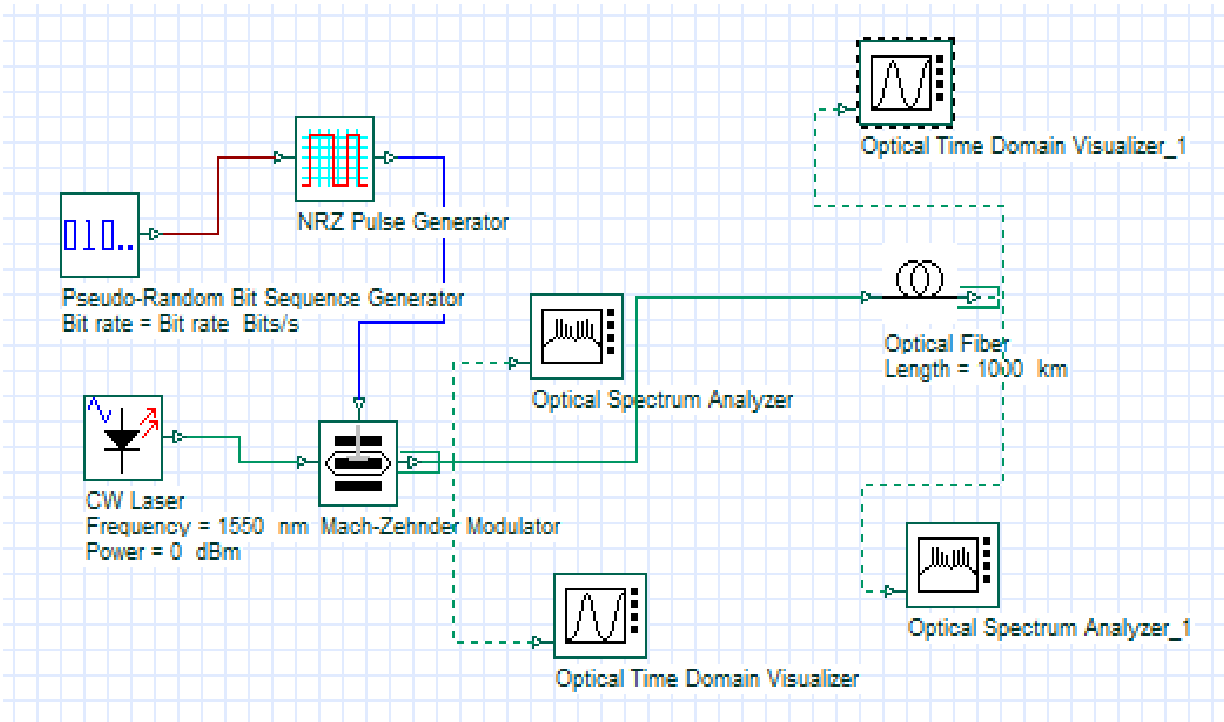

Fig-4.1: System layout

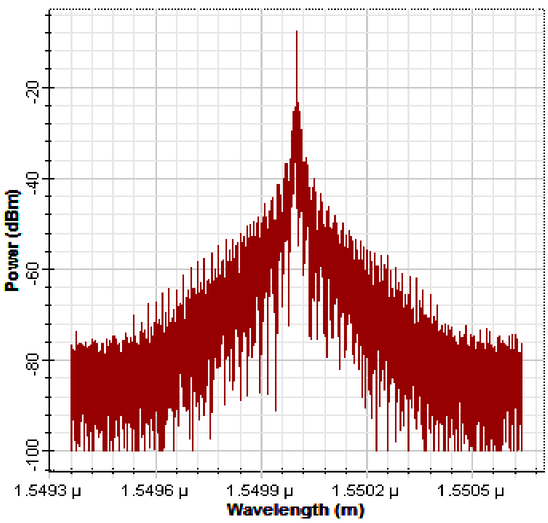

Fig-4.2: Input signal in frequency domain

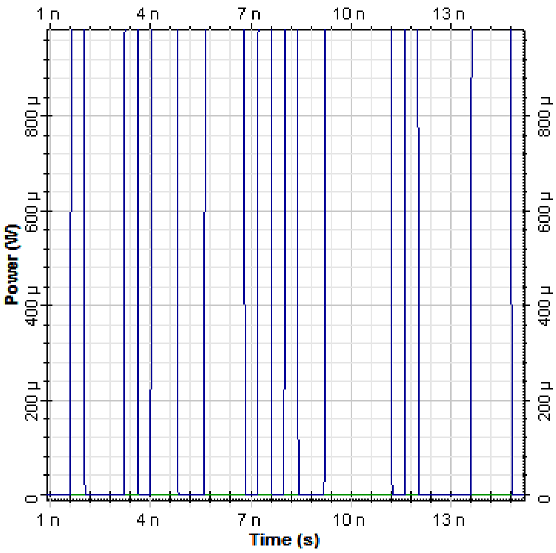

Fig-4.3: Input signal in time domain

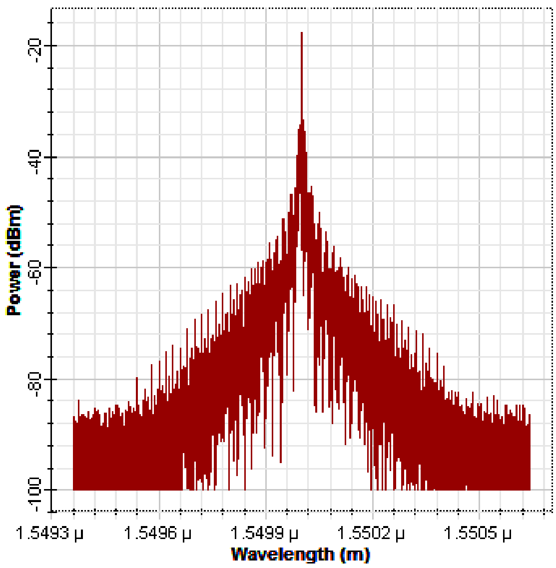

Fig-4.4: Dispersed output signal in frequency domain (without soliton parameters)

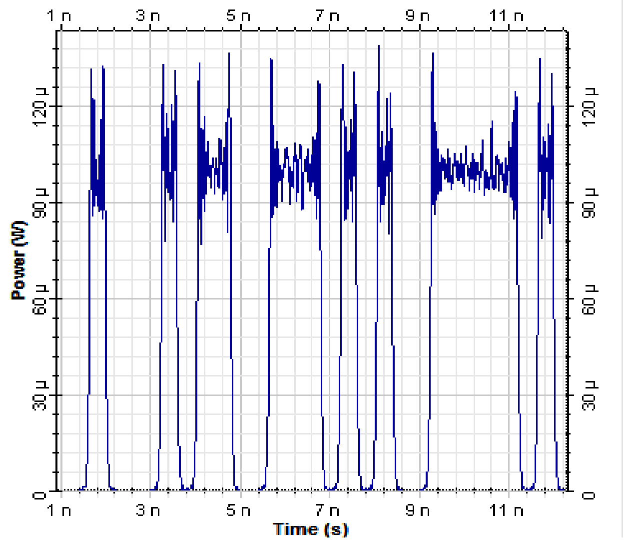

Fig-4.5: Dispersed output signal in time domain (without soliton parameters)

Figure 4.4 and 4.5 shows that the output pulse get dispersed after 1000 km as GVD and SPM causes the pulse to spread in optical fiber. GVD causes the optical pulse to spread in time domain and degrades the signal over long distance, as pulse contains different wavelengths travelling at different velocities and SPM changes the pulse spectrum as phase shift occurs due to pulse intensity. Both GVD and SPM cause the spreading of pulse. So dispersion management is important in optical communication systems because if dispersion is too high, a group of pulses carrying information will spread in time and merge, resulting in the dispersion of the signal.

One conceivable response to this issue is to utilize Soliton pulses in the anomalous dispersion regime, a form of optical pulse which uses non-linear optical effect to maintain its shape and width.

4.2 With using Soliton Parameters

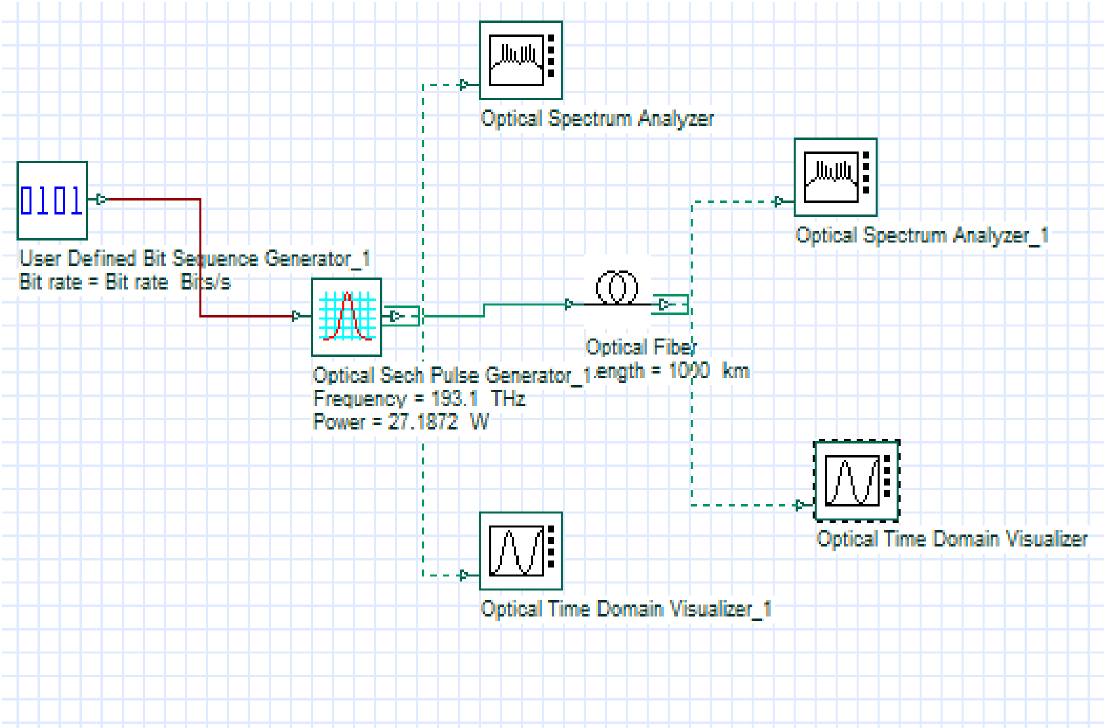

Fig-4.6: System layout

Figure4.6 shows the layout for fundamental soliton N=1.The simulation is done in OptiSystem software. For given n_2=2.5e-20 m^2/W, A_{eff}=50 μm^2, and λ=1550 nm - γ=1.5e-3 1/m/W. The fiber length is set to 1000km.

Initial pulse has a sech shape and FWHM pulse width is 33 ps, corresponding to T_0=15.7 ps. Pulse power for fundamental soliton is 27.18 mW.

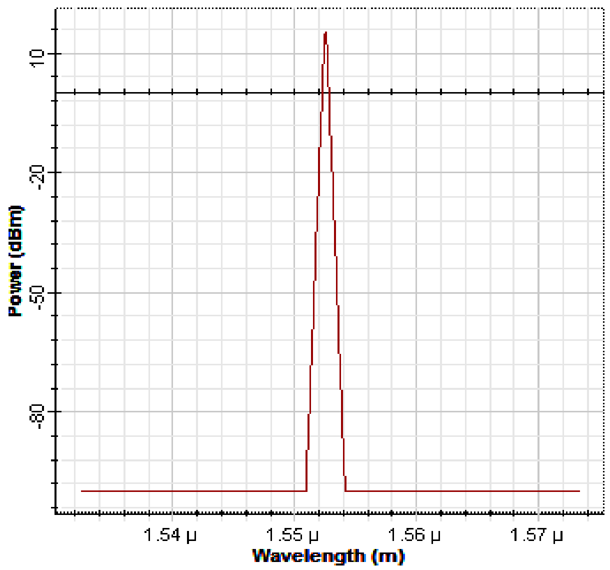

Fig-4.7: Input signal in frequency domain

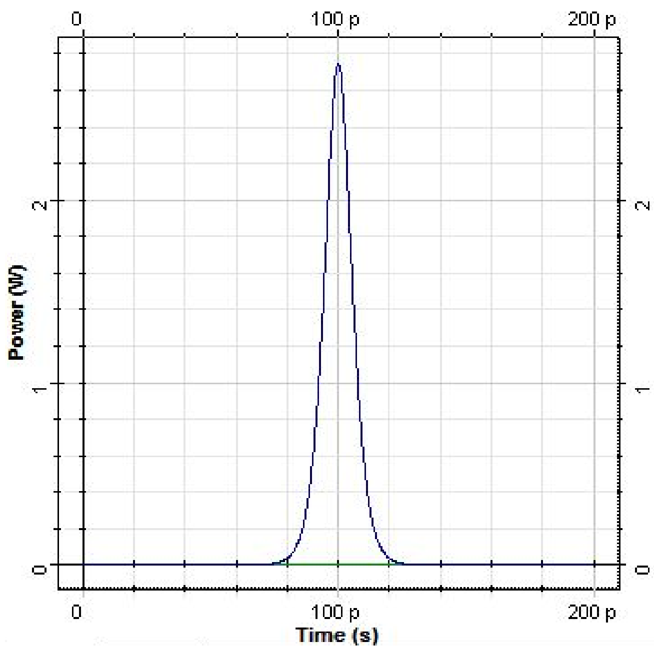

Fig-4.8: Input signal in time domain

Figure 4.9 and 4.10 shows the presence of a fundamental soliton, order (N=1). The fundamental soliton remains distortion less by both SPM and GVD, since in this case they cancel each other completely. The pulse remains chirp less, due to the exact compensation that occurs between the SPM-induced and GVD-induced frequency modulations.

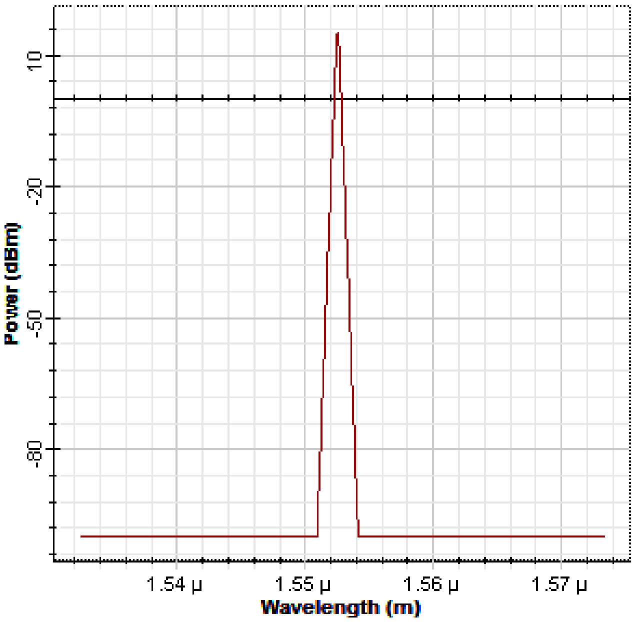

Fig-4.9: Undispersed output signal in frequency domain (with soliton parameters)

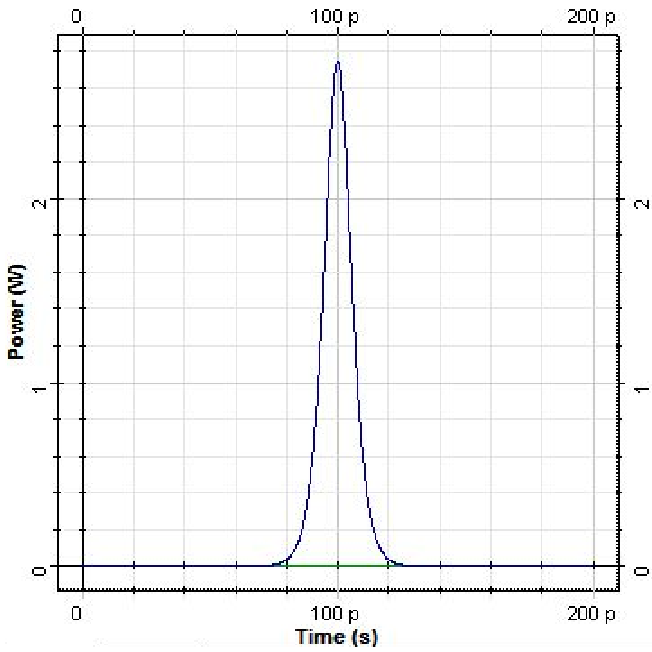

Fig-4.10: Undispersed output signal in time domain (with soliton parameters)

5. CONCLUSION

The optical fiber communication systems with soliton pulses are best suitable for long haul communication as they remain undispersed after travelling long distance. This is experimentally shown in the Fig-4.9 and 4.10 that the exact compensation is made between the SPM induced components and GVD induced components, as compare to the system without using soliton parameters shown in Fig-4.4 and Fig-4.5 where the signal get broaden due to various linear and non-linear factors.

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BIOGRAPHIES

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