Optical Soliton Simulation in Optical Fibers by OptiSystem

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Abstract. Fiber optic communication is often known to offer higher frequency transmission of signals with greater bit rate and larger data carrying capacity over a long distance with lower loss and interference as compared to copper wire electrical communication. However, several factors that would affect the performance of an optical fiber transmission are such as group velocity dispersion (GVD), fiber loss and also self-phase modulation (SPM). In this paper, the effects of GVD, SPM, optical soliton formation and fiber loss are simulated using OptiSystem 14. It is found that GVD broaden pulse in temporal domain without modifying its spectrum. Meanwhile, SPM creates chirp in spectrum with its temporal profile maintained. This work concluded that a balance between the GVD and SPM is essential to form solitons that are able to travel for a long distance without being distorted. It is also found that the decrease in the amplitude of the soliton is dependent on the fiber loss and this decay in the signal increases with the propagation distance.

1. Introduction
Fiber Optic communication uses pulses of light to transmit information through a fiber optic. Fiber Optic communication offers higher frequency transmission of signals with greater bit rate and larger data carrying capacity over a long distance. This means of data transmission is with a lower loss and interference if compared to the normal copper wire used in the electrical telecommunication systems. Optical fiber is widely used in the application of internet communication technology in developing countries largely due to its feasibility to transmit data over a longer distance. However, the good performance of optical fiber transmission are compromised by factors such as group velocity dispersion (GVD), fiber loss and also self-phase modulation (SPM).

The GVD phenomenon or Chromatic dispersion is due to the refractive index $n$ of the fiber, which is a frequency dependent parameter; and dispersion parameter, $D$ (ps/(km.nm)) is related to GVD parameter, $\beta_2$ as follows [1]:
\[ D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 \approx \frac{\lambda}{c} \frac{d^2 n}{d\lambda} \]

where \( \beta_1, c, \lambda \) are first order dispersion, speed of light in vacuum and wavelength, respectively. The unit of \( D \) denotes a pulse of bandwidth of 1 nm (measured in terms of wavelength) spreads by the corresponding number of 1 ps in 1 km.

The dispersion is normal when \( D < 0 \) and \( \beta_2 > 0 \), while the dispersion is anomalous if \( D > 0 \) and \( \beta_2 < 0 \). It must also be mentioned that higher frequency (blue-shifted) pulse traveled slower than lower frequency (red-shifted) pulse in the normal dispersion region. On the other hand, in anomalous dispersion region, higher frequency (blue-shifted) pulse traveled faster than lower frequency (red-shifted) pulse. Since light of different frequencies traveled along the optical fiber at different velocities, they arrived at the receiver at different times. This results in pulse broadening, which causes intersymbol interference and lowered peak intensity over a few kilometers as shown in figure 1. This renders an inaccurate detection of the transmitted signals. [2]

Figure 2(a) shows the intensity \( I \) or power of the light pulse over time \( t \). This diagram shows that when the higher intensity level of the pulse amplitude profile of an optical fiber encounter with higher refractive index \( n \) of the fiber, this yields the leading or front wave (smaller times) has a positive refractive index gradient \( (dn/dt) \) while trailing or back wave (large time) has a negative refractive index gradient \( -(dn/dt) \). [3]

This temporally varying refractive index results in a temporally varying phase shift as shown in the figure 2(b). Since the refractive index increases the most under that portion of the pulse with maximum intensity, the phase delay (shown as negative phase) is an extremum as shown by the curve in Figure 2 (b). [4]. This magnitude decreases as it progressed toward the front and the back of the pulse.

Figure 2(c) shows frequency (rate of change of phase) of the pulse versus time \( t \). It can be seen that the front wave has low frequencies, while back wave has high frequencies. At the center of the pulse, the frequency shift is approximately linear; hence SPM produces chirping phenomena (frequency change) caused by a phase shift induced by the pulse itself. [3] SPM causes spectral change in the waveform without modifying its temporal distribution. The pulse would be further broadened if SPM happened in normal dispersion region since high frequencies (blue-shifted) component of wave traveled slower than low frequencies (red-shifted) component of wave. The otherwise is true if SPM happened in anomalously dispersive region [1, 2]
Losses in fiber or signal attenuation will reduce peak power during transmission of optical signals inside the fiber as given in the formula below:

\[ P_{\text{out}} = P_{\text{in}} e^{-\alpha L}. \]  

(2)

where \( \alpha \) is the attenuation constant, \( L \) is fiber length, \( P_{\text{out}} \) is output power and \( P_{\text{in}} \) is input power. The parameter \( \alpha \) can be expressed as the unit of dB/km using the formula below:

\[ \alpha = -\frac{10}{L} \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right). \]  

(3)

This energy loss can cause interference with neighboring pulses and would adversely affect the system performance.

A balance between pulse narrowing effect caused by SPM and broadening effect due to GVD in the anomalous dispersion region renders a nonlinear wave which can propagate undistorted for long distance, which is known as “soliton”. Soliton-based optical communication systems can be used over distances of several thousands of kilometers with huge information carrying capacity by using optical amplifiers.

The propagation of the optical pulse inside the single mode optical fiber is governed by the nonlinear Schrödinger (NLS) equation which can be derived from Maxwell equation as follows:

\[ i \frac{\partial A}{\partial z} - \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A + i\alpha A = 0, \]  

(4)

where \( A \) is the amplitude of wave, \( \beta_2 \) is GVD parameter, \( \gamma \) is SPM parameter and \( \alpha \) is fiber loss parameter.

In this paper, the effects of GVD, SPM, fiber loss and soliton formation will be simulate by using OptiSytem 14 software.

2. Theoretical Consideration

Substituting the following parameters into Equation (4):

\[ U = \frac{A}{\sqrt{P_0}}, \quad \tau = \frac{T}{T_0} \]  

(5)

where \( P_0 \) is the peak power of the slowly varying envelope \( A(z, T) \), \( T_0 \) is temporal characteristic value of the initial pulse of full-width half maximum (FWHM), Equation (4) can also be expressed as follows:
\[
\frac{i}{\partial z} \frac{\partial U}{\partial z} - \frac{\beta_2}{2T_0^2} \frac{\partial^2 U}{\partial \tau^2} + \gamma P_0 |U|^2 U + \frac{i}{2} \alpha U = 0
\] (6)

Next, introducing dispersion length, \(L_D\) and nonlinear length, \(L_{NL}\) as
\[
L_D = \frac{T^2}{|\beta_2|}, \quad L_{NL} = \frac{1}{\gamma P_0}
\] (7)

and substitute this into Equation (6) gives
\[
\frac{i}{\partial z} \frac{\partial U}{\partial z} - \frac{s}{2L_D} \frac{\partial^2 U}{\partial \tau^2} + \frac{1}{L_{NL}} |U|^2 U + \frac{i}{2} \alpha U = 0
\] (8)

where \(s\) is the sign of \(\beta_2\). The \(s = -1\) corresponds to anomalous GVD which yields bright soliton, while \(s = 1\) is normal GVD which yields dark soliton.

Let \(\xi = \frac{z}{L_D}\) and introducing this into Equation (8) gives
\[
\frac{i}{\partial \xi} \frac{\partial U}{\partial \xi} - \frac{s}{2 \partial \tau^2} N^2 |U|^2 U + \frac{i}{2} L_D \alpha U = 0
\] (9)

where \(N^2 = \frac{L_D}{L_{NL}} = \frac{P_0 T^2}{|\beta_2|}, \quad N\) is soliton number.

The physical meaning of the parameter \(N\) are as follows:

1. if \(N \geq 1\), the nonlinear part of the equation can be neglected. This means \(L_D \gg L_{NL}\) therefore the field will be affected by the linear effect (dispersion) much earlier than the nonlinear effect.
2. if \(N \ll 1\), the nonlinear effect will be more evident than the dispersion and the pulse will be spectrally broaden because of self-phase modulation.
3. if \(N = 1\), the two effects balance each other and soliton solutions are possible.

By taking \(u = NU\), one get
\[
\frac{i}{\partial \xi} \frac{\partial u}{\partial \xi} - \frac{s}{2 \partial \tau^2} |u|^2 u + \frac{i}{2} L_D \alpha U = 0
\] (10)

When \(s = -1\) and \(\alpha = 0\) it gives the mathematical form of the NLS equation as follows:
\[
\frac{i}{\partial \xi} \frac{\partial u}{\partial \xi} + \frac{1}{2 \partial \tau^2} |u|^2 u = 0
\] (11)

Equation (11) is firstly solved by using inverse scattering method proposed by Zakharov and Shabat [5]. Accordingly, when an input pulse with initial amplitude \(u(0,\tau) = N \text{sech}(\tau)\) is launched into the fiber, its shape remains unchanged during propagation when \(N = 1\).

3. Research Method

Figure 3 shows the circuit used in Optisystem 14 in the study of the effects of GVD, SPM, fiber loss and the formation of soliton. Basically, there are three main parts in this circuit, which are transmitter, channel and receiver. User Defined Bit Sequence Generator and Optical Sech Pulse Generator used as a transmitter to generate the pulse, Optical Fiber as a channel for the propagation of pulse while Optical Spectrum Analyzer (OSA) and Optical Time Domain Visualizer (OTDV) as a receiver for users to view their input form and output form. OSA allowed users to view the pulse in the form of spectral while OTDV allowed the time domain view. The OSA and OTDV were placed before and after the optical fiber to allow the viewing of the input pulse and propagated output pulse in both frequency and time domain. Meanwhile, Table 1 shows the values used in the setting of the parameter of the components in Optisystem following the report of [6].


Figure 3. Optisystem Set up

Table 1. Parameters used in simulation of solitons

| Parameter                  | Component                      | Symbol | Value       | Unit       |
|---------------------------|--------------------------------|--------|-------------|------------|
| Bit rate                  | Layout                         | B      | 40          | Gb/s       |
| Sequence length           | Layout                         |        | 8           | bits       |
| Bit sequence              | Bit sequence generator         |        | 00001000    | -          |
| Frequency                 | Optical Sech Pulse Generator   | f      | 193.1       | THz        |
| Peak power                | Optical Sech Pulse Generator   | P₀     | 0.30208     | W          |
| Width                     | Optical Sech Pulse Generator   |        | 0.5         | bit        |
| Wavelength                | Optical fiber                  | λ      | 1550        | nm         |
| Length                    | Optical fiber                  | L      | 3.9482      | km         |
| Attenuation               | Optical fiber                  | α      | 0           | dB/km      |
| GVD                       | Optical fiber                  | β₂     | -20         | ps²/km     |
| Effective area            | Optical fiber                  | Aₑffect| 80          | μm²        |
| Nonlinear index of refraction | Optical fiber                  | n₂     | 2.6×10⁻²⁶   | m²/w       |
| Nonlinear coefficient     | Optical fiber                  | γ      | 1.317       | W⁻¹/km     |
| Birefringence type        | Optical fiber                  | -      | Deterministic|           |
| Differential group delay   | Optical fiber                  | -      | 0           | Ps/km      |
| Pulse Width parameter     | -                              | T₀     | 7.0902      | ps         |
| Dispersion length         | -                              | L₀     | 2.5135      | km         |
| Nonlinearity length       | -                              | L₉NL   | 2.5135      | km         |
| Soliton period            | -                              | z₀     | 3.9482      | km         |

4. Results
This section presents the simulation results of the effects of GVD, SPM, fiber loss and the formation of soliton by using OptiSystem.
4.1. GVD Effect
In the study of the effect of GVD, the GVD and frequency domain parameter function in Dispersion tab of optical fiber properties were checked as shown in figure 4. Meanwhile, SPM and fiber loss were left unchecked as shown in figures 7 and 8, respectively. In this case, \( L_D = 2.5135 \text{km} \), and \( L_{NL} = \infty \) since \( \gamma = 0 \text{w}^{-1} / \text{km} \), hence \( L_D \leq L_{NL} \) and the fiber is linear dispersive [1]. The GVD effect is tested for fiber length of \( L_D \), \( 2L_D \) and \( 4L_D \). Figure 5 shows that GVD broadens initial wave in temporal domain as fiber length increases from \( L_D \), \( 2L_D \) to \( 4L_D \), while maintains its shape in frequency domain as shown in figure 6. This observation is consistent with that reported in [1], which stated that the pulse width \( T(z) \) increased with the distance \( z \) as \( T(z) = \left[ 1 + \left( \frac{z}{L_D} \right)^2 \right]^{1/2} T_0 \). Since the optical pulse propagates at a distance equals to \( L_D \), \( 2L_D \) or \( 4L_D \), the pulse broadens by a factor of \( \sqrt{2} \), \( \sqrt{5} \) or \( \sqrt{17} \), respectively. This pulse broadening phenomenon happened due to the pulse of different frequencies traveled at different velocities and arrived at the receiver at different time point.

![Figure 4. GVD Properties](image)

![Figure 5. The effect of GVD in time domain](image)
Figure 6. The effect of GVD in frequency domain

4.2. SPM Effect
The SPM check box is checked on in order to study the effect of SPM as shown in figure 7. In this case, $L_0 = \infty \text{ km}$ since $\beta_2 = 0 \text{ ps}^2 / \text{ km}$ and $L_{NL} = 2.5135 \text{ km}$, hence $L_0 \gg L > L_{NL}$, wherein GVD effect is negligible while SPM dominates. To test the SPM effect, fiber length of two arbitrarily selected values of 10 km and 20 km were chosen as shown in figure 8 and figure 9. Figure 9 shows that SPM creates more chirp in frequency domain as fiber length increases, while the signals unchanged in time domain as shown in figure 8. The phase shift $\phi$ of an optical pulse propagates along fiber length $L$ with high pulse intensity $I$ and is reported by [7-8] as $\phi = \frac{2\pi}{\lambda} (n - n_{nl}I) L_{\text{eff}}$, where $L_{\text{eff}} = \frac{1-e^{-\alpha L}}{\alpha}$ is the effective length, $n$ is linear refractive index, $n_{nl}$ is nonlinear refractive index and $\lambda$ is wavelength. If the frequency of an optical carrier is modulated, then a new frequency is generated as $\omega' = \omega_0 + \frac{d\phi}{dt}$. The rate of change of phase shift $\phi$ is given by $\frac{d\phi}{dt} = -\frac{2\pi}{\lambda} n_{nl} L_{\text{eff}} \frac{dI}{dt}$. At the leading edge, $\frac{dI}{dt} > 0$ as seen in figure 2a, thus $\omega' = \omega_0 + \frac{d\phi}{dt} = \omega_0 - \frac{2\pi}{\lambda} n_{nl} L_{\text{eff}} \frac{dI}{dt}$. On the other hand, at trailing edge, $\frac{dI}{dt} < 0$ as seen in figure 2a, thus $\omega' = \omega_0 + \frac{d\phi}{dt} = \omega_0 + \frac{2\pi}{\lambda} n_{nl} L_{\text{eff}} \frac{dI}{dt}$. This variation in the frequency (chirping) from low frequency at leading edge to high frequency in trailing edge shown in figure 2c happened due to SPM. The chirping leads to spectral broadening of the pulse without any change in its temporal distribution. This result is considerably consistent with that presented in [1] who reported the generation of new frequency component due to SPM with the propagated distance.
Figure 7. SPM Properties

Figure 8. The Effect of SPM in Time Domain

Figure 9. The Effect of SPM in Spectrum
4.3. Formation of Soliton

The formation of soliton required both GVD and SPM in optical fiber component properties to be enabled to include the effects of both GVD and SPM. Besides, PMD tab option from optical fiber component properties need to be selected, Birefringence type was changed to Deterministic and the Differential Group Delay was set to 0 ps/km as shown in figure 10. The simulation of optical soliton propagation was run for fiber length of one soliton period, $z_0 = 3.9482$ km, $z = 10$ km, and $z = 20$ km. Figure 8 shows that soliton maintained its shape, width and amplitude for these three fiber lengths as the simulation results for these three fiber lengths overlapped exactly both in time domain (figure 8) or frequency domain (figure 9). According to [1], SPM-induced chirp is positive while the dispersion-induced chirp is negative for $\beta_2 < 0$. Thus, in this case the broadening effect of GVD is exactly canceled by the chirp created by SPM. This produces a soliton which is stable and undistorted for long propagation.

![Figure 10. PMD tab properties](image)

![Figure 11. Soliton in time domain](image)
4.4. Effect of Fiber Loss

In the study of the effect of fiber loss or attenuation on soliton propagation, the attenuation effect in figure 13 is enabled. The fiber loss was then tested for two conditions. The first condition is the attenuation being set at $\alpha = 0.3 \text{ dB/km}$ whereas fiber length, $L$ was varied for three different values of 3.9482 km, 10 km and 20 km through Sweep Mode as shown in figure 13. Figure 14 shows that as the fiber length increases, the amplitude of the original wave decreases. The second condition is fiber length, $L$ being fixed at 3.9482 km while fiber loss was varied for three arbitrarily selected values of $\alpha = 0.3 \text{ dB/km}$ $\alpha = 0.6 \text{ dB/km}$ and $\alpha = 0.9 \text{ dB/km}$ as depicted in figure 15. It can be seen that the amplitude of the initial wave decayed as fiber loss increased. These two conditions can be explained mathematically using Equation (2), as attenuation constant $\alpha$ or fiber length $L$ increases, then the output power, which is represented by the amplitude of the output pulse, will be further reduced due to the exponential term of $e^{-\alpha L}$ in Equation (2).

![Figure 12. Soliton in spectrum](image1)

4.5. Conclusion

The results from the study of soliton propagation in optical fibers with varying fiber loss and attenuation show that the attenuation constant $\alpha$ and fiber length $L$ both significantly affect the output power of the soliton pulse. The exponential decay of the pulse amplitude as a function of fiber length and attenuation provides insights into the limitations of soliton propagation in practical applications. Further research could explore different fiber materials and conditions to optimize soliton performance in various optical communication systems.
5. Conclusion
This paper has shown the effects of GVD, SPM and fiber loss in optical fiber. The GVD will broaden the wave in temporal domain, while remain its shape in frequency domain. On the other hand, SPM will change the wave in frequency domain, while its initial wave remained unchanged in temporal domain. The balance between SPM and GVD would produce soliton, which is able to maintain its shape and amplitude for long distance propagation. However, the existence of fiber loss in fiber optic would reduce the amplitude of soliton. As fiber loss increases, the soliton further decreases in its amplitude. This decrease in the magnitude of the soliton with fiber loss increases with the fiber length. The soliton properties which preserve their shape and amplitude over a long distance revealed a promising potential for long-haul optical communication. Unfortunately, as soliton propagated along the fiber for a long distance, the SPM effect would not be strong enough to compensate for the dispersion due to the fiber loss in fiber optic. Hence, to take care of fiber loss, optical amplifiers are introduced to compensate for accumulated fiber loss in each section of the optical system. Soliton-based optical communication system are yet to be deployed with the development of technology.

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