

Single Mode Optical Fiber – Nonlinearity

1 OBJECTIVE

Characterize analytically and through simulation the effects of nonlinearity on optical systems.

2 PRE-LAB

The effects of loss and dispersion have already been analyzed, both of which can limit the performance of an optical communication system. A naïve approach to compensating these detrimental effects would be to simply increase the input power of the signal, however as the input power increases so does the contribution of self-phase modulation (SPM), which is a nonlinear effect. At a certain point the optical system may no longer be a loss limited system, but a self-phase modulation limited system. Nonlinear effects is actually a very broad term for a large amount of interesting phenomena in optical fibers, but in this assignment, the nonlinear index responsible for SPM will be analyzed in particular.

SPM can also be exploited, with the proper conditions, to propagate a special case of optical pulses, called a soliton. These solitons propagate along a fiber without changing their shape over large distances.

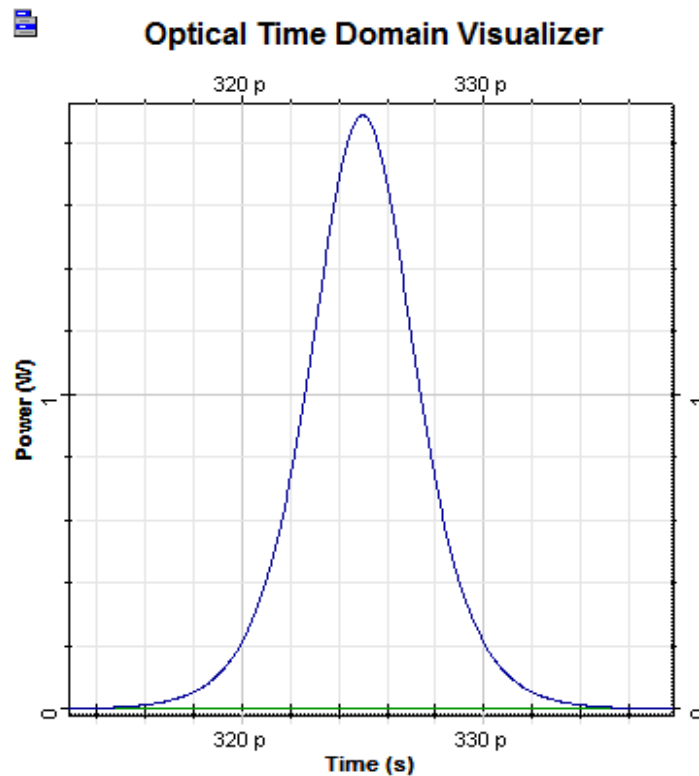


Figure 1: Profile of a hyperbolic secant optical pulse, which corresponds to the solution of the fundamental optical soliton.

Although nonlinearity can manifest itself in many different ways in fiber optics, generally their effect is quite small unless particular situations arise. However, self-phase modulation and cross phase modulation can accumulate over long distances of fiber for modest optical powers causing a real problem for communication systems.

2.1 NONLINEAR SCHRÖDINGER EQUATION

The index of refraction of a material is not only dependent on the frequency (dispersion), but it can also depend on the intensity of the optical signal. This is called the optical Kerr effect and is due to the dependence of the induced polarization, \mathbf{P}_{NL} , on the third-order susceptibility, $\chi^{(3)}$. The additional polarization manifests as an index of refraction that is a function of the intensity:

$$n = n_L + n_2|E|^2, \quad (1)$$

$$\alpha = \alpha_L + \alpha_2|E|^2. \quad (2)$$

The second term, α_2 , is the two photon absorption coefficient and is very small for silica fibers. Starting from the Helmholtz wave equation and approximating the optical signal as a slowly varying envelope, $A(z, t)$, the nonlinear Schrödinger equation can be written:

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{\alpha}{2} A = i\gamma|A|^2 A, \quad (3)$$

where β_1 is the first Taylor series coefficient of the wavenumber (responsible for Group Velocity Dispersion), α is the absorption coefficient and γ is the nonlinear parameter given by:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \quad (4)$$

with A_{eff} as the effective area calculated from the spatial distribution and λ the carrier wavelength. As discussed in a previous laboratory, dispersion causes optical pulses to broaden and chirp, because the frequencies begin to accumulate a delay or phase shift between them as they propagate at different speeds.

In self phase modulation on the other hand, the pulse experiences a power dependent phase change, which chirps the signal where the derivative of the pulse power is largest.

As dispersion and self-phase modulation only effect the pulse envelope over large distances, two quantities can be defined to describe their relative importance. Using the pulse width T_0 , and the peak power, P_0 , the length of the fiber can be compared to the dispersion length and nonlinear length.

$$L_D = \frac{T_0^2}{|\beta_2|}, \quad (5)$$

$$L_{NL} = \frac{1}{\gamma P_0}, \quad (6)$$

If the fiber length is comparable to these two quantities then it is no longer accurate to ignore these effects.

Questions:

- 2.1.1 For a Gaussian envelope, where would the signal experience the greatest nonlinear phase shift?
- 2.1.2 Remember that the chirp of a pulse can be found from the derivative of the instantaneous phase with respect to time. Does the maximum chirp occur at the same place as the maximum phase shift?
- 2.1.3 A fiber is 100 km long and assume the loss is 0. The group velocity dispersion is $-10 \text{ ps}^2/\text{km}$, effective area is $80 \mu\text{m}^2$, nonlinear index of $26\text{E-}21 \text{ m}^2/\text{W}$. For a system transmitting 1550 nm pulses with width 25 ps and power 5 mW, what are the dispersive and nonlinear lengths?
- 2.1.4 Is the system in the previous question limited by dispersion or nonlinearity?

2.2 SPM EFFECT ON PULSES

SPM causes pulses to experience a power dependent phase shift and a subsequent chirp. In this next section, the exact nature of this chirp will be investigated. Setup up the following layout:

- | | |
|--|---|
| • User Defined Bit Sequence Generator | Transmitters Library/Bit Sequence Generators |
| • Optical Gaussian Pulse Generator | Transmitters Library/Pulse Generators/Optical |
| • Fork 1x2 | Tools Library |
| • Optical Power Detector | Receivers Library/Photodetectors |
| • Optical Time Domain Visualizer | Visualizer Library/Optical |
| • Optical Spectrum Analyzer | Visualizer Library/Optical |
| • Dual Port Optical Time Domain Visualizer | Visualizer Library/Compare |

Normally in OptiSystem the simulation will deal with large bit sequences, but in this case particular attention to a single pulse is needed, so a couple modifications to the normal layout parameters take place. First a sequence length of 16 will be used and a samples per bit of 64. Set the Bit rate and symbol rate to 100 Gbps as well.

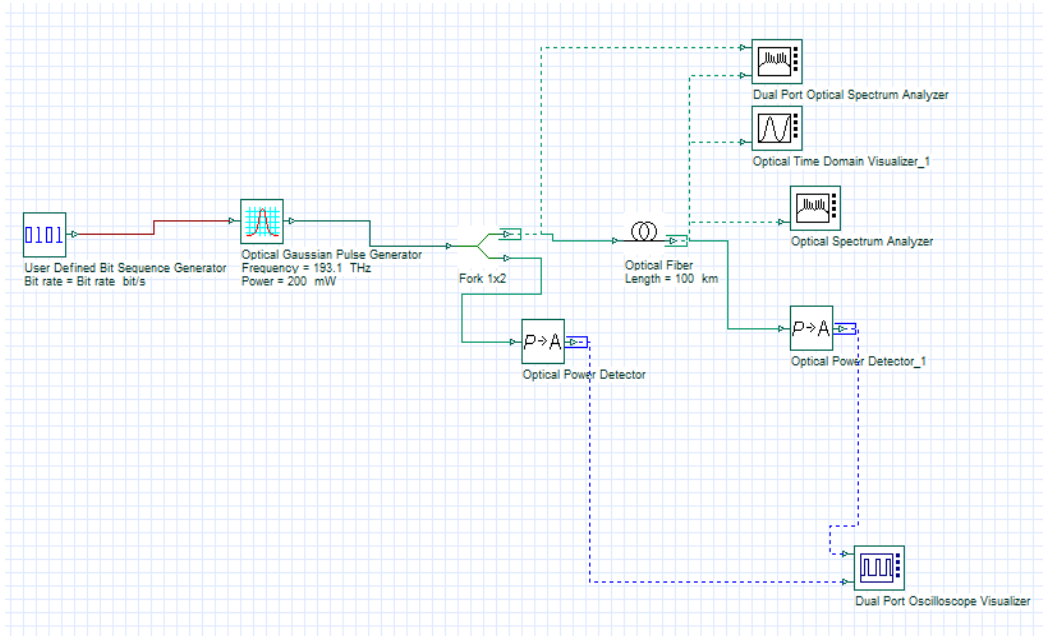


Figure 2: Layout for investigating the chirp induced on an optical pulse.

The focus of the simulation is on one pulse, so in the User Defined Bit Sequence Generator the sequence needs to be changed to “000000001”, since the total sequence length is 16 the defined sequence will be repeated leaving a single pulse in the center of the time window. The pulse generator options need to be also changed, since SPM depends on peak power the Power will be changed to a large value of 200 mW. To simulate only the effects of SPM, disable the attenuation and dispersion in the Optical Fiber component. In the PMD (polarization mode dispersion) tab, you will also need to change the Birefringence type to Deterministic and the differential group delay to 0 ps/km.

Questions:

- 2.2.1 The width parameter given in the pulse generator is actually the full width half maximum, which is a slightly different definition than T_0 . For a Gaussian pulse:

$$U(t) = e^{-t^2/T_0^2}, \quad (7)$$

find the relation between the full width half maximum and T_0 , which is the half-width at $1/e$ intensity.

- 2.2.2 Calculate the nonlinear length L_{NL} .
- 2.2.3 Perform a 6 step sweep of the fiber length from 10 km to 60 km. Export the optical spectrum analyzer data and superimpose the spectrums onto one plot. Describe the change.
- 2.2.4 Investigate the change on pulse in the time domain with the time domain visualizer over the same distances. Explain how the pulse changes and with using markers plot the chirp parameter (in the central linear portion) as a function of propagation distance.

From the theory on dispersion, the chirp parameter is scaled by the pulse width, T_0 in the equation:

$$\delta\omega = \frac{c}{T_0^2} t. \quad (8)$$

2.3 FUNDAMENTAL SOLITONS

As the previous simulations have just shown, SPM chirps the Gaussian pulse with a positive chirp. In fact the relationship is a little more complicated as near the edges of the pulse the chirp is not linear, but the central region is. In the previous dispersion laboratory it was found that chromatic dispersion can, in the case of anomalous dispersion, cause a negative chirp over the pulse. It can be shown through inverse scattering theory that there exists conditions where the self-phase modulation and dispersion balance each other out perfectly. This results in a pulse, called a soliton, which does not change its shape even over large propagation distances. The condition for a soliton is met when the nonlinear length and dispersion length are equal:

$$L_{NL} = L_D, \quad (9)$$

$$\frac{1}{\gamma P_0} = \frac{T_0^2}{|\beta_2|}. \quad (10)$$

Or the introducing a new variable, the condition can be met by enforcing $N = 1$.

$$N = \frac{\gamma P_0 T_0^2}{|\beta_2|} \quad (11)$$

It is also important to note that the profile is not Gaussian, in fact it is a hyperbolic secant. However, injecting a Gaussian pulse with the approximate form will converge to a soliton through propagation.

- 2.3.1 For the default optical fiber in OptiSystem, which is the same as the fiber used in the previous simulations, and using an optical pulse with full width at half maximum of 5 ps what is the peak power needed to excite a soliton. Calculate the associated nonlinear and dispersion lengths. Make sure the Frequency domain parameters option is checked, so that dispersion is described by Beta 2.
- 2.3.2 Simulate the propagation of a fundamental soliton with the aforementioned properties. Use the same project layout as for the previous section with one important change. The Optical Gaussian Pulse Generator should be replaced with an Optical Sech Pulse Generator. Plot the full width half maximum of the pulse as a function of the propagation distance to confirm soliton excitation.

2.4 NESTED SWEEPS

Another useful function in OptiSystem is the multi-parameter sweep, which has been introduced in earlier laboratories. In some cases, like in the next section, there might be more than one parameter that is of interest in the simulations. In this case, a nested sweep needs to be implemented. As a simple example, a nested sweep of the optical fiber length and input power will be simulated.

Start by changing the Modes to Sweep for both the Power of the pulse generator and the Length of the optical fiber. Then click the Parameter Sweeps tool on the toolbar.

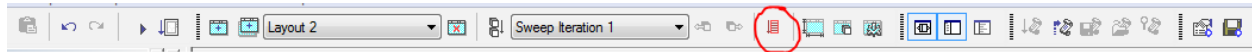


Figure 3: Toolbar snapshot

OptiSystem will then ask to set the total number of iterations, this example calls for 5 different values for power and 5 different values for the fiber length, which means the total iterations needs to be set to 25. In the Parameter Sweeps window choose the “Nested Parameters...” option.

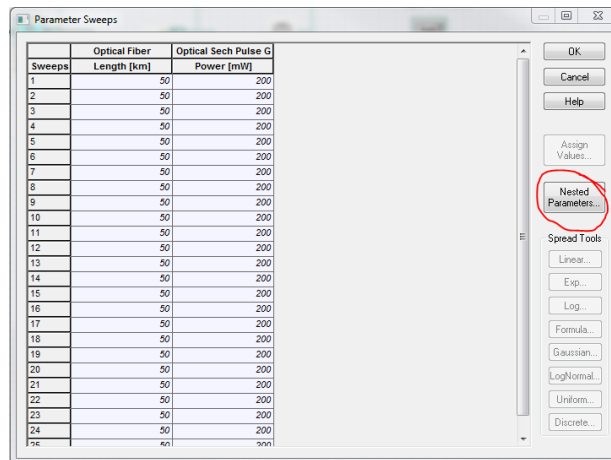


Figure 4: The parameter sweeps window.

Right-click the Nested Levels folder and choose to add a new level. After dragging the Power parameter into this new level, right-click the Level 2 folder and change the number of iterations to 5 and do the same for the Level 1 folder. Select the Power column and choose a linear spread from 150 to 250 mW.

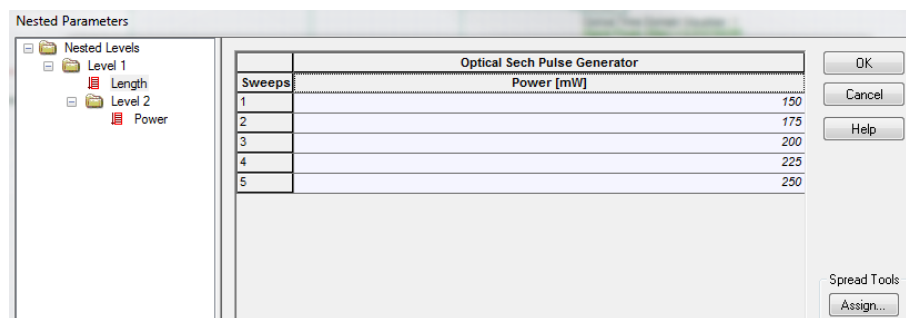


Figure 5: Nester Parameters window

Finally, select the Length column and create a linear spread starting from 20 km to 100 km. Now the Parameter sweep will formatted into a nested structure as seen in the Parameter Sweeps window.

| Parameter Sweeps | | |
|------------------|---------------|----------------------|
| | Optical Fiber | Optical Sech Pulse G |
| Sweeps | Length [km] | Power [mW] |
| 1 | 20 | 150 |
| 2 | 20 | 175 |
| 3 | 20 | 200 |
| 4 | 20 | 225 |
| 5 | 20 | 250 |
| 6 | 40 | 150 |
| 7 | 40 | 175 |
| 8 | 40 | 200 |
| 9 | 40 | 225 |
| 10 | 40 | 250 |
| 11 | 60 | 150 |
| 12 | 60 | 175 |
| 13 | 60 | 200 |
| 14 | 60 | 225 |
| 15 | 60 | 250 |
| 16 | 80 | 150 |
| 17 | 80 | 175 |
| 18 | 80 | 200 |
| 19 | 80 | 225 |

Figure 6: List of the parameter sweeps

3 SOLITON BASED COMMUNICATION SYSTEM

Solitons are a definite interest in communication research, but in practical communication systems it is hard to take advantage of their stable nature, because in many cases it is complicated to balance the required pulse power and pulse width. In addition, the amplification of solitons needs to be carefully engineered, so that the pulse remains a soliton. Furthermore, the soliton solution to the inverse scattering method assumes no nearby (in time) additional pulses. When two solitons propagate close to each other they can attract or repel and thus their position in time changes periodically over the propagation distance.

3.1 SOLITON SPACING

Using the following table of parameters setup a layout similar to the previous ones for simulating pulse propagation through the fiber. Leave all unspecified parameters as the default value. Remember that the pulse generator components expect the full width at half maximum as the parameter and not the pulse width.

| System Characteristics | |
|--------------------------|----------------------------|
| Optical Fiber | |
| Loss | 0 db/km |
| Third-order dispersion | Disabled |
| Beta 2 | -0.1 ps ² /km |
| Beta 3 | 0 |
| Birefringence type | Deterministic |
| Differential group delay | 0 ps/km |
| Effective area | 10 μm ² |
| n ₂ | 6.17E-21 m ² /W |

| Signal | |
|-----------------|----------|
| Type | Sech |
| Pulse width | 2 ps |
| Bit rate | 100 Gbps |
| Sequence length | 16 |
| Samples per bit | 64 |

Questions:

- 3.1.1 Find the proper peak power for soliton generation.
- 3.1.2 Propagate two soliton pulses through the fiber, so that they are separated by 1 bit period. In multiples of the dispersion length, how long does it take for the pulses to overlap? Plot the evolution of the peak power to accurately predict this point.
- 3.1.3 Plot the merging length as a function of the soliton spacing, starting with 10 ps and ending at a spacing of 5 ps. Describe this relationship and explain what it means for communication systems exploiting solitons.

4 REPORT

In your lab report include the following:

- Brief overview of the background and theory.
- Answers to all pre lab questions, clearly showing your work.
- Brief description of the simulation method and setup, including screenshots.
- Final results including figures and discussion.

5 REFERENCES

- [1] Agrawal, G. P. *Fiber-optic Communication Systems*. New York: Wiley, 1997. Print
- [2] G. Agrawal, *Nonlinear Fiber Optics*, 5th ed. Rochester: The Institute of Optics University of Rochester, 2000.