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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

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Prepared By: Dr.A.Rajasekaran, Assistant Professor
Sri.T.Dineshkumar, Assistant Professor
Dr.M.Sivakumar, Sr.Lab Instructor

Approved By: Prof.V.Swaminathan, Professor & Head



OptiSystem

Getting Started

Optical Communication System Design Software

Version 12



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Getting Started

Optical Communication System Design Software

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Technical Support

If you purchased Optiwave software from a distributor that is not listed here, please send technical questions to your distributor.

Optiwave

Tel (613) 224-4700

Fax (613) 224-4706

E-mail support@optiwave.com

URL www.optiwave.com

Canada/US

Optiwave Japan

Tel +81.43.375.2644

Fax +81.43.375.2644

E-mail support@optiwave.jp

URL www.optiwave.jp

Japan

Optiwave Europe

Tel +33 (0) 494 08 27 97

Fax +33 (0) 494 33 65 76

E-mail support@optiwave.com

URL www.optiwave.eu

Europe

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Installing OptiSystem

Before installing OptiSystem, ensure the system requirements described below are available.

Hardware and software requirements

OptiSystem requires the following minimum system configuration:

- PC with Pentium 3 processor or equivalent
- Microsoft Windows XP, Windows Vista or Windows 7 or 8 (32-bit or 64-bit).
- 400 MB free hard disk space
- 1024 x 768 graphic resolution, minimum 65536 colors
- 128 MB of RAM (recommended)
- Internet Explorer 5.5 or higher
- DirectX 8.1 or higher

Protection key

A hardware protection key is supplied with the software.

Note: Please ensure that the hardware protection key is NOT connected during the installation of OptiSystem.

To ensure that OptiSystem operates properly, verify the following:

- The protection key is properly connected to the parallel/USB port of the computer.
- If you use more than one protection key, ensure that there is no conflict between the OptiSystem protection key and the other keys.

Note: Use a switch box to prevent protection key conflicts. Ensure that the cable between the switch box and the computer is a maximum of one meter long.

OptiSystem directory

By default, the OptiSystem installer creates an OptiSystem directory on your hard disk. The OptiSystem directory contains the following subdirectories:

- **\bin** — executable files, dynamic linked libraries, and help files
- **\components** — OptiSystem component parameters from vendors
- **\documentation** — OptiSystem support documentation
- **\libraries** — OptiSystem component libraries
- **\samples** — OptiSystem example files

Note: For the users of the **Amplifier Edition** of OptiSystem, refer to the 'Optical Amplifiers' folder under '\Samples'. For the users of the **Multimode Edition** of OptiSystem, refer to the '\Multimode' folder under '\Samples'.

Installation

We recommend that you exit all Windows programs before running the setup program. To install OptiSystem, perform the following procedure.

- | Step | Action |
|------|---|
| 1 | Log on as the Administrator, or log onto an account with Administrator privileges. |
| 2 | Insert the OptiSystem CD into your CD ROM drive. |
| 3 | On the Taskbar, click Start and select Run .
<i>The Run dialog box appears.</i> |
| 4 | In the Run dialog box, type F:\setup.exe , where F is your CD ROM drive. |
| 5 | Click OK and follow the screen instructions and prompts. |
| 6 | When the installation is complete, reboot your computer. |

Technical support

Phone	(613) 224-4700—Monday to Friday, 9:00 a.m. to 5:00 p.m. Eastern Standard Time
Fax	(613) 224-4706
E-Mail	support@optiwave.com
URL	www.optiwave.com

Introduction

Optical communication systems are increasing in complexity on an almost daily basis. The design and analysis of these systems, which normally include nonlinear devices and non-Gaussian noise sources, are highly complex and extremely time-intensive. As a result, these tasks can now only be performed efficiently and effectively with the help of advanced new software tools.

OptiSystem is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcasting systems to intercontinental backbones.

OptiSystem is a stand-alone product that does not rely on other simulation frameworks. It is a system level simulator based on the realistic modeling of fiber-optic communication systems. It possesses a powerful new simulation environment and an hierarchical definition of components and systems. Its capabilities can be extended easily with the addition of user components, and can be seamlessly interfaced to a wide range of tools.

A comprehensive Graphical User Interface (GUI) controls the optical component layout and netlist, component models, and presentation graphics (see [Figure 1 on page 10](#)).

The extensive library of active and passive components includes realistic, wavelength-dependent parameters. Parameter sweeps allow you to investigate the effect of particular device specifications on system performance.

Created to address the needs of research scientists, optical telecom engineers, system integrators, students, and a wide variety of other users; OptiSystem satisfies the demand of the booming photonics market for a powerful and easy-to-use optical system design tool.

Benefits

- Rapid, low-cost prototyping
- Global insight into system performance
- Straightforward access to extensive sets of system characterization data
- Automatic parameter scanning and optimization
- Assessment of parameter sensitivities aiding design tolerance specifications
- Dramatic reduction of investment risk and time-to-market
- Visual representation of design options and scenarios to present to prospective customers

Applications

OptiSystem allows for the design automation of virtually any type of optical link in the physical layer, and the analysis of a broad spectrum of optical networks, from long-haul systems to MANs and LANs.

OptiSystem's wide range of applications include:

- Optical communication system design from component to system level at the physical layer
- CATV or TDM/WDM network design
- Passive optical networks (PON) based FTTx
- Free space optic (FSO) systems
- Radio over fiber (ROF) systems
- SONET/SDH ring design
- Transmitter, channel, amplifier, and receiver design
- Dispersion map design
- Estimation of BER and system penalties with different receiver models
- Amplified system BER and link budget calculations

Samples library

OptiSystem includes an extensive library of sample optical design (.osd) files (in excess of 200) that can be used as templates for optical design projects or for learning and demonstration purposes. These files can be found in the "samples" folder of the root directory where Optiwave is installed.

Main features

The main features of the OptiSystem interface include:

Feature	Description
Component Library	To be fully effective, component modules must be able to reproduce the actual behavior of the real device and specified effects according to the selected accuracy and efficiency. The OptiSystem Component Library includes hundreds of components, all of which have been carefully validated in order to deliver results that are comparable with real life applications.
Measured components	The OptiSystem Component Library allows you to enter parameters that can be measured from real devices. It integrates with test and measurement equipment from different vendors.
Integration with Optiwave Software Tools	OptiSystem allows you to employ specific Optiwave software tools for integrated and fiber optics at the component level: OptiAmplifier, OptiBPM, OptiGrating, WDM_Phasar, OptiFiber & OptiSPICE.
Mixed signal representation	OptiSystem handles mixed signal formats for optical and electrical signals in the Component Library. OptiSystem calculates the signals using the appropriate algorithms related to the required simulation accuracy and efficiency.
Quality and performance algorithms	In order to predict the system performance, OptiSystem calculates parameters such as BER and Q-Factor using numerical analysis or semi-analytical techniques for systems limited by inter symbol interference and noise.
Advanced visualization tools	Advanced visualization tools produce OSA Spectra, signal chirp, eye diagrams, polarization state, constellation diagrams and much more. Also included are WDM analysis tools listing signal power, gain, noise figure, and OSNR per channel.
Data monitors	You can select component ports to save the data and attach monitors after the simulation ends. This allows you to process data after the simulation without recalculating. You can attach an arbitrary number of visualizers to the monitor at the same port.
Hierarchical simulation with subsystems	To make a simulation tool flexible and efficient, it is essential to provide models at different abstraction levels, including the system, subsystem, and component levels. OptiSystem features a truly hierarchical definition of components and systems, enabling you to employ specific software tools for integrated and fiber optics at the component level, and allowing the simulation to be as detailed as the desired accuracy dictates.

Feature	Description
User-defined components	You can incorporate new components based on subsystems and user-defined libraries, or use co-simulation with a third party tool such as MATLAB or Simulink.
Powerful Script language	You can enter arithmetical expressions for parameters and create global parameters that can be shared between components and subsystems using standard VB Script language. The script language can also manipulate and control OptiSystem, including calculations, layout creation and post-processing when using the script page.
State-of-the-art calculation data-flow	The Calculation Scheduler controls the simulation by determining the order of execution of component modules according to the selected data flow model. The main data flow model that addresses the simulation of the transmission layer is the Component Iteration Data Flow (CIDF). The CIDF domain uses run-time scheduling, supporting conditions, data-dependent iteration, and true recursion.
Multiple layouts	You can create many designs using the same project file, which allows you to create and modify your designs quickly and efficiently. Each OptiSystem project file can contain many design versions. Design versions are calculated and modified independently, but calculation results can be combined across different versions, allowing for comparison of the designs.
Report page	A fully customizable report page allows you to display any set of parameters and results available in the design. The produced reports are organized into resizable and moveable spreadsheets, text, 2D and 3D graphs. It also includes HTML export and templates with pre-formatted report layouts.
Parameter sweeps and optimizations	Simulations can be repeated with an iterated variation of the parameters. OptiSystem can also optimize any parameter to minimize or maximize any result or can search for target results. You can combine multiple parameter sweeps and multiple optimizations.
OptiPerformer	For any given system topology and component specification scenario, a full OptiSystem project can be encrypted and exported to OptiPerformer. OptiPerformer users can then vary any parameter within defined specification ranges, and observe resulting system effects via detailed graphics and reports.
Bill of materials	OptiSystem provides a cost analysis table of the system being designed, arranged by system, layout or component. Cost data can be exported to other applications or spreadsheets.

Notes:



INTRODUCTION



Quick Start

This section describes how to load a design, run a simulation, edit local and global parameters, and obtain results. The most efficient way to become familiar with OptiSystem is to complete the lessons in the Tutorials, where you learn how to use the software by solving problems.

Note: For the users of the **Amplifier Edition** of OptiSystem we recommend to follow **Lesson 7: Optical Amplifiers - Designing optical fiber amplifiers and fiber lasers**, and for the users of the **Multimode Edition** of OptiSystem we recommend to follow **Lesson 8: Optical Systems - Working with multimode components**. Both lessons are available in the OptiSystem tutorials book.

Starting OptiSystem

To start **OptiSystem**, perform the following action.

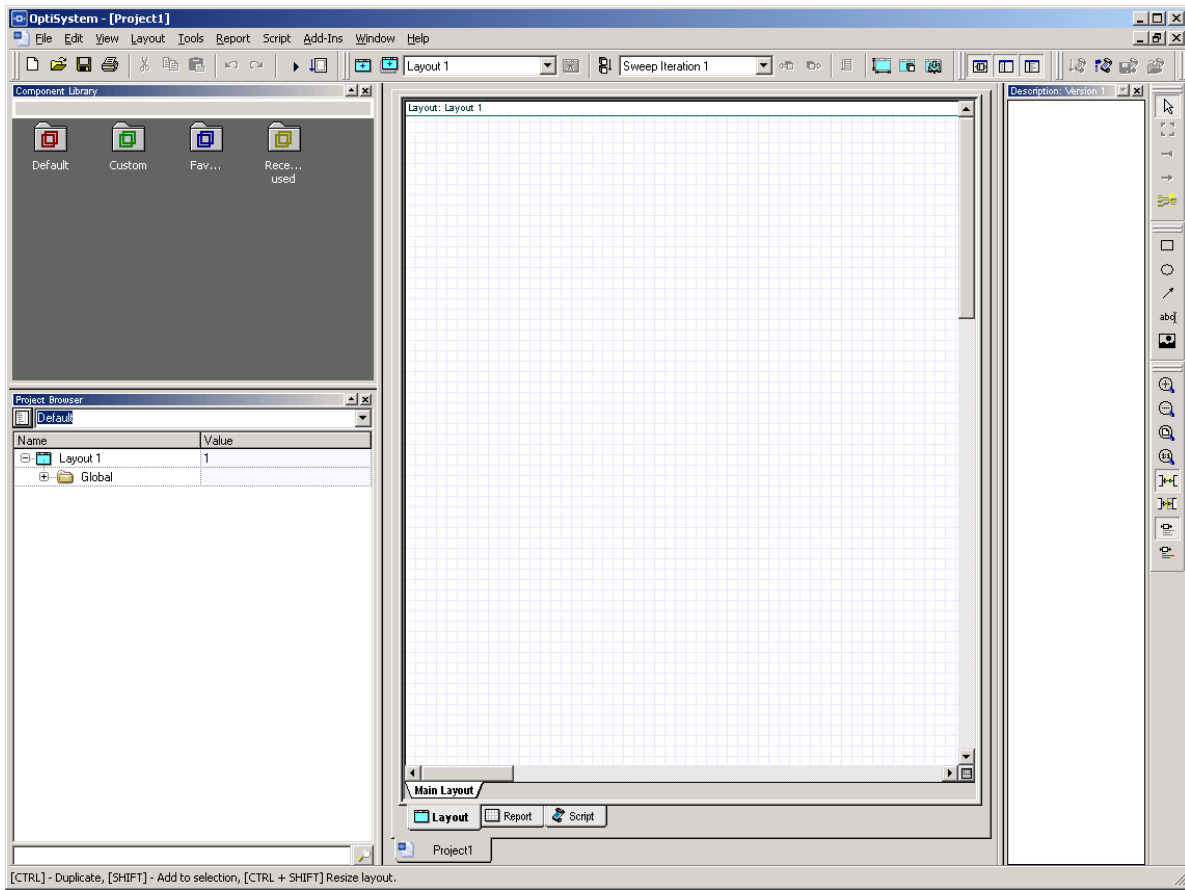
Action

- From the **Start** menu, select **Programs > Optiwave Software > OptiSystem 12 > OptiSystem**.
OptiSystem loads and the graphical user interface appears (see [Figure 1](#)).



QUICK START

Figure 1 OptiSystem graphical user interface (GUI)



Main parts of the GUI

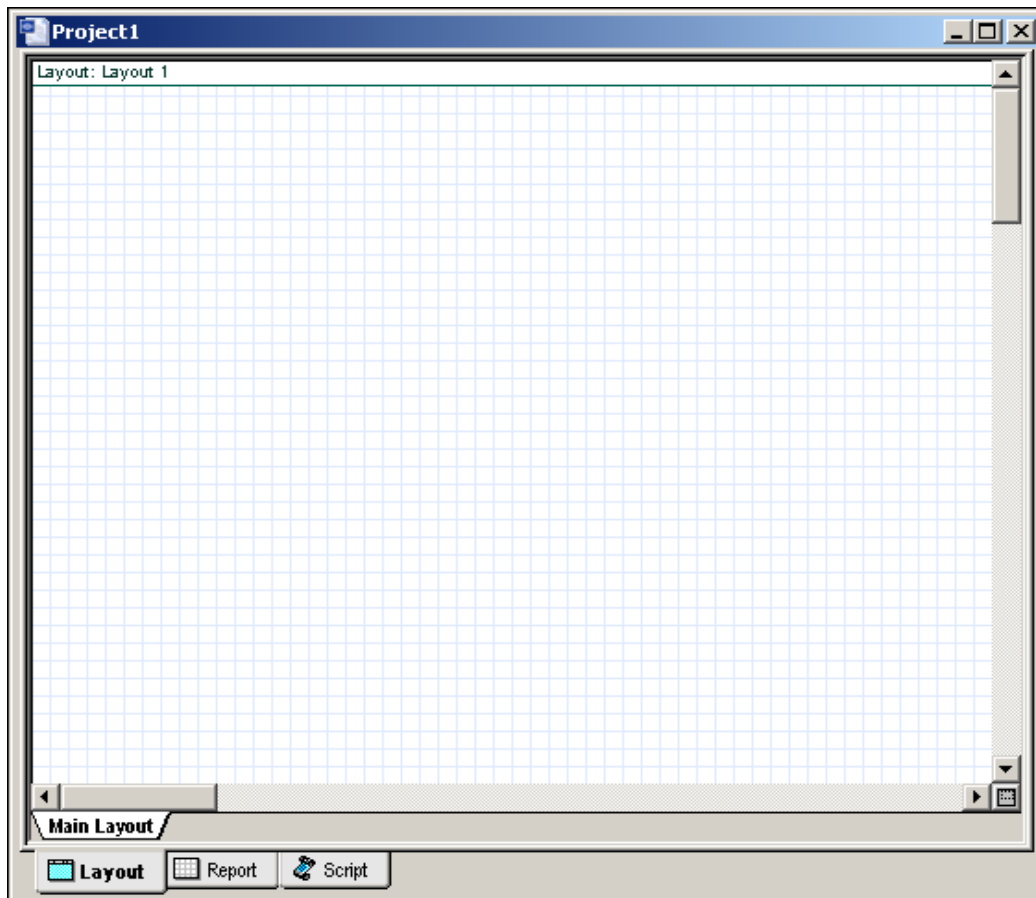
The OptiSystem GUI contains the following main windows:

- [Project layout](#)
- [Dockers](#)
 - [Component Library](#)
 - [Project Browser](#)
 - [Description](#)
- [Status Bar](#)

Project layout

The main working area where you insert components into the layout, edit components, and create connections between components (see [Figure 2](#)).

Figure 2 Project layout window



Dockers

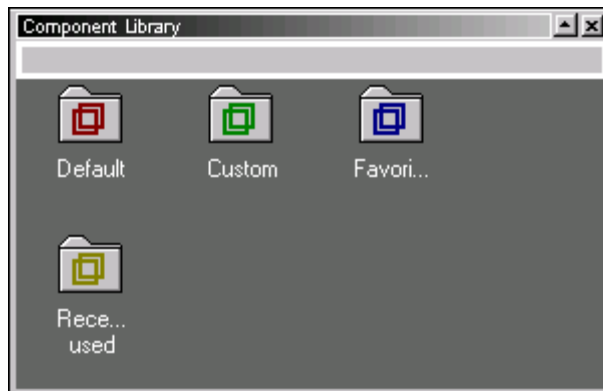
Use dockers, located in the main layout, to display information about the active (current) project:

- [Component Library](#)
- [Project Browser](#)
- [Description](#)

Component Library

Access components to create the system design (see [Figure 3](#)).

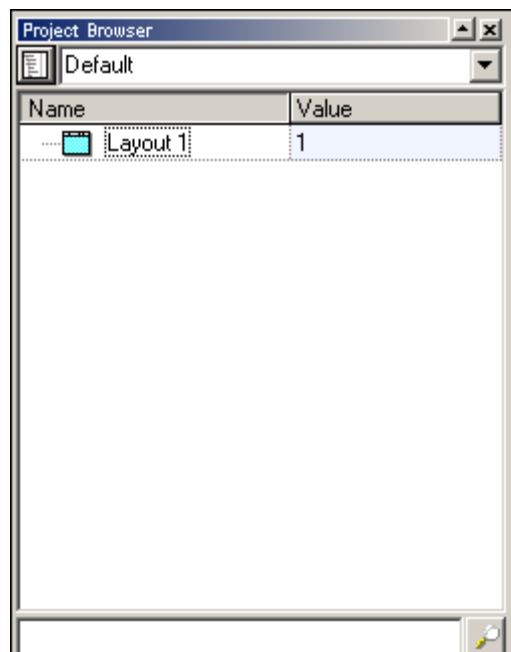
Figure 3 Component Library window



Project Browser

Organize the project to achieve results more efficiently, and navigate through the current project (see [Figure 4](#)).

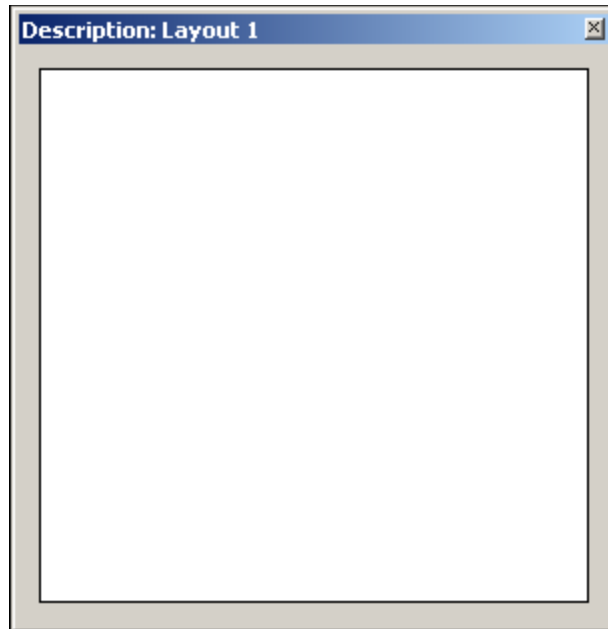
Figure 4 Project Browser window



Description

Display detailed information about the current project (see [Figure 5](#)).

Figure 5 Description window

**Status Bar**

Displays project calculation progress information, useful hints about using OptiSystem, and other help. Located at the bottom of the **Project Layout** window.

Figure 6 Status Bar

[CTRL] - Duplicate, [SHIFT] - Add to selection, [CTRL + SHIFT] Resize layout.

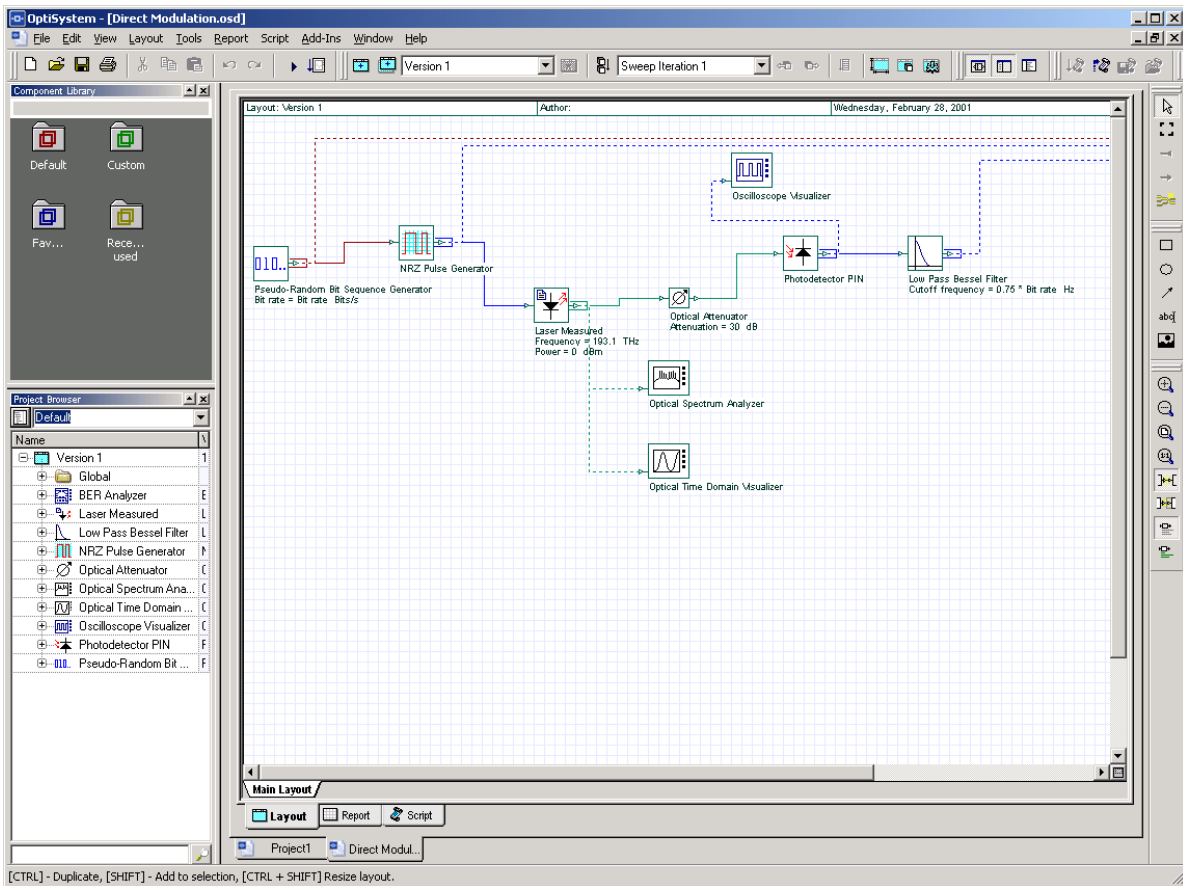


Loading a sample file

To load a sample file, perform the following procedure.

- | Step | Action |
|------|--|
| 1 | From the File menu, select Open . |
| 2 | In Samples > Introductory Tutorials , select Quick Start Direct Modulation.osd .
The Direct Modulation sample file appears in the Main layout (see Figure 7). |

Figure 7 Direct Modulation sample file



The transmitter is built using a direct laser modulation scheme, and consists of the following components:

- **Pseudo-Random Bit Sequence Generator:** Sends the bit sequence to the **NRZ Pulse Generator**. The pulses modulate the **Laser Measured**. The **Photodetector PIN** receives the optical signal attenuated by the **Optical Attenuator**. The **Low Pass Bessel Filter** filters the electrical signal.
- **Optical Spectrum Analyzer:** Displays the modulated optical signal in the frequency domain



- **Optical Time Domain Visualizer:** Displays the modulated optical signal in the time domain.
- **Oscilloscope Visualizer:** Displays the electrical signal after the PIN in time domain.
- **BER Analyzer:** Measures the performance of the system based on the signal before and after the propagation.

Note: More than one visualizer can be attached to a component output.

Running a simulation

To run a simulation, perform the following procedure.

Step Action

- 1 From the **File** menu, select **Calculate** (see [Figure 8](#)).
*The **OptiSystem Calculations** dialog box appears (see [Figure 9](#)).*

Figure 8 File menu

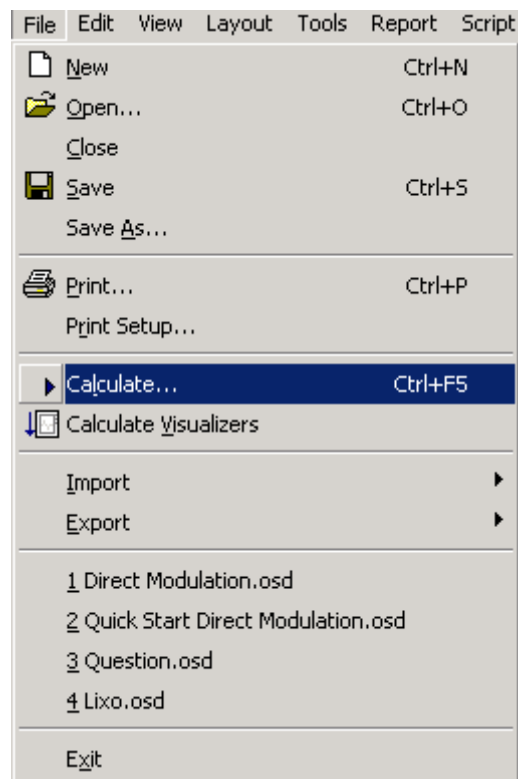
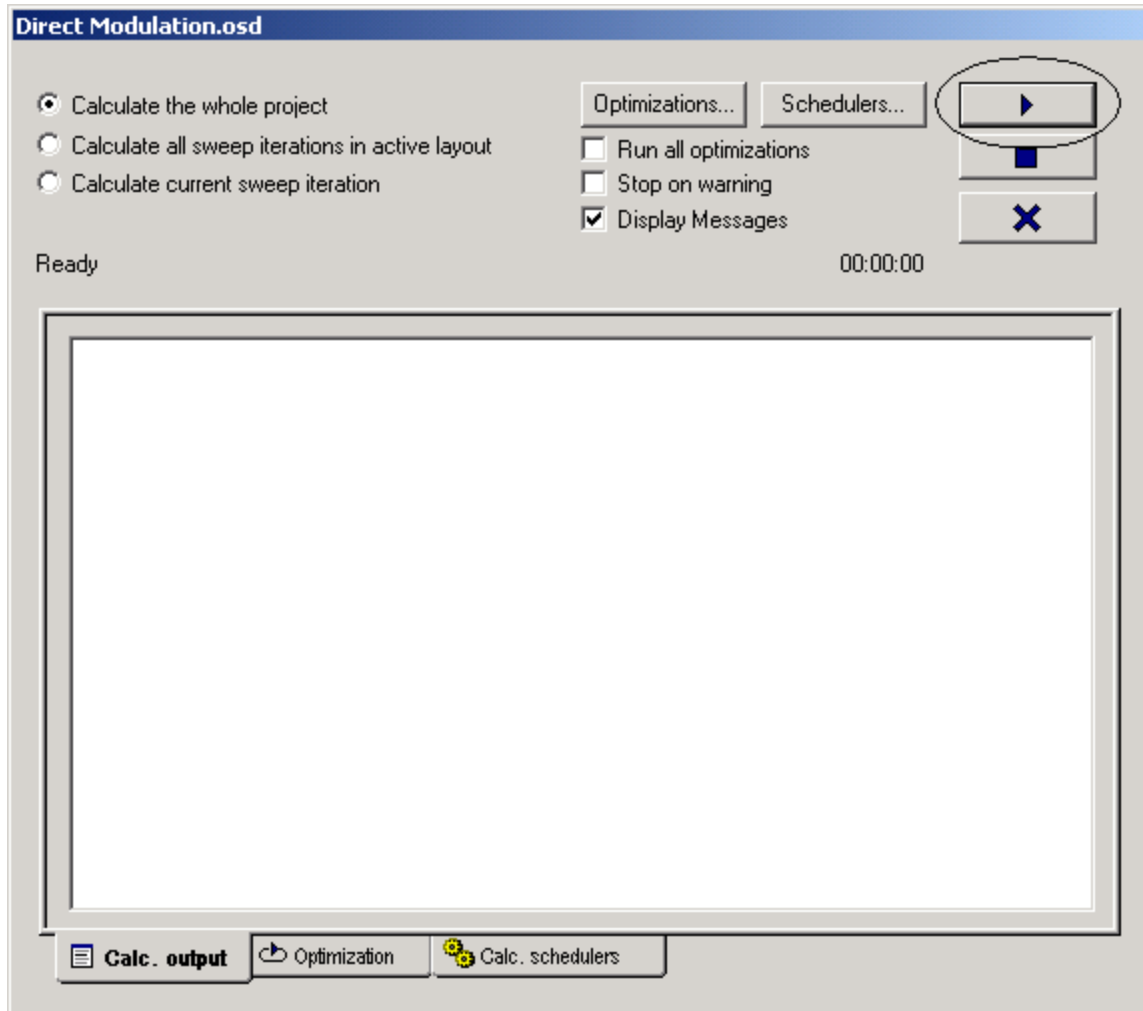


Figure 9 OptiSystem Calculations dialog box



- 2 In the **OptiSystem Calculations** dialog box, click the **Run** button (see [Figure 9](#)).
*The results appear in the **Calculation Output** window.
The calculation output appears in the **Calculation Output** window, and the simulation results appear below the components that were included in the simulation.*

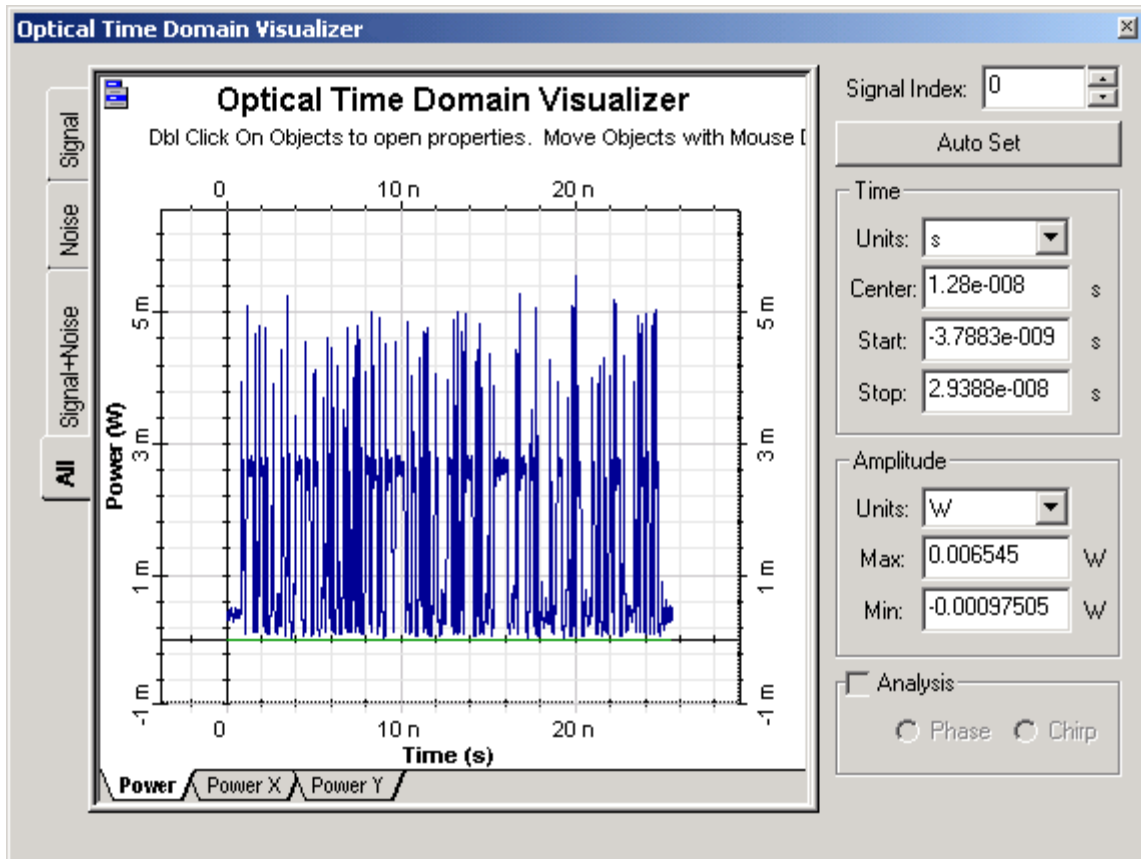
Displaying results from a visualizer

To view the simulation results, perform the following action.

Action

- Double-click a visualizer in the **Project layout** to view the graphs and results that the simulation generates (see [Figure 10](#)).

Figure 10 Optical Time Domain Visualizer results



Component parameters

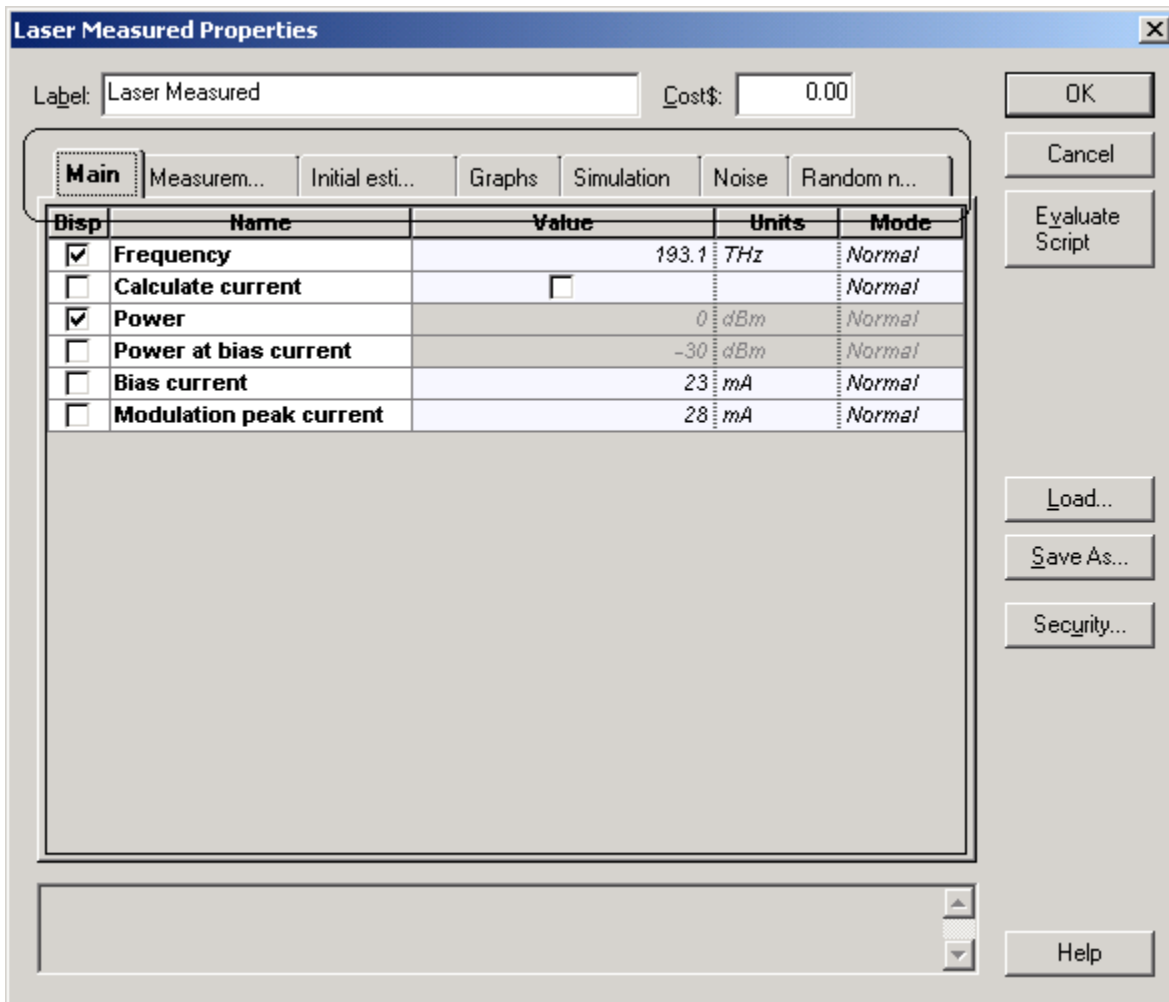
Viewing and editing component parameters

Double-click a component to view and edit the parameters for the component. To view the properties for **Laser Measured**, perform the following action.

Action

- In the **Project layout**, double-click the **Laser Measured** component. *The **Laser Measured Properties** dialog box appears.*

Figure 11 Component parameters – Laser Measured



Component parameters are organized by categories. **Laser Measured** has seven parameter categories, each represented by a tab in the dialog box (see [Figure 11](#)).

- Main
- Measurements
- Initial estimate
- Numerical
- Graphs
- Simulation
- Noise
- Random numbers

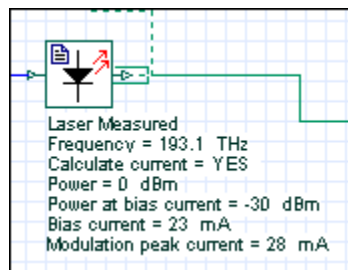
Each category has a set of parameters. Parameters have the following properties:

- Disp
- Name
- Value
- Units
- Mode

The first category in the **Laser Measured** dialog box is **Main**. You can enter the signal **Frequency** and **Power** using the **Main** tab.

The first parameter in the **Main** category is **Disp**. When you select a check box beside a parameter listed in the **Disp** column, the parameter value appears under the component in the **Project layout**. For example, if you select the **Frequency** and **Power** check boxes in the **Disp** column, these parameter values appear in the **Project layout** (see [Figure 12](#)).

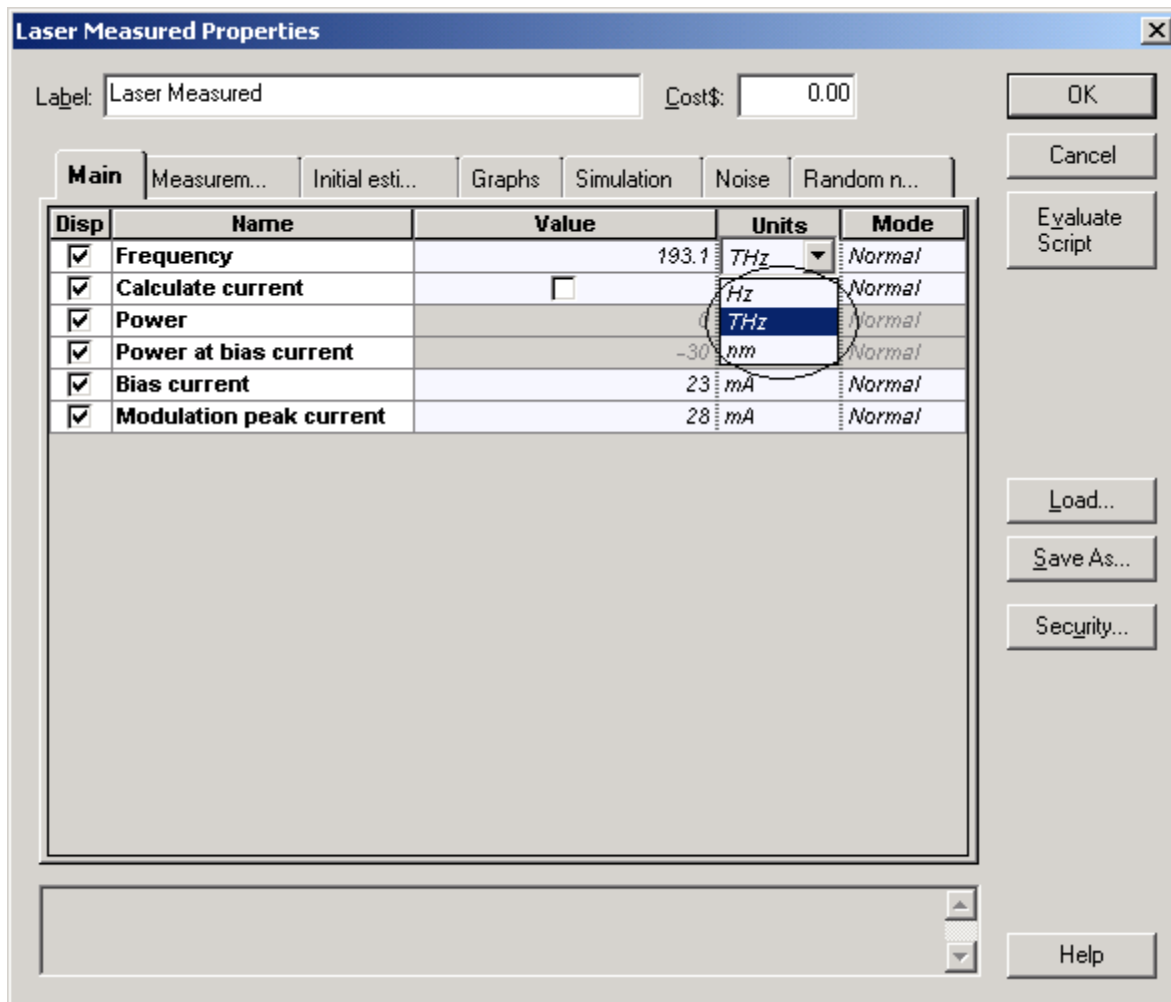
Figure 12 Laser Measured with displayed parameter values



Each parameter can have a value in the columns **Name**, **Value**, **Units**, and **Mode**. Some parameters can have different units. For example, you can select the **Frequency** parameter to be in Hz, THz, or nm. When you change your unit selection, the conversion is automatic (see [Figure 13](#)).



Figure 13 Choosing parameter values



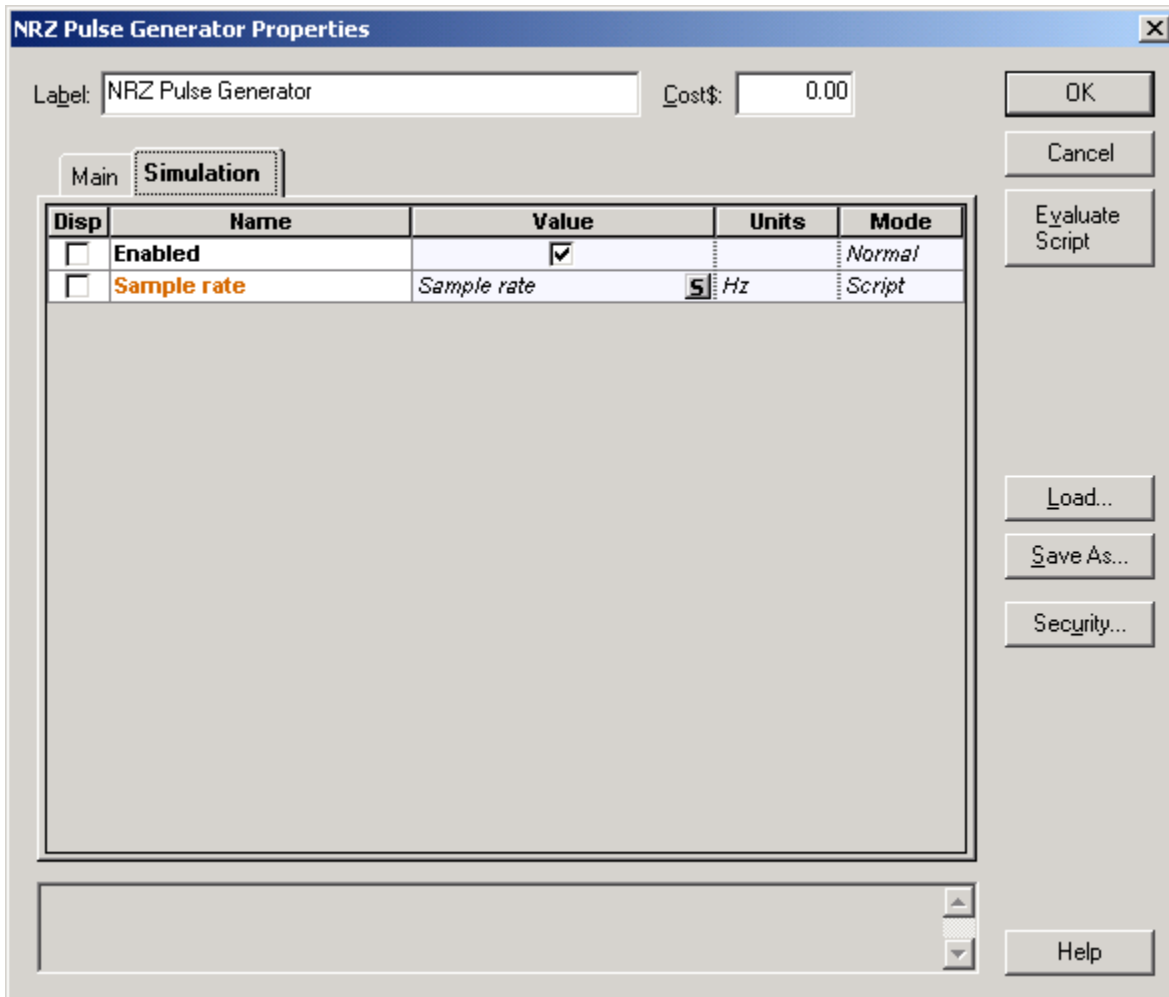
Editing parameters

To edit the **NRZ Pulse Generator** parameters, perform the following procedure.‘

Step Action

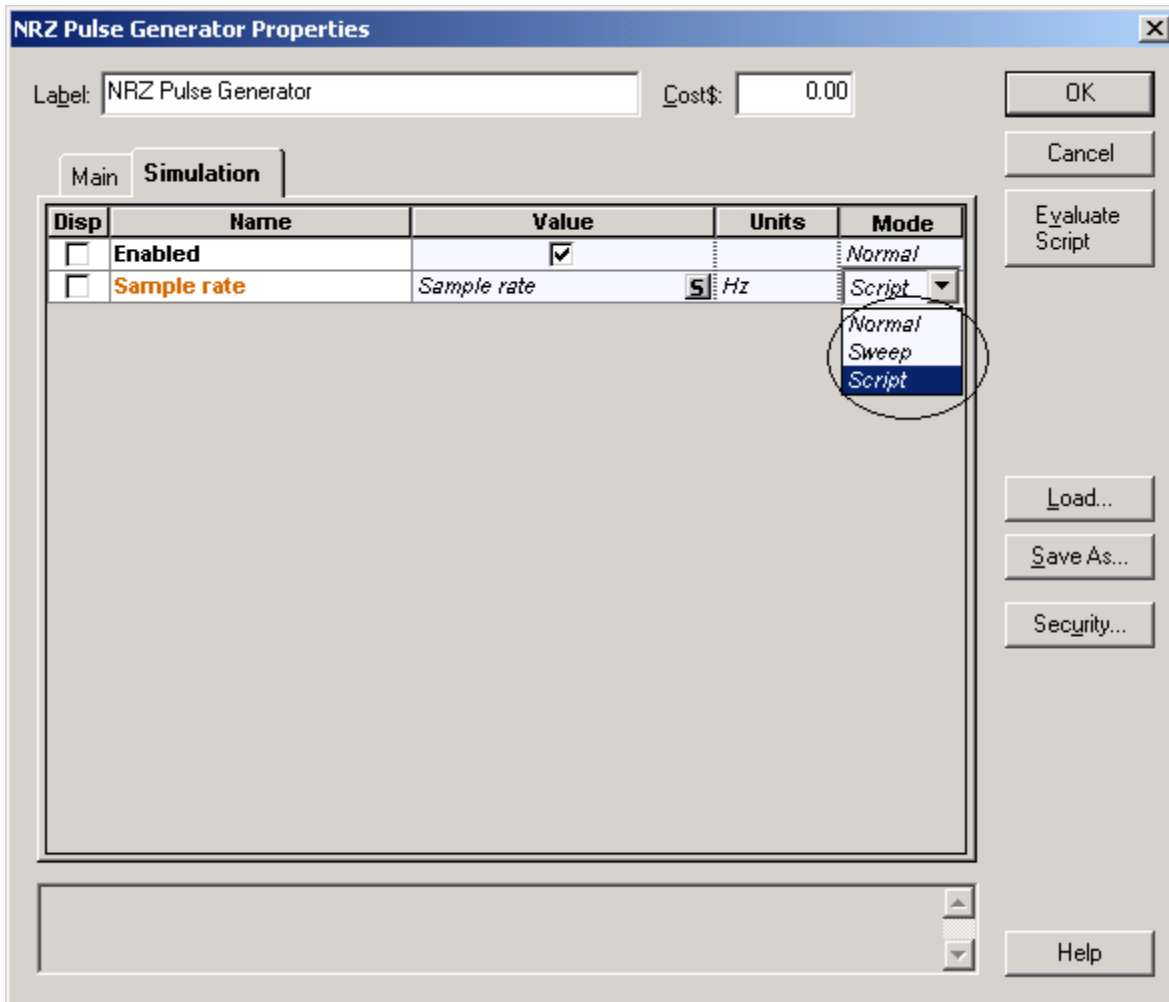
- 1 Double-click the **NRZ Pulse Generator** in the **Project layout**.
The **NRZ Pulse Generator Properties** dialog box appears (see [Figure 14](#)).
- 2 Click the **Simulation** tab.

Figure 14 Laser NRZ Pulse Generator simulation options



For the **Sample rate** parameter, the **Mode** is **Script** (see Figure 15). This parameter will be evaluated as an arithmetic expression. The **Sample rate** parameter of the **Laser Measured** component also refers to a Global parameter with the same name.

Figure 15 Scripted parameters

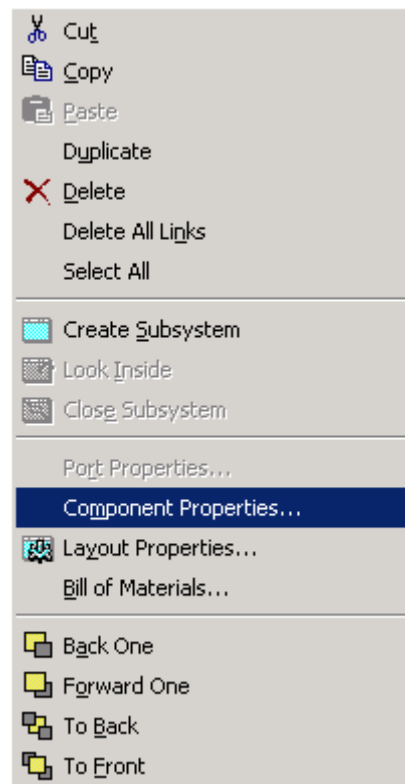


Editing visualizer parameters

To access the parameters for the **Optical Spectrum Analyzer**, perform the following procedure.

- | Step | Action |
|------|---|
| 1 | Right-click the Optical Spectrum Analyzer .
<i>A shortcut menu appears (see Figure 16).</i> |

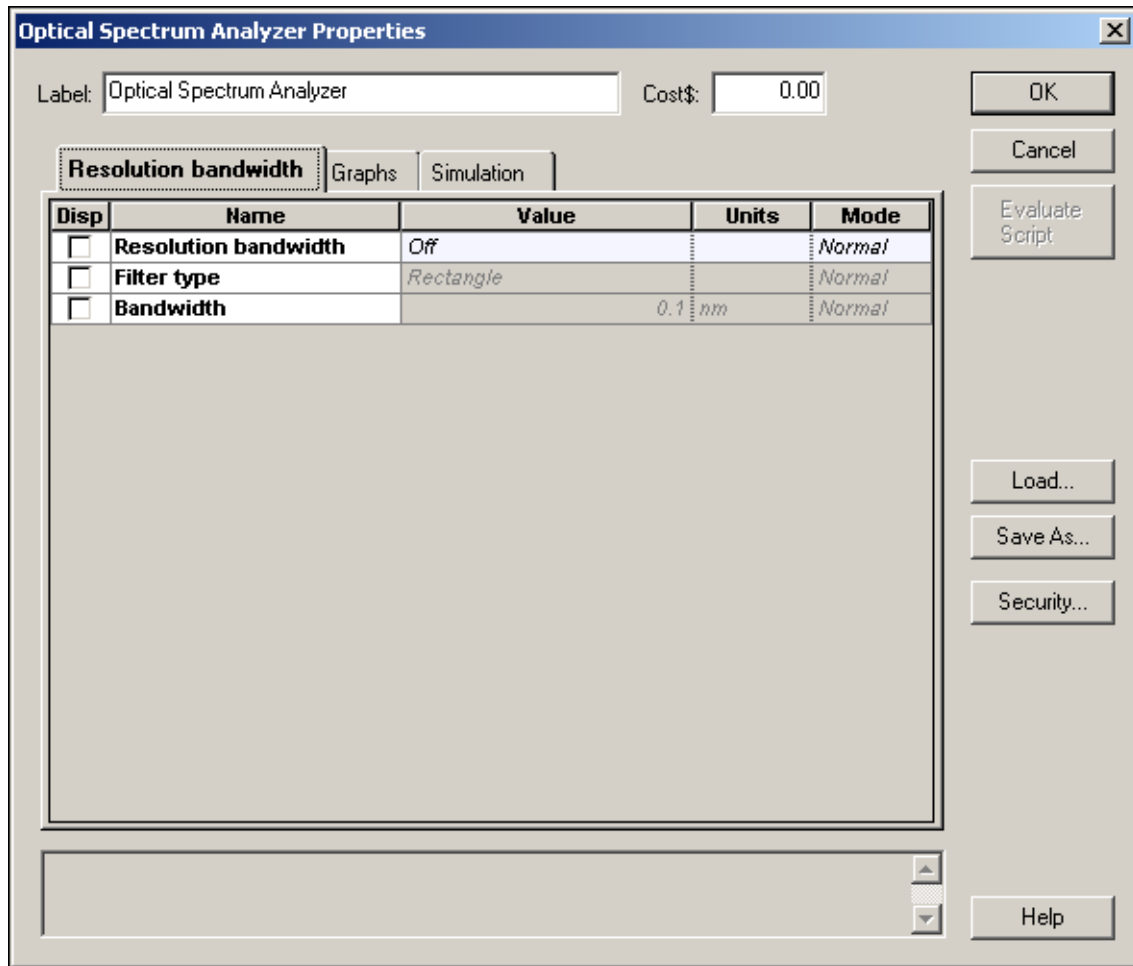
Figure 16 Shortcut menu



- | | |
|---|--|
| 2 | Select Component Properties .
<i>The Optical Spectrum Analyzer Properties dialog box appears (see Figure 17).</i> |
|---|--|



Figure 17 Optical Spectrum Analyzer Properties dialog box



Global parameters

The global parameters are common to all OptiSystem simulations. (See [Appendix A: Global Parameters](#) for more information on global parameters.) In this particular case, you indirectly define the simulation time window, the number of samples, and the sample rate using three parameters:

- Bit rate
- Bit sequence length
- Number of samples per bit

These parameters are used to calculate the **Time window**, **Sample rate**, and **Number of samples**.

- **Time window** = Sequence length * 1/Bit rate = $256 * 1 / 10e9 = 25.6 \text{ ns}$
- **Number of samples** = Sequence length * Samples per bit = 32768 samples
- **Sample rate** = Number of samples / Time window = 1.28 THz

The time window of the simulation is 25.6 ns. 32768 samples will be generated by each component, and the signal bandwidth is 1.28 THz.

OptiSystem shares the parameter **Time window** with all components. This means that each component works with the same time window. However, each component can work with different sample rates or number of samples (see [Figure 18](#)).



Figure 18 Global parameters values

Layout 1 Parameters

Label:

Simulation | Signals | Spatial effects | Noise | Signal tracing

Name	Value	Units	Mode
Simulation window	<i>Set bit rate</i>		<i>Normal</i>
Reference bit rate	<input checked="" type="checkbox"/>		<i>Normal</i>
Bit rate	10e+009	Bits/s	<i>Normal</i>
Time window	25.6e-009	s	<i>Normal</i>
Sample rate	1.28e+012	Hz	<i>Normal</i>
Sequence length	256	Bits	<i>Normal</i>
Samples per bit	128		<i>Normal</i>
Number of samples	32768		<i>Normal</i>
Cuda GPU	<input type="checkbox"/>		<i>Normal</i>

OK
Cancel
Add Param...
Remove Par...
Edit Param...
View GPU Info...
Help



Editing global parameters

To edit global parameters, perform the following procedure.

Step Action

- 1 Double-click in the **Project layout**.
The **Layout 1 Parameters** dialog box appears (see [Figure 18](#)).
- 2 Select or clear global parameters as required.

These parameters can be accessed by any component using the script mode. The **NRZ Pulse Generator** refers by default to the global parameter **Sample rate** using script mode (see [Figure 19](#)). The **Low Pass Bessel Filter** has the Cutoff parameter frequency as $0.75 * \text{Bit rate}$. In this case, **Bit rate** is a global parameter (see [Figure 20](#)).

Figure 19 NRZ Pulse Generator properties

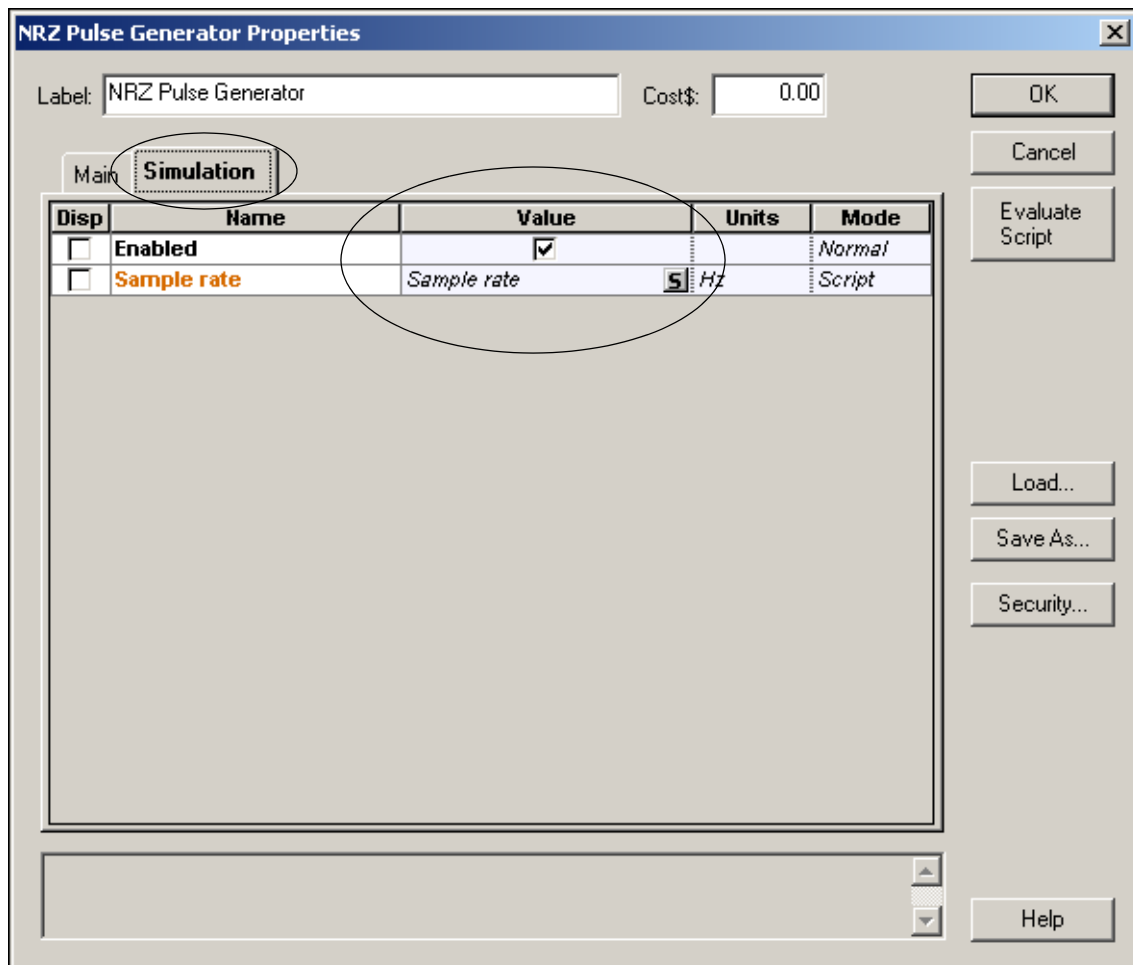
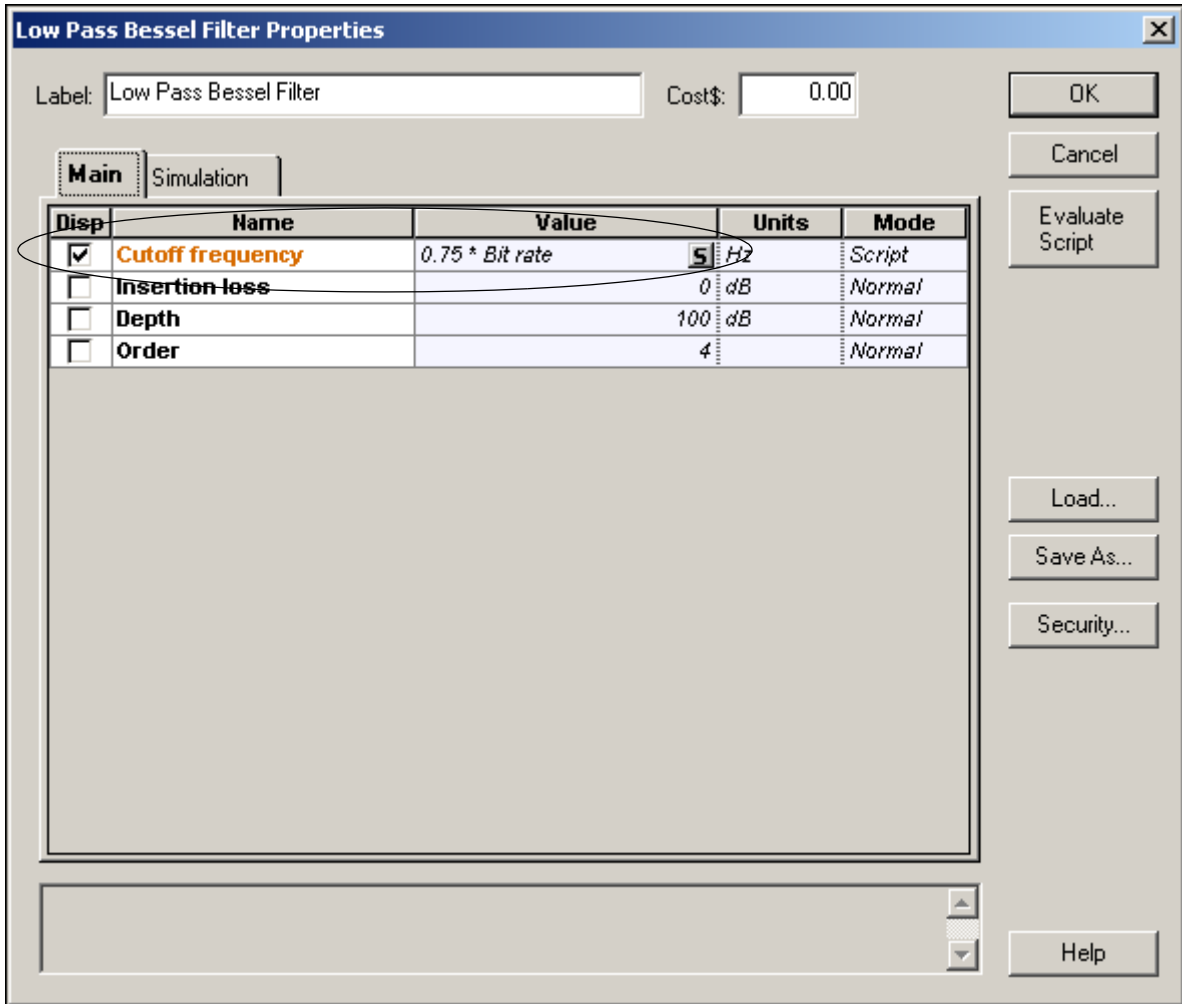


Figure 20 Low Pass Bessel Filter properties



Using the Layout Editor

In the following example, you will modify a design that you create. You will change the laser modulation scheme from direct to external modulation by replacing some of the components in the design and adding components from the Component Library.

To use the **Layout Editor**, perform the following procedure.

Step Action

- 1 To delete the **Laser Measured** component, select the **Laser Measured** component in the **Project layout** and press the **Delete** key.

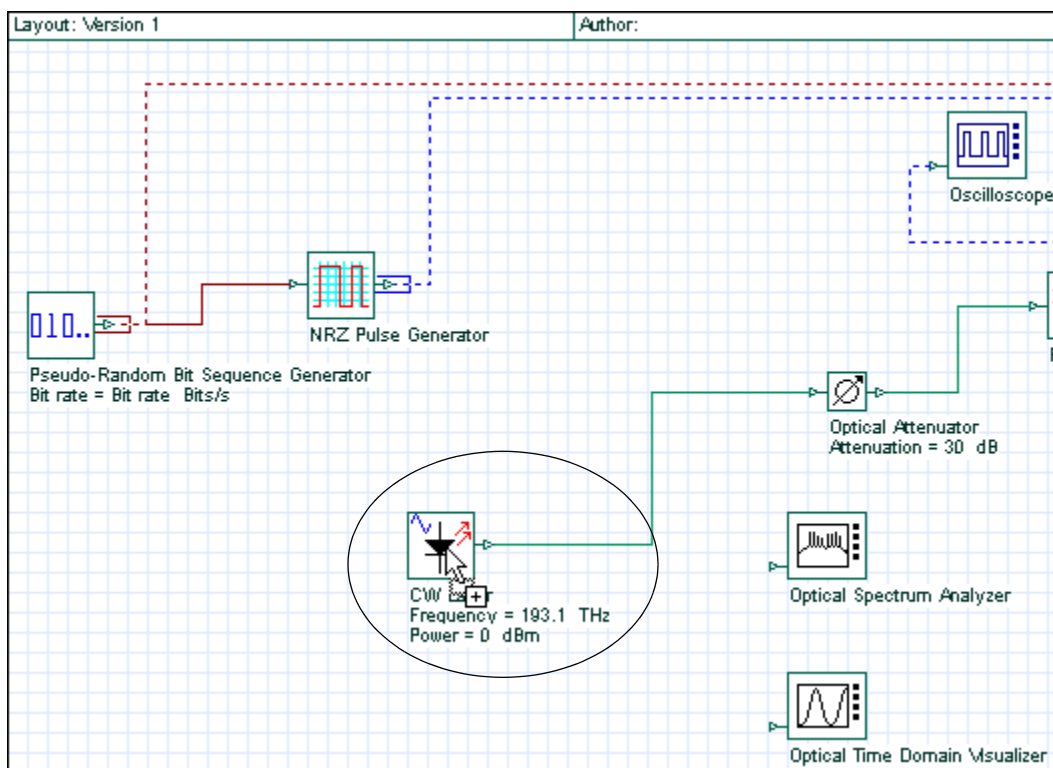
*The **Laser Measured** component is deleted from the layout.*

- 2 From the Component Library, select **Default > Transmitters Library > Optical Sources**.

- 3 Drag the **CW Laser** to the **Project layout** (see [Figure 21](#)).

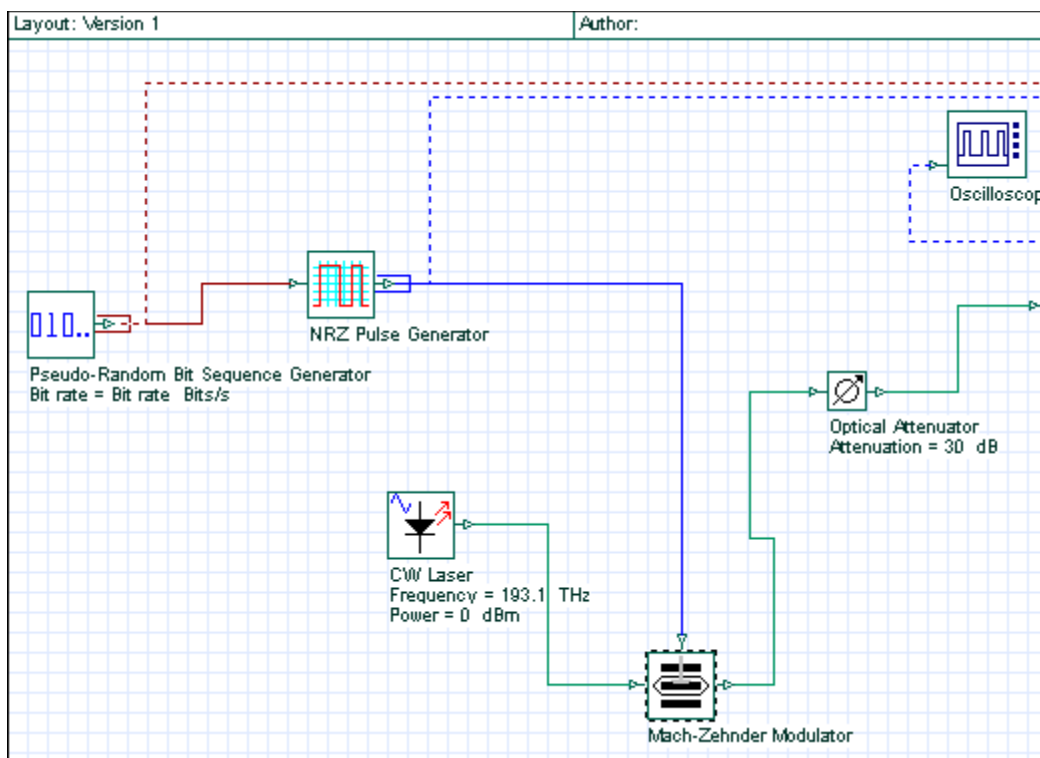
Note: The autoconnect feature automatically connects components in the **Project layout**. If connections are not made automatically, see “Connecting components manually” on page 31.

Figure 21 CW Laser added to Main Layout



- 4 From the Component Library, select **Default > Transmitters Library > Optical Modulators**.
- 5 Drag the **Mach-Zehnder Modulator** to the **Project layout** (see [Figure 22](#)).
- 6 Place the **Mach-Zehnder Modulator** in the **Project layout** so the following connections are generated:
 - a. **NRZ Pulse Generator** output port to the **Mach-Zehnder** modulation input port
 - b. **CW Laser** output port to the **Mach-Zehnder Modulator** Carrier input port
 - c. **Mach-Zehnder Modulator** output port to the **Optical Attenuator** input port

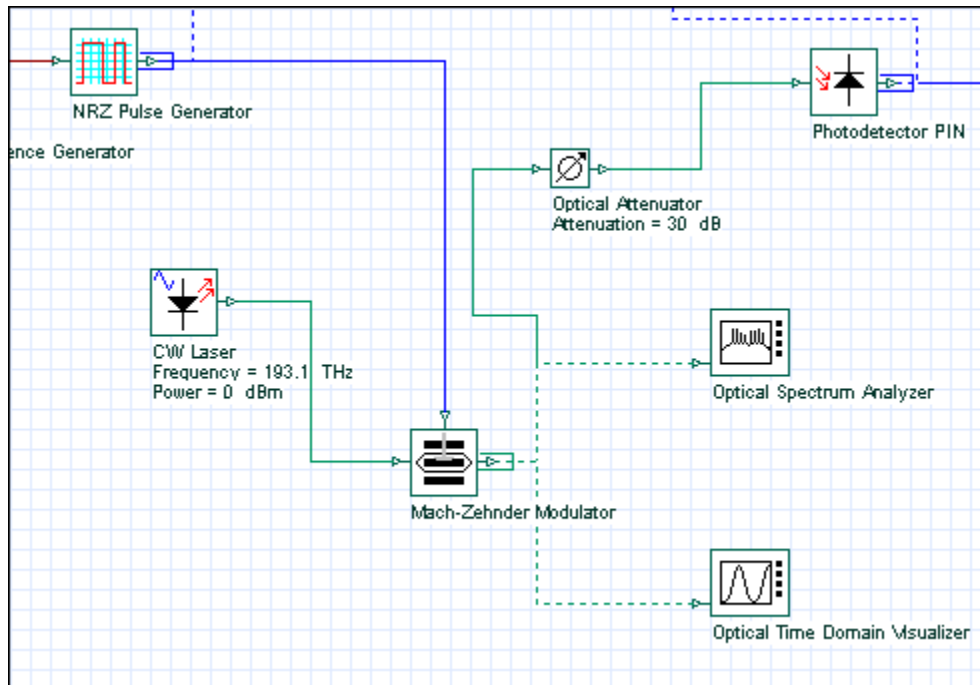
Figure 22 Connecting components



- 7 Connect the **Mach-Zehnder Modulator** output port to the **Optical Spectrum Analyzer** input port and to the **Optical Time Domain Visualizer** input port (see [Figure 23](#)).



Figure 23 Mach-Zehnder Modulator connected to visualizers



- 8 From the **File** menu, select **Calculate**.
*The **OptiSystem Calculations** dialog box appears.*
- 9 Click the **Run** button.
*The results appear in the **Calculation Output** window.*
- 10 To view the graphs and results, double-click on the visualizers (see [Figure 25](#) and [Figure 26](#) for examples of visualizer results).

Connecting components manually

To connect components using the layout tool, perform the following procedure.

Step Action

- 1 Place the cursor over the initial port.
*The cursor changes to the rubber band cursor (chain link) (see [Figure 24](#)).
A tool tip appears that indicates the type of signal that is available on this port.*
- 2 Click and drag to the port to be connected.
The ports are connected.

Note: You can only connect output to input ports and vice versa.

Figure 24 Rubber Band cursor



Figure 25 Visualizer results — OSA example

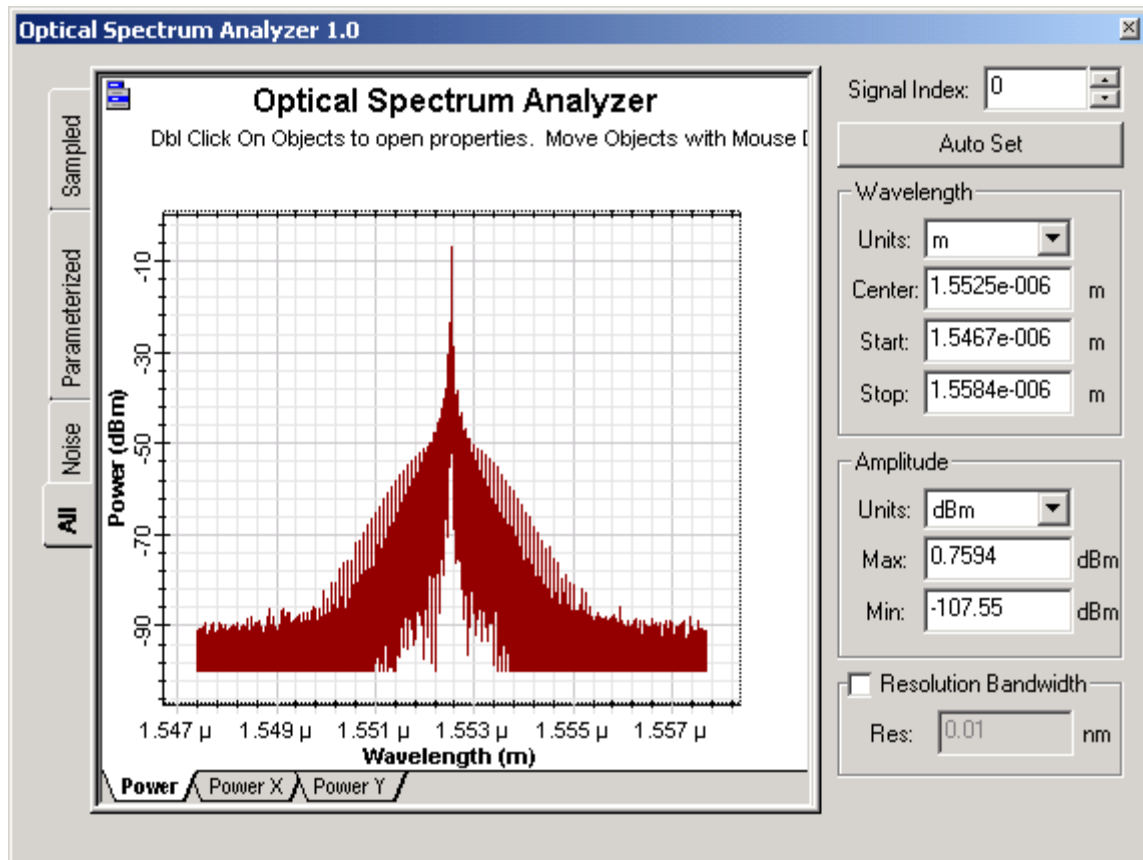
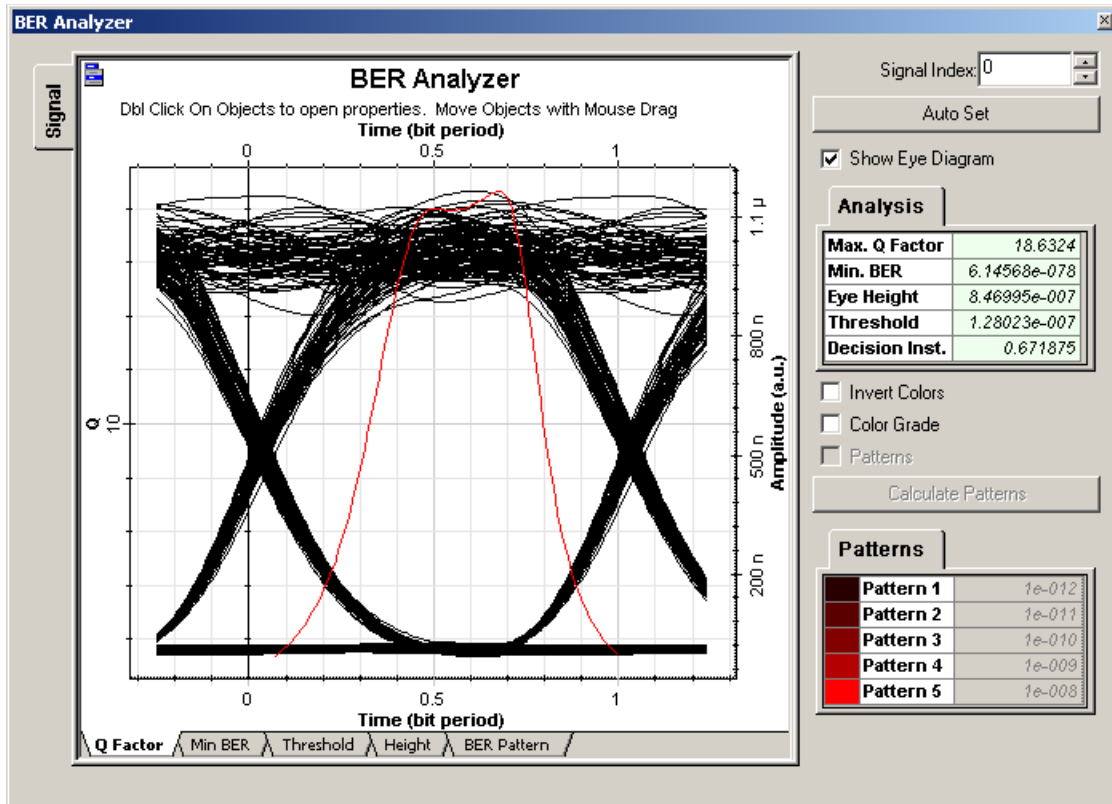


Figure 26 Visualizer results — BER example



Saving the design and closing OptiSystem

To save the design and close OptiSystem, perform the following procedure.

Step Action

- 1 From the **File** menu, select **Save**.
The Quick Start Direct Modulation.osd design is saved.
- 2 From the **File** menu, select **Exit**.
OptiSystem closes.



QUICK START

Notes:



Appendix A: Global Parameters

Opening the global parameters dialog

To open the global parameters dialog, perform the following action.

Action

- Double-click in the **Project layout** window.
*The **Layout Parameters** dialog opens (see [Figure 27](#)).*

OR

- Select **Layout > Parameters** from the **Menu** tool bar.
*The **Layout Parameters** dialog opens (see [Figure 27](#)).*

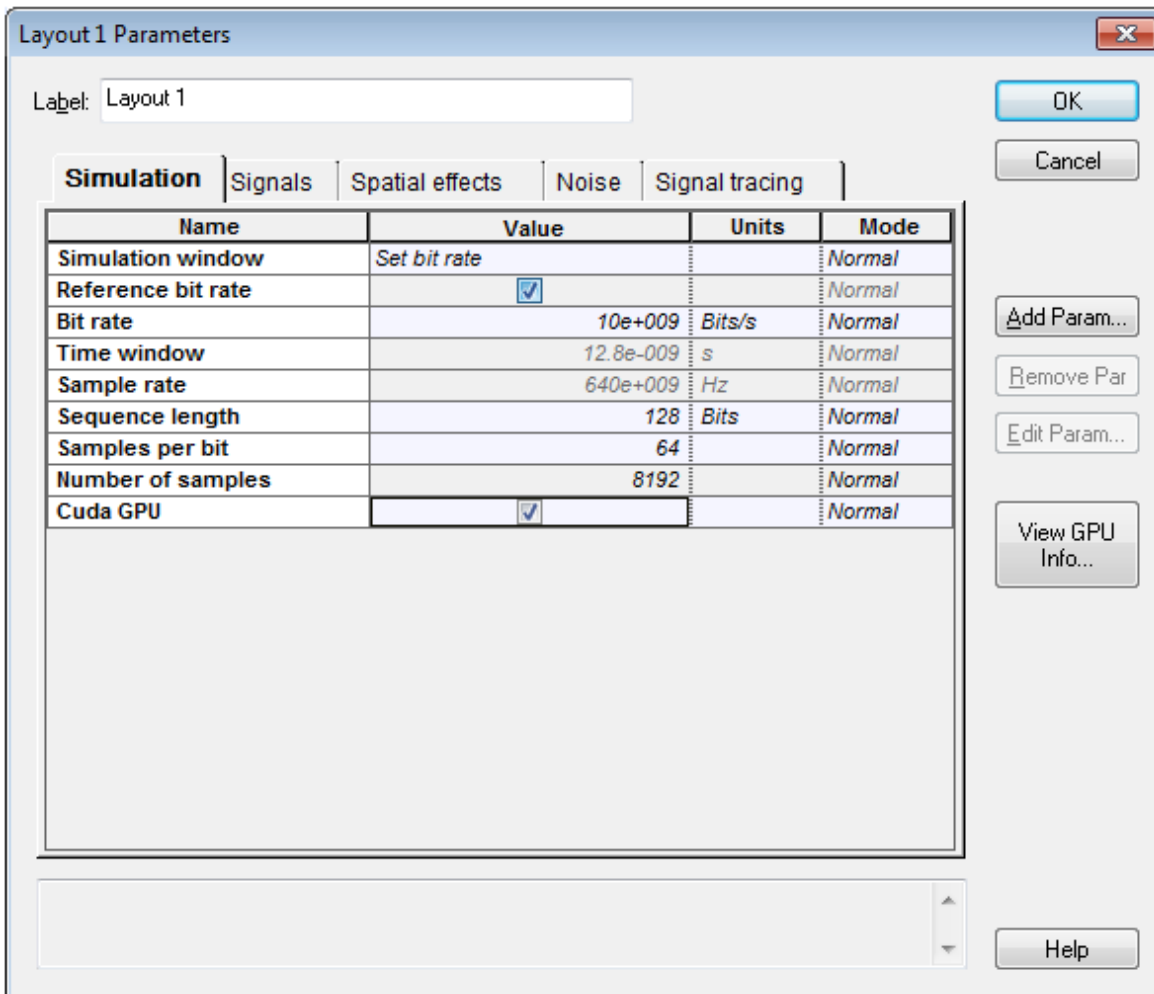
Editing global parameters

To edit global parameters, perform the following procedure.

Step Action

- 1** Double-click in the **Project layout**.
*The **Layout Parameters** dialog box appears (see [Figure 27](#)).*
- 2** Select or clear global parameters as required.

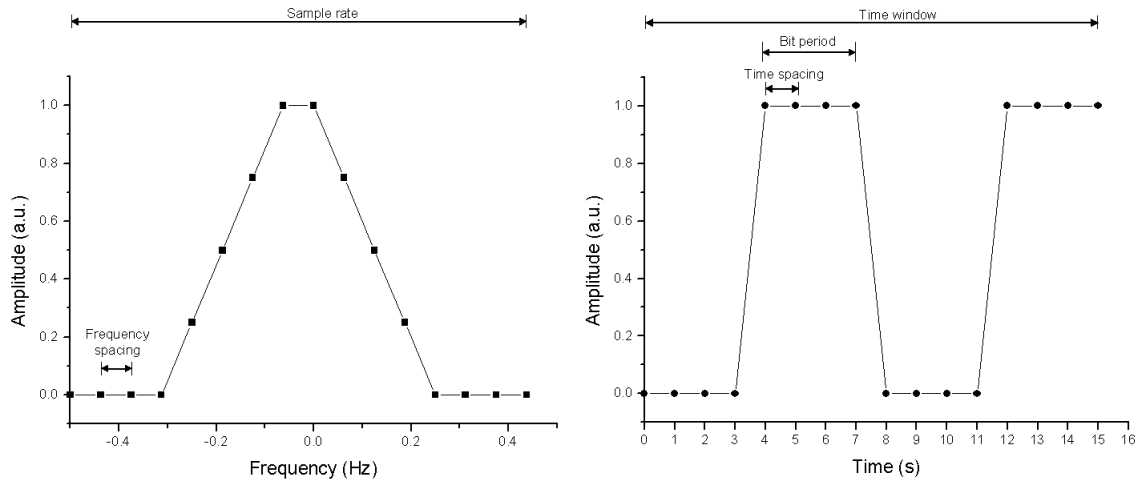
Figure 27 Layout Parameters dialog



When you create a new design, you must define the global simulation parameters. These parameters are critical to the simulation.

They show the speed, accuracy, and memory requirements for a particular simulation during the system design stage. It is important to understand what the global parameters are, because they have an impact on all the components that use these parameters (see [Figure 28](#)).

Figure 28 Global parameters relationships



Time spacing = $1 / \text{Sample rate} = \text{Time window} / \text{Number of samples}$

Frequency spacing = $1 / \text{Time window} = \text{Sample rate} / \text{Number of samples}$

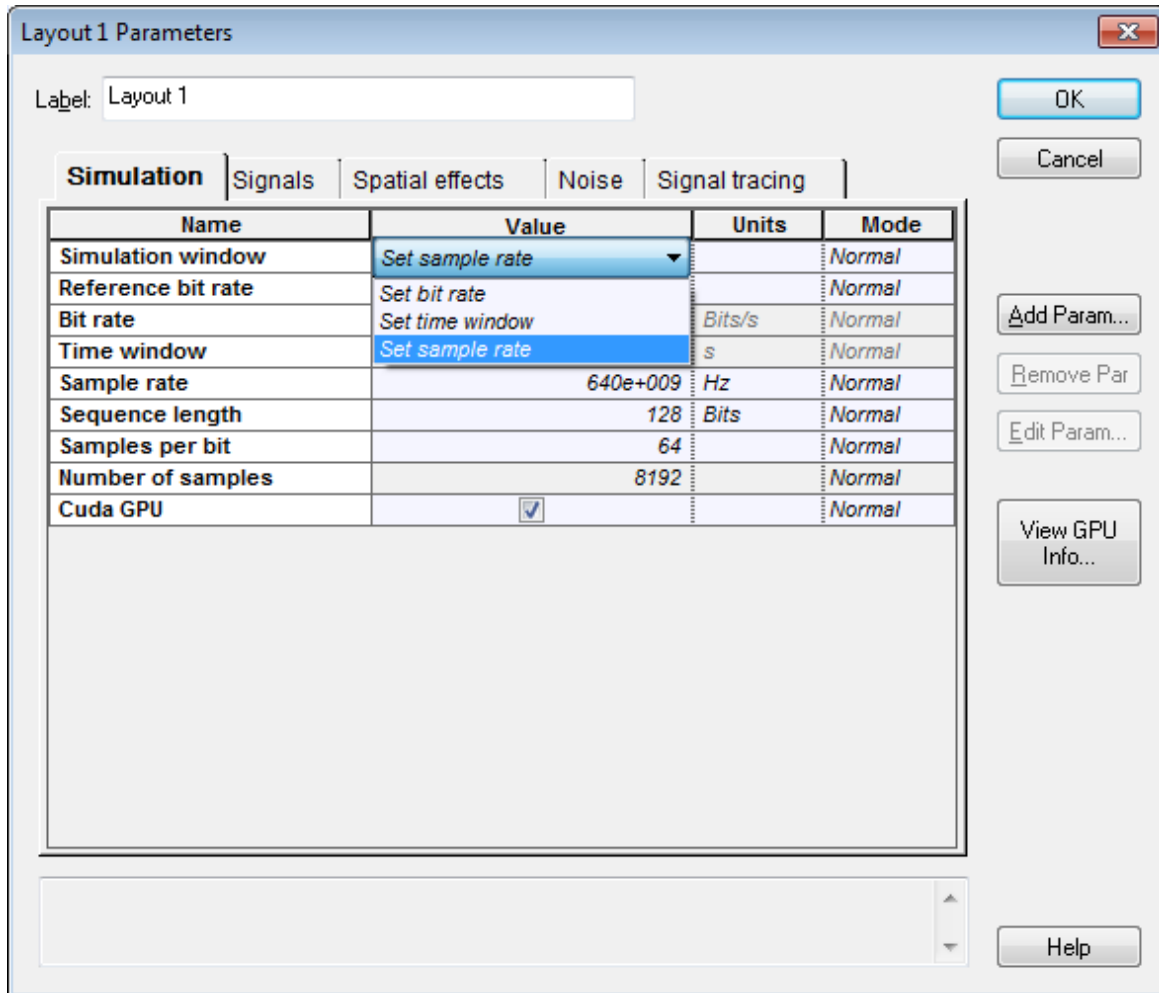
Time window = $\text{Sequence length} * \text{Bit period} = \text{Sequence length} / \text{Bit rate}$

Number of samples = $\text{Sequence length} * \text{Samples per bit} = \text{Time window} * \text{Sample rate}$



Simulation parameters

Figure 29 Simulation parameters



Simulation window

Specifies the setup mode for entering the parameters that define the main simulation parameters:

- **Set bit rate:** Allows you to enter the **Bit rate**. This is the default mode — you can easily set up the simulation using typical parameters such as **Bit rate**, **Sequence length**, and **Samples per bit**.
- **Set time window:** Allows you to enter the **Time window** value
- **Set sample rate:** Allows you to enter the **Sample rate**

The parameter **Bit rate** recalculates based on these parameters.



Reference bit rate

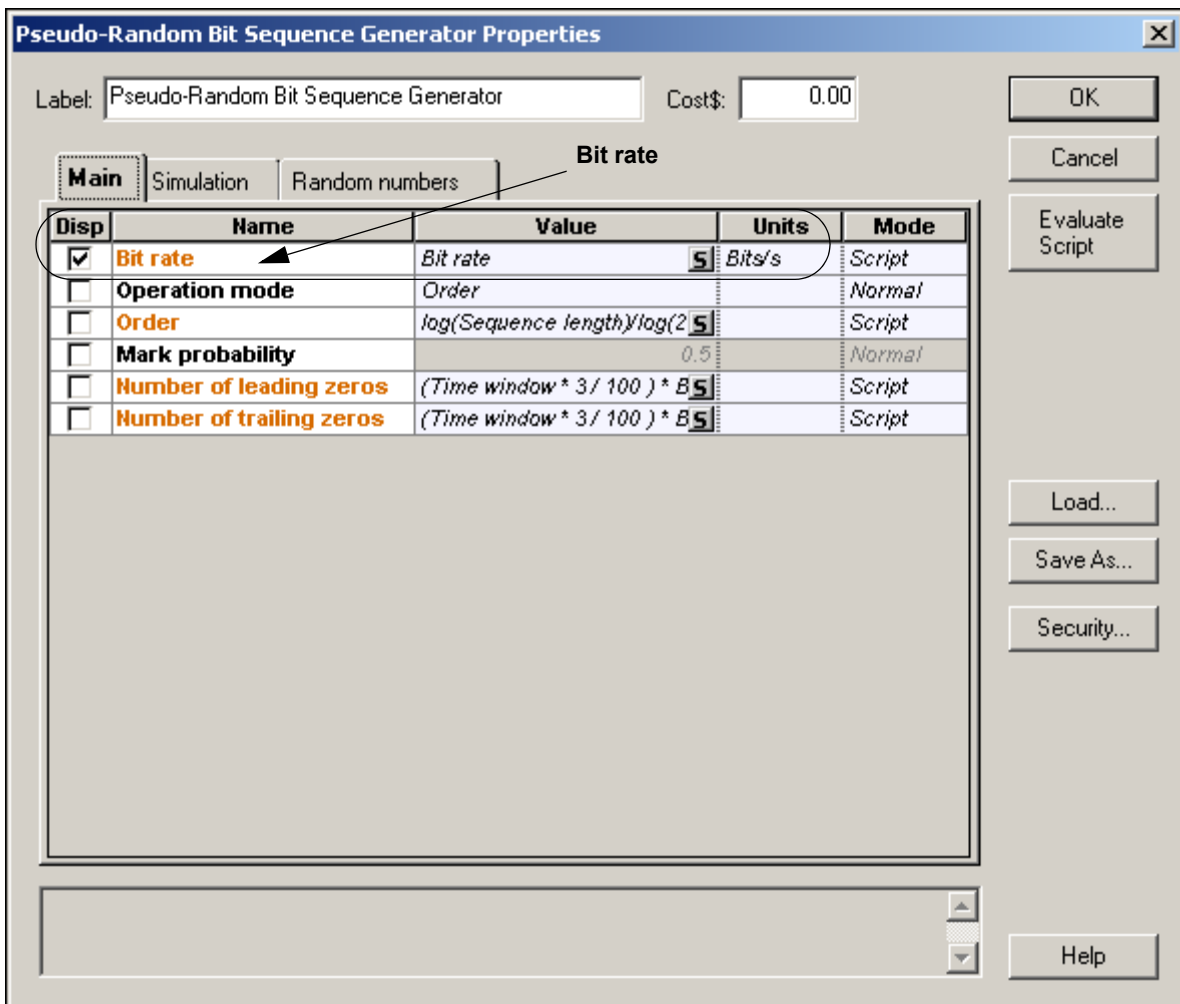
If this parameter is enabled, when you select **Set time window** or **Set sample rate** in the **Simulation** window, it will find the closest **Time window** or **Sample rate** without changing the **Bit rate**.

Bit rate

The value of the global bit rate is in bits per second. All components can access this parameter (see [Figure 30](#)). The global bit rate can affect components such as Bit sequence generators because components that require this parameter use it as a default value.

An expression relative to this bit rate value is used to define the default value for the bandwidth or cutoff frequency of most electrical filters. When you change this global parameter, you can change the bit rate setting of all modules in the design simultaneously.

Figure 30 Global parameter Bit rate



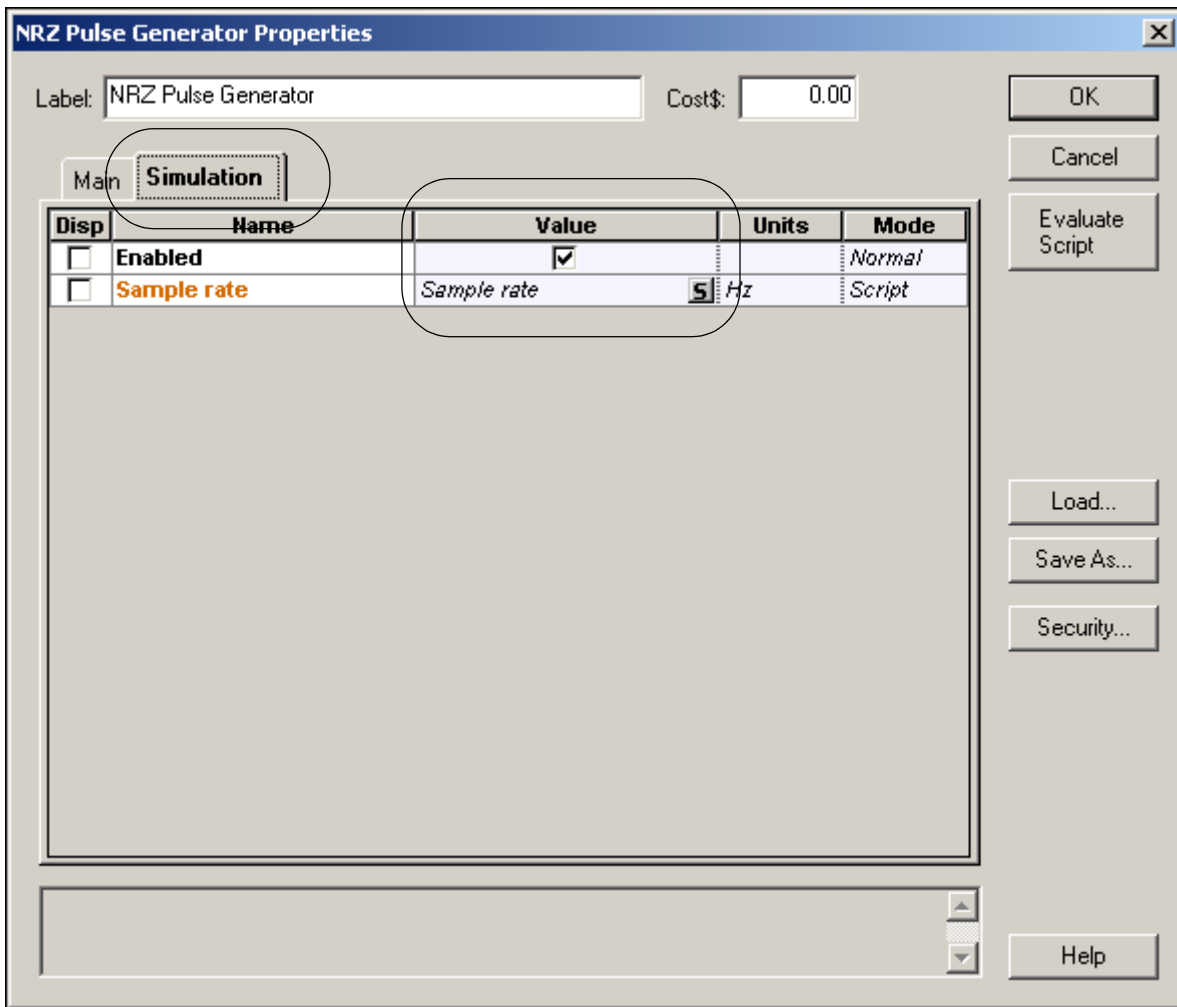
Time window

Specifies in seconds the **Time window** of the simulation. OptiSystem shares the parameter **Time window** with all components. This means that each component works with the same **Time window**. Since the **Time window** defines the frequency spacing in the frequency domain, the sampled signal will always have the same frequency spacing. This parameter is best expressed in terms of the sequence length and the bit rate used during the simulation. It affects all components.

Sample rate

Specifies the frequency simulation window or simulation bandwidth in Hz (see [Figure 31](#)). It can affect components such as pulse generators and optical sources that generate signals at different sample rates. It is often convenient to operate all modules in the design at the same sample rate. This can be done easily by using this global parameter. The default parameter for all components requiring sample rate is referred to as the global sample rate. When you change this global parameter, you can change the sample rate setting of all modules in the design simultaneously.

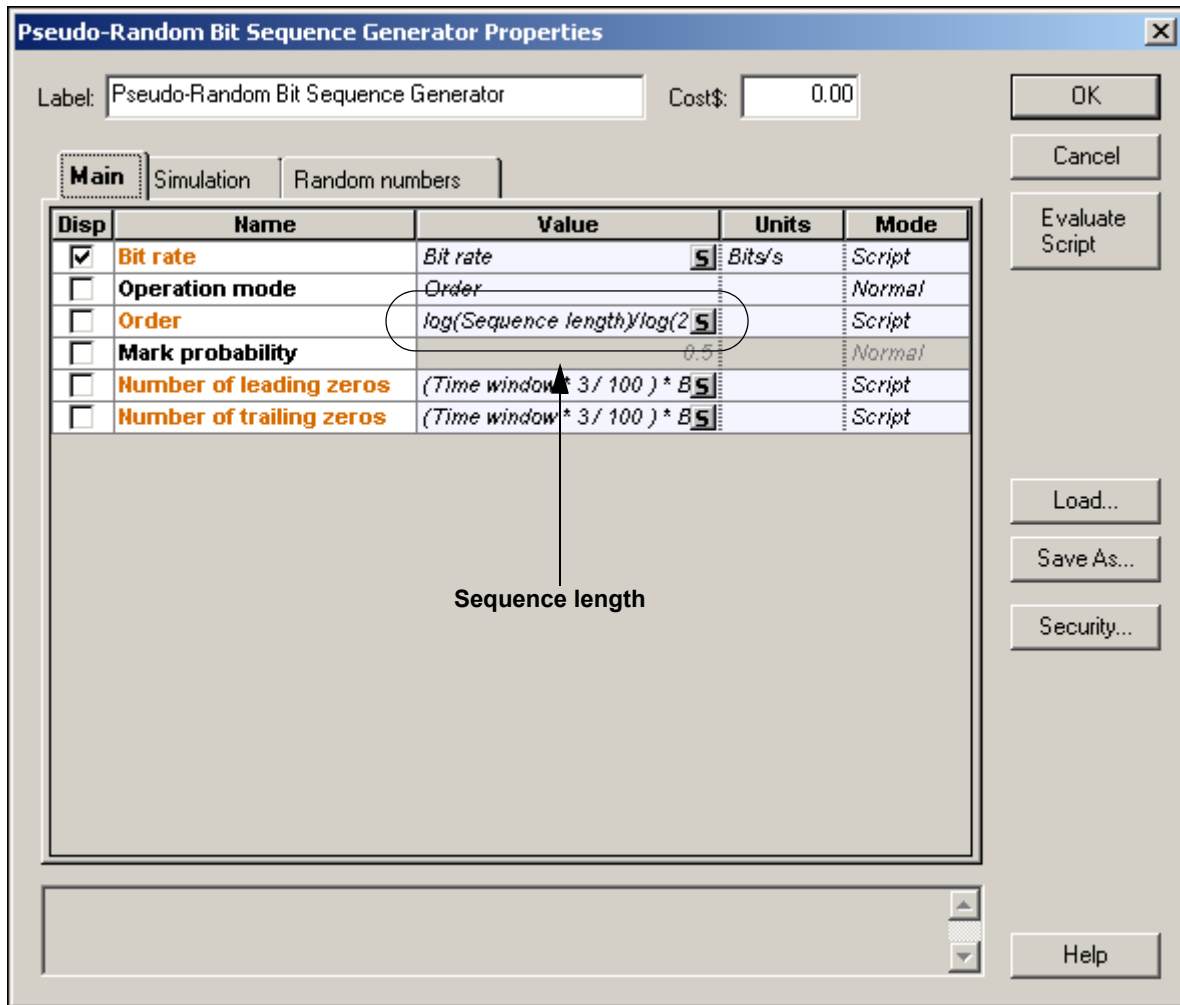
Figure 31 Global parameter Sample rate



Sequence length

The length of the bit sequence in number of bits. It must be a power of two.

Figure 32 Global parameter Sequence length



Samples per bit

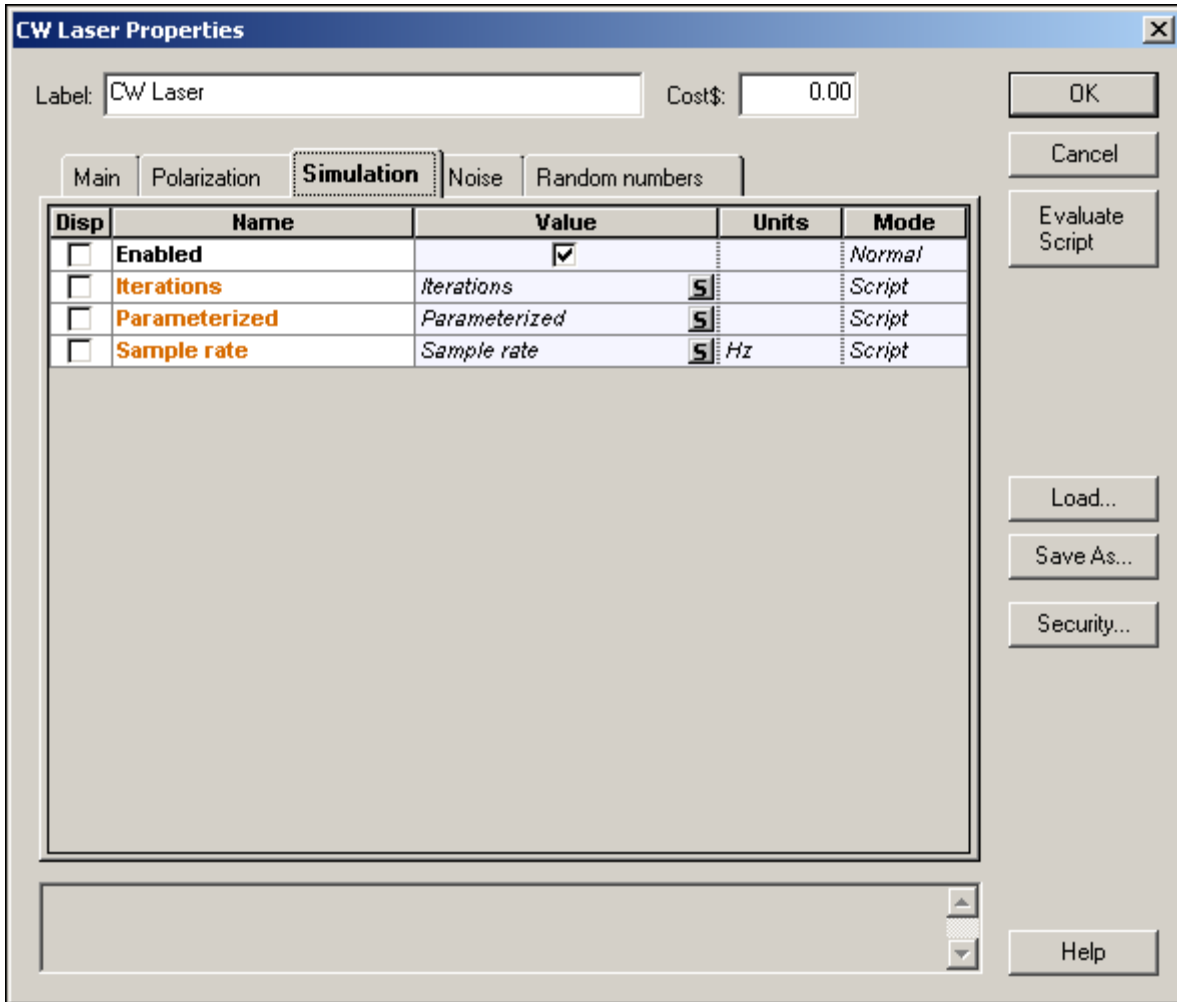
Number of samples for bit used to discretize the sampled signals. It must be a power of two.

Number of samples

This read-only parameter shows the number of samples calculated by the product of **Sequence length** and **Samples per bit**.

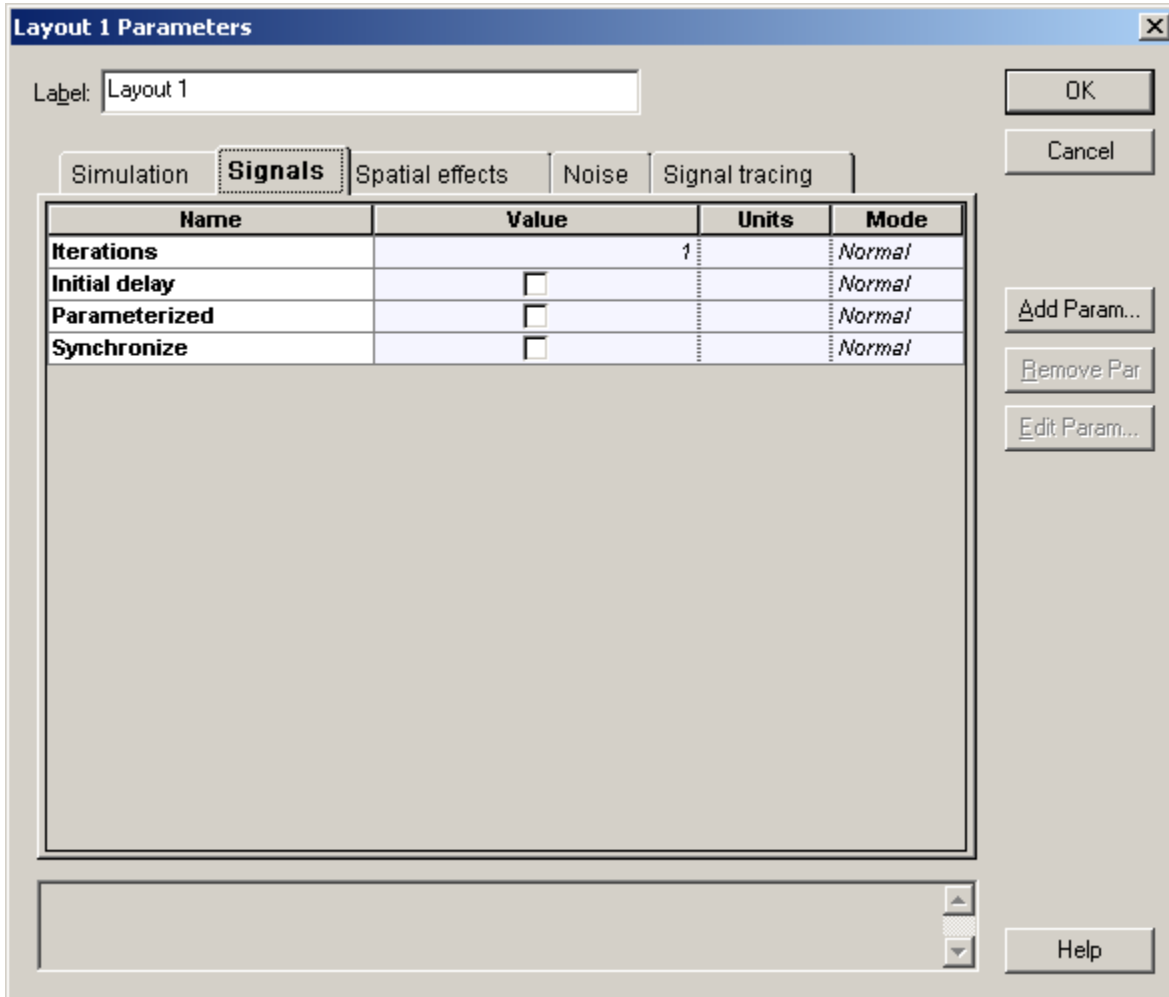


Figure 33 Global parameter iterations



Signals parameters

Figure 34 Global parameters Signals



Iterations

Number of signal blocks generated by each simulation. It mainly affects transmitters and components used in bidirectional simulations and in network ring design.

By increasing the parameter iterations a component will repeat the previous calculation until the number of calculations is equal to the iterations. Refer to the tutorial lesson: *Working with multiple iterations*.

Initial Delay

This parameter forces a component to generate a null signal at each output port. It affects all components and it is mainly used in bidirectional simulations. The user does not have to add delays at the component input ports if using this parameter. Refer to the tutorial lesson: *Working with multiple iterations*.

Parameterized

Defines whether the signal output will be sampled signals (disabled) or parameterized signals (enabled). It can affect components such as optical sources and optical pulse generators.

Synchronize

Defines whether bit rates will be recalculated in order to make sure that the number of samples and the number of bits are both power of two numbers. It can affect components such as pulse generators, decoders and BER analyzers. It forces compatibility mode with previous versions of OptiSystem 7.

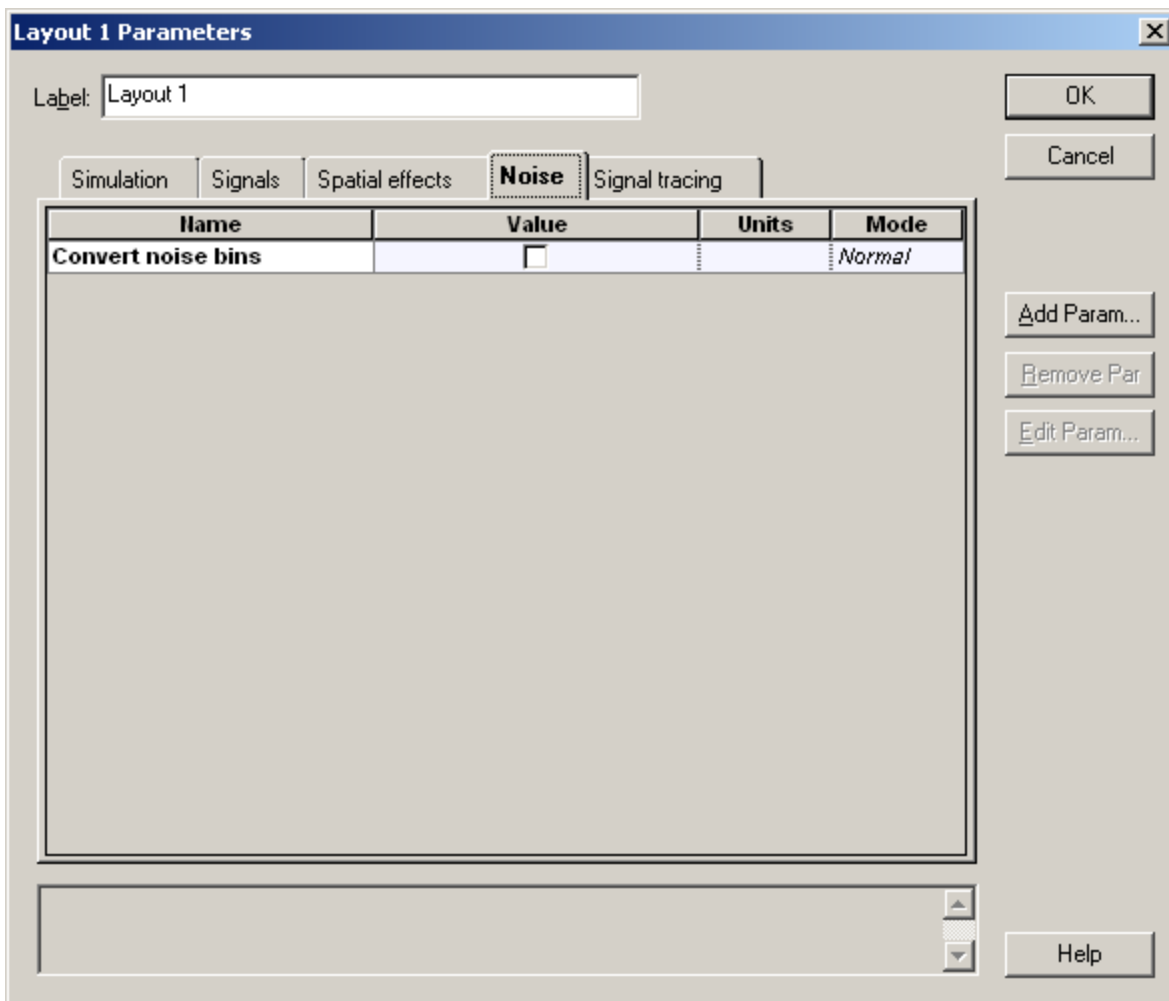


Noise parameters

Convert noise bins

Selects whether noise within a sampled band's frequency range is added to the sampled signal or represented separately as noise bins. The default value is disabled, which means the noise propagate is separated from the signals. It can affect the Erbium doped fiber amplifiers and the photo detectors.

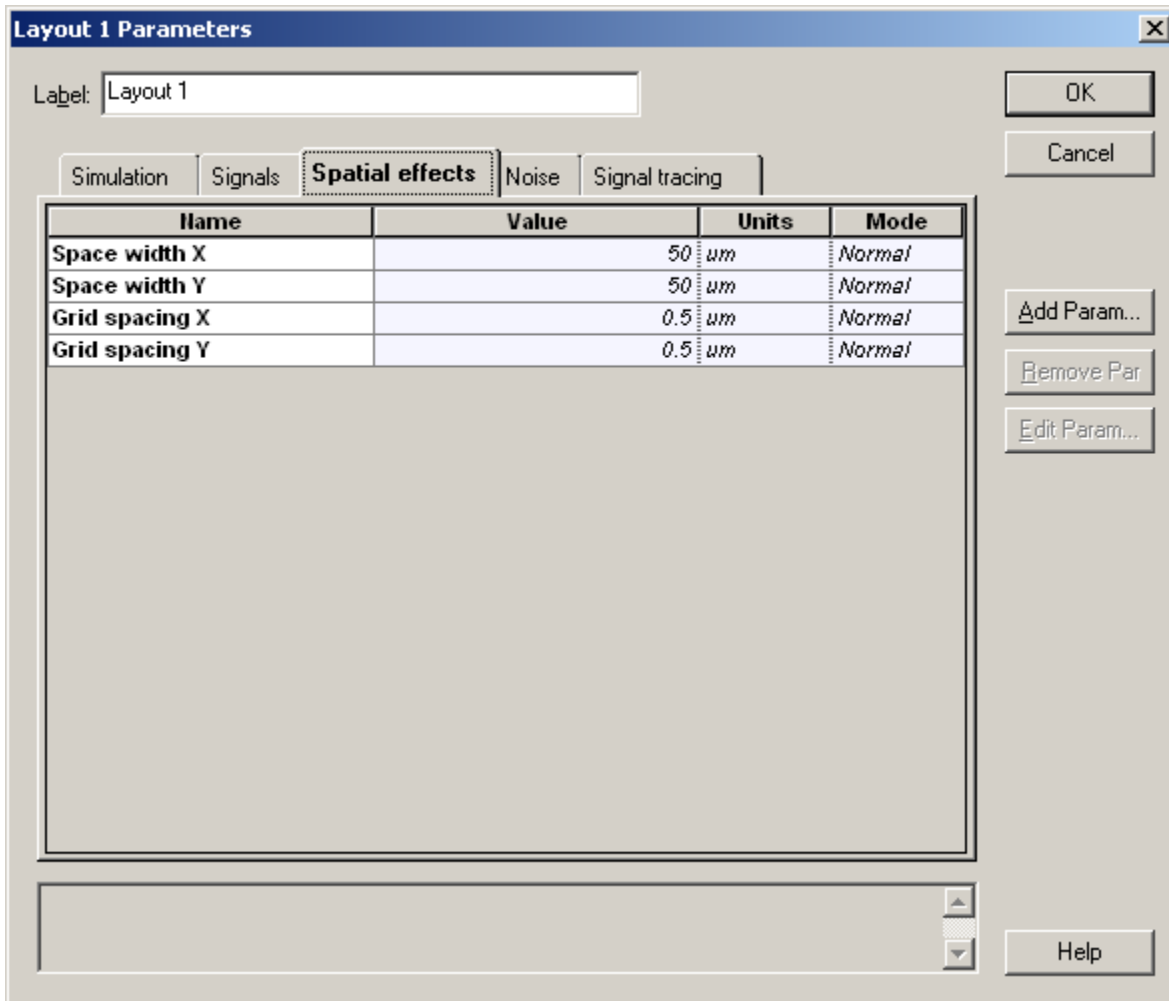
Figure 35 Global parameters Noise



Spatial Effects Parameters

The spatial effects parameters affect the components that generate spatial modes, where the discretization space and the level of the discretization should be defined. The number of points per spatial mode is defined as the product of the number of points in the X and Y coordinates.

Figure 36 Global spatial effects parameters



Space Width X

This is the space for the X coordinate.

Space Width Y

This is the space for the Y coordinate.



Grid Spacing Width X

The grid spacing for the X coordinate. The space width divided by the grid spacing gives the number of points in the X coordinate.

Grid Spacing Width Y

The grid spacing for the Y coordinate. The space width divided by the grid spacing gives the number of points in the Y coordinate.

Signal Tracing Parameters

OptiSystem allows for fast estimation of power and noise at each output port. This estimation is calculated every time a signal is sent to the component output port. The signal tracing parameters allow the user to control the calculation and presentation of the results.

Figure 37 Global signal tracing parameters

Layout 1 Parameters

Label:

Simulation Signals Spatial effects Noise **Signal tracing**

Name	Value	Units	Mode
Calculate signal tracing	<input checked="" type="checkbox"/>		Normal
Power unit	<i>dBm</i>		Normal
Frequency unit	<i>THz</i>		Normal
Decimal places	4		Normal
Sensitivity	-100	<i>dBm</i>	Normal
Resolution	0.1	<i>nm</i>	Normal
Calculate noise floor	<input type="checkbox"/>		Normal
Interpolation offset	0.5	<i>nm</i>	Normal

OK
Cancel
Add Param...
Remove Par
Edit Param...
Help



Calculate Signal Tracing

Defines if the signal will be traced.

Power Unit

The units used to display the results (dBm, W or mW).

Frequency Unit

The units used to display the results (Hz, m, THZ or nm).

Decimal Places

The number of decimal places to use when displaying the results.

Sensitivity

The minimum output power that the calculation can detect.

Resolution

The spectral resolution bandwidth of the calculation.

Calculate Noise Floor

Defines if the noise floor will be calculated using interpolation. This is an important parameter when the noise is added to the signal.

Interpolation Offset

The interpolation offset from the signal channel center frequency used to estimate the noise floor.



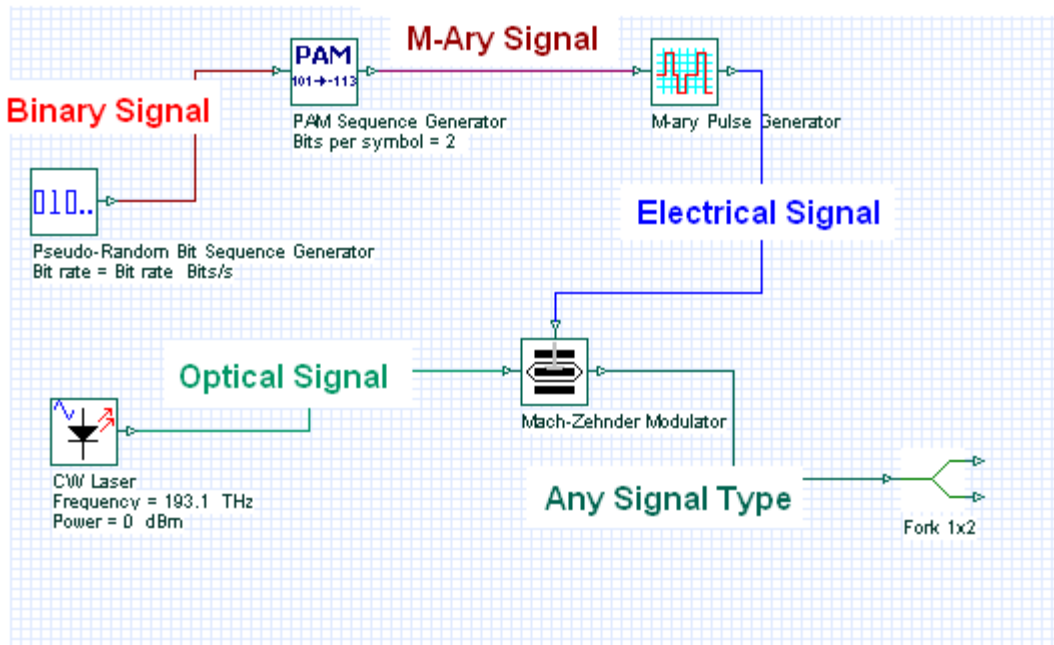
Appendix B: Signal representation

To make the simulation tool more flexible and efficient, it is essential that it provides models at different abstraction levels, including the system, subsystem, and component levels. OptiSystem features a hierarchical definition of components and systems, allowing you to employ specific software tools for integrated and fiber optics in the component level and allowing the simulation to go as deep as the desired accuracy requires. Different abstraction levels imply different signal representations. The signal representation must be as complete as possible in order to allow efficient simulation.

There are five types of signals in the signal library:

Signal	Connection color
Binary	Red
M-Ary	Dark Red
Electrical	Blue
Optical	Green
Any Type	Dark Green

Figure 38 Signal types and connections

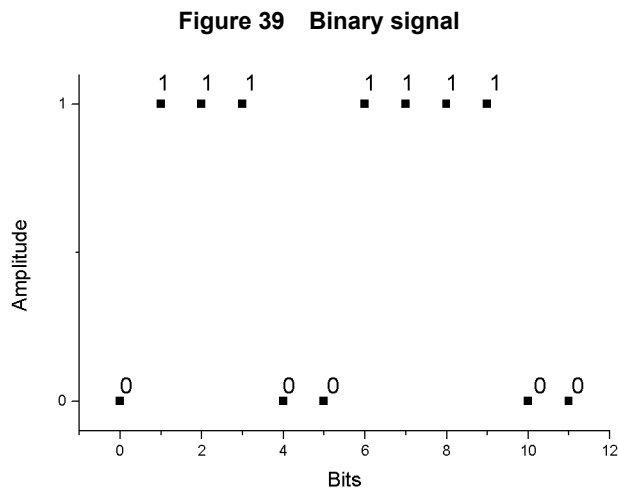


OptiSystem handles mixed signal formats in the Component Library for optical and electrical signals. It calculates the signals using different algorithms according to the desired simulation accuracy and efficiency.

Binary signals

Binary signals are generated by components such as bit sequence generators. Pulse generators in the Transmitters Library and digital switches in the Network Library use this signal as input data.

A binary signal consists of a sequence of ones and zeros, or marks and spaces. The main property of the binary signal is the Bit rate (see [Figure 39](#)).



M-Ary Signals

M-Ary signals are multilevel signals used for special types of coding, such as PAM, QAM, PSK, and DPSK. M-Ary signals are similar to the binary signals. However, M-Ary signals can have any level instead of only high (1) and low (0) levels, or marks and spaces. Refer to the digital modulation tutorial lessons.

Electrical signals

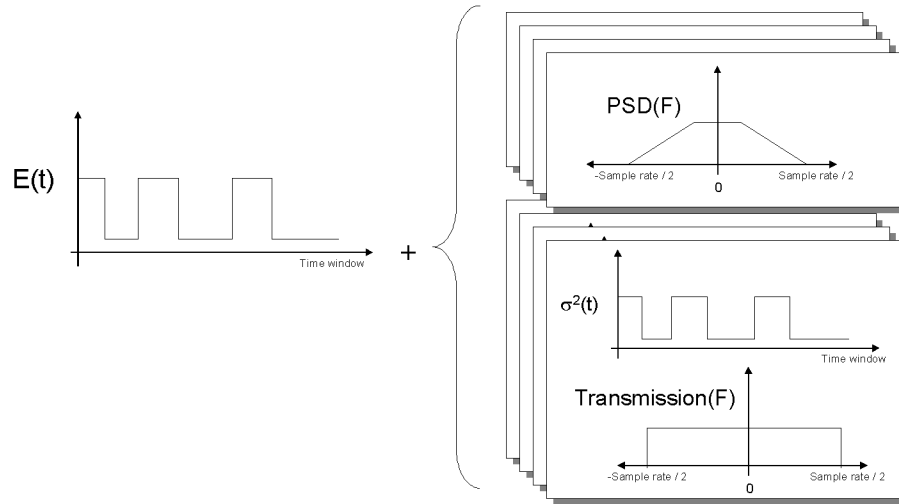
Electrical signals are generated by components such as pulse generators in the Transmitters Library and photodetectors in the Receivers Library.

Electrical signals consist of the sampled signal waveform in time domain. The main properties of the electrical signal are the signal noise variances in the time domain and the noise power spectral densities in the frequency domain.



When a pulse generator generates the electrical signal, there is no noise information with the signal because the signal is pure. If the electrical signal is generated by a photodetector, there are different sources of noise, some of which are time dependent and must be characterized by the time variance (for example, shot noise). Some of them are given as power spectral density (for example, thermal noise). The electrical signal creates the noise information according to the properties and the number of noise sources in the component (see [Figure 40](#)).

Figure 40 Electrical signal - noise variance - PSD



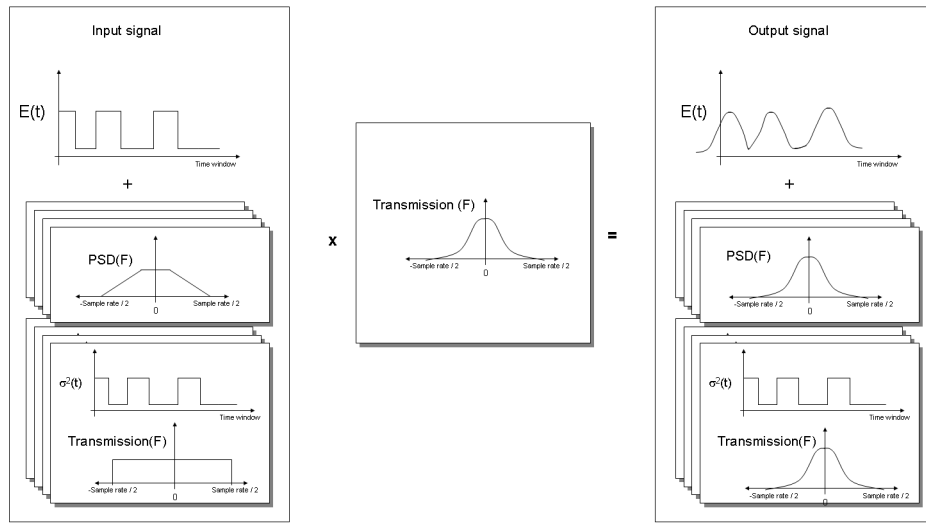
If the electrical signal is filtered, the noise PSD is affected immediately because the PSD is filtered based on the filter transfer function in frequency domain. If the noise is also characterized by the noise variance, it is not affected immediately. The information about the filter transfer function is saved in the frequency domain as a property of the noise. As a result, you can have a cascade of electrical filters and the electrical signal will keep track of the equivalent transfer function of the filters.

When using the noise variance for calculation of the signal noise, the information about the filters will be used to generate the equivalent noise bandwidth and will be applied to the noise variance (see [Figure 41](#)).

Electrical signals can also be represented by individual samples, allowing for time driven simulations. In order to simulate using individual samples the user should explicitly add the component "Convert to Individual Electrical Samples" into the layout. The signal and noise at the input signal will be added and converted into multiple samples. The number of samples is defined by the global parameter Number of samples. Refer to the tutorial lesson: *Working with individual samples*.



Figure 41 Filtering electrical signal

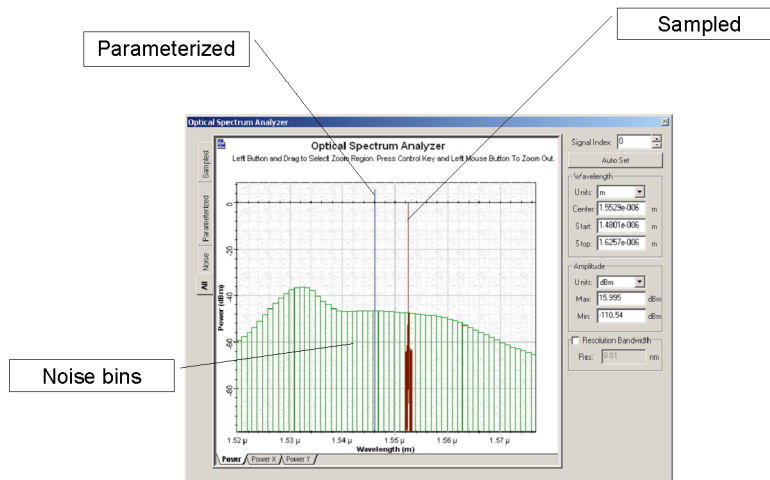


Optical signals

Optical signals are generated by components such as lasers in the Transmitters Library. Optical signals accommodate different signal representations:

- [Sampled signals](#)
- [Parameterized signals](#)
- [Noise bins](#)

Figure 42 Mixed optical signal representation - Frequency domain



Sampled signals

Optical signals can accommodate any arbitrary number of signal bands. In the simplest case, there is one single frequency band when a single, continuous frequency band represents the waveforms of all the modulated optical carriers. A single optical source (for example, CW Laser) produces a single frequency band. The band represents the complex sampled optical field of the signal in two polarizations. This type of optical signal is called a Sampled signal.

When two or more Sampled signals are combined, the individual signals will join into a new sampled signal if their simulation bandwidths overlap, or they are kept separated if the simulation bandwidth does not overlap. The resulting signal is called Sampled signals — in this case, each sampled signal is propagated using a separate sampled optical field.

Example

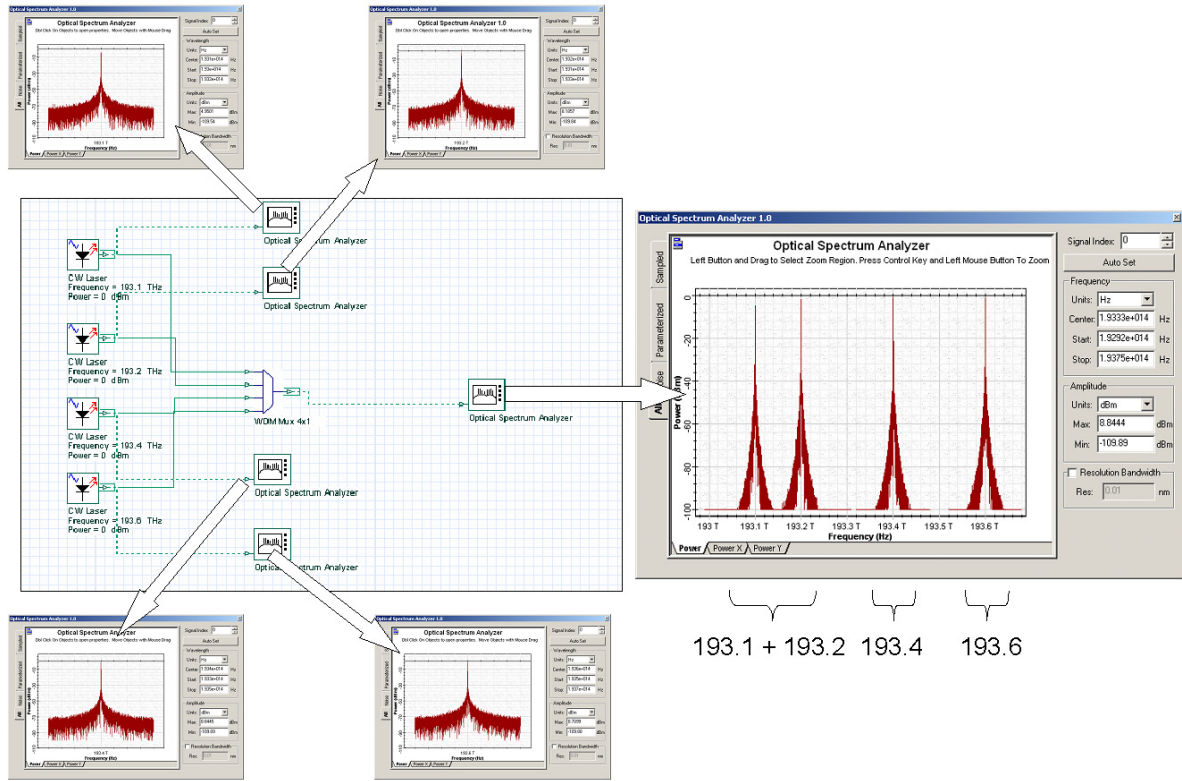
Signals are generated in each laser and are combined in the multiplexer. After the multiplexer, the channels at frequencies 193.1 and 193.2 THz overlap, so they are added to the same band (see [Figure 43](#)).

Sampled signals can also have spatial representation for the spatial modes. If you are using the multimode component library, the sampled signals will also have the spatial distribution of the signal power for both polarizations.

Optical signals can also be represented by individual samples, allowing for time-driven simulations. In order to simulate using individual samples, the user should explicitly add the component "Convert to Individual Optical Samples" into the layout. Only sampled signals can be converted into individual samples. The number of individual samples is defined by the global parameter Number of samples. If the input signal has multiple channels, each channel will have an individual sample and center frequency, allowing for WDM and Time-driven simulations. Refer to the tutorial lesson: *Working with individual samples*.



Figure 43 Overlapping channel frequencies



Parameterized signals

The signal description based on the Sampled signals covers the majority of physical phenomena affecting the system design. When designing a system where the power budget analysis and the fast signal-to-noise ratio estimations are the main performance evaluation results, signal channels can be approximated by their average power, assuming that the detailed waveform of their data streams are not important. One application example is the investigation of the transmission behavior of the central channels in dense WDM systems, or an estimation of the EDFA performance in the steady-state regime.

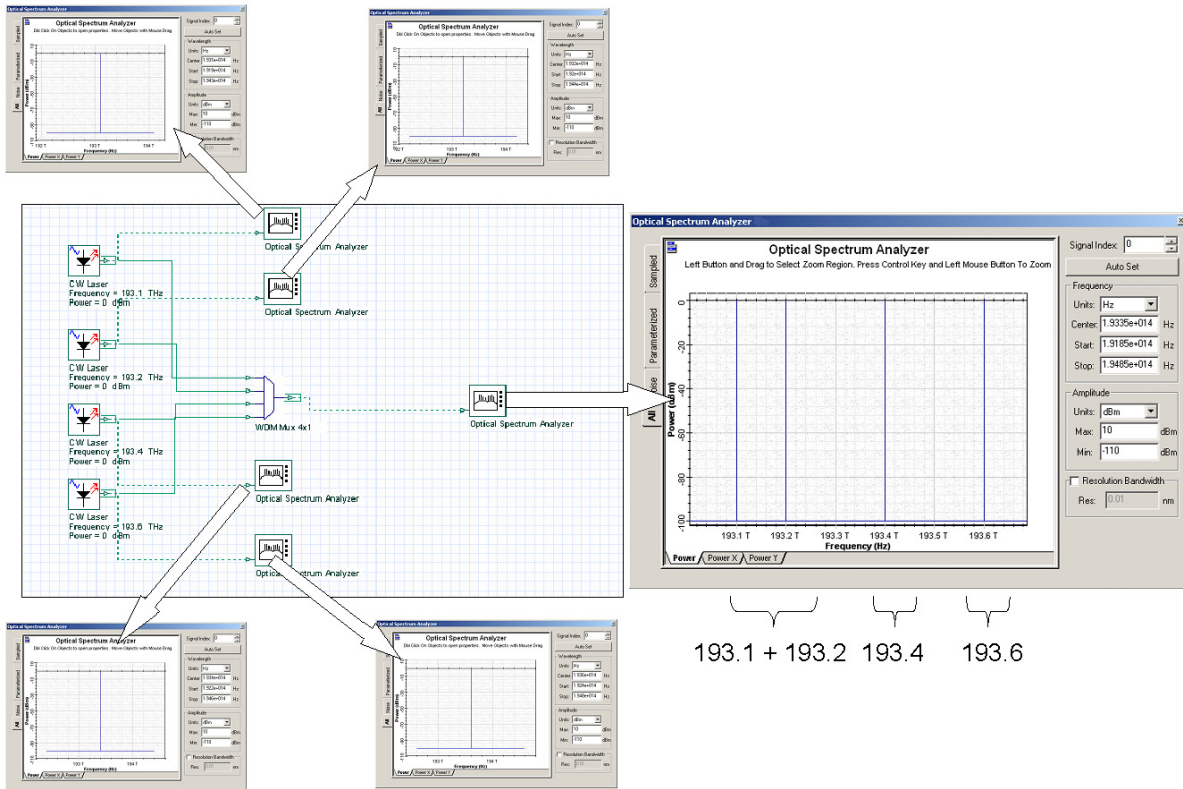
Parameterized Signals are time-averaged descriptions of the sampled signals based on the information about the optical signal (for example, Average power, Central frequency, and Polarization state).

Example

Signals are generated in each laser using parameterized representation and combined in the multiplexer. Signals are represented by power and frequency (see Figure 44).



Figure 44 Signals combined in the multiplexer



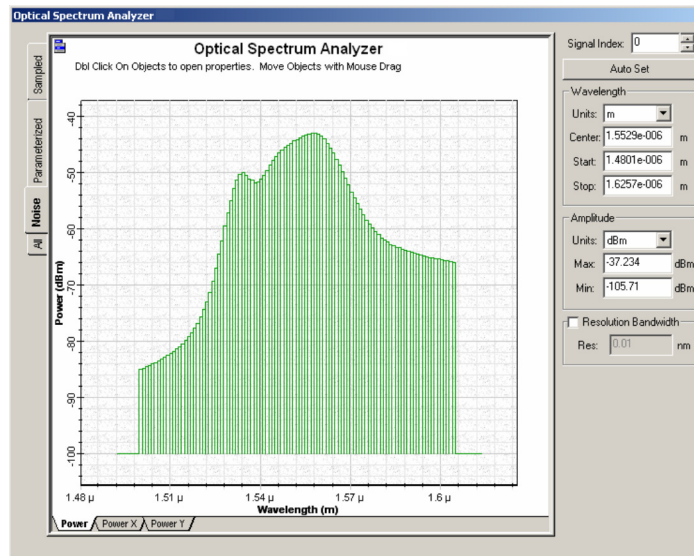
In the typical simulation of optical amplifiers in a WDM system, the model of an EDFA uses the static solution of the rate equations. Each WDM channel is a sampled signal with the information about the signal waveform (for example, center frequency, sample rate and a large number of samples). The WDM channels are close to each other, and can be in separate channels or together in the same band using a total field approach. The center frequency of the signal pump is far from the signal channels, making it inefficient to include the pump in the same band as the signal channels. There is no information content in the bandwidth range between the channels and pumps. The signal pump is also a CW signal, and can be represented as a parameterized signal by such statistical parameters as its power and wavelength.

The other type of signal is the ASE generated by the amplifier, which can also be represented in an alternative way by the power spectral density of the ASE bandwidth instead of the sampled signal. OptiSystem separates noise and signals in the spectrum, describing the noise by modifying the parameterized signals to another signal representation — Noise bins.

Noise bins

Noise bins represent the noise by the average spectral density in two polarizations using a coarse spectral resolution. The resolution can be adapted to maintain the accuracy of the simulation. The main advantage of using Noise bins is to cover the wide spectrum of the optical signals or to represent the noise outside the Sample signals bandwidths. The noise bin representation is similar to the parameterized signals, including the polarization. The main difference is that noise bins are defined by the noise power density and the bandwidth of each noise bin instead of by the average power (see [Figure 45](#)).

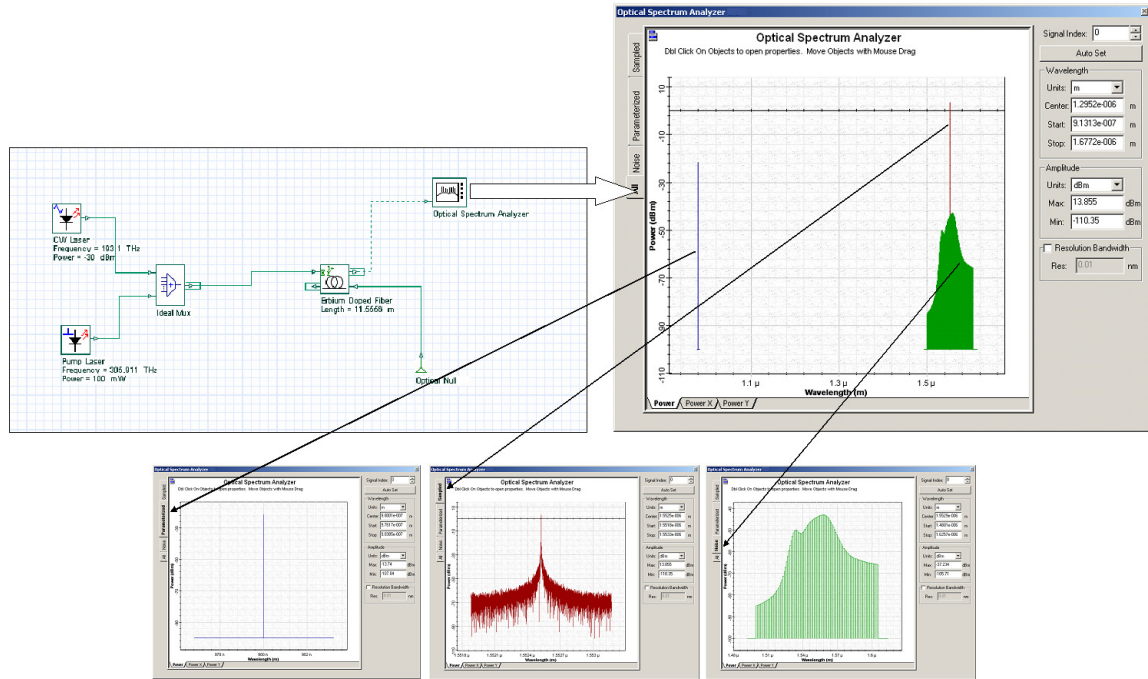
Figure 45 Noise bins generated by EDFA



Noise Bins can be created whenever there is a source of optical noise, such as optical amplifiers. You define the initial resolution and bandwidth of the noise (see [Figure 46](#)).

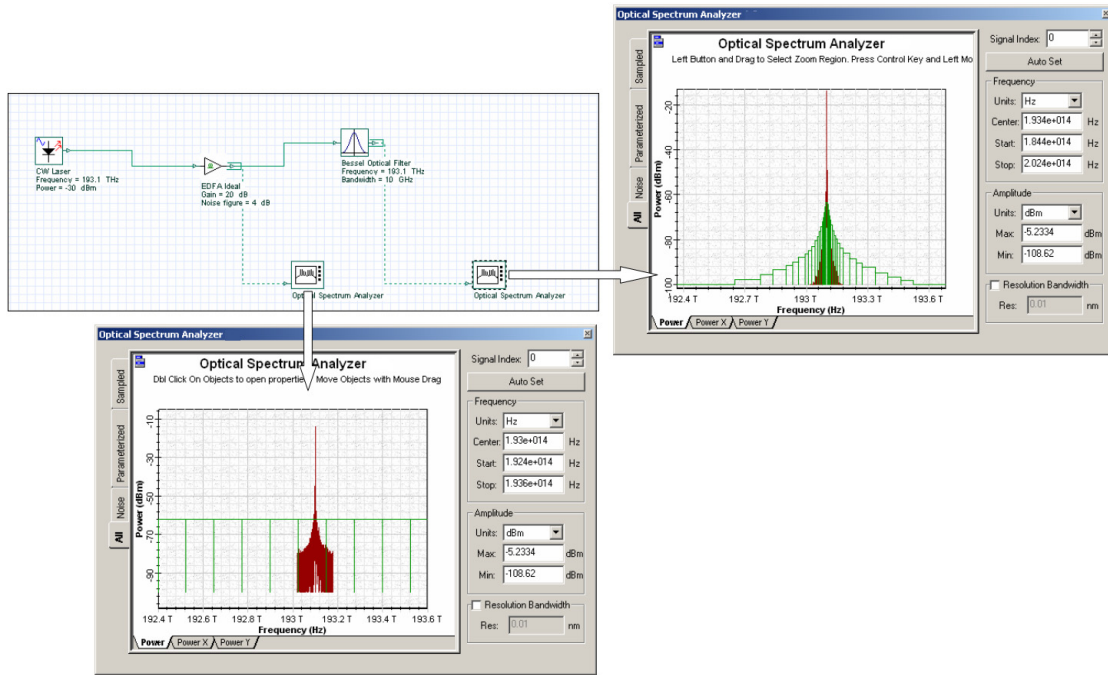


Figure 46 Mixed signals generated by EDFA



During transmission, the widths of the noise bins are adapted automatically to describe the filtering of the noise with a specified precision. The noise bins shrink in width as they propagate through the simulation in order to maintain the discretization accuracy (see [Figure 47](#)).

Figure 47 Filtering noise bins – adaptive band of each bin





Optiwave
7 Capella Court
Ottawa, Ontario, K2E 7X1, Canada

Tel.: 1.613.224.4700
Fax: 1.613.224.4706

E-mail: support@optiwave.com
URL: www.optiwave.com

LASER Transmitters

1 OBJECTIVE

Investigate the L-I curves and spectrum of a FP Laser and observe the effects of different cavity characteristics. Learn to perform parameter sweeps in OptiSystem.

2 PRE-LAB

A laser depends on three main components to function: gain medium, energy pump and resonator. In a semiconductor laser, a current source is used to inject carriers into the gain medium. The carriers in the gain medium pass their energy and emit photons by spontaneous and stimulated emission. Finally, the photons are confined in the optical cavity and emitted through one of the facets. Modifying or controlling any of these components can have observable and quantifiable effects on the performance of the laser.

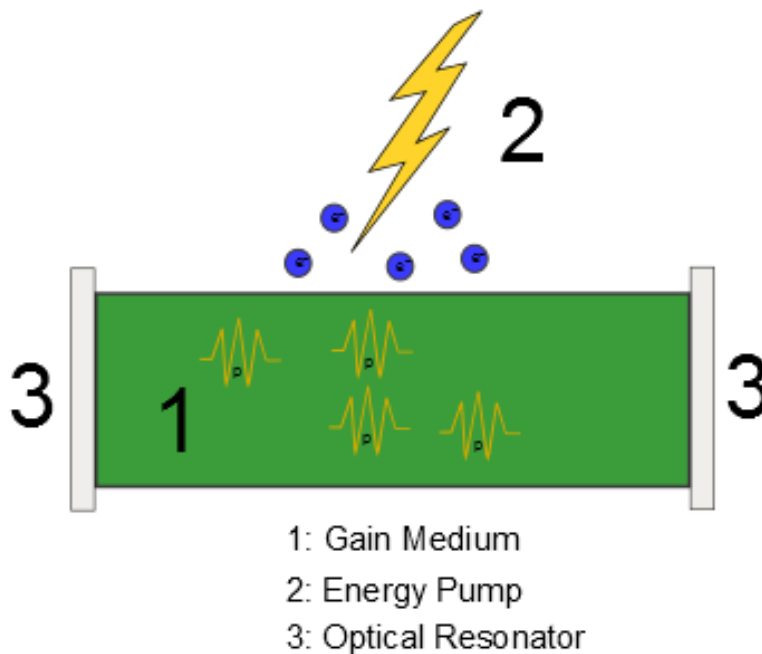


Figure 1: Schematic demonstrating the main components in a laser.

2.1 GAIN AND THRESHOLD

There are two regimes of laser operation: before threshold, where losses are larger than the gain, and at threshold, where the losses match the gain. When an optical mode cannot sustain itself for a complete

roundtrip of the cavity there is a low number of photons in the cavity and the dominant source of photons is spontaneous emission. Once an optical mode is able to make an entire trip, the number of photons increases dramatically and the dominant source of photons switches to stimulated emission.

The relationship between losses and gain in a Fabry Perot cavity can be expressed by:

$$e^{gL} \sqrt{R_1 R_2} e^{-\alpha_{int} L} e^{-2i\beta L} = 1, \quad (1)$$

where g is the gain experienced by the optical mode, L is the length of the cavity, R is the reflectivity of the facets, α_{int} is the internal losses and β is the phase constant.

The modal gain, g , is naturally dependent on the current injected into the gain medium and can be approximated by:

$$g = \sigma_g (N - N_t), \quad (2)$$

where σ_g is the differential gain, N is the carrier density and N_t is the carrier density at transparency.

Questions:

- 2.1.1 What effect does increasing the reflectivity of the end facets have on the threshold current?
- 2.1.2 Manipulating the equation for the threshold condition express the quantity α_{mir} in terms of the reflectivity. Hint: The equation will take the form of $g = \alpha_{mir} + \alpha_{int}$
- 2.1.3 For a cavity with gain 110 cm^{-1} and loss 35 cm^{-1} calculate the required length of the cavity to reach threshold, assuming total mirror loss of 0.4. What is the restriction on the phase constant?
- 2.1.4 For the cavity described above what is the threshold carrier density? Assume differential gain of $4 \times 10^{-16} \text{ cm}^2$ and transparent carrier density of $1 \times 10^{18} \text{ cm}^{-3}$.

2.2 LASER RATE EQUATIONS

As an optoelectronic device, a Laser is governed by the interaction between electrons and photons in the active region. For a single mode laser, the number of electrons to number of photons can be described by two coupled differential equations:

$$\frac{dP}{dt} = GP + R_{sp} - \frac{P}{\tau_p}, \quad (3)$$

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - GP, \quad (4)$$

P = number of photons

τ_p = photon lifetime

q = electron charge

N = number of electrons

τ_c = carrier lifetime

I = injected current

R_{sp} = rate of spontaneous emission into the lasing mode

G = net rate of stimulated emission

For lasers with more optical modes, simply adding more coupled equations can be used to extend the model, but the solution becomes more complex. G , the net rate of stimulated emission is linked to the modal gain, g , and group velocity by:

$$G = gv_g. \quad (5)$$

The group velocity and photon lifetime are related to the loss of the cavity as:

$$\frac{1}{\tau_p v_g} = \alpha_{mir} + \alpha_{int}. \quad (6)$$

Questions:

- 2.2.1 Assuming a spontaneous emission rate approaching 0, write the rate equations in steady state form.
- 2.2.2 Using this form of the rate equation determine the threshold condition and the subsequent expression for the threshold current.
- 2.2.3 Determine the threshold current for the cavity in the previous questions with an active region area of $0.3 \mu\text{m}^2$ and carrier lifetime of 1.5 ns.

In addition to the threshold current another important and easily extractable quantity of a laser is the slope efficiency, which relates the input current to the output optical power. From the steady state equation derived in question 2.2.1, it can be written as:

$$P_e = \frac{hf}{2q} \frac{\eta_{int} \alpha_{mir}}{\alpha_{mir} + \alpha_{int}} (I - I_{th}). \quad (7)$$

In equation 7, hf is the energy of the photons with h as Planck's constant and f the frequency. Furthermore, η_{int} is the internal quantum efficiency, which is the ratio of photons created by stimulated emission to electrons injected into the active region. Above threshold, η_{int} is remarkably close to 1. The slope efficiency is the derivative of this equation and is strongly related to the losses of the cavity. It should also be noted that the mirror loss, α_{mir} , is calculated strictly from the front facet of the Laser, so that the ratio describes the fraction of useful optical output power to total loss.

- 2.2.4 Calculate the slope efficiency of a laser with properties from the previous questions and operating at $1.55 \mu\text{m}$.

2.3 LONGITUDINAL MODES

The rate equations are accurate only if there is a single optical mode for photons to populate. In a more realistic description, the photons can spontaneously emit and couple to different modes. Photons created by stimulated emission will couple to the same mode as the photon that stimulated it and the resultant output spectrum will have one or more frequency peaks. These frequency peaks correspond to the longitudinal modes of a Fabry–Perot cavity.

As optical waves propagate back and forth in a Fabry–Perot cavity their accumulated phase shifts can cause them to interfere constructively or destructively. Wavelengths that interfere constructively are preferred and make up the different longitudinal modes. The spacing between adjacent longitudinal modes can be expressed by:

$$\Delta\nu = \frac{c}{2n_g L'} \tag{8}$$

where c is the speed of light, n_g is the group index and L is the length of the cavity.

For long haul communications a single mode laser is preferred, as adding unwanted frequencies can exacerbate dispersion. The wavelength dependent gain, resulting from the bandgap of the semiconductor, translates to a mode dependent gain. The result is one or two modes are favored over the rest.

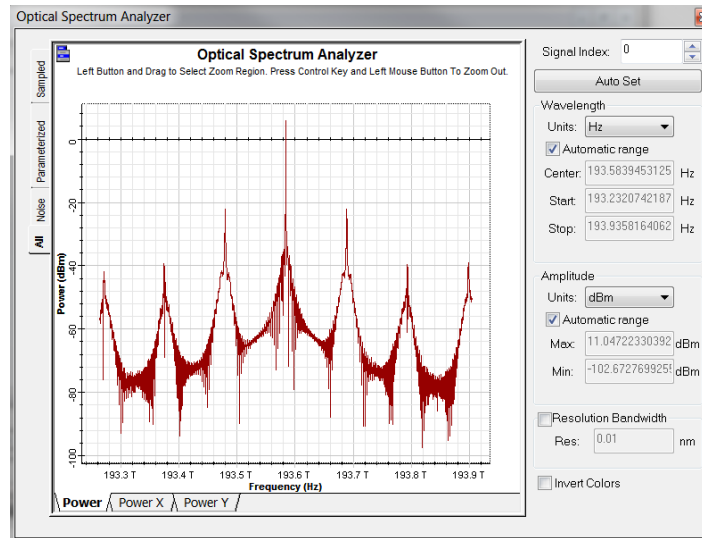


Figure 2: The wavelength dependent gain of the semiconductor favors one of the longitudinal modes over the others.

The side mode suppression ratio (SMSR) is commonly used to quantify the difference in power between the dominant and adjacent mode. It is calculated by comparing the dominant mode’s peak power and that of the adjacent mode.

Questions:

- 2.3.1 Calculate the mode spacing of a 500 μm long cavity with a group index of 3.5.

3 MEASURING THRESHOLD CURRENT AND SMSR

Once the injection current has increased passed the threshold value, a very large percentage of carriers efficiently recombine to create photons and the output optical power to current graphs becomes linear. To measure the threshold current of a laser, increasing the current bias slowly and recording the optical power is straightforward method that is used experimentally and can also be simulated with OptiSystem.

3.1 OPTISYSTEM PROJECT FILE

Start a new project in OptiSystem and place the following components in the same fashion as the layout below:

- | | |
|----------------------------------|--|
| • Bias Generator | Transmitters Library/Pulse Generators/Electrical |
| • Fabry Perot Laser | Transmitters Library/Optical Sources |
| • Optical Time Domain Visualizer | Visualizer Library/Optical |
| • Optical Spectrum Analyzer | Visualizer Library/Optical |
| • Optical Null | Tools Library |

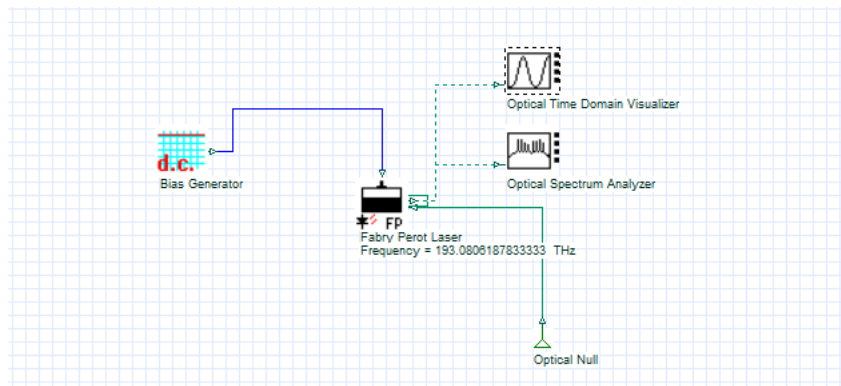


Figure 3: Simulation layout of a Fabry–Perot Laser

Testing the steady state operation of the Fabry Perot Laser requires a constant electrical signal, in OptiSystem a Bias Generator can be used. To locate the threshold current the electrical bias needs to be swept through a linear range, while the output optical power is monitored.

In OptiSystem, electrical pulse generators are measured in arbitrary units, which then can be interpreted as either current or voltage by the driven electrical component. In this case, the Fabry Perot Laser interprets it as a current and scales it according to:

$$I(t) = I_{DC} + I_{in}(t) \times I_{pk}(t), \quad (9)$$

where I_{DC} and I_{pk} are the Fabry Perot Laser parameters “Bias current” and “Modulation peak current”. The Bias Generator creates the I_{in} value, which in this case is 1. For this simple DC signal, the “Bias current” parameter can be set to 0 and the output of the Bias generator can be directly controlled by the “Modulation peak current”.

3.2 SETTING UP AND RUNNING PARAMETER SWEEP

Perform a parameter sweep of the “Modulation peak current” parameter by first opening the Fabry Perot Laser component properties and changing the “Modulation peak current” mode to sweep. Clicking on the table icon will allow you to set the total number of iterations, which should be set to 10. Make sure to also change the “Laser model” to Transmission Line.

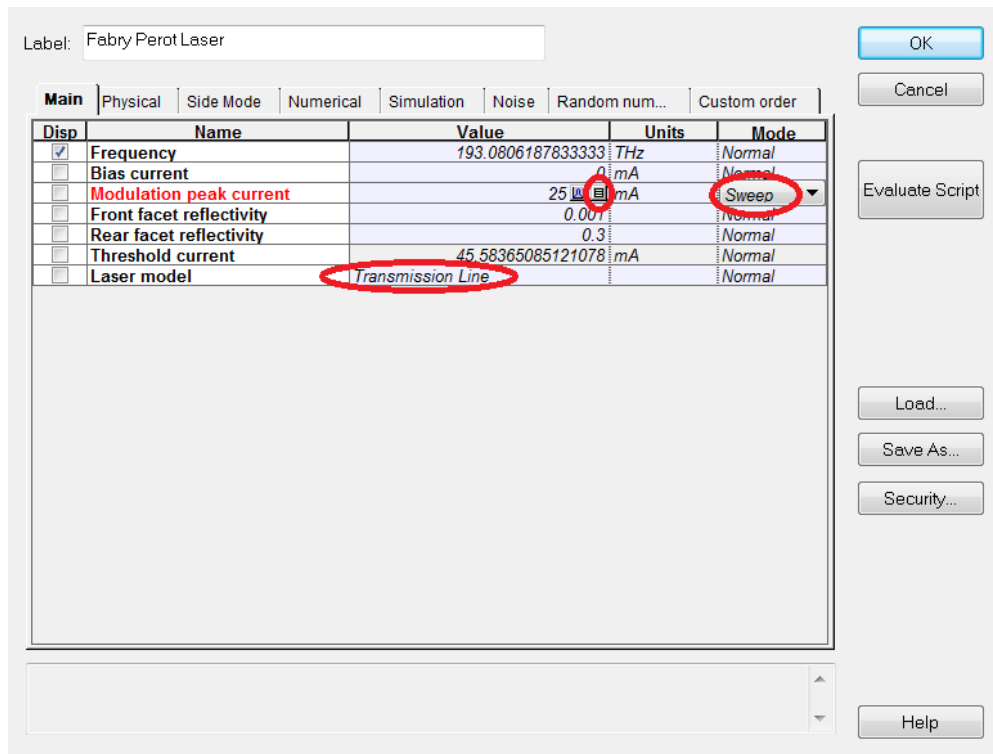


Figure 4: Component Properties window

Click on the “Modulation peak current” column and choose a linear distribution from the spread tools and choose a start and end value of 25 and 70.

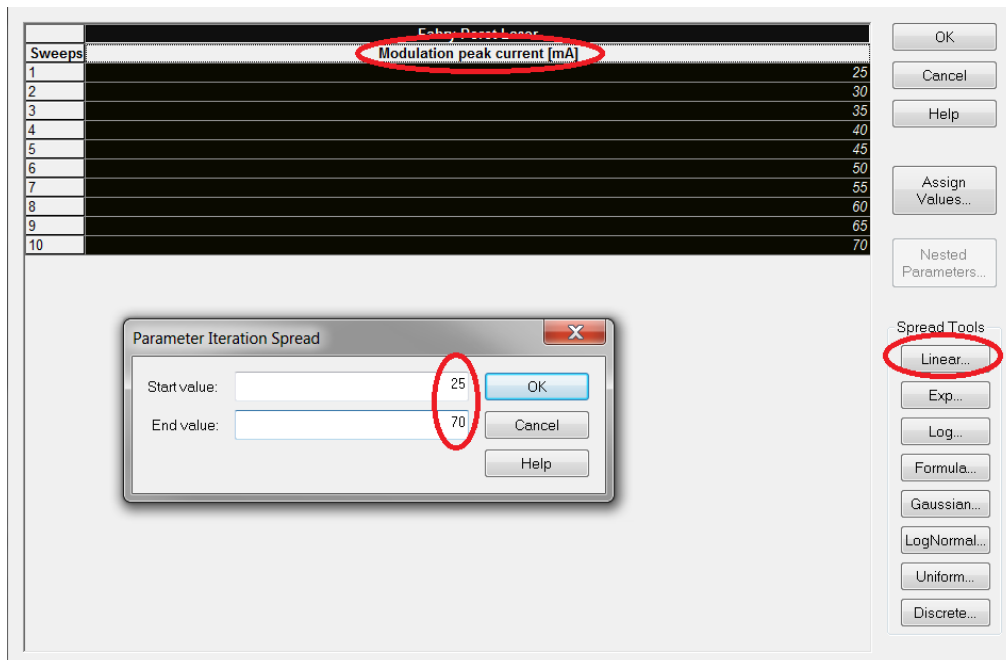


Figure 5: Parameter sweep window

Open the calculation window (Ctrl + F5) and run the simulation, using multithreading if you desire.

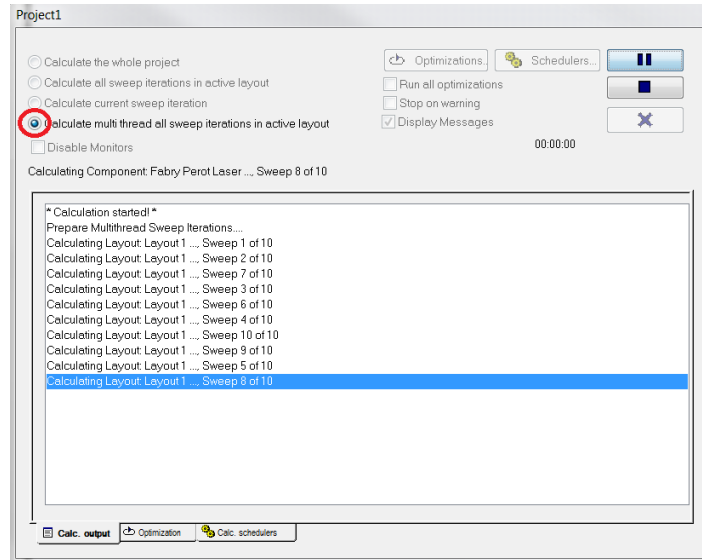


Figure 6: Calculation window

3.3 RESULTS

The threshold current will be clear once the optical power is compared to the injection current. Head to the report page and choose the Opti2DGraph. Dragging a box creates a graph to your desired dimensions

In the project browser on the left locate the “Modulation peak current” parameter and drag it to the x axis.

Finally drag the “Signal Power (Mean)” optical time domain visualizer result to the y axis.

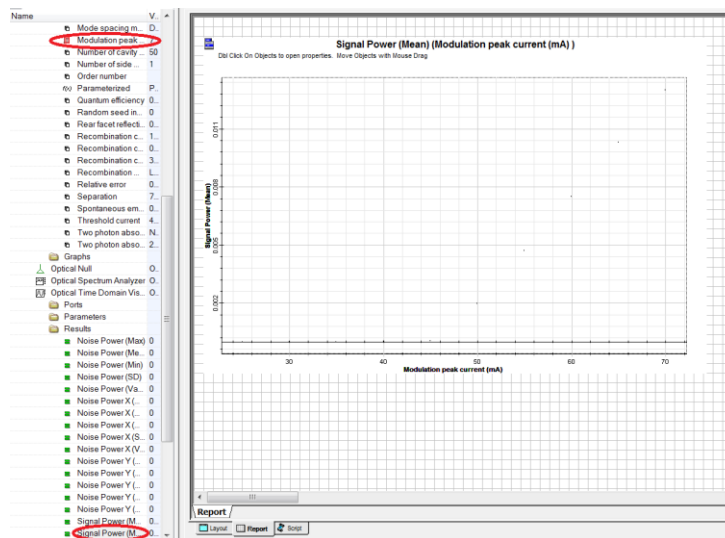


Figure 7: Report page

Using this feature the threshold current can be found graphically. Right-clicking the plot and activating it will allow the placement of Markers, which then can be used to accurately measure the current.

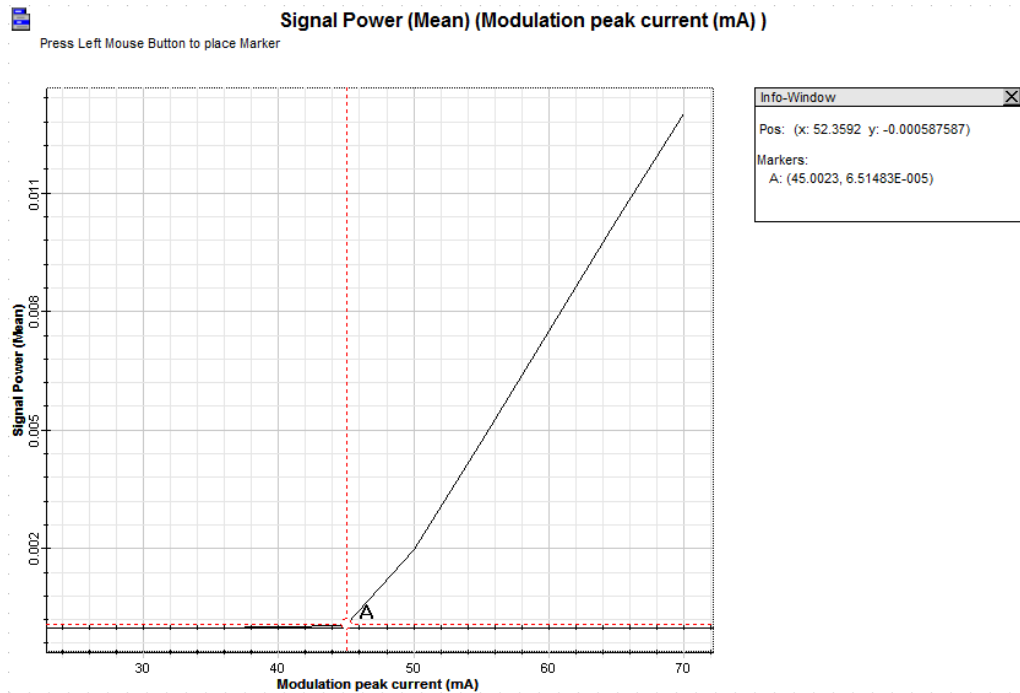


Figure 8: Plot of optical power as a function of the injection current.

For this laser the threshold current is estimated to be 45 mA.

3.4 CHARACTERIZATION OF AN INGAASP LASER

Using the previous section as a guide and using the same project layout find the threshold current of a Laser with the following parameters:

Wavelength	1.55 μm
Front facet reflectivity	0.178
Rear facet reflectivity	0.9
Active length	0.01 cm
Active layer width	1.5 μm
Active layer depth	0.2 μm
Group Index	3.5
Quantum efficiency	0.45
Differential gain coefficient	$0.4 \times 10^{-15} \text{ cm}^2$
Carrier density at transparency	$1\text{e}18 \text{ cm}^{-3}$
Mode confinement factor	0.4
Carrier lifetime	1.5 ns
Spontaneous emission factor	0.001
Loss	35 cm^{-1}
Laser model	Transmission Line

Keep all other parameters their default value.

Questions:

- 3.4.1 Using the graphical method demonstrated plot the P – I curve of this Laser and determine its threshold current.
- 3.4.2 Find the slope efficiency graphically.
- 3.4.3 Using a spectrum analyzer determine whether the laser is operating in a single mode manner.
- 3.4.4 Change the length of the cavity to 500 μm and determine the mode spacing and SMSR at approximately double the new threshold current. Hint: The larger cavity means that the number of cavity sections used in the numerical method must be increased. In the numerical tab of the FP Laser try 100 sections.

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] Saleh, Bahaa E. A., and Malvin Carl. Teich. *Fundamentals of Photonics*. New York: Wiley, 1991. Print.

PIN Photodiode

1 OBJECTIVE

Investigate the characteristics of PIN Photodiodes and understand the usage of the Lightwave Analyzer component.

2 PRE-LAB

In a similar way photons can be generated in a semiconductor, they can be detected by one. Instead of stimulated emission, stimulated absorption is the process of interest. As long as the incident photons have similar energies to the band-gap of the semiconductor, efficient conversion into carriers is possible. In a simple *p-i-n* photodetector, two regions of heavily doped semiconductor are separated by an undoped intrinsic semiconductor. This creates a large depletion region with a voltage difference across it. When photons excite electrons into a higher conduction band, the voltage imparts a drift velocity on the electron and it moves towards the *n*-doped side creating a current.

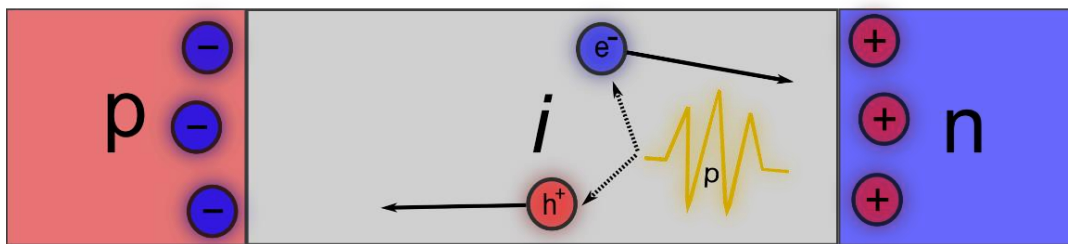


Figure 1: Structure of a PIN photodetector.

2.1 EFFICIENCY AND BANDWIDTH

The ratio of input optical power to current produced is called, R_D , the responsivity.

$$I_p = R_D P_{in}. \quad (1)$$

The responsivity can be broken down further in terms of the ratio of generated electrons to incident photons by the quantum efficiency, η :

$$R_D = \frac{hf\eta}{q}, \quad (2)$$

where hf is the energy of the incident photons and q is the electron charge. A simple model can be made for the quantum efficiency. It relates the loss, α , and length, L , of the absorbing material to the absorbed power and thus efficiency.

$$\eta = 1 - e^{-\alpha L}. \quad (3)$$

Once the electron-hole pairs are created somewhere in the middle region, they still have to make it to one of the doped regions, where they can enter an electrical circuit. This time along with the capacitance of the electrical circuit creates a finite rise time and as a result a limited bandwidth. The rise time, or time it takes a circuit to rise from 10% to 90% of its final value is given by:

$$T_r = \ln 9 (\tau_{tr} + \tau_{RC}), \quad (4)$$

where τ_{tr} is the transit time of the electron and τ_{RC} is the time constant of the equivalent electrical circuit. The bandwidth of the circuit can be defined in the same manner as a simple RC circuit.

$$\Delta f = \frac{1}{2\pi(\tau_{tr} + \tau_{RC})}. \quad (5)$$

Questions:

- 2.1.1 An InGaAs based photodetector centered at 1.55 μm is 2.5 μm in length and has a responsivity of 0.85 A/W. Determine the quantum efficiency and loss per cm.
- 2.1.2 Calculate the drift velocity and bandwidth of the above photodetector if it is assumed a majority of electrons are created in the center. Assume an RC time constant of 1 ps and a rise time of 20 ps.

2.2 NOISE

Noise added to a signal in a photodetector can be categorized into two types: shot noise and thermal noise. Shot noise is generated by the quantum nature of photons and electrons, whereby the random generation of electrons with respect to time can change the instantaneous current. Thermal noise is a much simpler concept to understand and is attributed to the random movement of electrons at a finite temperature. Using Δf , as the effective noise bandwidth, they can both be expressed by:

$$\sigma_s^2 = 2q(I_p + I_d)\Delta f, \quad (6)$$

$$\sigma_T^2 = (4k_B T/R_L)\Delta f. \quad (7)$$

σ_s = RMS value of shot noise I_d = dark current k_B = Boltzmann constant

σ_T = RMS value of thermal noise T = absolute temperature R_L = load resistance

I_p = average current

The dark current is the current detected when there is no signal, it is attributed to unwanted light leaking into the detector or thermally created carriers and fortunately it is quite small. The signal to noise ratio, expressed often in dB is a very useful quantity that relates the signal's power to the noise power.

$$SNR = I_p^2 / (\sigma_s^2 + \sigma_T^2). \quad (8)$$

Questions:

- 2.2.1 A photodetector has an effective bandwidth of 15 GHz and a dark current of 8 nA. For an incident optical signal that produces 10 μ A of current what is the associated shot noise root mean square value?
- 2.2.2 For the same photodetector above connected to a 45 Ω resistor at a temperature of 21 degrees Celsius, calculate the root mean square value for the thermal noise.
- 2.2.3 Now calculate the SNR of the photodetector.

3 RESPONSIVITY AND BANDWIDTH SIMULATION

The responsivity relates the incident optical power to the current generated. Naturally, a larger responsivity is desired. The bandwidth of a detector is also an important quantity, which determines the maximum a bit rate that can be detected. These quantities could be found from creating a parameter sweep, as was the focus of the laser simulation. However, using the built-in Lightwave Analyzer component can save a lot of time.

3.1 OPTISYSTEM PROJECT FILE

The setup is very simple for this simulation place the two components below in a similar manner to the screenshot:

- Lightwave Analyzer
 - PIN Photodiode
- Test Sets
Receivers Library/Photodetectors

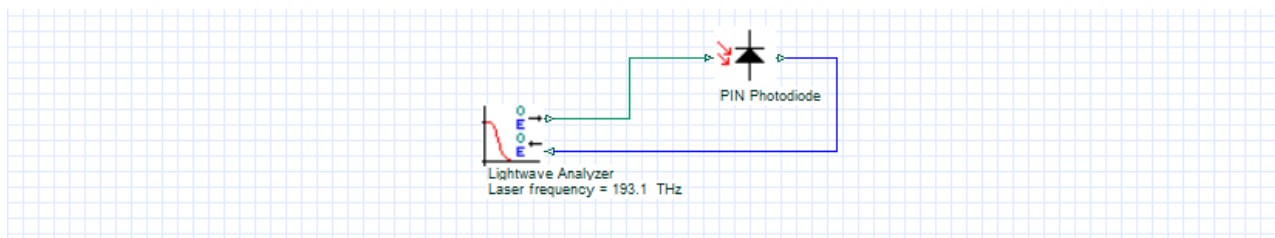


Figure 2: Layout using the Lightwave Analyzer.

Before the output of the PIN Photodiode can be attached to the input of the Lightwave Analyzer the Test configuration parameter has to be changed to “Optical-electrical”, since the photodiode output is electrical.

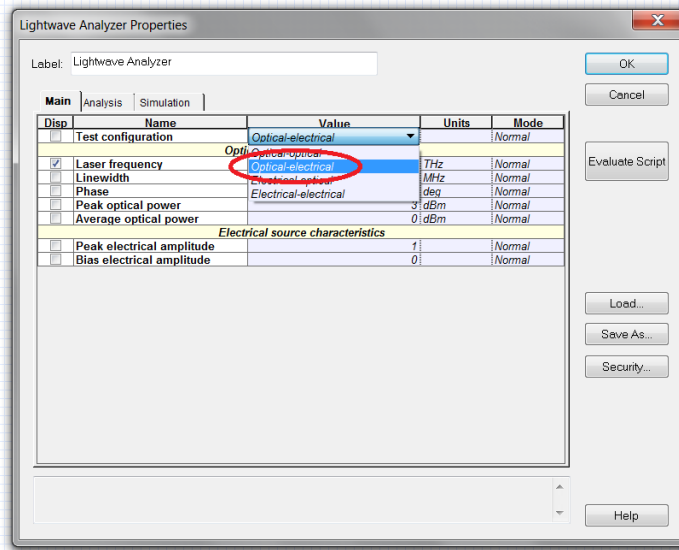


Figure 3: Lightwave Analyzer component properties.

The Lightwave Analyzer serves as a quick way to investigate the frequency response and also the conversion efficiency of a device, in this case the responsivity of the photodetector. The frequency response is found, by creating multiple sine waves signals at linearly spaced frequencies and monitoring the output.

On the Analysis tab, the frequencies swept can be viewed and the number of steps can be changed. Change the starting frequency to 0.1 GHz. Setting the starting frequency too low can result in an unrealistic frequency response, as the signal can lack the frequency resolution to accurately represent the slowly varying signal.

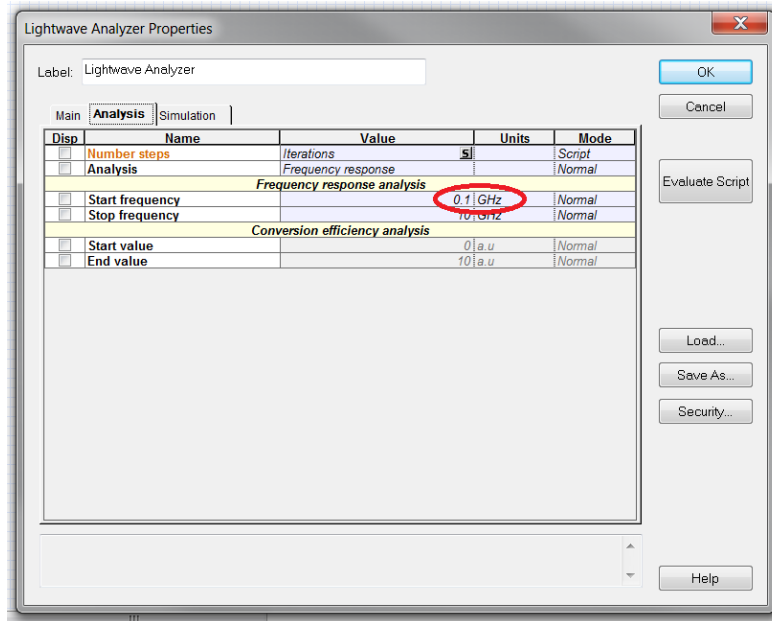


Figure 4: Setting parameters on the Analysis tab.

The default number of steps is linked to the global parameter “Iterations”, which can be changed from the layout parameters. Change the number of iterations to 20 by modifying the layout parameters.

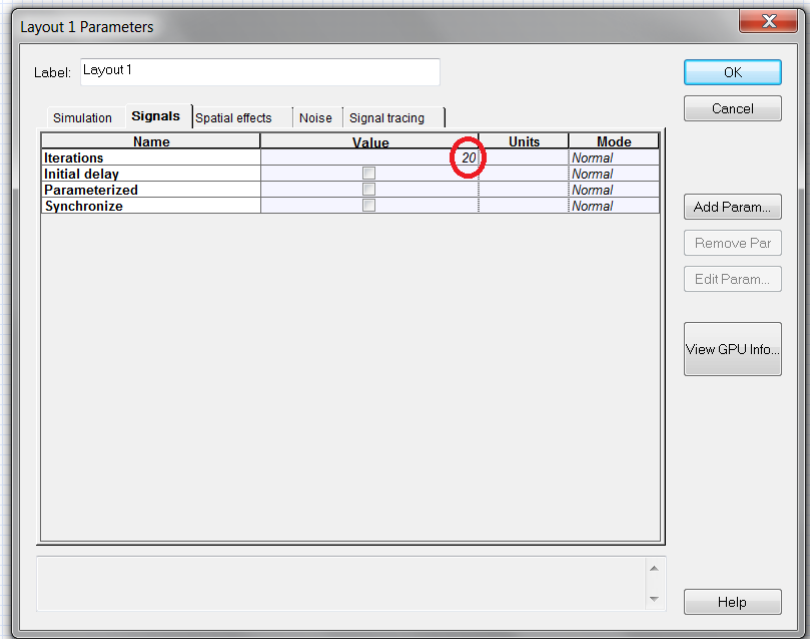


Figure 5: Layout parameters window.

Include a realistic frequency response by changing the transfer function model of the PIN Photodiode from Ideal to Defined.

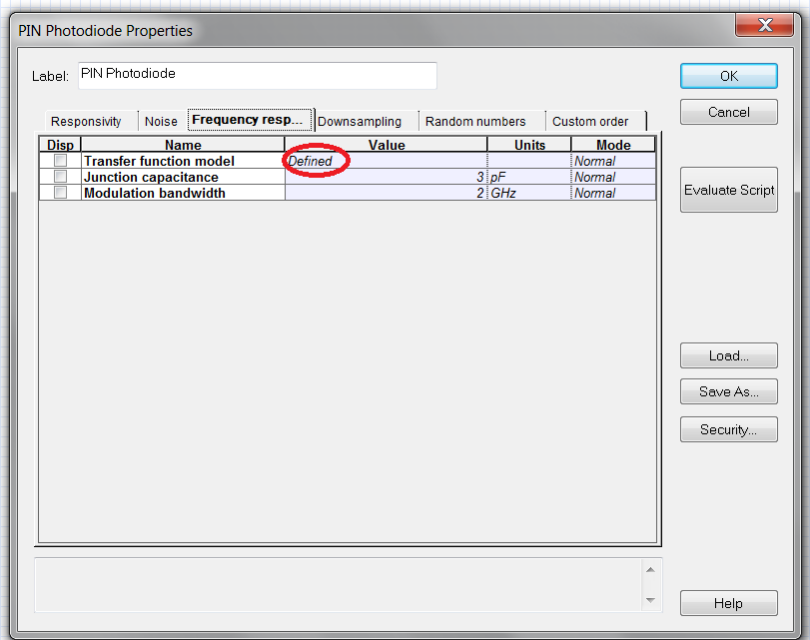


Figure 6: PIN Photodiode properties window.

All that remains is to run the simulation. Once the simulation is complete expand the Project Browser in the bottom left and open the Transmission response graph.

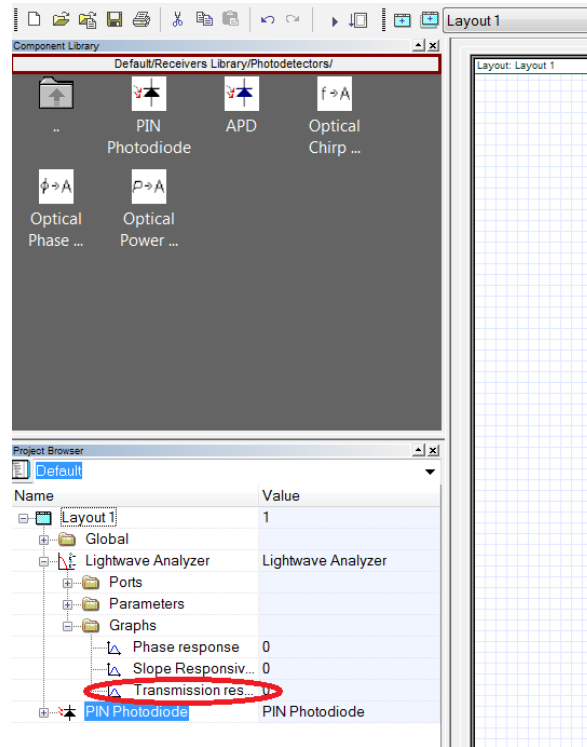


Figure 7: Finding the Transmission response graph in the Project Browser.

From the transmission response the 3 dB bandwidth is easily identifiable. Right-click the graph to interact with the curve and place markers to determine the 3 dB bandwidth accurately.

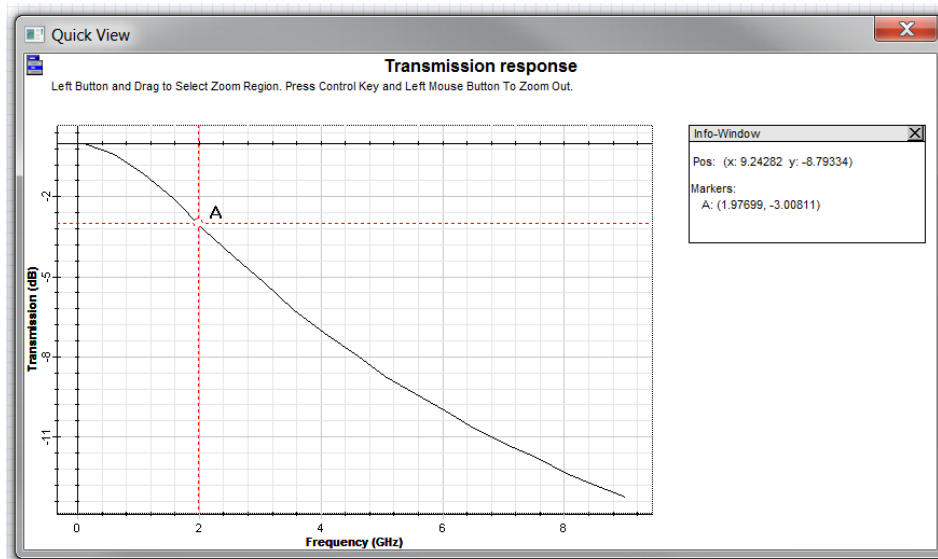


Figure 8: Frequency response of the PIN photodiode.

With a few changes the same component can be used to determine the responsivity of the PIN photodetector. First change the analysis type of the Lightwave Analyzer to “Conversion”.

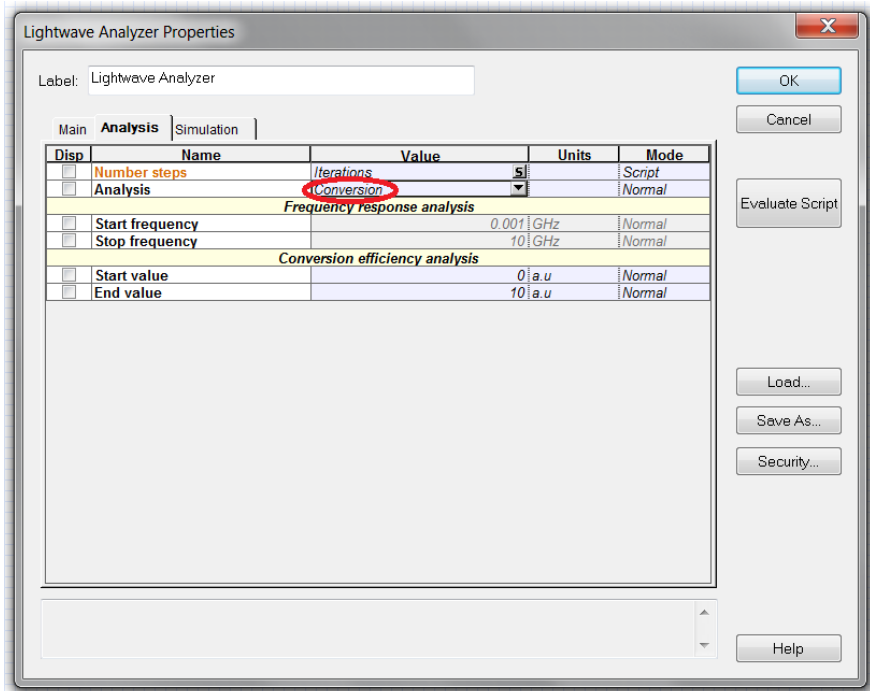


Figure 9: Changing the operation of the Lightwave Analyzer.

Instead of sending multiple frequency signals, multiple DC signals of varying magnitude are probed into the PIN photodiode. Then running the simulation and viewing the Slope Responsivity graph gives:

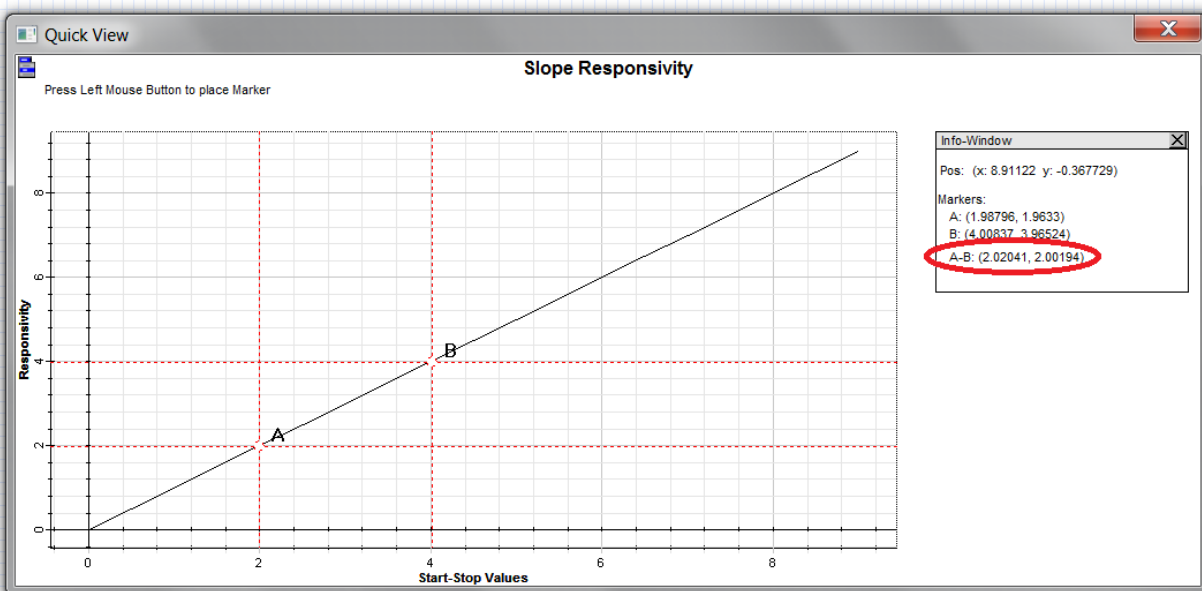


Figure 10: Plotting the conversion efficiency.

Again right-clicking the graph and interacting with the curve allows the user to calculate the responsivity accurately. In this case the slope of the graph is of interest so choose two points and then calculate the slope. In this simple case it comes to $\sim 1A/W$.

3.2 CHARACTERIZATION OF PIN PHOTODIODES

Using the outlined procedure investigate the 3dB-bandwidth and responsivity of two PIN Photodiodes with the following parameters, both at the default optical frequency of 193.1 THz.

InGaAs Photodiode		Ge Photodiode	
Responsivity type	InGaAs	Responsivity type	Ge
Transfer function type	RC Limited	Transfer function type	RC Limited
Thermal Noise calculation	Defined	Thermal Noise calculation	Calculated
Load resistance	50 Ω	Load resistance	20 Ω
Junction capacitance	2 pF	Junction capacitance	1 pF

Keep all other parameters as their default for the PIN Photodiode component and when simulating the frequency response keep the responsivity type at a constant 1 A/W.

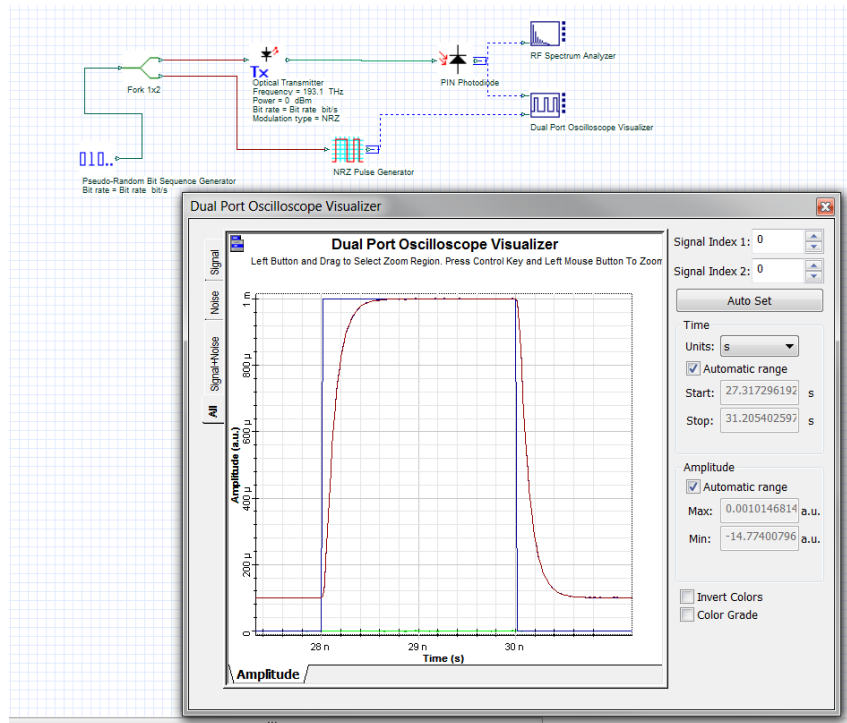


Figure 11: Calculating the bandwidth from the rise and fall time.

Finally using a setup similar to the Figure 11 find the rise time of both of the PIN Photodiodes and compare it to the bandwidth calculated. To make it easier, try using the dual port oscilloscope visualizer to plot an ideal rectangular pulse versus the detected signal. The amplitude and rise time of the NRZ Pulse Generator need to be changed from their default values. Do not forget to set the rise and fall time to 0 s in the Optical Transmitter.

Questions:

- 3.2.1 What are the bandwidth and responsivity of the InGaAs Photodiode?
- 3.2.2 What are the bandwidth and responsivity of the Ge Photodiode?
- 3.2.3 Compare the responsivity of the two photodiodes and the semiconductors respective band gap energies. Explain the differences.
- 3.2.4 Determine the rise times of both photodiodes. Calculate the bandwidth again from this value.

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] Saleh, Bahaa E. A., and Malvin Carl. Teich. *Fundamentals of Photonics*. New York: Wiley, 1991. Print.

Loss and Power Budget

1 OBJECTIVE

Investigate the effect of loss on optical system performance and characterize the system with the power budget equation. Use OptiSystem to optimize the fiber length of a communication system.

2 PRE-LAB

Optical system performance can be limited by many physical processes for example loss, dispersion and receiver noise. If the optical signal power at the receiver is lower than the receiver sensitivity, then the signal will not be correctly detected. The power margin is the difference between the detected signal power and the receiver sensitivity.

The budget equation given by equation 1, compares the loss of system to the difference between the transmitter power and receiver sensitivity:

$$P_t - S_r = AL_f + L_c + L_a + M, \quad (1)$$

P_t = transmitter power	AL_f = fiber loss	L_a = additional loss
S_r = receiver sensitivity	L_c = coupler loss	M = power margin

Power can be measured both in linear units (Watts) or logarithmic units (dBm). The Decibel-milliwatts scale has the added benefit that losses can be easily subtracted from a signal rather than multiplied. The power budget equation above is expressed using dBm units, which can be calculated using the following relation:

$$P_{dBm} = 10 \log_{10} \frac{P_{Watts}}{1mW}, \quad (2)$$

and the dimensionless unit for loss is calculated from the ratio of input and output powers by:

$$L_{dB} = 10 \log_{10} \frac{P_{out}}{P_{in}}. \quad (3)$$

Fiber loss is then calculated by multiplying the attenuation A (dB/km) by the length of the fiber L_f (km).

Receiver sensitivity, also usually given in dBm, can be defined as the signal power required to achieve a certain bit error rate.

Questions:

- 2.1.1 Convert 0 dBm to Watts.
- 2.1.2 A 5 dBm signal is sent through a component and detected at its output as 0.5 mW, what is the loss of the component in dB?
- 2.1.3 Determine the maximum length of optical fiber that should be used in the 1 Gb/s system in Figure 1 below, to obtain a 6 dB power margin. Assume a -30 dBm receiver sensitivity.

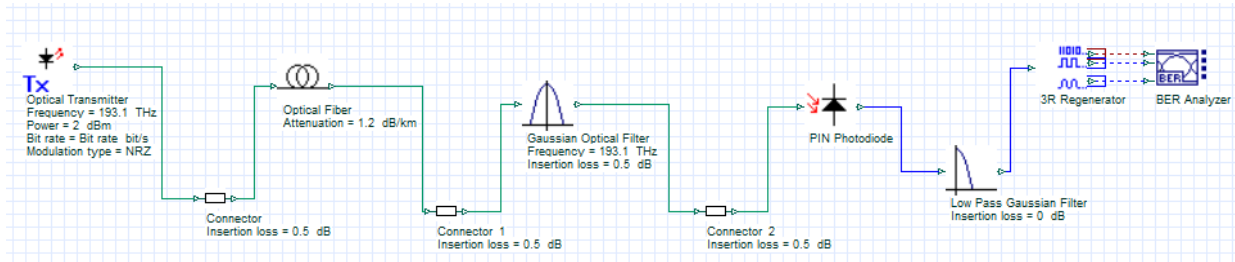


Figure 1: A loss limited system.

3 SYSTEM PERFORMANCE

Refer to the system in Figure 1 and build it in OptiSystem. Correctly set the power and bit rate of the optical transmitter to 2 dBm and 1 Gb/s respectively. To simulate a receiver with a -30 dBm sensitivity set the PIN photodiode’s Thermal power density to 15e-24 W/Hz. You will need to place the following components:

- | | |
|----------------------------|---|
| • Optical Transmitter | Transmitters Library/Optical Transmitters |
| • Optical Fiber | Optical Fibers Library |
| • Connector | Passives Library/Optical/Connectors |
| • Gaussian Optical Filter | Filters Library/Optical |
| • Low Pass Gaussian Filter | Filters Library/Electrical |
| • PIN Photodiode | Receivers Library/Photodetectors |
| • 3R Regenerator | Receivers Library/Regenerators |
| • BER Analyzer | Visualizer Library/Electrical |

Set the optical fiber length to the value calculated in question 2.1.3 and simulate the project. You should be achieving a BER less than 1e-8.

3.1 EFFECT OF LOSS ON SYSTEM PERFORMANCE

A more accurate calculation of the bit error rate can be performed if a larger sequence length is used for the simulation. In the layout properties, change the sequence length from 128 to 1024.

Create a parameter sweep of the optical fiber length and vary it from 18 km to 25 km with 10 total steps.

Questions:

- 3.1.1 Plot the minimum BER as a function of fiber length.
- 3.1.2 Discuss the trend of the bit error rate.
- 3.1.3 By sweeping the fiber length and using an appropriately placed optical power meter determine the receiver sensitivity for a desired Q factor of 8.

3.2 OPTISYSTEM OPTIMIZATIONS

OptiSystem has a built-in optimizer tool that can make designing a system simpler. In this section, the proper procedure for setting up an optimization will be demonstrated.

Starting from the same project file as used above, an optimization will be run to determine the optimal bandwidth of the Gaussian filter. First remove the parameter sweep, by changing the fiber length parameter from sweep to normal and assign it a value of 23 km and set the total number of sweep iterations to 1.

The objective of this optimization will be to determine the best cutoff frequency for the low pass electrical filter. Open the optimizations window by finding it in the Tools tab.

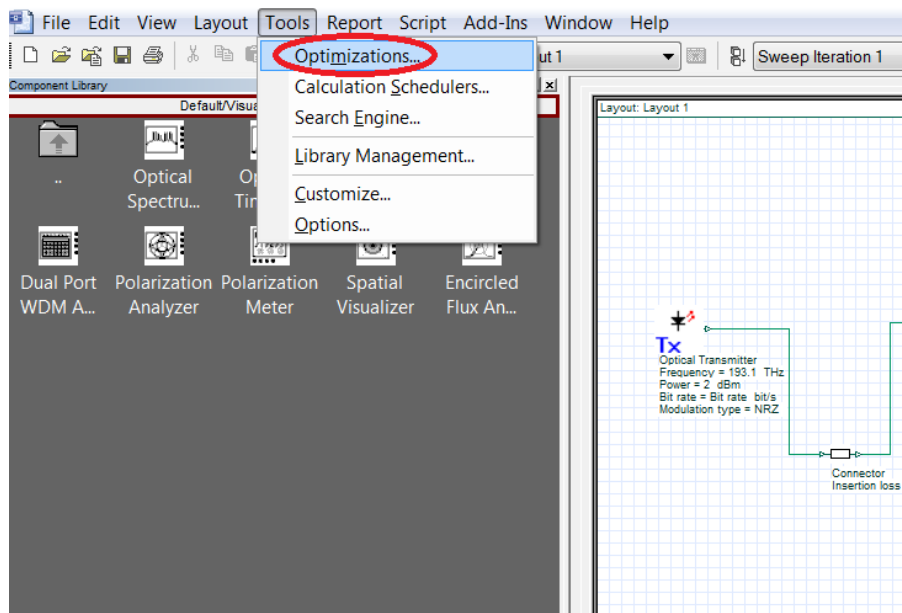


Figure 2: Opening the Optimizations window.

Choose the SPO Optimization (Single Parameter Single Result) and click Insert.

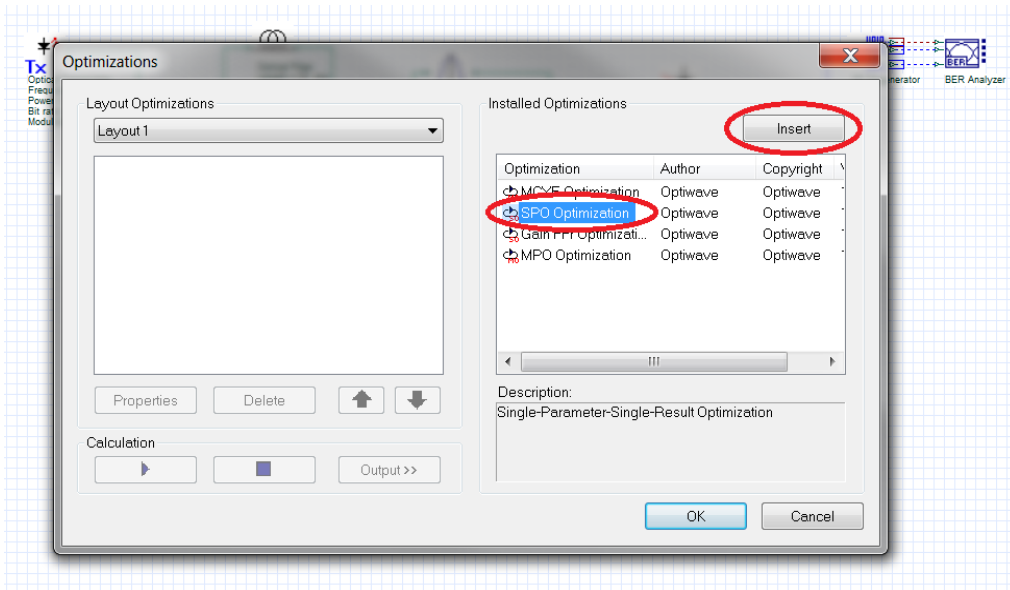


Figure 3: Selecting the SPO Optimization from the Optimizations window.

Before the optimization can be inserted, the properties have to be set. The goal for this optimization will be maximizing the Q factor result of the BER Analyzer within a 0.001 accuracy.

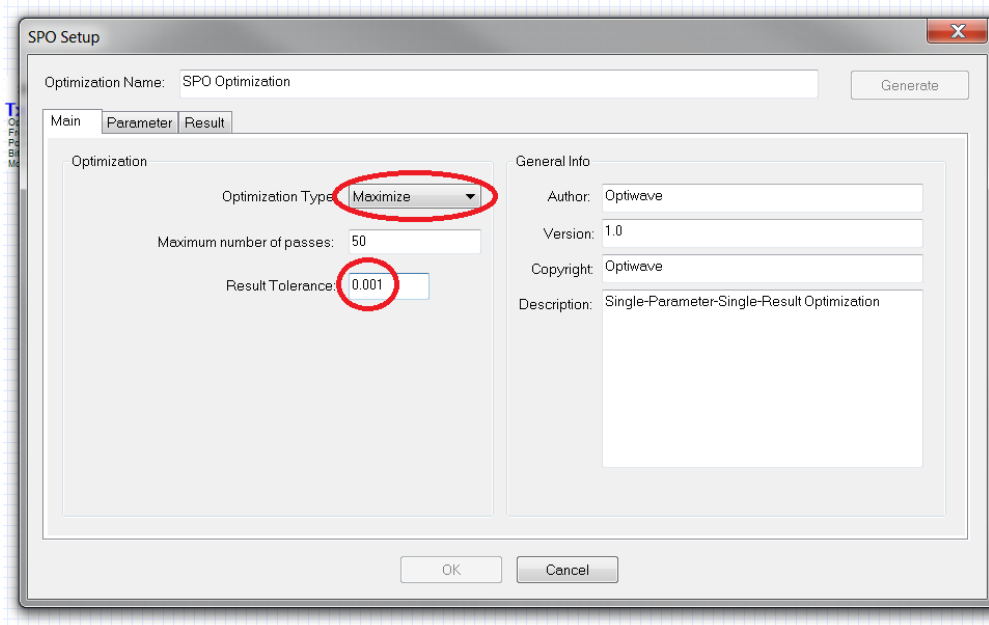


Figure 4: Setting up the optimization type.

In the Parameter tab locate the cutoff frequency in the electrical Gaussian filter and set the range from 100 MHz to 1.5 GHz.

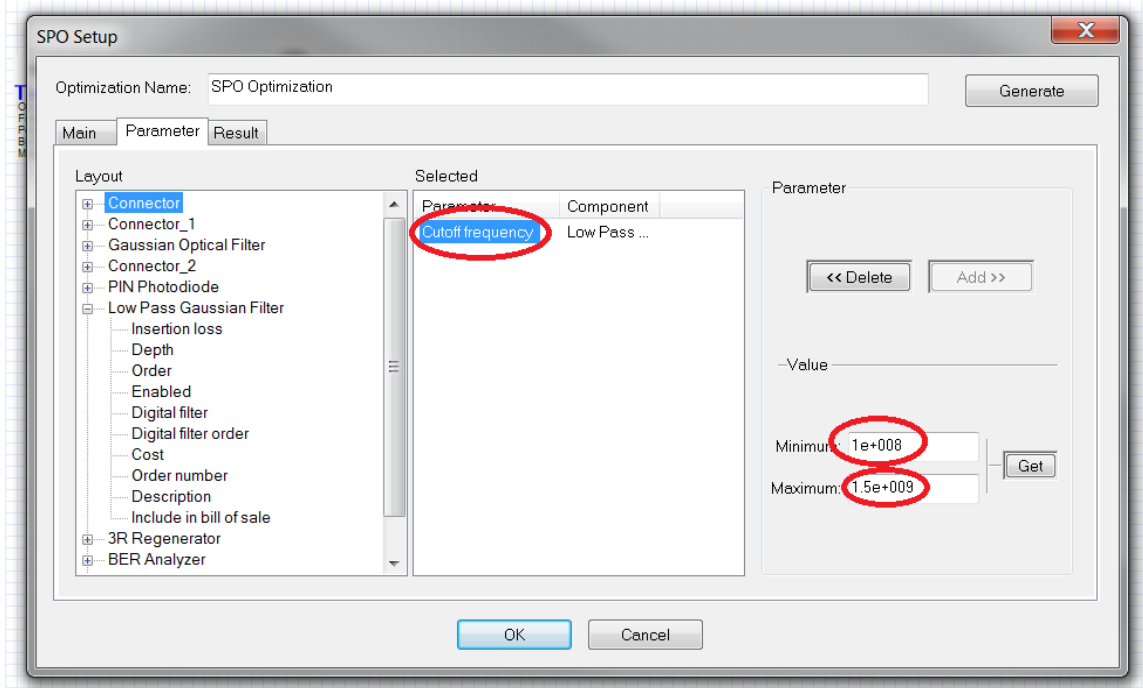


Figure 5: Selecting the parameter to optimize.

Locate the Max Q Factor result in the BER Analyzer and add it to the optimization.

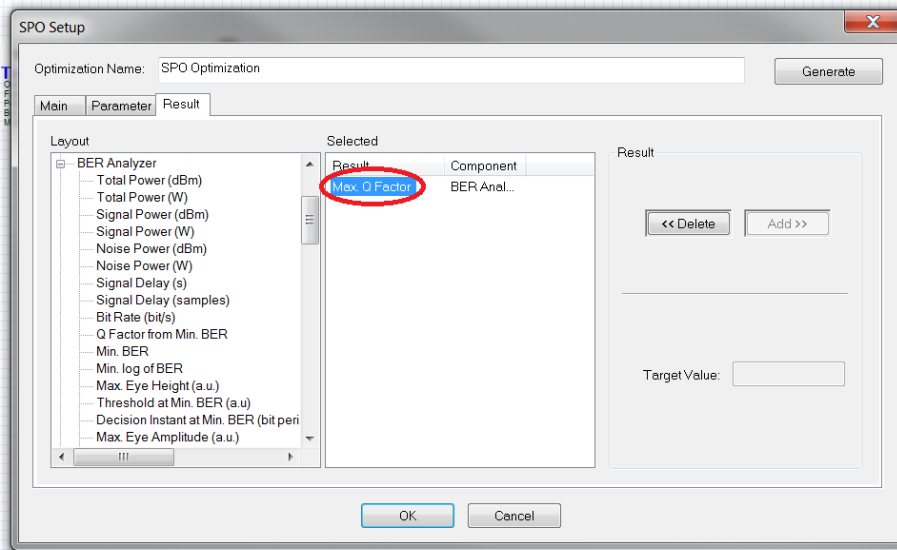


Figure 6: Choosing the result to maximize.

The simulation is ready to run. At the calculation window make sure to run all optimizations. During the simulation you can go to the optimizations tab to observe the optimization in progress.

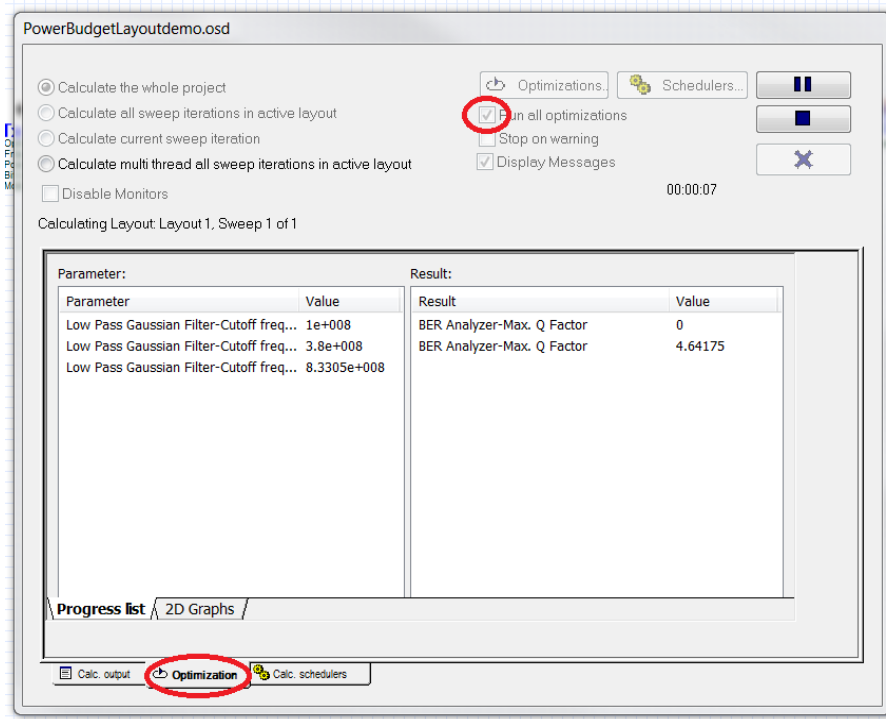


Figure 7: Running the simulation and optimizations.

The cutoff frequency should be optimized to around 505 MHz for this system.

3.3 OPTIMIZE FIBER LENGTH

Set the cutoff frequency of the Gaussian low pass filter to 505 MHz and using the above procedure find the longest fiber length that will result in a Q factor of 10.

Questions:

- 3.3.1 What is the length of fiber?
- 3.3.2 What is the associated BER of this system?
- 3.3.3 What is the new Power Margin of this system? Assume a 30 dBm receiver sensitivity.

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] Saleh, Bahaa E. A., and Malvin Carl. Teich. *Fundamentals of Photonics*. New York: Wiley, 1991. Print.

Multimode Optical Fiber

1 OBJECTIVE

Determine the optical modes that exist for multimode fibers and investigate their performance on optical systems.

2 PRE-LAB

The backbone of optical systems is optical fiber. It allows for the propagation of very short pulses, which translates to high bit rates, extremely long distances while experiencing modest signal degradation. Understanding how signals propagate in a fiber allows for better control and optimization of an optical system.

From the principle of total internal reflection it is understood that rays of light can be guided by propagating them through a region of high index of refraction surrounded by a region of low index of refraction. If the rays have a larger angle of incidence than the critical angle the light will be reflected back into the core region.

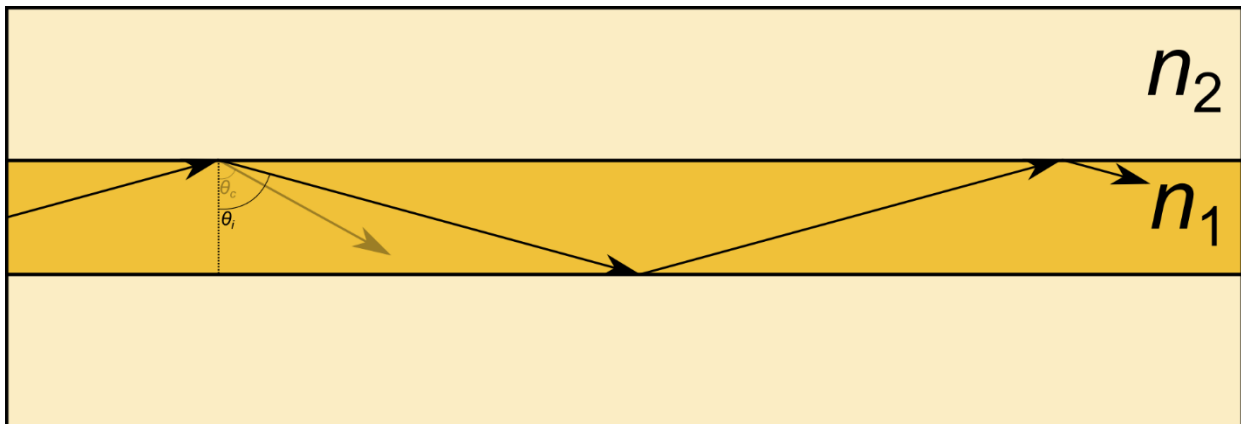


Figure 1: Rays with a larger angle of incidence are kept confined to the high index core of a multimode waveguide.

In this example, the core region n_1 has a higher index than the outer cladding region n_2 . There then exists a critical angle, θ_c , such that rays incident at a greater angle will be completely reflected. This is a useful approximation for large core fibers, but when the core radius becomes comparable to the wavelength of the light the wave nature dominates. The Maxwell equations must then be used to solve for the guiding conditions.

Starting from the Maxwell equations in cylindrical coordinates and continuing on from the Helmholtz equation the problem can be stated as a Bessel differential equation of the form:

$$\frac{d^2 E_z(r)}{dr^2} + \frac{1}{r} \frac{dE_z(r)}{dr} + \left(\gamma^2 + k_0^2 \epsilon_r - \frac{m^2}{r^2} \right) E_z(r) = 0, \quad (1)$$

In cylindrical coordinates, the z component of the electric field as a function of the radius r , can be related to the propagation constant γ , the electric permittivity ϵ_r , and an integer m which represents the periodic conditions for the ϕ component of the electric field.

Assuming lossless media, $\gamma = j\beta$, the solution of this differential equation are Bessel functions. In addition, approximating as a weakly guided fiber $n_1 \approx n_2$, and matching the fields at the boundary between the core and cladding the solution can be expressed by a characteristic equation.

$$X \frac{J_{m\pm 1}(X)}{J_m(X)} = \pm \frac{K_{m\pm 1}(Y)}{K_m(Y)}. \quad (2)$$

The solutions to the characteristic equation provide the propagation constant and the field profiles for the LP_{mn} modes. For a more exhaustive derivation please refer to the reference [1]. In equation 2, J and K are the Bessel functions of the first kind and the modified Bessel functions of the second kind. The values X and Y are given by:

$$X = a\sqrt{k_0^2 n_1^2 - \beta^2}, \quad (3)$$

$$Y = a\sqrt{\beta^2 - k_0^2 n_2^2}, \quad (4)$$

where a is the radius of the core. We can introduce a variable called the V parameter defined by:

$$X^2 + Y^2 = V^2, \quad (5)$$

$$V = 2\pi \frac{a}{\lambda} \sqrt{n_1^2 - n_2^2}. \quad (6)$$

For optical fiber with large V parameters the number of modes can be approximated by:

$$M = \frac{4}{\pi^2} V^2. \quad (7)$$

Questions:

- 2.1 From Snell's Law derive the expression for the critical angle.
- 2.2 Approximate the number of modes of a fiber using a wavelength of 850 nm, a core radius of 80 μm and core index of 1.56 and cladding index of 1.50.

2.1 MODAL DELAY

Arriving at equation 1 requires setting the z dependence of the propagating field proportional to $e^{j\beta z}$. The phase velocity for a harmonic field evolving in time as $e^{j\omega t}$ is then equal to

$$v_p = \frac{\omega}{\beta}. \quad (8)$$

However, the speed at which a pulse envelope centered at ω travels, also known as the group velocity, is given by

$$v_g = \frac{d\omega}{d\beta}. \quad (9)$$

This arises from the fact that the phase constant β is a function of frequency. From Fourier theory, even if a monochromatic source is used, the modulated pulse will contain frequencies other than the carrier frequency and each frequency will travel at slightly different phase velocities. This is the basis for understanding dispersion, which broadens time pulses after propagating over fiber.

The group velocity can be used to calculate the overall time delay of an optical pulse through a fiber by rearranging the equation into

$$t_g = \frac{L}{c} \left(N_{eff} - \lambda \frac{dN_{eff}}{d\lambda} \right), \quad (10)$$

where N_{eff} is the mode effective index and calculated from $N_{eff} = \beta\lambda/2\pi$. Using the mode solver built in to OptiSystem the effective index can be found and then approximating the derivative with a difference the group delay can be calculated.

The goal of this next step is to demonstrate calculating the group delay of the stock measured-index multimode component at the carrier wavelength of 850 nm and length of 1 km. Start by placing the Measured-Index Multimode Fiber into a blank layout. Set the mode solver to use 850 nm as the solver wavelength.

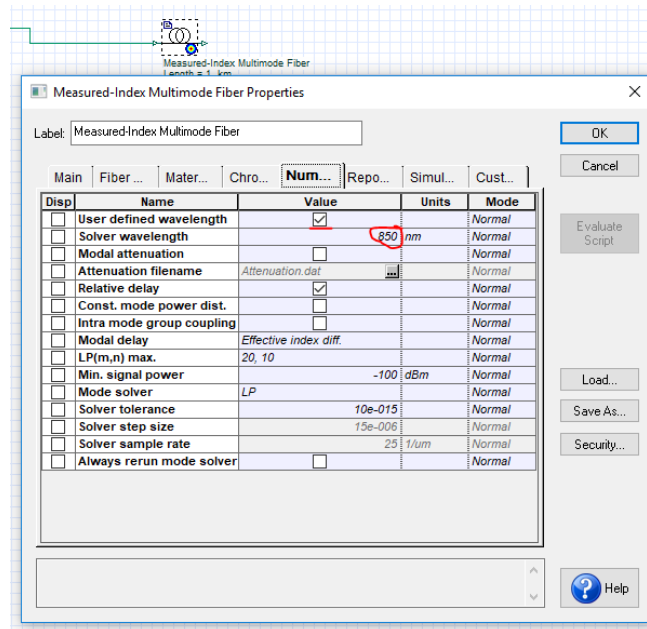


Figure 2: Measured-Index Multimode Fiber component properties

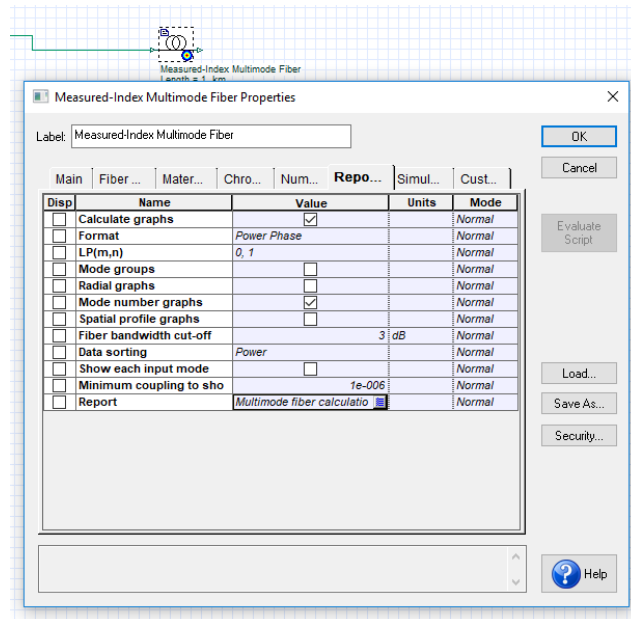


Figure 3: Changing the graph options of the multimode fiber.

In the Reports tab, enable Calculate graphs and set the wavelength to 850 nm. Exit the component properties and run the simulation. From the Project Browser, you will be able to see the various graphs the component calculates, in particular double click the effective index graph and open it up. This graph will show the effective indices for different excited propagating modes. To calculate which modes are excited a suitable source is required. Place the default Spatial CW Laser on the layout and connect it to the input of the multimode fiber.

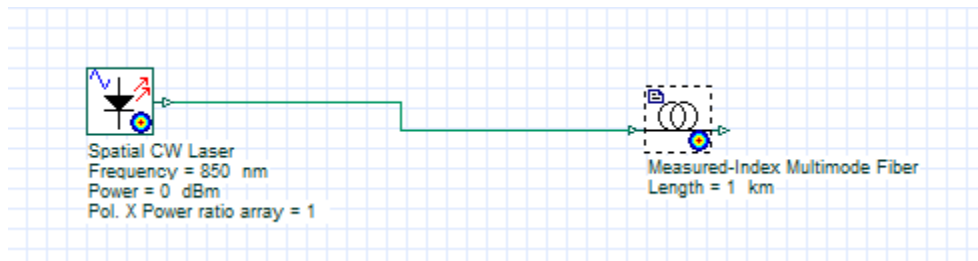


Figure 4: Layout of simulation

Run the simulator and then open the Graphs folder in the Project Browser. View the modal effective indices by double clicking the graph "Effective index".

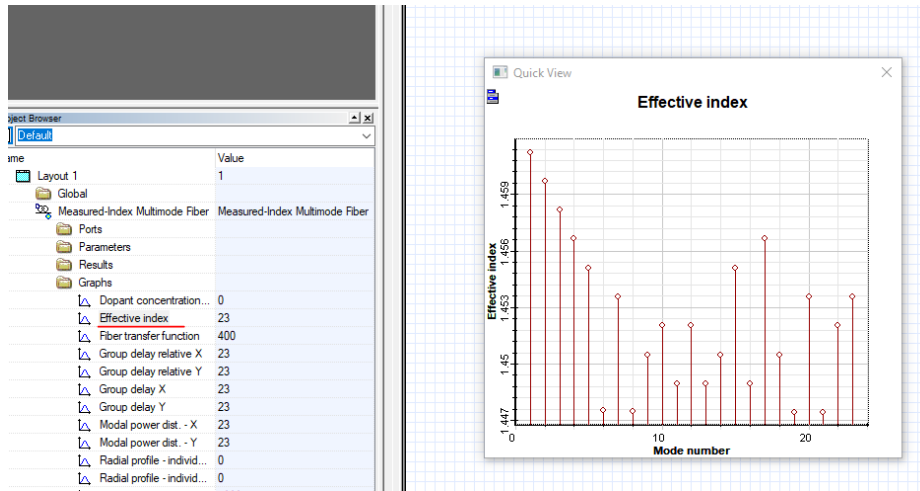


Figure 5: Plotting the effective index as a function of the mode number.

Double clicking the blue tab at the top left corner of the graph and choosing export data allows the creation of a data file with the exact numerical values. These files can then be imported into a different program to perform operations on them or to plot data, like Excel or Matlab.

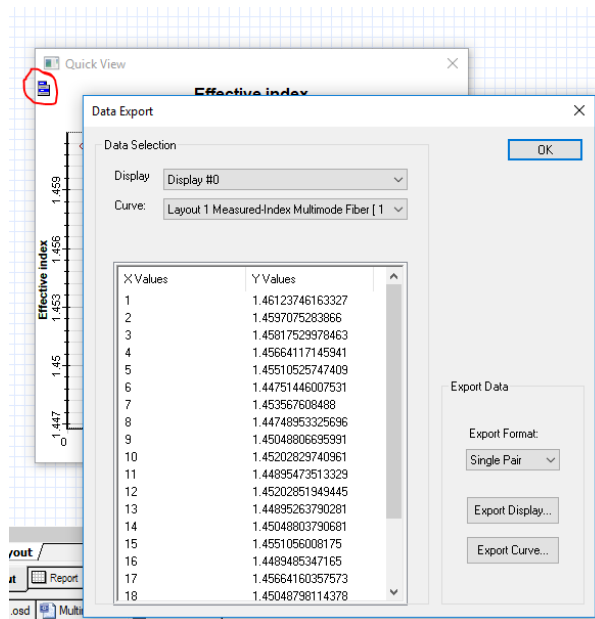


Figure 6: Exporting data to a text file.

Perform these steps two more times for wavelengths of 850.1 nm and 849.9 nm and match the table below relating wavelength to effective index of the 0th mode.

Wavelength	Effective Index
849.9 nm	1.46123755153895
850 nm	1.46123746163327
850.1 nm	1.46123737172757

Using these values and the central difference approximation for a derivative:

$$\frac{dF(x)}{dx} \approx \frac{F(x+\Delta x) - F(x-\Delta x)}{2\Delta x} = \frac{1.46123737172757 - 1.46123755153895}{0.2} = -8.990569E - 7.$$

Now that the derivative is known all that remains is using the central wavelength and index of refraction in the group delay expression for the result.

$$t_g = \frac{1 \text{ km}}{299792 \frac{\text{km}}{\text{s}}} (1.46123746163327 + 850 \text{ nm} \times 8.990569E - 7 \text{ nm}^{-1}) = 4.87672 \mu\text{s}$$

Questions:

- 2.1.1 Showing your work, find the group delay of the 6th mode LP(0,10) with the default Measured-Index Multimode Fiber at the same wavelength.
- 2.1.2 Two pulses, one travelling with the group velocity of mode 0 and the other with mode 9, propagate a distance of 100 km. Which pulse will reach the detector first and what will be the delay of the second pulse?
- 2.1.3 Generally when injecting light into a multimode fiber more than one mode is excited at the same time. If a pulse of light excites both the first and tenth mode, what will be the general tendency of the pulse as it propagates through the fiber?

2.2 EXCITING MODES

Different spatial modes of a multimode fiber travel with different group velocities. If an input optical pulse excites more than a single mode the different group velocities will tend to broaden the pulse over the propagation distance. This in turn limits the length and bandwidth of multimode fiber based systems, since as the pulses broaden they may begin to overlap with adjacent bits.

The excited modes in a multimode fiber depend on the injected field. The amount of power coupled to specific mode can be calculated via an overlap integral. In special cases, like where the injected field is exactly the same as a specific fiber mode then all of the incident power will be coupled into that specific mode. In physical fibers, although one mode might be excited at the input of the fiber, power will spread to other modes through imperfections and bends.

Using the Spatial Visualizer in OptiSystem and attaching an input field at a wavelength of 850 nm to the fiber in the previous section, the fields supported by the fiber can be viewed.

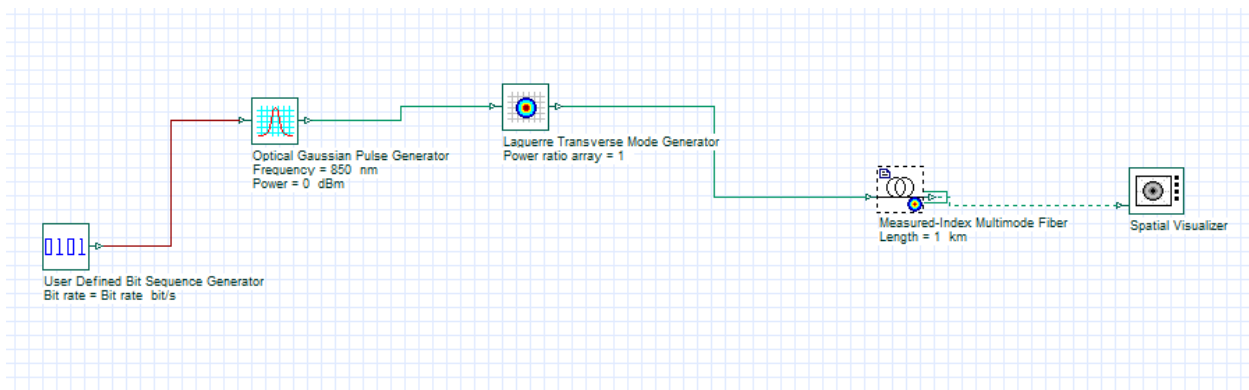


Figure 7: Exciting modes in a multimode fiber layout.

The first couple of modes of the fiber are given in Figure 7:

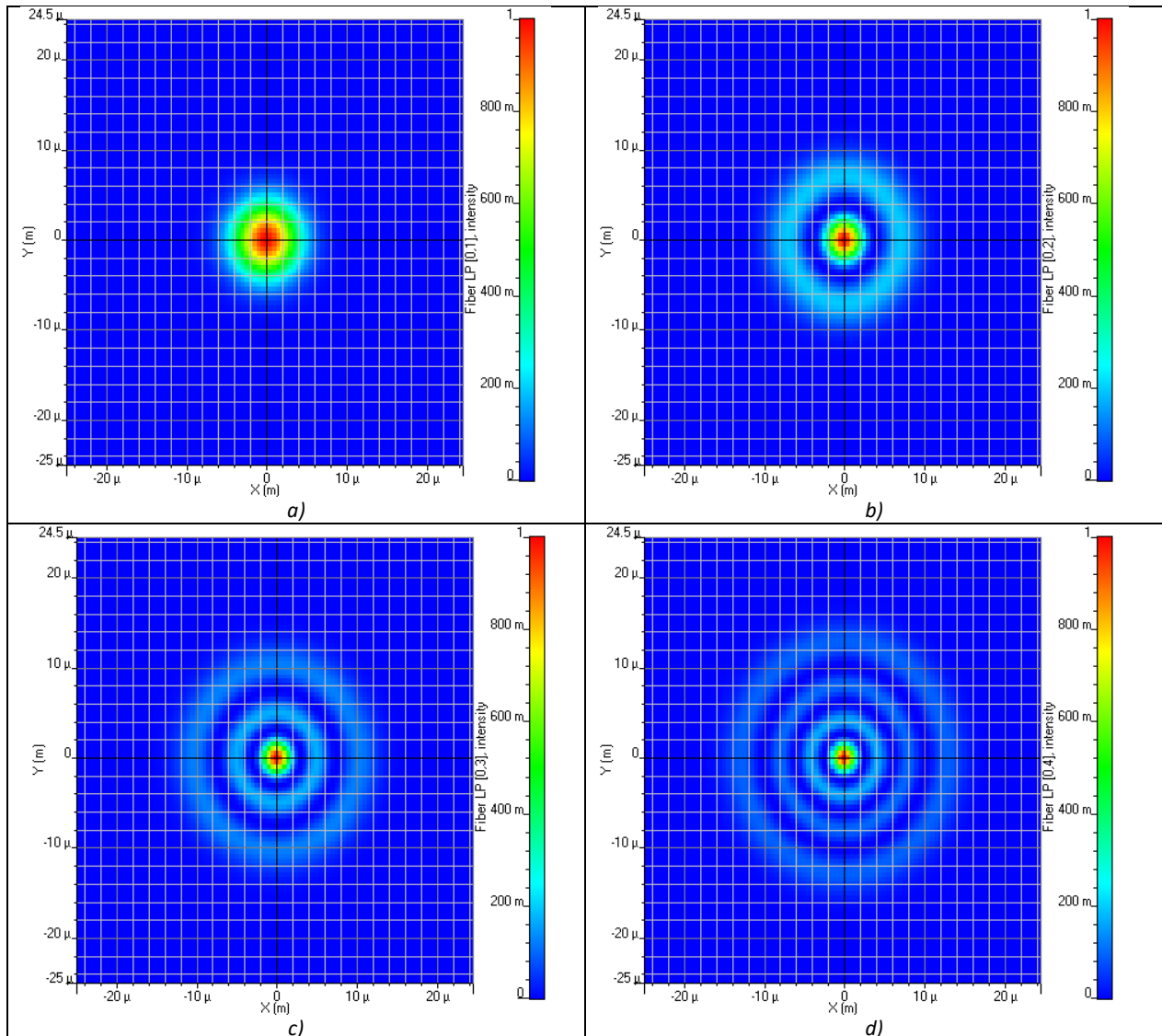


Figure 8: Different LP_{mn} modes of an optical fiber from top left to bottom right: LP_{01} , LP_{02} , LP_{03} , LP_{04} .

These figures show the intensity of the E_r field as a function of the transverse dimensions. The multimode component also calculates the coupling of power from the incident field into the different fiber modes. Navigate to the Numerical tab and at the bottom beside the Report parameter click on the small string editor button.

The coupling coefficient can be viewed for each LP_{mn} mode.

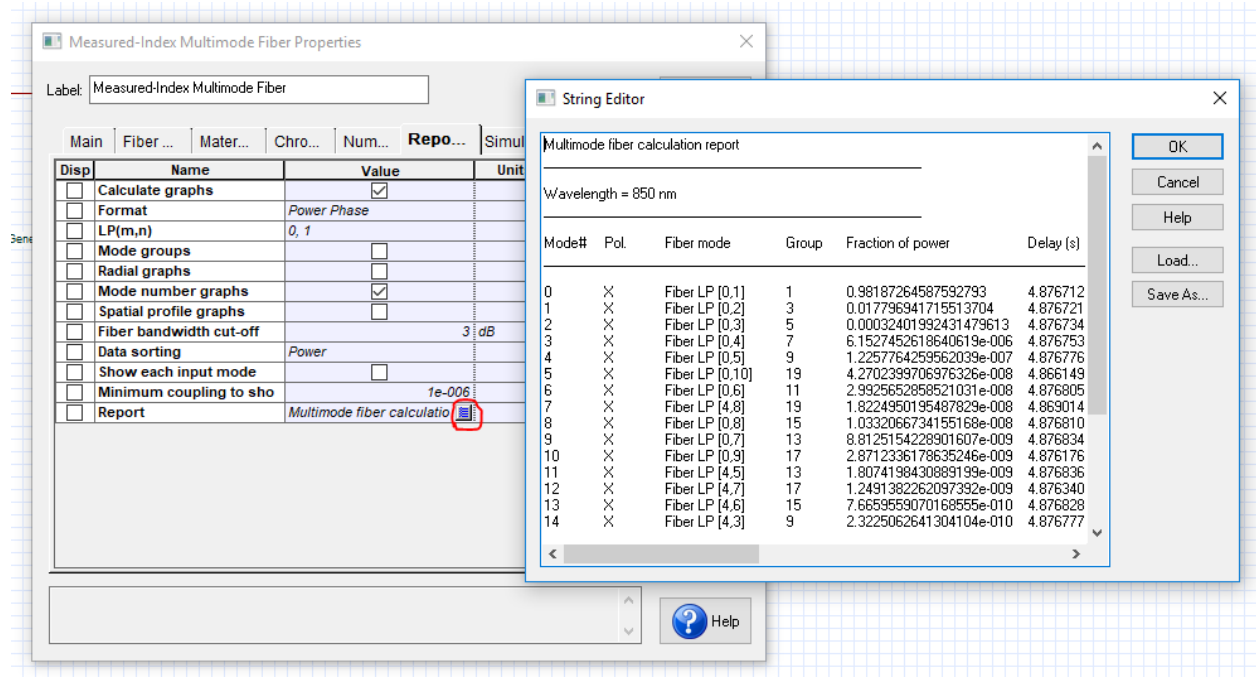


Figure 9: Opening the multimode fiber calculation report.

Questions:

- 2.2.1 Create a parameter sweep for the Laguerre Transverse Mode Generator to plot the coupling power coefficient for the LP_{01} mode as a function of the injected mode spot size. Plot the relation and determine which injected spot size would minimize the modal dispersion.

3 MINIMIZING MODAL DISPERSION

Modal dispersion is unwanted in optical communication systems as it places a limit on the propagation distance and bandwidth. There are two popular ways that modal dispersion can be limited. Using a parabolic index fiber, where the index of refraction varies smoothly as a function of the radius, can be design to support modes all with very similar group velocities. The other direction is to eliminate multiple modes altogether, by using a single mode fiber. This can be achieved simply by reducing the core radius.

The default index of refraction profile is an Alpha or exponential distribution. Thus, to approximate the step index fiber set the Alpha parameter to $10e+009$ and a suitable number of radial steps to resolve the small radius changes (>1000).

Questions:

- 3.1 Find the core radius that will modify the default Measured-Index Multimode Fiber to act as a single mode fiber with a carrier wavelength of 850 nm. Hint: Use the Graphs to view the different effective indices of the modes.
- 3.2 Using the dimensions of the fiber that give single mode operation, what is the associated V parameter?

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] Saleh, Bahaa E. A., and Malvin Carl. Teich. *Fundamentals of Photonics*. New York: Wiley, 1991. Print.
- [2] Agrawal, G. P. *Fiber-optic Communication Systems*. New York: Wiley, 1997. Print.

Single Mode Optical Fiber - Dispersion

1 OBJECTIVE

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

2 PRE-LAB

A single mode fiber, as the name implies, supports only a single transverse mode. The benefits of supporting only a single mode is that modal dispersion is eliminated since all pulses travel with the same modal group velocity. The fundamental mode of optical fibers is shown below in figure 1. For a core/cladding fiber structure the field follows a Bessel function, which can be approximated quite well by a Gaussian field for weakly guiding structures.

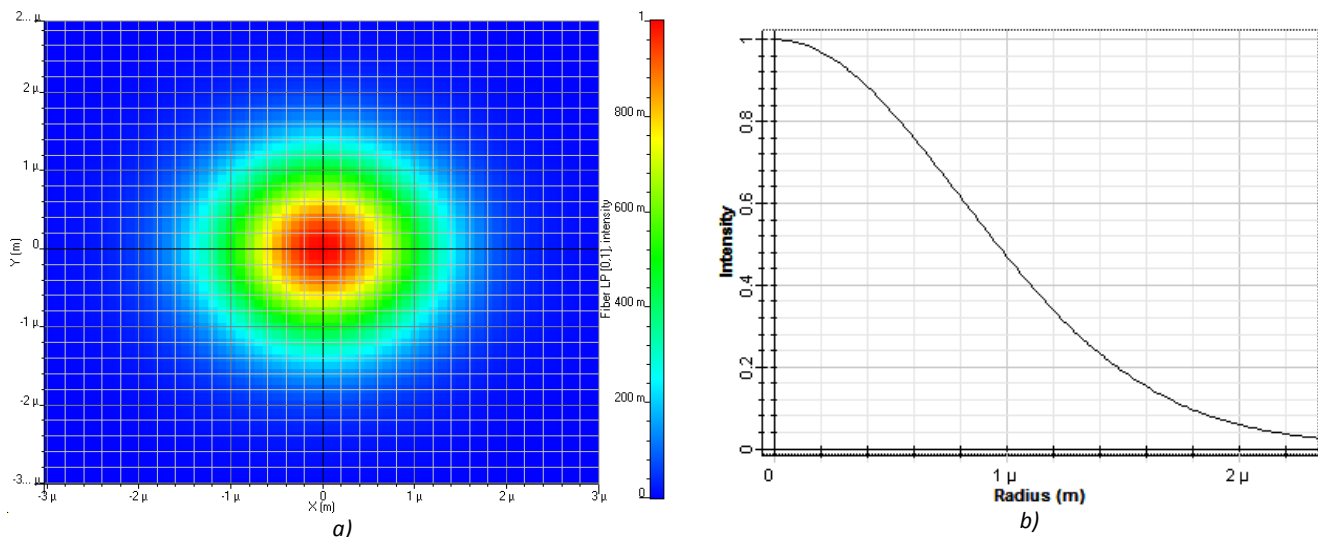


Figure 1: The fundamental mode of a single mode fiber: a) The intensity profile in the transverse direction. b) Intensity as a function of radius.

Questions:

- 2.1 How many orthogonal modes exist in a single mode fiber? Hint: Consider the rotational symmetry of the fiber and vector field attributes of the electric field.

2.1 CHROMATIC DISPERSION

Although there is no modal dispersion between different propagating modes, dispersion has not been completely eliminated. For a single mode fiber, the dominant forms of dispersion are material and waveguide dispersion. Material dispersion stems from the frequency dependence of the index of refraction, whereas the waveguide dispersion arises from the frequency dependence of the propagation

constant for the fundamental mode. Together these two related effects force a frequency dependence for the group velocity of a pulse.

If the derivative of the group velocity with respect to the frequency, $v_g = \frac{d\omega}{d\beta}$, is non-zero then a time pulse will broaden through propagation as the different spectral components will arrive at different times. The pulse broadening, ΔT , is related to the derivative of the phase constant, β by:

$$\Delta T = L \frac{d^2\beta}{d\omega^2} \Delta\omega = L\beta_2 \Delta\omega, \quad (1)$$

where $\Delta\omega$ is the spectral width of the pulse. In another form the pulse broadening can be given in terms of the wavelength range:

$$\Delta T = LD\Delta\lambda, \quad (2)$$

where D is called the dispersion parameter.

$$D = -\frac{2\pi c}{\lambda^2} \beta_2 \quad (3)$$

If a fiber has a positive dispersion parameter it is called anomalous dispersion and higher frequency components travel faster. If the dispersion parameter is negative it is called normal dispersion and lower frequency components travel faster.

Below is an example of a dispersion broadened pulse, notice that in addition to the pulse width increasing, so does the peak power decrease.

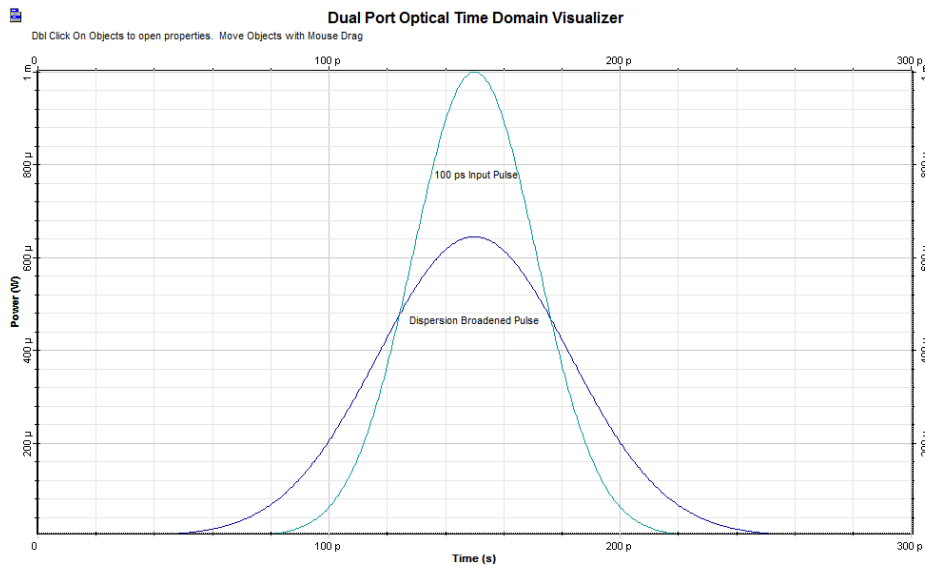


Figure 2: Dispersion Broadening of a 100 ps time pulse after 50 km propagation through an anomalous dispersive fiber.

Dispersion is quite simple to model by itself. In fact, its effect on a pulse can be modelled by the differential equation:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = 0. \quad (4)$$

This equation is set in the reference frame of the moving pulse with pulse shape $A(z, t)$. The higher order dispersion term β_3 is ignored for now, which makes solving the equation much simpler.

Questions:

- 2.1.1 Calculate the time delay after 50 km of propagation between two frequency components separated by 2 nm and with a dispersion parameter of 16.75 ps/km · nm
- 2.1.2 Derive an expression for $\Delta\omega$ as a function of $\Delta\lambda$ using $c = \frac{\omega}{2\pi} \lambda$.
- 2.1.3 For an optical pulse of constant phase propagating in a normal dispersion fiber. Which frequency components will be detected first to at the leading edge of the pulse?

2.2 CHIRPING OF PULSES

Optical signals can be represented by complex envelopes modulated at a carrier frequency, ω . That is to say, the optical pulses can be represented mathematically as:

$$E_x(t) = |A(t)|e^{j\varphi(t)}e^{j\omega t}, \tag{5}$$

where $A(t)$ is a complex valued function and:

$$\varphi(t) = \text{arg}[A(t)]. \tag{6}$$

A simple Gaussian pulse would be of the form:

$$E_x(t) = e^{-(t)^2}e^{j\omega t}. \tag{7}$$

Below is an example of what the magnitude and real part of these functions would look like. The $\varphi(t)$ value is constant 0 for this signal. The real part of the signal would be the actual electric field value, but representing the field as an envelope and removing the explicit representation of the carrier frequency is a useful tool, for example in the description of chromatic dispersion in the previous chapter.

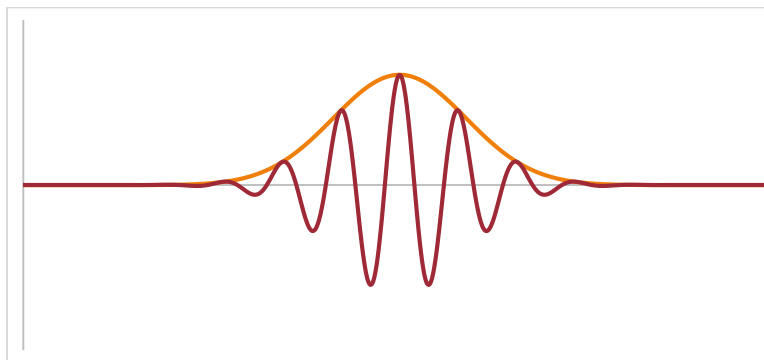


Figure 3: Gaussian pulse envelope with the real part of the signal shown as well.

Instead of a purely real Gaussian pulse, we will introduce a time dependent phase $\varphi(t)$. This will be represented by the equation:

$$E_x(t) = e^{-(t)^2} e^{jCt^2} e^{j\omega t}. \quad (8)$$

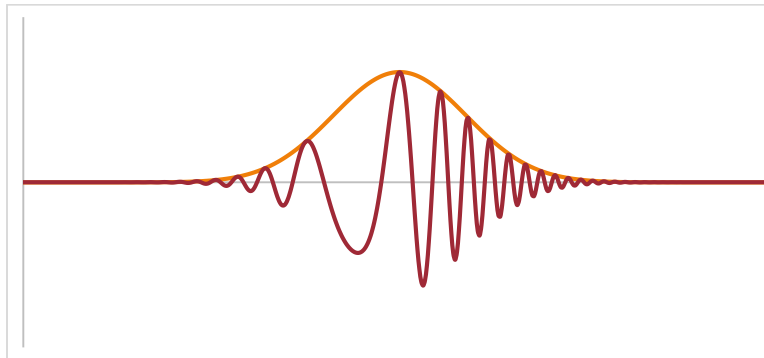


Figure 4: A chirped Gaussian envelope clearly showing the change in the carrier frequency as the phase changes over the pulse.

This effect is known as chirp, described by the constant C , the chirp parameter. This time dependent phase results in a linear change in the instantaneous frequency. Changing the phase of the envelope has no effect on the magnitude of the original envelope, but it does change the frequency content.

Questions:

- 2.1.1 From the expression for the simple chirped Gaussian pulse, find the instantaneous frequency $\omega(t)$ which can be derived from the derivative of the phase with respect to time.

3 EFFECT OF DISPERSION ON PULSES

Short pulses in optical fiber are broadened by group velocity dispersion. Naturally in OptiSystem it is possible to simulate these effects on pulses. Setting up a layout, as in the example below the effects can be investigated in more detail.

3.1 BROADENING OF GAUSSIAN PULSES

Only a few changes to the default parameters is needed to begin the simulation. Place a User Defined Bit Sequence Generator, setting the bit sequence to “0100000000000000” and the Sequence length in the Layout parameters to 16 bits. This allows for the injection of a single pulse. In the Optical Fiber disable the Attenuation effect, Third-order Dispersion and Self-phase modulation. In the PMD tab, set the Birefringence type to “Deterministic” and set Differential group delay to 0. This creates an optical fiber model that only includes group velocity dispersion. For an increase in simulation accuracy setting the Samples per bit to 256 will be large enough to provide very accurate simulations while keep the simulation time low.

- | | |
|---------------------------------------|---|
| • 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 |

- Time Delay
 - Clock Recovery
 - Optical Time Domain Visualizer
 - Optical Spectrum Analyzer
 - Dual Port Optical Time Domain Visualizer
 - Dual Port Optical Spectrum Analyzer
- Passives Library/Optical
 - Receivers Library/Regenerators
 - Visualizer Library/Optical
 - Visualizer Library/Optical
 - Visualizer Library/Compare
 - Visualizer Library/Compare

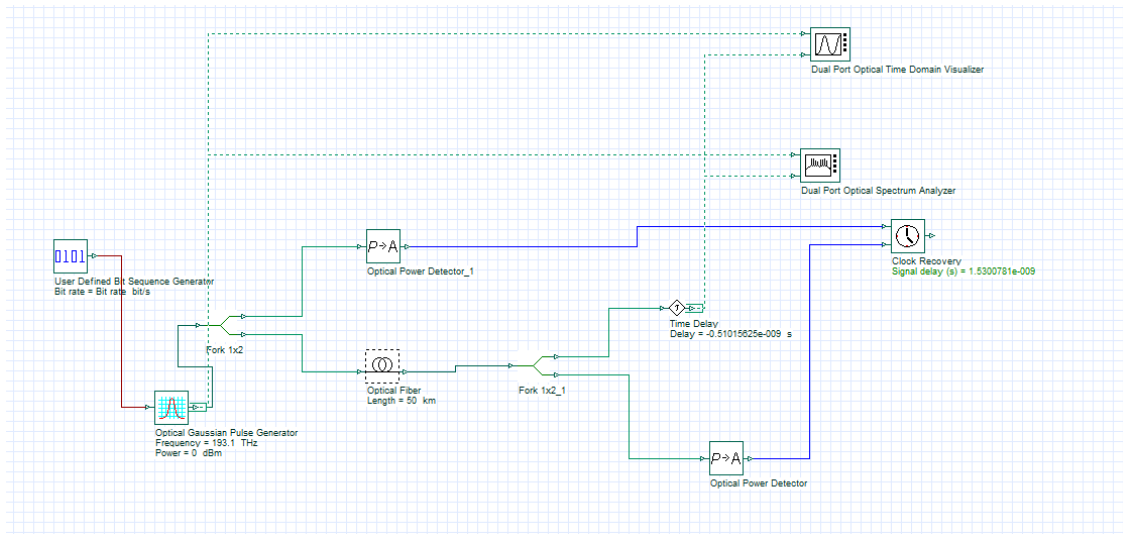


Figure 5: Layout for simulating dispersion.

The group velocity dispersion will also cause a slight delay to the entire envelope in relation to the input pulse, so the Clock Recovery component is used in conjunction with the Time Delay component to re-center the pulse with the input. Using markers in the time domain graph it is straightforward to calculate the FWHM of the pulses.

Questions:

- 3.1.1 Using this setup and the default setting for group velocity dispersion, plot the T_{FWHM} as a function of distance. Describe the relation.
- 3.1.2 Using this setup and the default setting for group velocity dispersion, plot the ω_{FWHM} as a function of distance. Describe the relation.
- 3.1.3 Does dispersion modify the magnitudes of the frequency components? Does it affect the phase or time delay of the frequency components?

3.2 BROADENING OF HIGHER ORDER GAUSSIAN PULSES

- 3.3.1 Change the order of the Gaussian pulse to 4 and plot the T_{FWHM} as a function of distance. Describe the relation.

- 3.3.2 Explain the strange behavior of the full width half maximum for short distances. Is the T_{FWHM} the best method for measuring spreading? Compared to the first order Gaussian the fourth order spreads much more quickly, by comparing the spectrums of both explain why.

3.3 BROADENING OF CHIRPED GAUSSIAN PULSES

The chirp parameter for a Gaussian pulse of pulse width $T_0 \approx T_{FWHM}/1.665$ is defined as the rate of change of the instantaneous frequency multiplied by T_0^2 with the equation for the instantaneous frequency being:

$$\delta\omega = \frac{c}{T_0^2} t. \quad (9)$$

- 3.3.3 Plot T_{FWHM} for a regular and chirped Gaussian pulse as a function of distance. In the Optical Gaussian Pulse Generator set the Chirp factor in the Chirp tab to 1 rad/s. Describe the difference.
- 3.3.4 Plot the chirp for a regular and chirped Gaussian pulse as a function of distance. In the Optical Gaussian Pulse Generator set the Chirp factor in the Chirp tab to 1 rad/s. Describe the difference.

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] Saleh, Bahaa E. A., and Malvin Carl. Teich. *Fundamentals of Photonics*. New York: Wiley, 1991. Print.

Optical Amplifiers – Erbium Doped Fibers

1 OBJECTIVE

Study the characteristics of EDFAs alone and in a system. Reanalyze the importance of receiver noise and the effect of amplification on the quality of an optical system.

2 PRE-LAB

Loss in optical fiber is a major limiting factor in optical system design. Before the advent of efficient optical amplifiers, electrical regenerators were used to reproduce the optical signal after a certain propagation distance, but these became too difficult to implement, especially when wavelength demultiplexed systems were introduced. Erbium doped fiber amplifiers (EDFAs) do not have this issue and soon replaced regenerators in optical fiber networks.

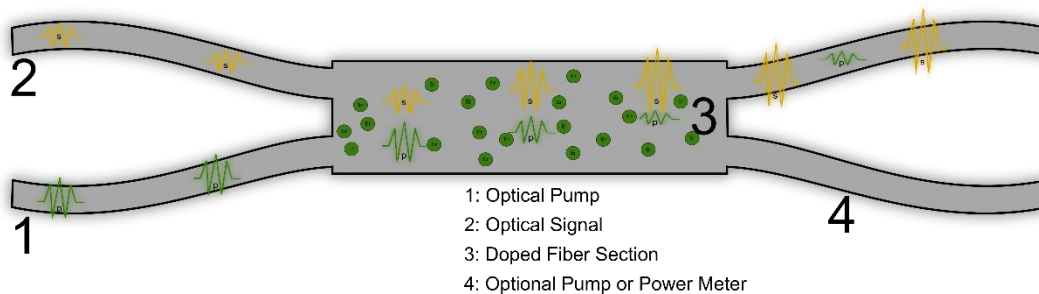


Figure 1: Schematic of an Erbium Doped Fiber Optical Amplifier

The basic principle of an EDFA is much similar to that of a semiconductor Laser, differing by the lack of feedback (the reflective end facets) and an electrical pump. An EDFA exploits the stimulated emission process from an excited ion, in this case Erbium, in a similar manner. The Erbium ions are excited by a high frequency optical pump into a higher unstable state and subsequently lose energy nonradiatively and drop to a slightly lower metastable state, and emit photons by stimulated emission that are direct copies of the incident signal and as a result the signal is amplified.

The importance of using Erbium ions becomes clear because of their particular energy states, which correspond to the range of wavelengths that experience the lowest loss in silica fiber, known as the C band 1530-1565 nm.

2.1 ENERGY LEVELS AND CROSS SECTIONS

There are two main pumping schemes used for EDFAs: in the first method light at the wavelength 1450 nm is used to excite Er^{3+} ions to a sub-level of the $^4I_{13/2}$ state and the second method where light at a lower wavelength 980 nm is used to excite the Er^{3+} ions to a completely different state $^4I_{11/2}$. The first

method has a higher power efficiency because of the smaller energy lost in the relaxation of the ion, however it also introduces more noise in to the signal.

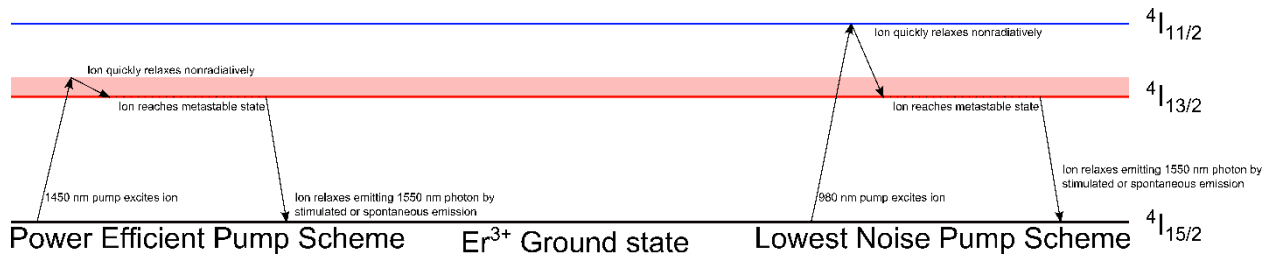


Figure 2: Energy levels of Er^{3+} ion and two popular pumping schemes

Since the lifetime of the higher energy state is much less than the metastable state this process can be modelled by a two-level system with rate equations:

$$\frac{dN_2}{dt} = -\frac{dN_1}{dt} = -\Gamma_{21}N_2 + (N_1\sigma_a - N_2\sigma_e)\phi_s - (N_2\sigma_e - N_1\sigma_a)\phi_p. \quad (1)$$

Here N_1 and N_2 are the population densities of the first and second level respectively. Γ_{21} is the probability of a spontaneous transition from the second to first level and σ_a , σ_e are the absorption and emission cross sections, which together with the signal and pump light intensity fluxes ϕ_s , ϕ_p calculate the probability of a stimulated absorption or stimulated emission. The cross section data is very important for calculating the gain and the noise spectrum and so an accurate model will capture its wavelength dependence. The cross sections also depend not only on the dopant, but also the host material. This data is generally found experimentally and can then be loaded into OptiSystem as a text file. The default option is data from a silica host.

Questions:

- 2.1.1 Calculate the portion of energy lost due to nonradiative relaxation for both pump schemes, for this simple model.
- 2.1.2 For a small signal flux what is the threshold condition for the pump flux to reach population inversion? $N_2 = N_1$

2.2 AMPLIFIED SPONTANEOUS EMISSION NOISE

Although population inversion allows for incoming optical signals to be amplified by stimulated emission, it also introduces the problem of spontaneous emission. Ions randomly relaxing radiatively lead to a source of noise that is also amplified throughout the fiber and ultimately limits the performance of the amplifier.

The amplified spontaneous emission (ASE) depends on the degree of population inversion as well as the particular cross sections of the fiber, as an example the ASE profile of common EDFAs look like Figure 3. Although the exact ASE can depend on the pump power, length of the EDFA, and even the incident signal itself due to broadening.



Optical Spectrum Analyzer

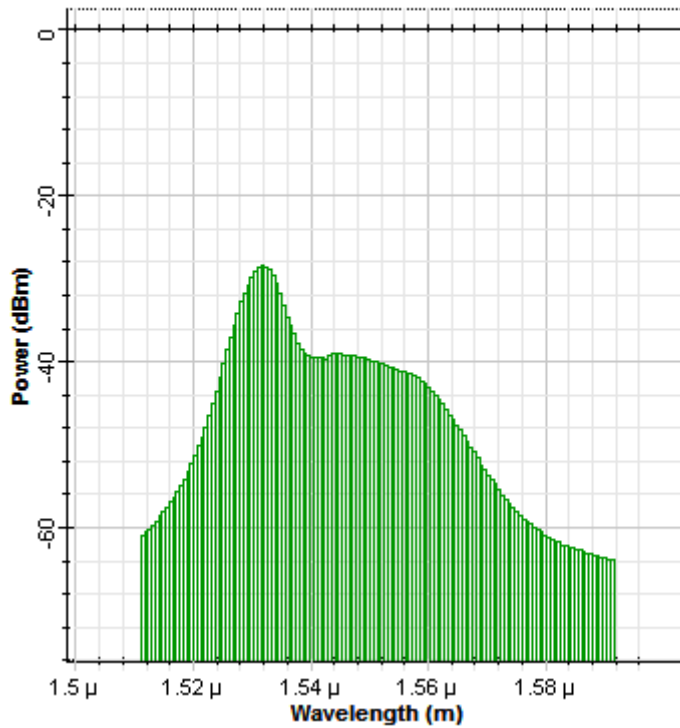
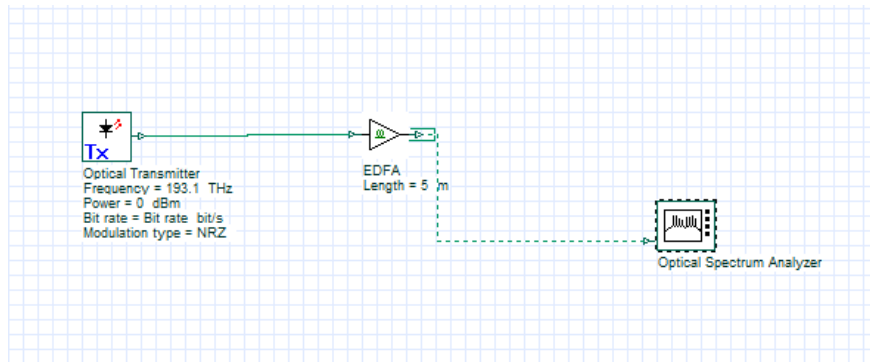


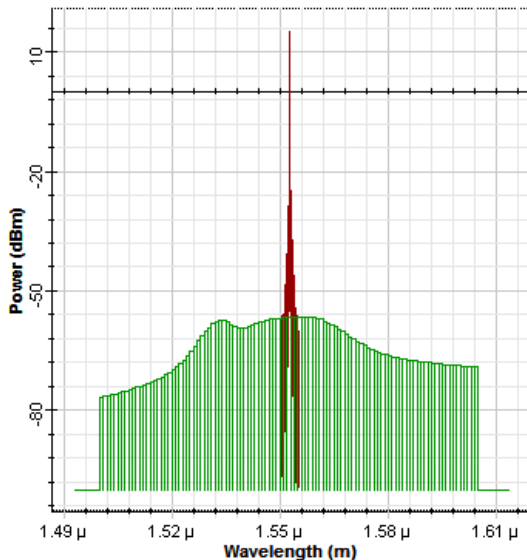
Figure 3: ASE spectrum from EDFA

ASE, along with some other sources of noise in OptiSystem are represented by noise bins. The noise bins themselves contain information about the power contained in a certain range of frequencies. This allows for very large bandwidths of noise to be represented without using a sampled signal, which would waste a lot of computer memory. Thus, in some sections of the simulation the noise bins are treated separately than the optical sampled signal, but the user can control this aspect with the convert noise bins parameter. For example, the following setup was simulated of a simple NRZ signal at 193.1 THz propagating through an EDFA with the above ASE. In the first case the noise bins are not converted and in the second they are.



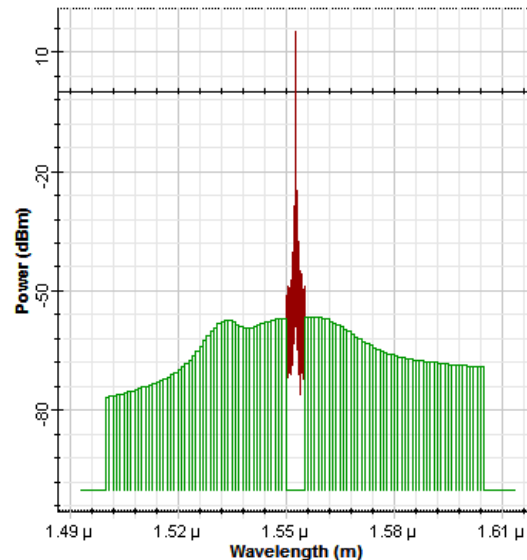
a)

Optical Spectrum Analyzer



b)

Optical Spectrum Analyzer



c)

Figure 4: a) Layout of simulation b) Simulation without converting noise bins c) Simulation with converting noise bins

When the noise is added to the sampled signal it is then also converted to a random sampled signal and added as you would expect. The noise bins also allow the user to make easy calculations of the signal to noise ratio, because it explicitly separates the noise from the signal.

Questions:

- 2.2.1 Estimate the signal to noise ratio from the graphs in Figure 4.
- 2.2.2 Remove the Optical Transmitter component from the Layout in Figure 4 and replace it with an Optical Null. Explain the effect of increasing pump power on the ASE spectrum

2.3 NOISE FIGURE

The ASE that is introduced to a signal results in degrading initial Signal to Noise ratio. It is characterized by the quantity known as the Noise Figure and is calculated by:

$$N_f = \frac{SNR_{in}}{SNR_{out}}, \quad (2)$$

where SNR_{in} is the input signal to noise ratio and SNR_{out} is the output signal to noise ratio. Another useful quantity is called the optical SNR or OSNR. On account of the bandwidths in optical communications being very large and an even larger noise bandwidths. The SNR is calculated over a certain range of frequencies, most commonly a resolution bandwidth of 0.1 nm. For example, the OSNR would be given as:

$$OSNR = \frac{P_{s_{0.1\text{ nm}}}}{P_{n_{0.1\text{ nm}}}}. \quad (3)$$

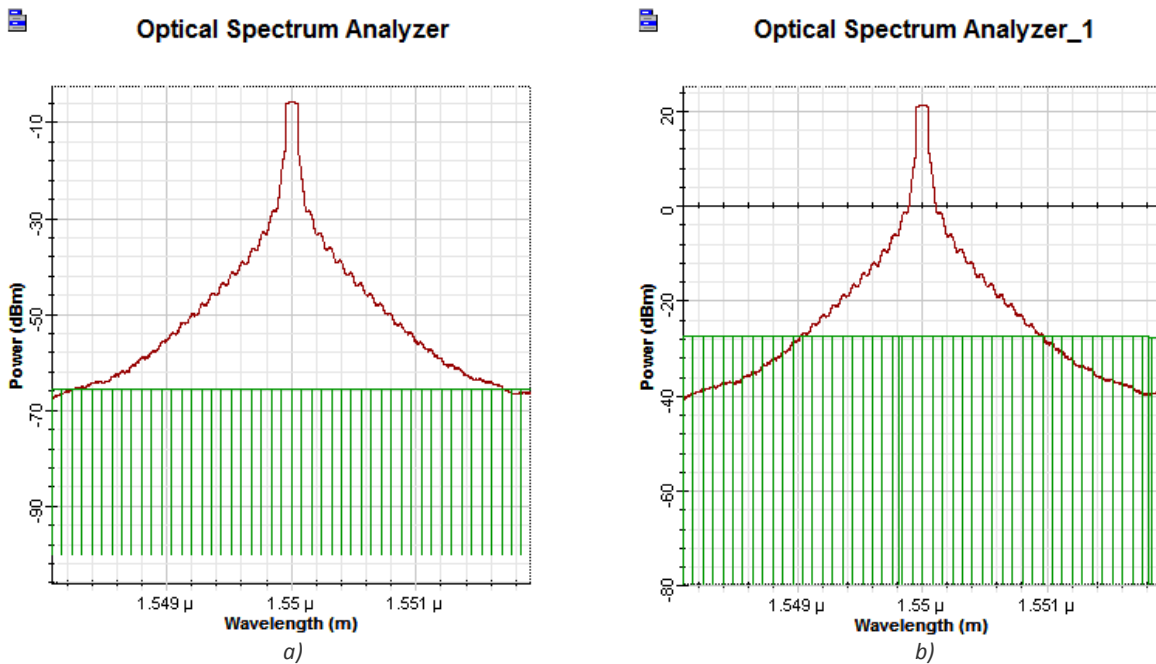


Figure 5: Comparison of the SNR before and after an EDFA

Questions:

- 2.3.1 Estimate the signal to noise ratio for the input and output signals in Figure 5.
- 2.3.2 Calculate the noise figure of the amplifier tested in Figure 5.

3 CHAINS OF EDFAs

In optical communication systems, EDFAs are equally spaced throughout the fiber links to counteract loss of the fibers. Numerous EDFAs of low gain are generally favored over less high gain EDFAs because the lower gain amplifiers introduce less ASE that can be exacerbated by subsequent amplifiers.

3.1 NOISE BUILDUP

Build the following layout to experimentally test the buildup of noise in amplifier chains. In this simulation the optical fibers will be replaced by simple attenuators to model the loss only. The loss of the attenuators will be set to 20 dB to model a fiber around 100 km in length. The EDFAs simulated will have a length of 1.9 m and a forward pump of 50 mW.

- Optical Transmitter Transmitters Library/Optical Transmitters
- Optical Attenuator Passives Library/Optical/Attenuators
- EDFA Amplifiers Library/Optical
- Optical Spectrum Analyzer Visualizer Library/Optical
- Dual Port WDM Analyzer Visualizer Library/Optical

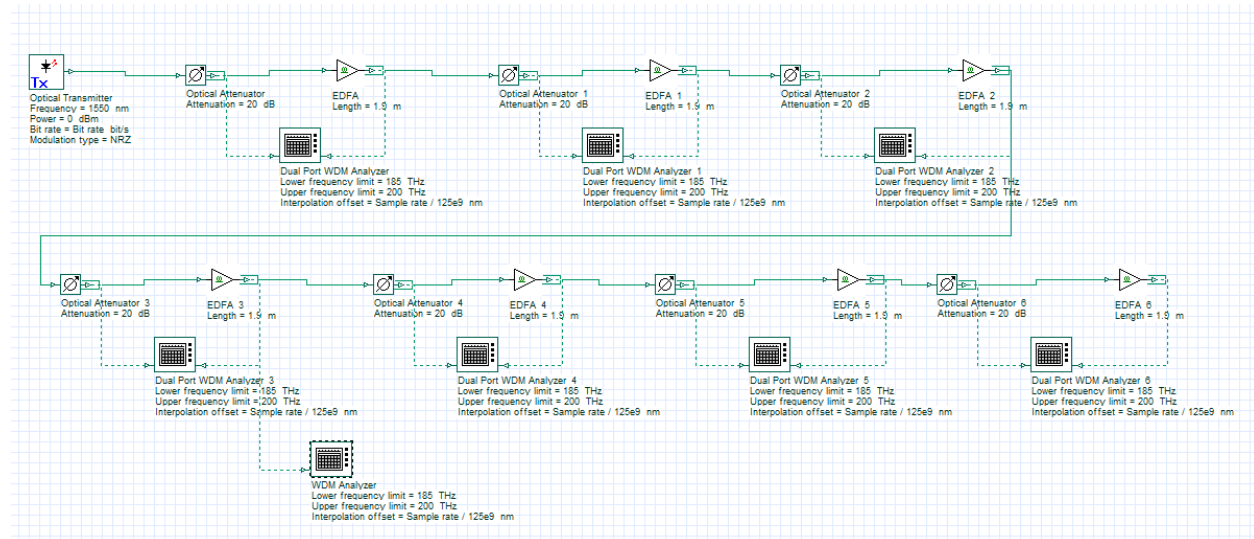


Figure 6: Layout of EDFA chain simulation.

As the original signal with no noise propagates through successive attenuator-amplifier pairs, the SNR degrades. Using a Path, quantities like signal power and OSNR can be plotted as the signal moves through the transmission link. Once the project above has been made click on the “Draw path” icon at the top right

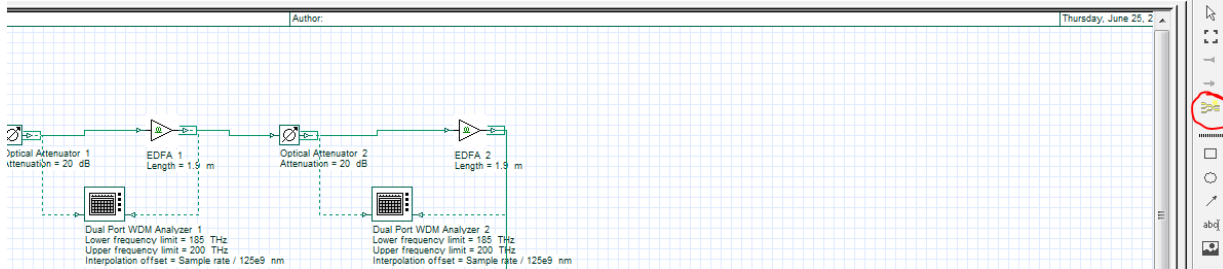


Figure 7: Finding the path tool.

Left-click on the Optical Transmitter and the final EDFA, then hit Accept on the Path Tool window and give your path the name “EDFACHain”.

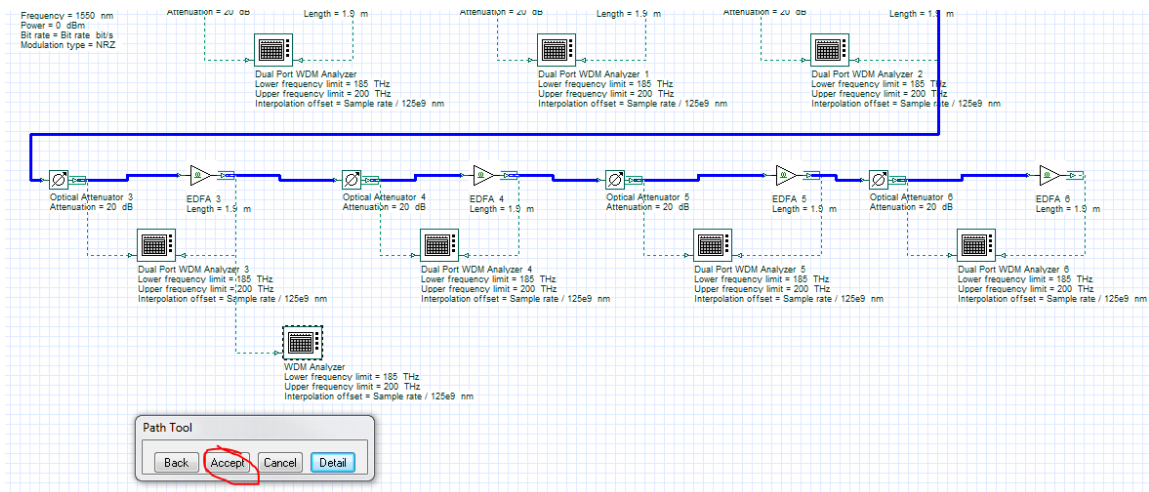


Figure 8: Creating a path through the EDFA chain.

Run the simulation, once complete the results are ready to view in the Project Browser. Find the folder Paths under Global in Layout 1 and right-click the path EDFACHain. Choose preview from the list of options and the Trace Display will open.

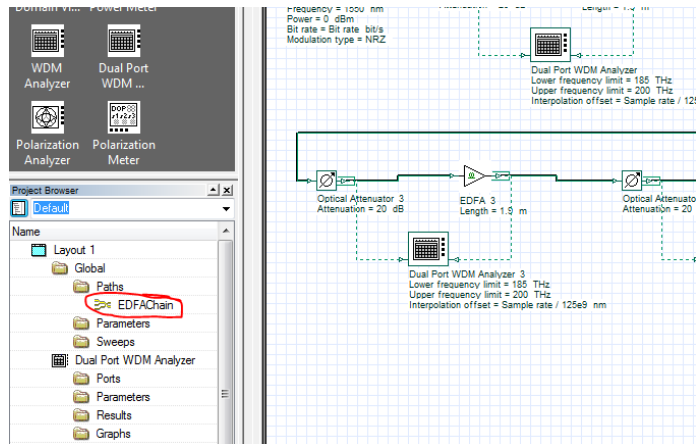


Figure 9: The created path can be found in the project browser.

From the Trace Display the quantities can be displayed as a function of distance, which is more useful for simulations involving more fiber, or by discrete components, choose the latter option. The OSNR is shown in the top portion of the graph starting very large from the lack of noise in the optical transmitter.

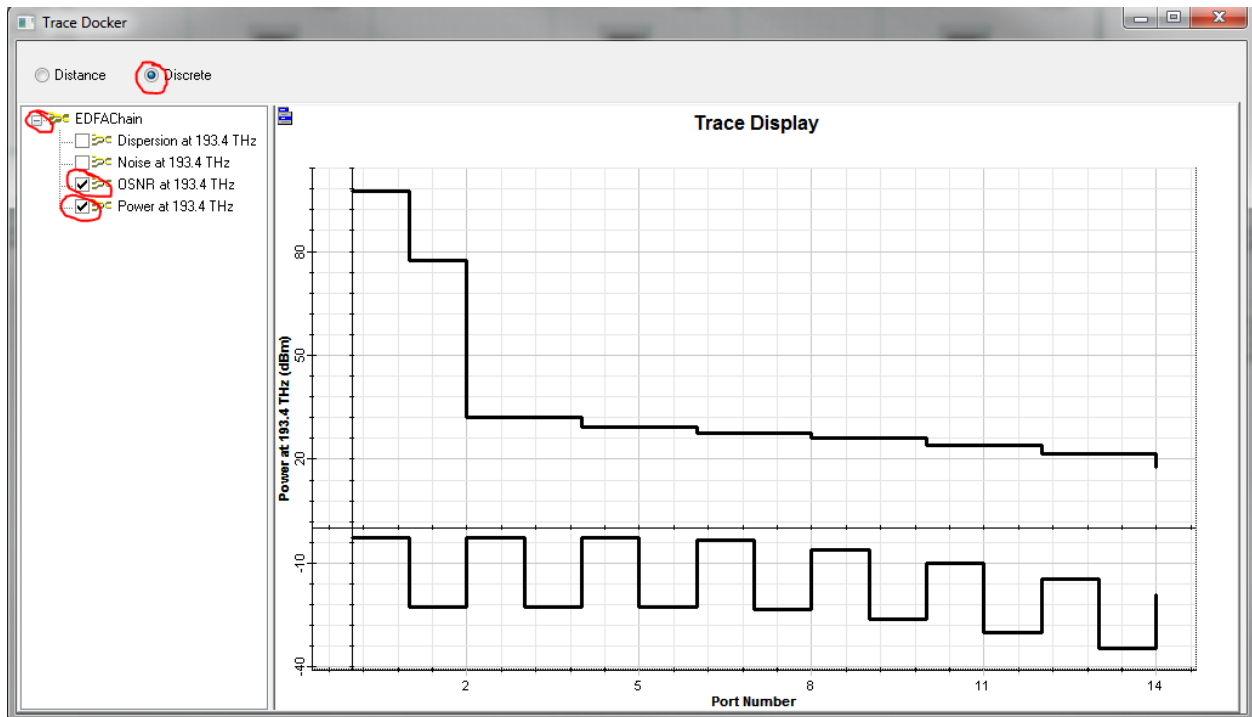


Figure 10: The trace plotting the power and OSNR of the signal as it propagates through the link.

Another useful tool is the Dual Port WDM Analyzer, double clicking the visualizer will allow the user to quickly find out many of the same quantities.

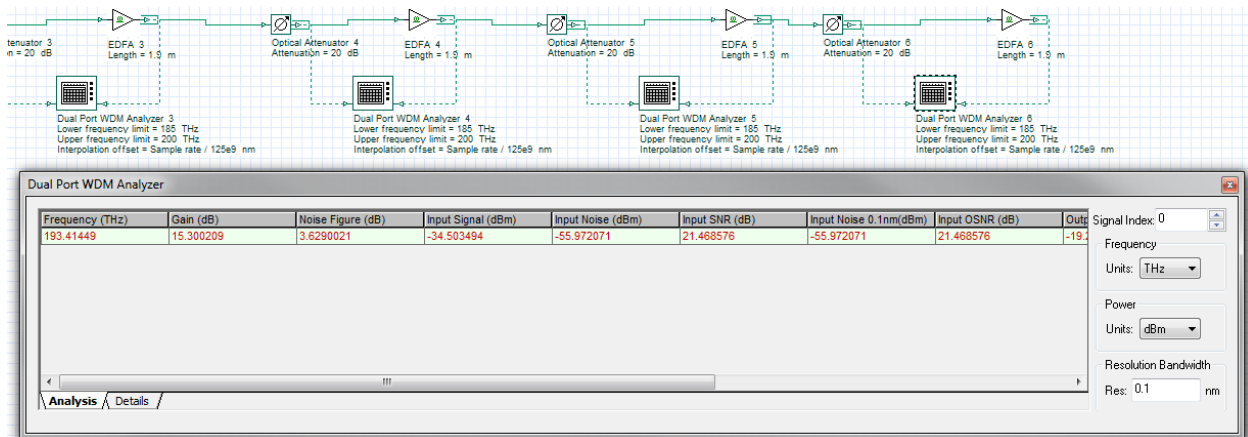


Figure 11: Viewing the results calculated by the WDM Analyzer.

The component automatically calculates the Gain, Noise Figure, SNR and OSNR both input and outputs. The calculation can also be refined over a bandwidth with the Resolution Bandwidth parameter.

Questions:

- 3.1.1 From this graph and using Markers estimate the OSNR before and after each attenuator-EDFA pair. Estimate the noise figure.
- 3.1.2 For the first stages of the amplifier chain the gain is large enough that the signal power is brought back to its original value. However, in the later stages the signal power begins to drop. Explain why this happens. Hint: Look at the noise power as well.
- 3.1.3 Explain how using optical filters the problem in the previous question can be mitigated.

3.2 MAXIMUM LENGTH OF EDFA CHAINS

Using the Path Trace or any other method find the proper length of the EDFA that compensates for 10 dB of loss at each attenuator with a 75 mw pump. Reproduce the system in the previous section but with these new parameters.

- 3.2.1 What is the optimal length to compensate 10 dB?
- 3.2.2 What is the effect of doubling the pump power on gain? What does this say about the ratio N_2/N_1 of the population densities?
- 3.2.3 Duplicate these attenuator-EDFA pairs a number of times using the initial pump power and discovered optimal length. Then for a resolution bandwidth of 0.1 nm find the maximum number of attenuator-EDFA pairs that can be placed before the OSNR drops below 20 dB.
- 3.2.4 Comparing the total loss over the entire link of these two different compensation schemes (high gain/low gain), which provides the better performance?

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

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.

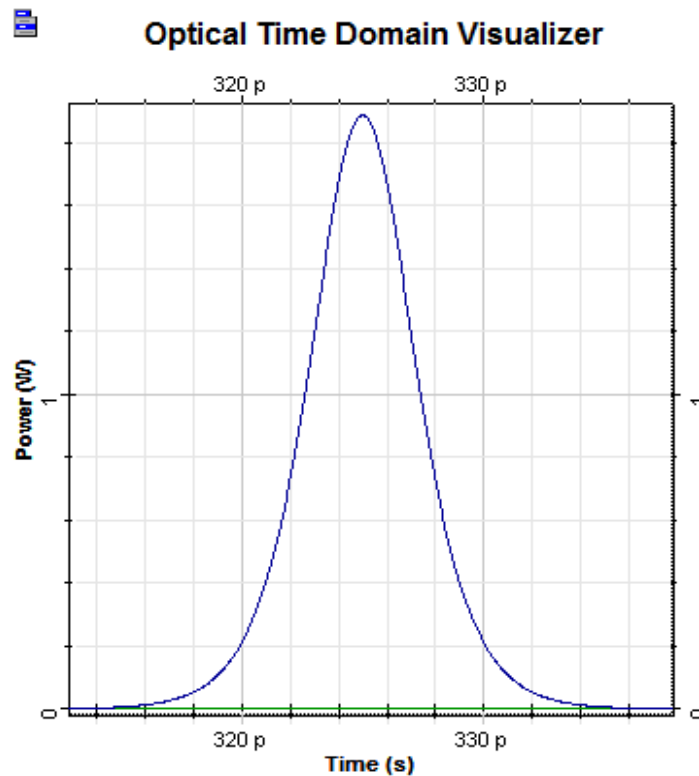


Figure 1: Profile of a hyperbolic secant optical pulse, which corresponds to the solution of the fundamental optical soliton.

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 $80 \text{ }\mu\text{m}^2$, 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.

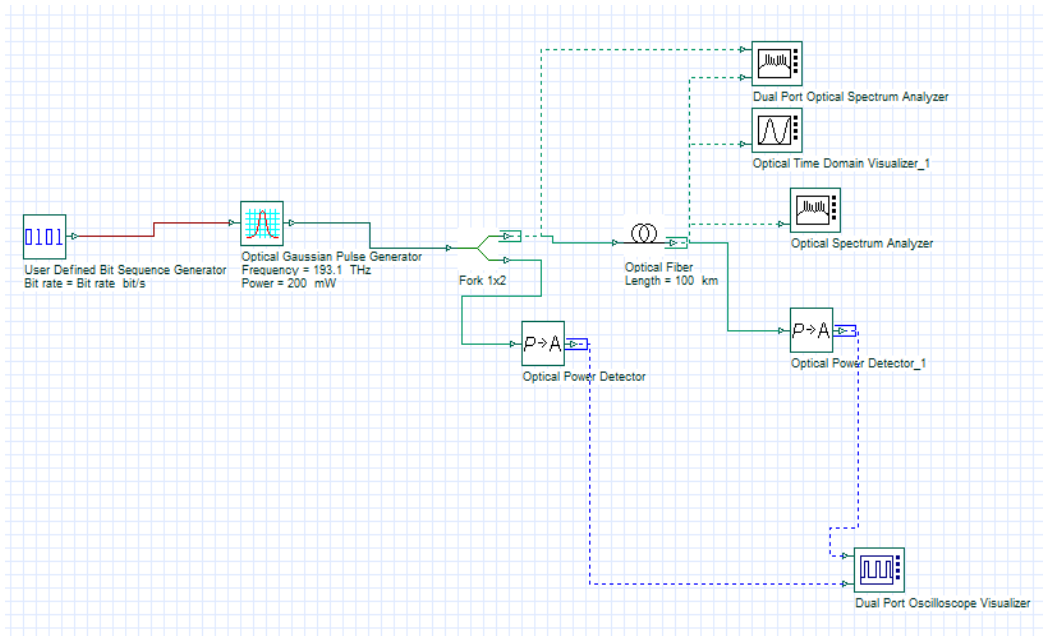


Figure 2: Layout for investigating the chirp induced on an optical pulse.

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.

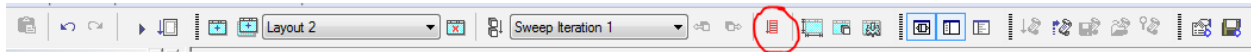


Figure 3: Toolbar snapshot

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.

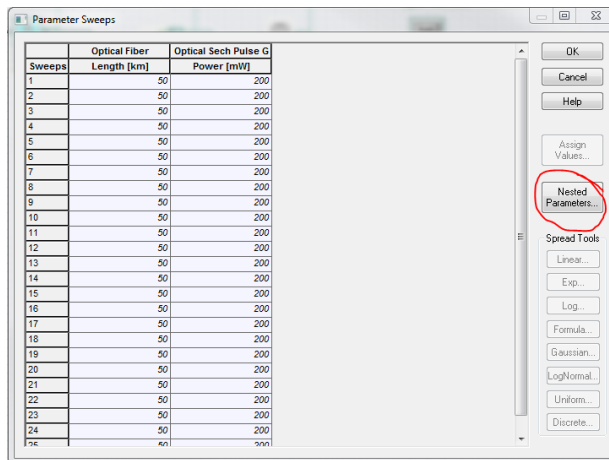


Figure 4: The parameter sweeps window.

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.

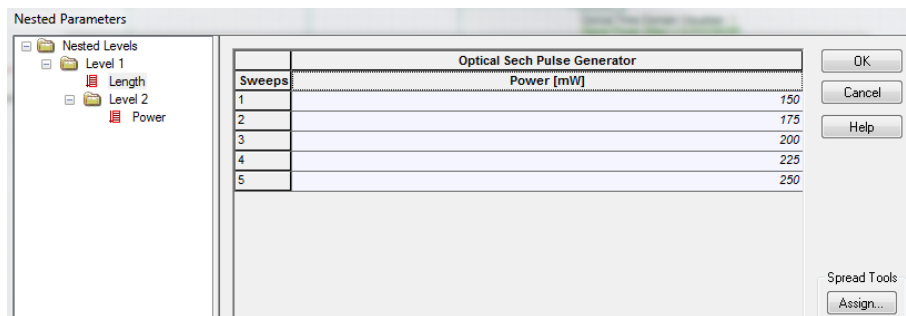


Figure 5: Nester Parameters window

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.

QAM Transmitter

1 OBJECTIVE


Investigate the method for measuring the BER accurately and the distortions present in coherent modulators.

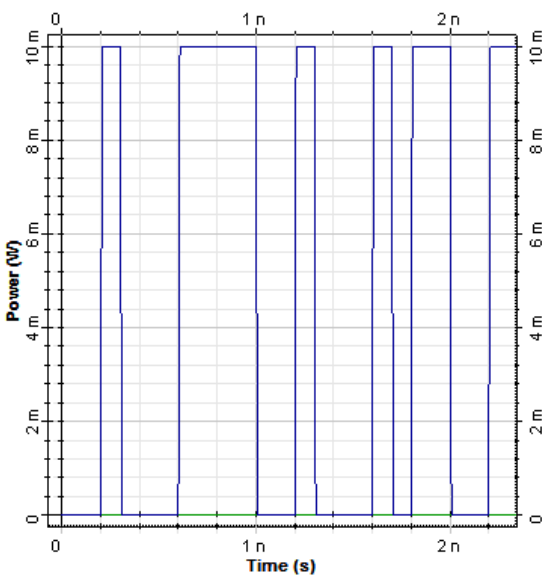
2 PRE-LAB

The goal of optical communication systems is to transmit data from one point to another. Generally, this data takes the form of a binary signal. The binary data needs to be used to modulate an optical signal and then correctly demodulated at the receiver into a readable binary signal. Some simple schemes have already been described, like the pervasive on off keying, where the optical power is used to represent a '1' or '0'. However, power is only one aspect of the electric field and the phase can also be modulated. Describing the electric field with the complex envelope makes this clear:

$$\mathbf{E}_t(t) = \text{Re}[E_x e^{i\phi_x - i\omega t} \hat{x} + E_y e^{i\phi_y - i\omega t} \hat{y}]. \quad (1)$$

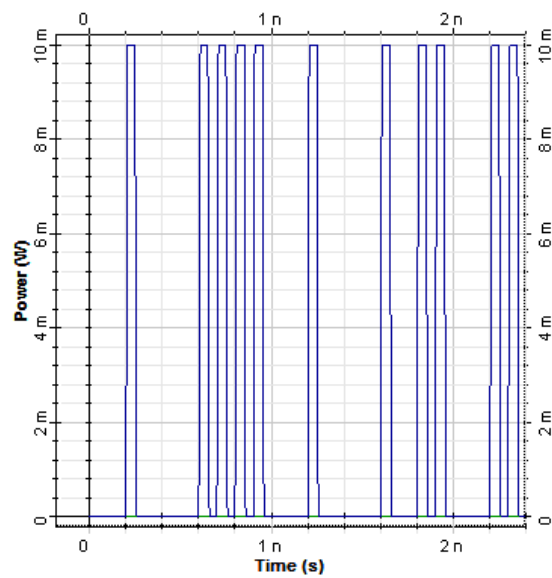
From this equation, it is evident that for each polarization the amplitude can be changed and also the phase, ϕ_x . Amplitude modulation is a more general case of on-off keying (OOK) where the amplitude may take on more than two different levels. Modifying the phase, called phase shift keying (PSK), does not have an effect on the power of the output, but the phase of the optical carrier. Then there is the logical next step to modulate the amplitude and the phase at the same time called Quadrature Amplitude Modulation (QAM).

 **Optical Time Domain Visualizer**



a)

 **Optical Time Domain Visualizer**



b)

Figure 1: An example of two different yet similar modulation formats. Figure a) represents an on off keying non return to zero format, while Figure b) shows a return to zero format.

2.1 BIT RATE, SYMBOL RATE AND BIT ERROR RATE

At this point the reader should be fairly confident to describe what the bit rate is. In any case, the bit rate is defined as the number of bits per second transmitted. The bit period, T_B , and in the special case of NRZ also the pulse width, would be given by:

$$T_B = 1/B \quad (2)$$

In advanced modulation schemes instead of only having two states (on or off) there might be 4 or even 64 different states. The term bit is then replaced with symbol and bit rate replaced with symbol rate.

$$S = B / \log_2 M \quad (3)$$

Here S is the symbol rate and M is the number of states that a symbol can take. For example, a system where the amplitude can be 0, 0.5, 1, 1.5 would have $M = 4$ and result in a symbol rate half that of a regular OOK format.

The bit error rate (BER) is an extremely useful metric for describing the quality of communication system. Simply put it is the number of misinterpreted bits per bit sequence transmitted.

$$BER = \frac{\text{number of bit errors}}{\text{length of bit sequence}} \quad (4)$$

The goal of communication systems is to keep this value low, while increasing the bit rate and at the same time keeping pecuniary costs low. This means that an accurate calculation of the BER depends on the length of the bit sequence. Suppose the true BER of a system is quite low, one error in a million bits or a BER of 10^{-6} , a simulation or laboratory test with only 1000 bits would only have a 0.1% chance of encountering a single bit error. Assuming that the experiment did result in an error, the BER would be incorrectly calculated as 10^{-3} , which is of course far off from the true BER.

The BER can also be estimated by inspecting the eye diagram from a NRS/RZ type format and for more advanced formats the constellation diagram can be used. In both of these cases though the longer the bit sequence the more accurate the results.

Build the following layout in OptiSystem to investigate the sequence length's effect on the BER.

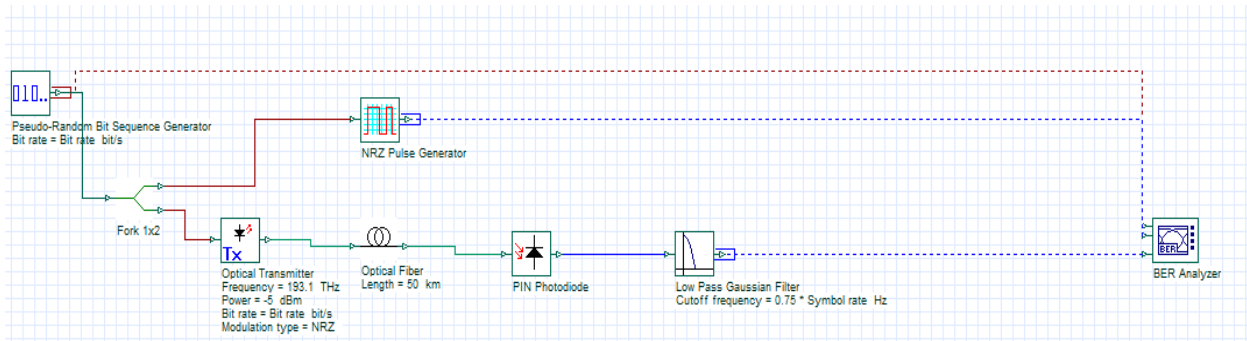


Figure 2: Layout for calculating BER of NRZ.

Once the components have been placed change the Power of the Optical Transmitter to -10 dBm and the Symbol rate, found in the layout parameters, to 10e+009 symbols/s

Questions:

- 2.1.1 Calculate the average BER and standard deviation from the Min. BER result given by the BER Analyzer for 25 identical simulations. The random noise and exact bit sequence will be the only changes.
- 2.1.2 Change the sequence length to 1024 and calculate the average BER and standard deviation from the Min. BER result given by the BER Analyzer for 25 identical simulations.
- 2.1.3 Change the sequence length to 4096 and calculate the average BER and standard deviation from the Min. BER result given by the BER Analyzer for 25 identical simulations. You may need to uncheck the BER Analyzer option “Eye must be open”, since the eye becomes crowded from the numerous bits.
- 2.1.4 What is the effect of the sequence length on the calculated BER?

2.2 MODULATING LIGHT

Understanding the modulation scheme of OOK is quite simple, the receiver simply detects the power levels of signal and decodes it as a one or a zero. The important question is how to translate the electrical signal to an optical signal. In some simple systems, the pump current to the laser is modulated to change the intensity. This scheme is called direct modulation and normally results in pulses that are chirped from induced change in refractive index due to the change in carrier density. As chirped pulses are strongly affected by dispersion in optical fibers, directly modulated lasers are rarely used. A better method is to keep the laser at a steady current and modulate the signal externally with an alternate device.

A Mach Zehnder Modulator (MZM) can be used to modulate both the amplitude and phase of an optical signal. Without getting too detailed, the MZM splits the optical signal into two branches and induces a phase shift on each branch independently. At the output, the two signals are recombined and can result in a change in amplitude or phase. The response is given by:

$$E_{out} = \frac{E_{in}}{2} \left[e^{j\left(\frac{\pi V_1}{V_\pi}\right)} + e^{j\left(\frac{\pi V_2}{V_\pi}\right)} \right], \quad (5)$$

where V_1 is the applied voltage at the top branch and V_2 is the applied voltage at the bottom branch. V_π is the required voltage to induce a PI phase shift to one of the arms. By varying the voltage on each arm, the amplitude can be modulated via constructive or destructive interference. By applying the same voltage to the top and bottom arms the phase can be changed as well.

Questions:

- 2.2.1 What does the MZM response simplify to in the case where $V_2 = -V_1$?
- 2.2.2 In the previous expression, consider the case where $V_1 = V(t) + V_{bias}$, what value of V_{bias} should be used such that the response is close to linear for small $V(t)$.
Hint: $\sin x \approx x$ for $x \rightarrow 0$

2.3 QUADRATURE AMPLITUDE MODULATION

A special type of modulation which can easily be expanded to carrying many bits per symbol is quadrature amplitude modulation (QAM). At its core, it is the combination of modulating the phase as well as the amplitude and is expressed by the complex signal:

$$E(t) = Re[(I(t) + iQ(t))e^{i\omega t}]. \quad (6)$$

One can take the view point that $Q(t)$ modulates the imaginary component of the complex envelope while $I(t)$ modulates the real part of the complex envelope. Removing the complex notation it becomes:

$$E(t) = I(t) \cos \omega t - Q(t) \sin \omega t. \quad (7)$$

The $Q(t)$ signal is out of phase by 90 degrees and gets the name quadrature phase carrier, while the other is the in-phase carrier. To visualize these different symbols, they are plotted on a complex plane or constellation. For example, a 4 QAM signal has two bits per symbol and $I(t)$ and $Q(t)$ can both take values of 1 and -1 , representing a bit value 1 and 0. By removing the time domain from the equation, a constellation diagram can be used to view which symbols are present. For example, take Figure 1 below which is a representation of a 4 QAM signal. The binary sequence is cut into 2 bit length symbols where the first bit is translated for the $I(t)$ component and the second is translated for the $Q(t)$ component. To create the final signal, all that is needed is a way to modulate two sinusoids that differ in phase. To accomplish this, a CW laser can be split by a 3 dB cross coupler, which by its nature induces a $\pi/2$ phase shift.

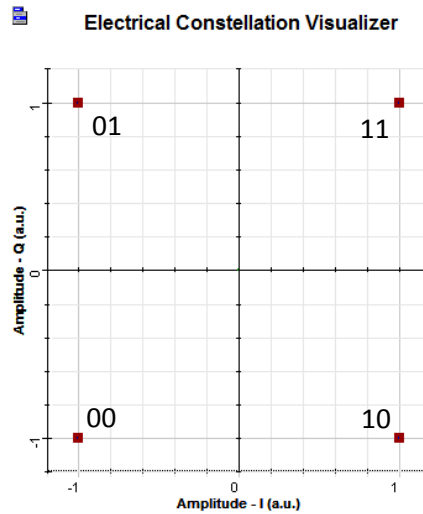


Figure 3: Constellation diagram of 4 QAM signal. Binary signals cut into 2 bit long symbols.

The following diagram demonstrates how a coherent transmitter could be designed. The binary sequence is split into and subsequently converted to the electrical signals, $I(t)$ and $Q(t)$. The electrical signals modulate their respective carriers, which differ by a $\pi/2$ phase shift due to the cross coupler.

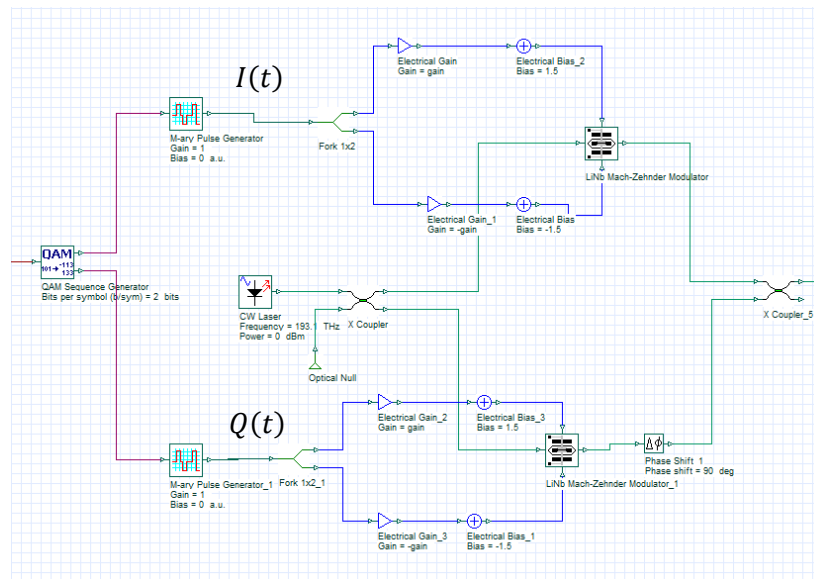
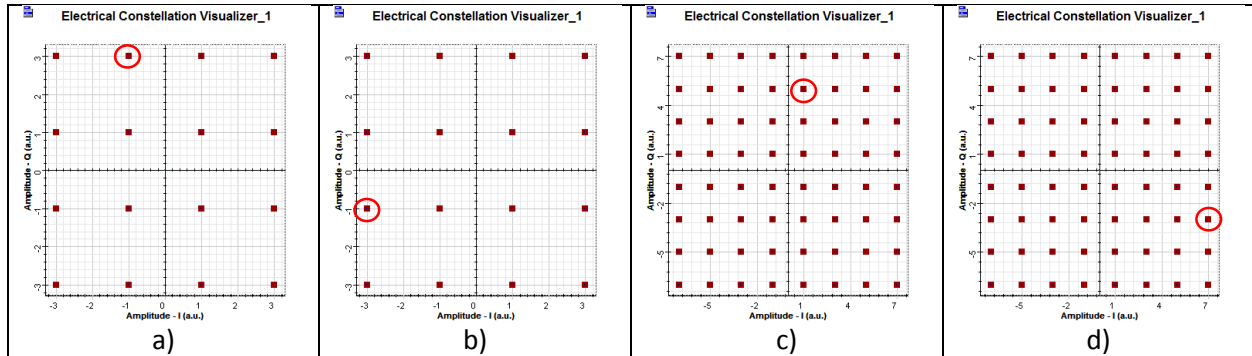


Figure 4: QAM transmitter design

- 2.3.1 The MZMs are held at the null bias point or a total bias voltage equal to V_{π} . This allows the time dependent portion of the signal to sweep through the maximum range of values before the periodic nature of the response duplicates values. What should the gain be if the M-ary Pulse Generator is outputting pulses of -1 and 1 Volts? What about a signal that ranges between -5V, -3V, -1V, 1V, 3V, 5V? Assume a V_{π} of 3 V.
- 2.3.2 In the constellation diagrams below convert the symbols in to bit sequences by the following protocol. First find the number of bits per symbol. The first half of the bits will

represent the $I(t)$ amplitude and the last half will represent the $Q(t)$ amplitude. Then, number the possible amplitudes starting from the smallest to the largest for each axis. Finally, locate the highlighted symbol and represent it as a binary sequence.



Example: In a) there are 16 possible states, which can be represented by 4 bits. The first two bits will represent the possible amplitudes for the in phase portion while the last two will represent the quadrature phase.

Bit Sequence	$I(t)$	$Q(t)$
0000	'00'→ -3	'00'→ -3
0001	'00'→ -3	'01'→ -1
0010	'00'→ -3	'10'→ 1
0011	'00'→ -3	'11'→ 3
0100	'01'→ -1	'00'→ -3
0101	'01'→ -1	'01'→ -1
0110	'01'→ -1	'10'→ 1
0111	'01'→ -1	'11'→ 3
1000	'10'→ 1	'00'→ -3
1001	'10'→ 1	'01'→ -1
1010	'10'→ 1	'10'→ 1
1011	'10'→ 1	'11'→ 3
1100	'11'→ 3	'00'→ -3
1101	'11'→ 3	'01'→ -1
1110	'11'→ 3	'10'→ 1
1111	'11'→ 3	'11'→ 3

In this labelling scheme the circled symbol results in the bit sequence '0111'.

3 DISTORTION IN QAM TRANSMITTERS

Build a QAM transmitter from the layout shown in Figure 3 and after creating a subsystem out of the components attach a bit sequence generator and a pre-built Optical Coherent QAM Receiver as in the diagram below:

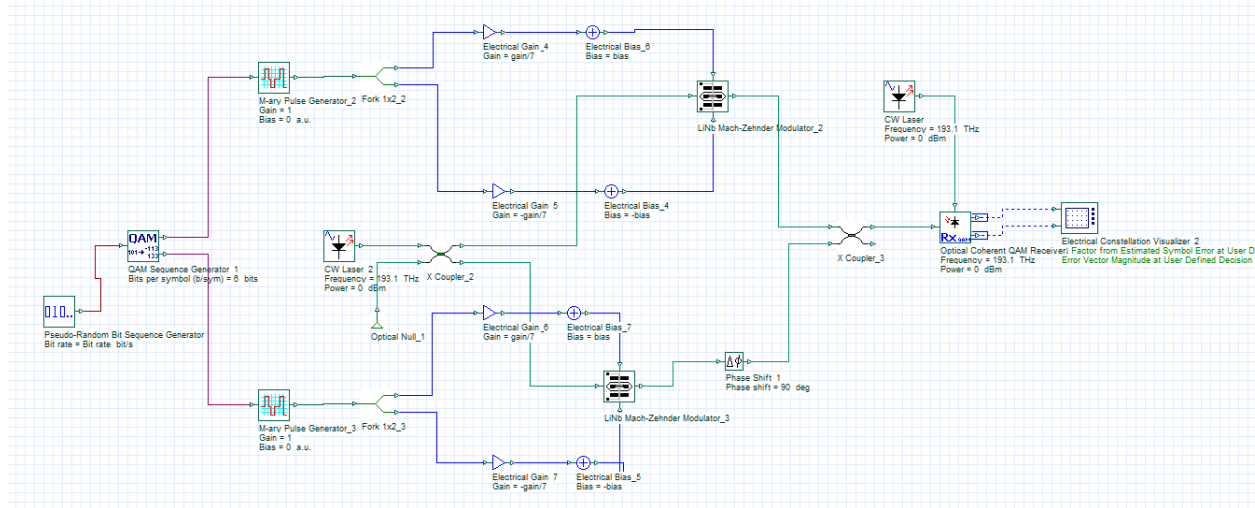


Figure 5: Layout of QAM transmitter.

- | | |
|--|--|
| • Pseudo-Random Bit Sequence Generator | Transmitters Library/Bit Sequence Generators |
| • QAM Sequence Generator | Transmitters Library/Coders |
| • M-ary Pulse Generator | Transmitters Library/Pulse Generators/Electrical |
| • Fork | Tools Library |
| • CW Laser | Transmitters Library/Optical Sources/ |
| • Electrical Gain | Signal Processing/Arithmetic/Electrical |
| • Electrical Bias | Signal Processing/Arithmetic/Electrical |
| • LiNb Mach-Zehnder Modulator | Transmitters Library/Modulators/Optical |
| • Phase Shift | Passives Library/Optical |
| • X Coupler | Passives Library/Optical/Couplers |
| • Optical Coherent QAM Receiver | Receivers Library/Optical Receivers |
| • Electrical Constellation Visualizer | Visualizer Library/Electrical |

The DC bias point for the two MZMs will be the null point or V_{π} and in this case that corresponds to a 1.5V bias at the top port and a -1.5V on the bottom port. In the LiNb MZMs make sure to change the Extinction Ratio to 25 dB, both switching voltages to 3V and the insertion loss to 1 dB. The X Couplers should also include a 1 dB insertion loss. The CW Lasers in this project are also slightly different as in coherent transmission links you need better phase characteristics of the transmitter. For the two CW Lasers change the Linewidth to 0.1 MHz and set them to operate at 193.1 THz. The optical coherent receiver can be set to accept an external local oscillator (laser), a necessary additional component in coherent receivers that will be explained in a later laboratory. At this stage the assumption that both

lasers have the exact same phase characteristics will be made to simplify the design. In the Component Properties of the two CW Lasers change the Random seed index to 0 for both.

3.1 EFFECT OF GAIN

The constructed QAM Optical Transmitter can be modified easily to obtain both 4 QAM and 64 QAM, first set the transmitter to function as a 4 QAM transmitter by setting the Bits per symbol appropriately.

Questions:

- 3.1.1 Assuming the default bit rate of 10 Gbps, what should the Layout Parameter Symbol rate be set to for 4 QAM and 64 QAM?
- 3.1.2 What is the maximum gain that should be used for the case of 4 QAM and 64 QAM?
- 3.1.3 Simulate the effect of the gain on the 4 QAM constellation at the output starting from the maximum gain value and ending at 0.1. Compare the first and final constellations and describe what the effect of the gain on the constellation. There will be some random noise generated by the photodetectors in the optical receiver.
- 3.1.4 The off center characteristic of the constellation is due to an additional term in the transfer function of the MZMs, that was not explained in the pre-lab but has an important effect nevertheless. Find the transfer function in the technical background and explain which parameter is responsible for this behavior.
- 3.1.5 Simulate the effect of the gain on the 64 QAM constellation at the output starting from the maximum gain value and ending at 0.1. Compare the first and final constellations and describe what the effect of the gain on the constellation.

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

QAM Receiver

1 OBJECTIVE

Build a coherent receiver based on the 90 degree optical hybrid and further investigate the QAM format.

2 PRE-LAB

In the Modulation Formats – QAM Transmitters laboratory, a method of encoding data onto the amplitude and phase of the electric field was demonstrated. However, to extract this modulated signal from the optical signal a different detection scheme is required since photodetectors only capture the power of the incident field and not the phase. Previously, the electric field was found at the output of the Mach-Zehnder Modulators (MZMs) to be:

$$E_{out}(t) = -E_{in} \sin \frac{\pi V_1(t)}{V_\pi} e^{j\omega t}. \quad (1)$$

The secondary MZM used to modulate the quadrature phase carrier produces a phase shifted version:

$$E_{out}(t) = jE_{in} \sin \frac{\pi V_2(t)}{V_\pi} e^{j\omega t}. \quad (2)$$

2.1 COHERENT DETECTION WITH 90-DEGREE OPTICAL HYBRID

The method for retrieving the two signals $V_1(t)$ and $V_2(t)$ involves a continuous wave laser (called the local oscillator) and four photodiodes. The scheme is presented below in Figure 1.

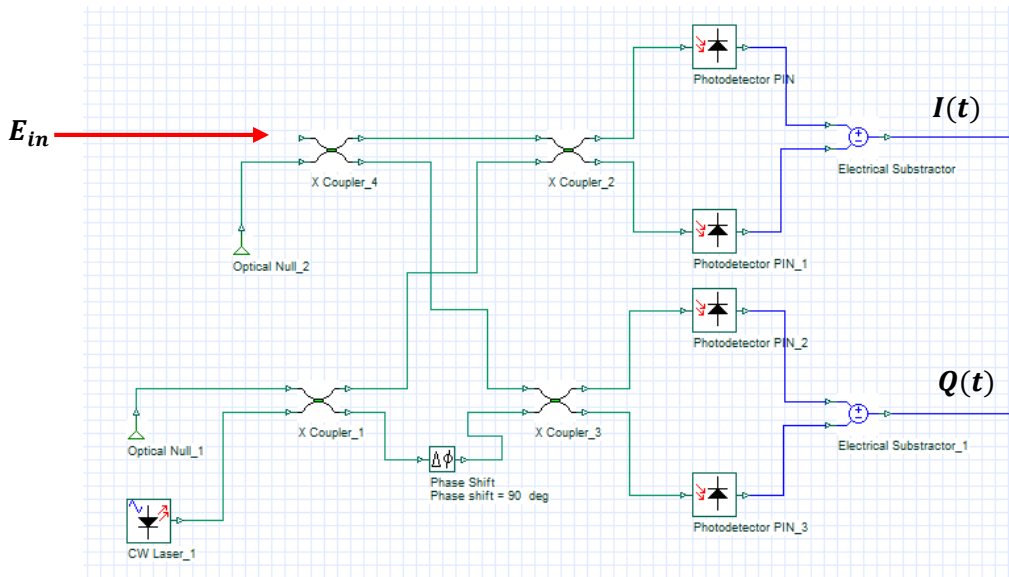


Figure 1: A 90-degree optical hybrid used to extract the electrical signals.

- PIN Photodiode Receivers Library/PIN Photodiode
- QAM Sequence Decoder Receivers Library/Decoder
- Decision Receivers Library/Demodulators
- Fork Tools Library

Component Properties	
BER Test Set	
Number of leading zeros	32
Number of trailing zeros	32
Polarization Type	Single
CW Laser	
Linewidth	0.1 MHz
Generate random seed	Disabled
LiNb Mach-Zehnder Modulator	
Extinction Ratio	25 dB
Switching bias voltage	3 V
Switching RF voltage	3 V
Insertion Loss	1 dB
Phase Shift	
Phase shift	90 degrees
X Coupler	
Additional Loss	1 dB
PIN Photodiode	
Noise calculation type	Numerical – Convert noise bins
Decision	
Polarization Type	Single
Modulation Format	16QAM
DC Blocking	Enabled
Normalize	Enabled

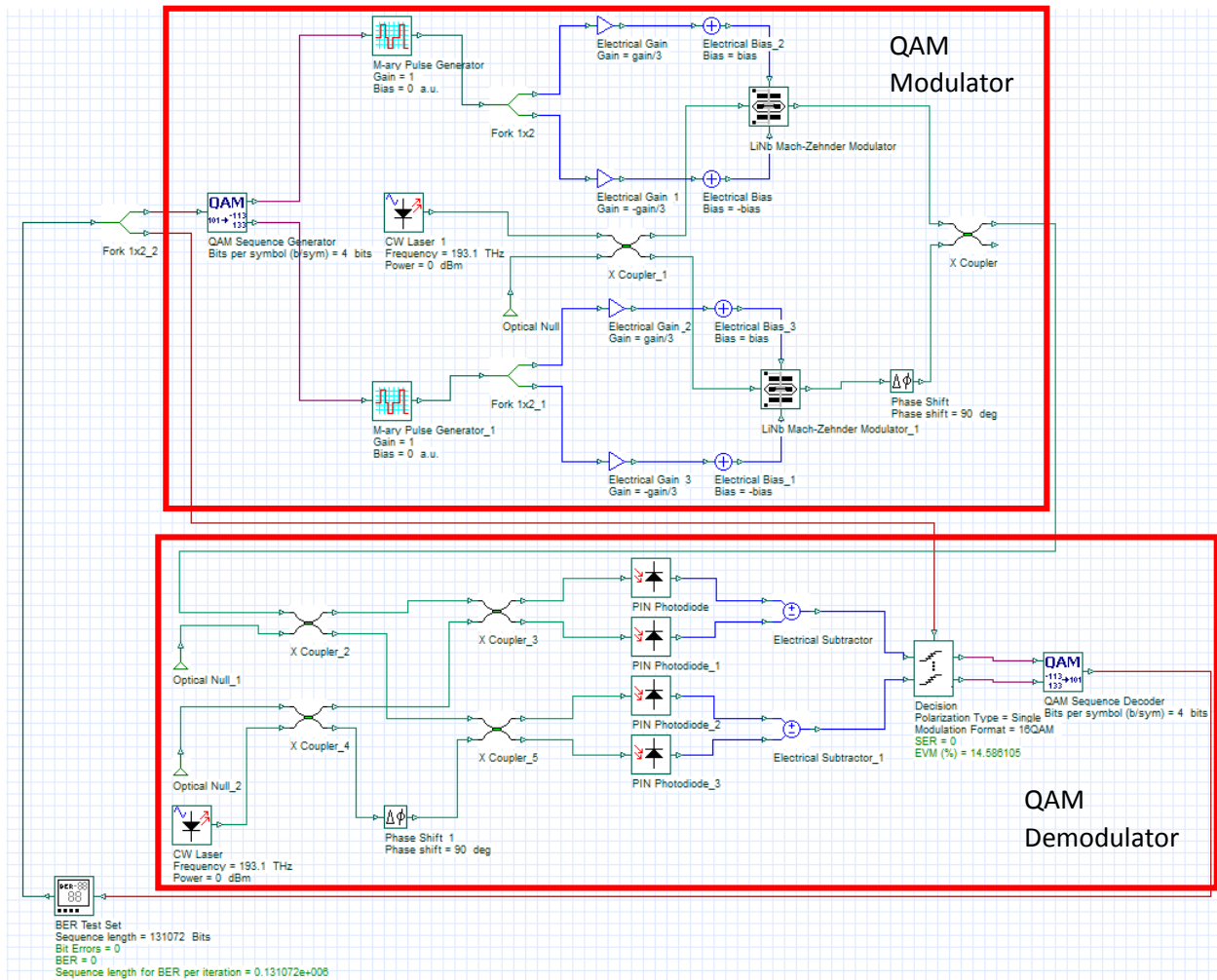


Figure 2: A back to back 16 QAM system consisting of a quadrature modulator and a coherent receiver making use of a 90 degree optical hybrid.

Questions:

- 3.1.1 Set the electrical bias to ± 1.5 V and electrical gain to ± 0.32 for the top and bottom arms of the MZMs. Place a constellation visualizer after the Electrical Subtractors to confirm the correct constellation of 16 QAM. To achieve a full constellation the Sequence length may need to be increased, so that the chances of generating all the possible symbols is greater.
- 3.1.2 This coherent receiver design is in fact unrealistic. The receiver design relies on the fact that the local oscillator has the same phase as the transmitter laser, but unless the same exact laser is used there will be a random difference in phase between the two lasers. Run the simulation again but set the local oscillator laser to generate a random seed in the component properties. Describe the constellation diagram.

- 3.1.3 Return the CW Lasers to the initial parameters, where they each have the same random seed of 0. As shown in the pre lab the detected electrical signals are not the exact input voltages. For a suitably long bit sequence length plot the BER as a function of the electrical gain starting from 0.5 and ending at 0.1. Explain why the gain effects the BER as it does.

3.2 QAM SPECTRAL EFFICIENCY

The ideal QAM transmitter creates a perfect constellation diagram with no distortion introduced from the MZMs or the random phase from the continuous wave laser. One of the main benefits of a QAM transmission format is that the spectral range is used more efficiently. This can be seen qualitatively from the fact that the symbol periods of a 4 QAM system are twice as long as the bit periods of an On-Off Keying format, which means you need roughly half the signal bandwidth.

The spectral efficiency gives a measure of how many bits per second can be transmitted per Hertz of bandwidth used. The expression for spectral efficiency is given by Equation 5.

$$Spectral\ Efficiency = \frac{Gross\ Bit\ Rate}{Signal\ Bandwidth} \quad (5)$$

For many types of signals the bandwidth can be difficult to give an exact value and that is because the Fourier transform of rectangular pulses gives a sine cardinal shape to the frequencies amplitudes. Although the frequencies drop in amplitude as they get larger, discarding the higher frequencies can distort the time domain signal. Simpler modulation formats like NRZ allow for simply filtering out the higher frequencies, for example the signal below can filtered out to leave only the first hump. This translates to a signal bandwidth of 10 GHz.

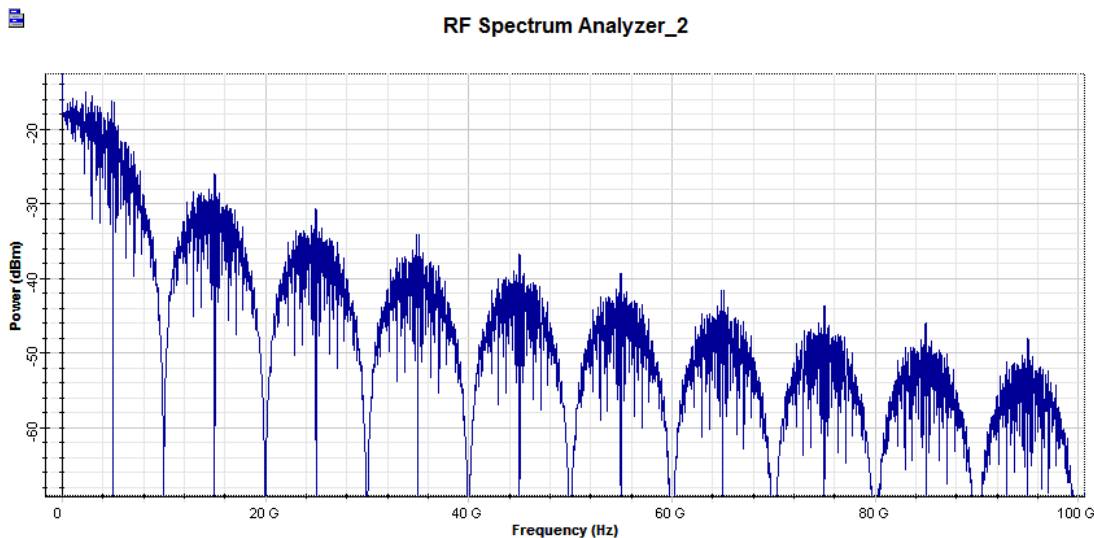


Figure 3: Power spectrum of detected 10 Gbps NRZ format.

If the same trick is applied to a modulation such as 16 QAM, the signal will be heavily distorted and the decision component will have a hard time decoding the proper symbols. However, instead of using an M-ary Pulse Generator in the modulator, which generates multilevel rectangular pulses, a pulse which

has a frequency limited property can be employed. In fact the answer is shown in Figure 3! If the rough signal shape of Figure 3 is used as the time domain pulse, the Fourier transform will be constrained within the low frequencies. The M-ary Raised Cosine Pulse Generator is the exact component that can be used to create this type of signal. The raised cosine pulse overlaps with adjacent bits and can cause errors near the beginning and end of the bit sequence. For this reason, the first and last few bits are ignored from the sequence and are called guard bits.

The frequency domain signal in Figure 4 is tightly confined to frequencies less than 10 GHz. It is much clearer in this case that the signal bandwidth is indeed 10 GHz. Thus, the spectral efficiency of this format is 1 (bit/s)/Hz.

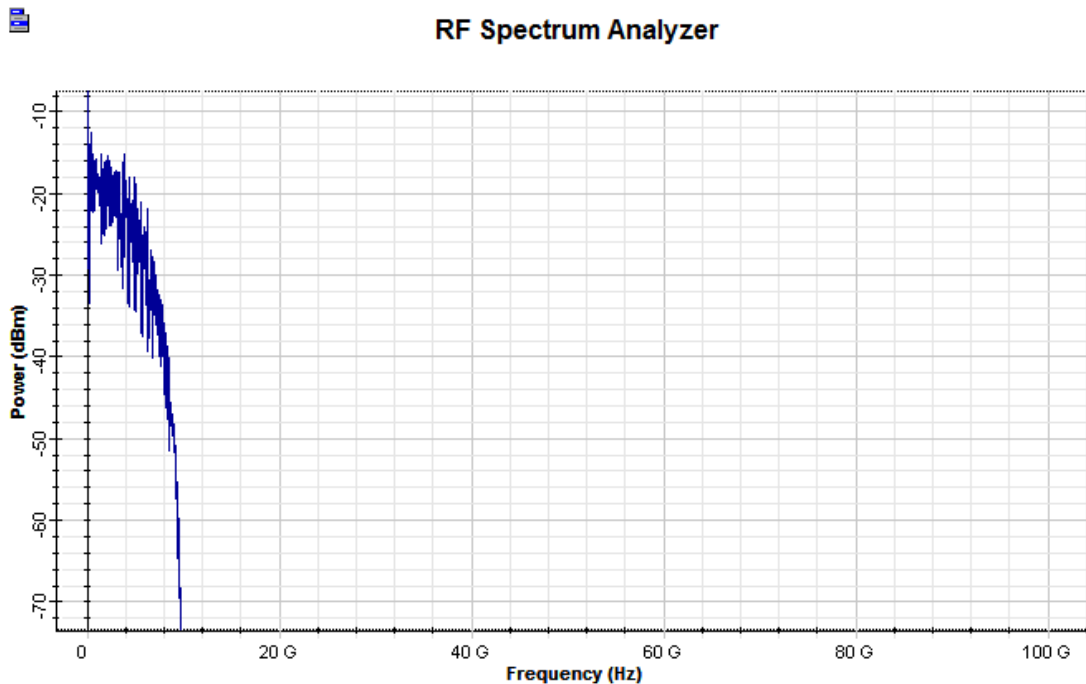


Figure 4: Power spectrum of detected 10 Gbps using the raised cosine pulse generator.

- 3.2.1 Create a subsystem that encapsulates the QAM Transmitter built in Figure 2. To idealize the transmitter, change the laser line width, MZM extinction ratio and the losses present in both the MZMs and the X couplers to values that will minimize distortion and noise. Idealize the receiver by modifying the local oscillator linewidth and by removing the noise from the photodetectors.
- 3.2.2 Replace the M-ary Pulse Generator components in the modulator with M-ary Raised Cosine Pulse Generators. Set the number of guard bits in the layout parameters to 16. Using the ideal transmitter find the spectral efficiency of 16 QAM, 64 QAM and 256 QAM formats. Plot the measured signal bandwidth at one of the Electrical Subtractor outputs.
- 3.2.1 Explain the significance of spectral efficiency and how it relates to a wavelength division multiplexed system.

4 REPORT

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- Brief overview of the background and theory.
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5 REFERENCES

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