Introduction to Fiber-Optic Communication Systems I
FOC I

Interactive learning module

University Program
Photonics Curriculum Version 8.0

Preface

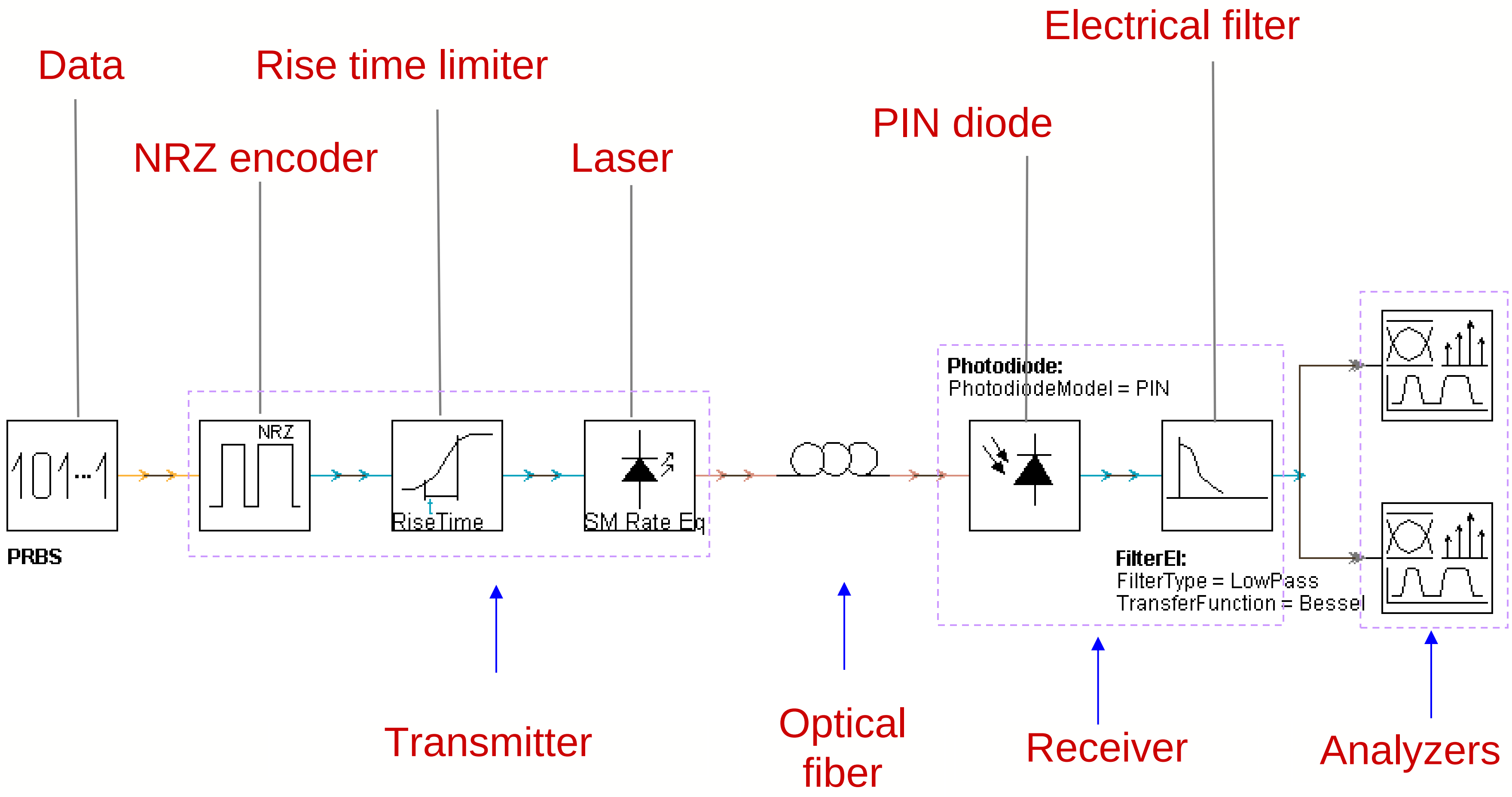
In this module, a simple but complete fiber-optic transmission link will be studied. The setup consists of the three basic elements common to all fiber-optic communication systems:

- An *optical transmitter* converts an electrical signal into optical pulses. In the simulation setup, a single longitudinal mode semiconductor laser is directly modulated with a pseudo random bit sequence (PRBS).
- The optical pulses are transmitted over the *fiber-optic channel*, which in this case consists of one section of optical fiber.
- The transmitted pulse stream is converted back into the electrical domain by the *optical receiver*. In the system under consideration, it consists of a photodetector followed by an electrical filter to enhance the signal quality. Signal Analyzers (Time and frequency) are used to evaluate the simulation results.

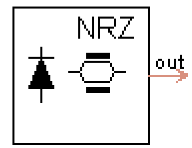
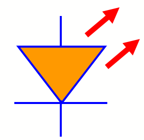
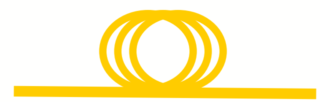
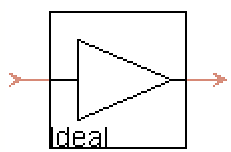
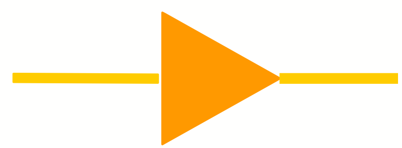
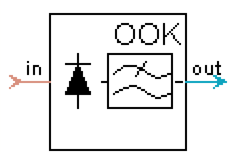
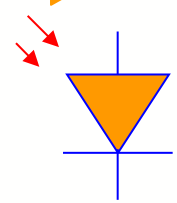
Note:

For details on the handling of VPItransmissionMaker / VPIcomponentMaker please read the *User's Manual* before starting this unit.

Computer Model of an IMDD

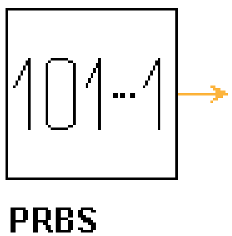


Commonly Used Symbols

	Icons in VPIsystems tools	Symbols used in the lecture
Transmitter		
Fiber		
Amplifier		
Receiver		

Computer Model: Data Source

Data sequence generated

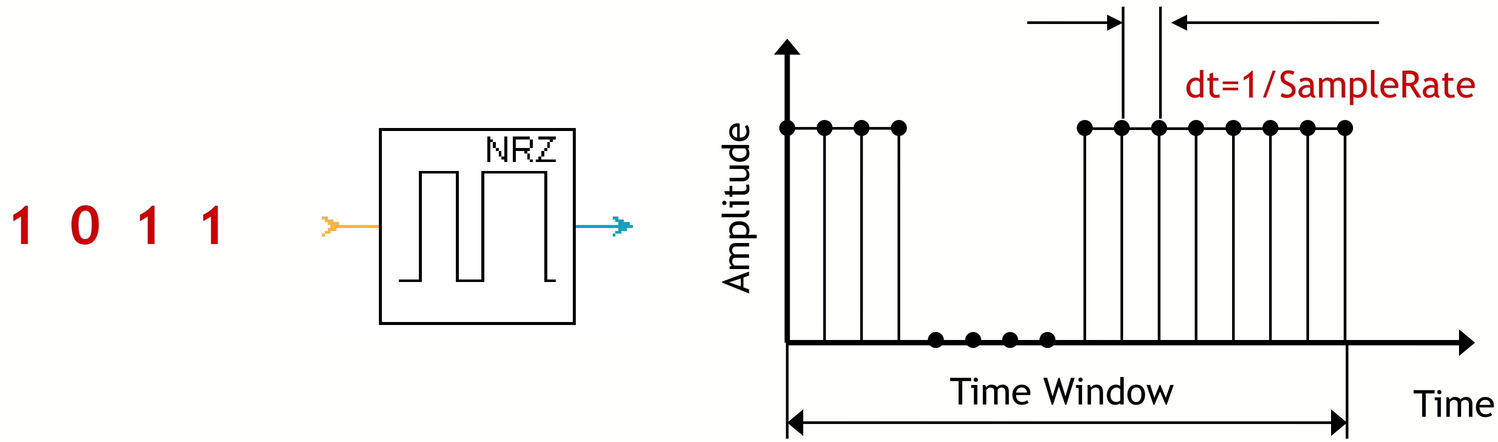


• • •1 0 0 1 0 1 1 0 1 0 1 0 1 0• • •

Generates a Pseudo Random Bit Sequence (PRBS)

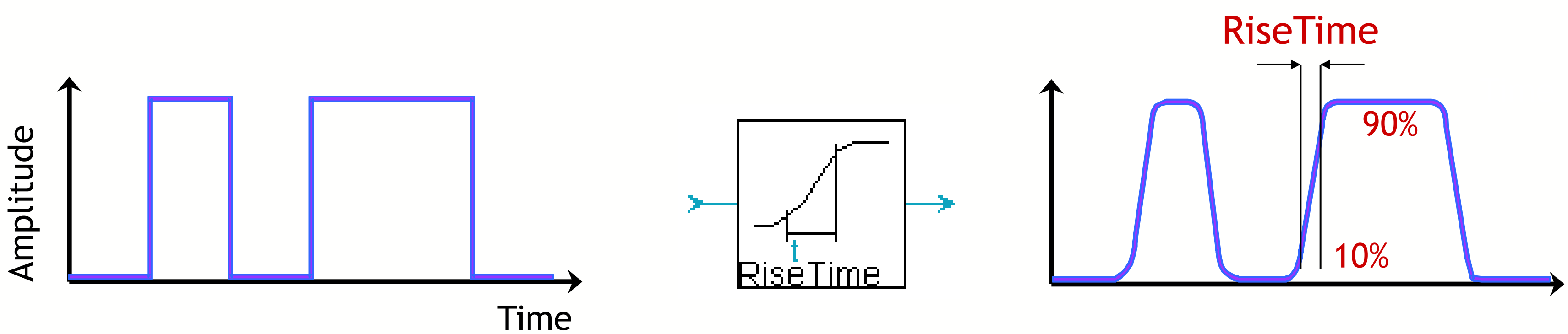
- The output of the PRBS generator can be modified, for example:
  - fixed mark number (assures a fixed number of ‘1’s)
  - sequences of ‘0’s, ‘1’s, or alternating ‘1’s and ‘0’s
  - other features (see *Reference Manual* for more details)

Computer Model: NRZ Coder



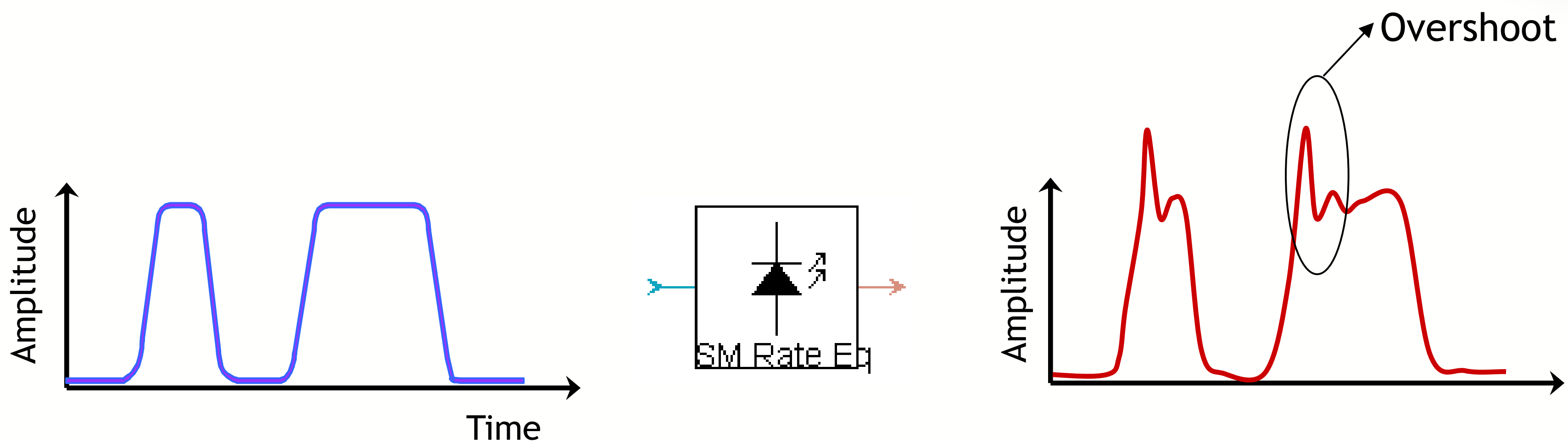
- Generates a NRZ-encoded train of electrical pulses defined by the train of bits at its input
- Pulse waveform at the output of the coder is sampled
- See the *Optical Systems User's Manual* for more details on TimeWindow and sampling. There is also another unit which discusses numerical modeling in greater depth.

Computer Model: Rise Time Adjustment



- Realistic electrical pulses do not have sharp edges. The edges have a finite *RiseTime*
- *RiseTime* refers to the ratio 10% / 90% of amplitude values
- Typical value: RiseTime = 0.25 / BitRate
  Other values may be used where appropriate.

Computer Model: Laser Rate Equations

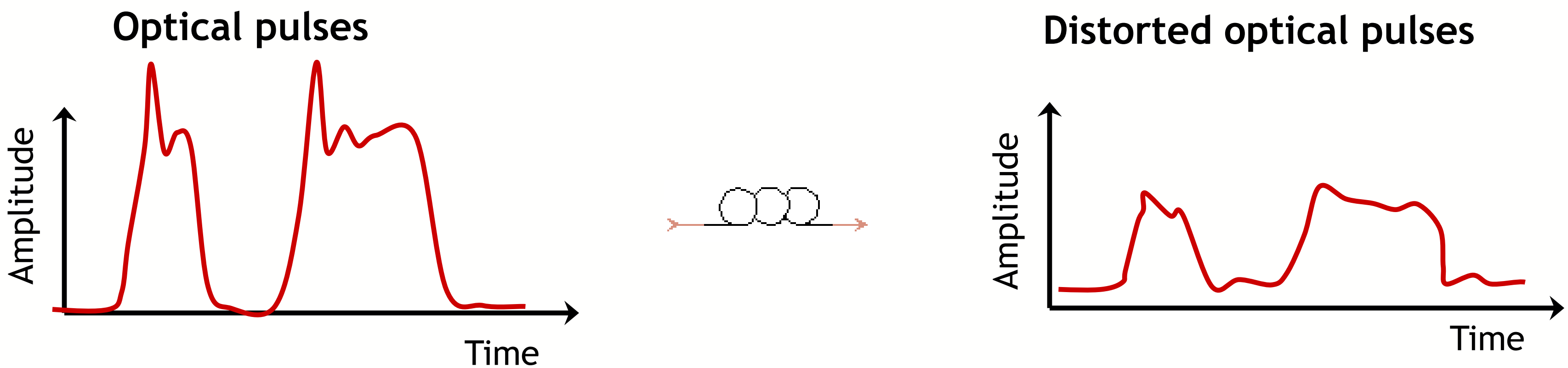


Electrical drive signal

Optical pulses

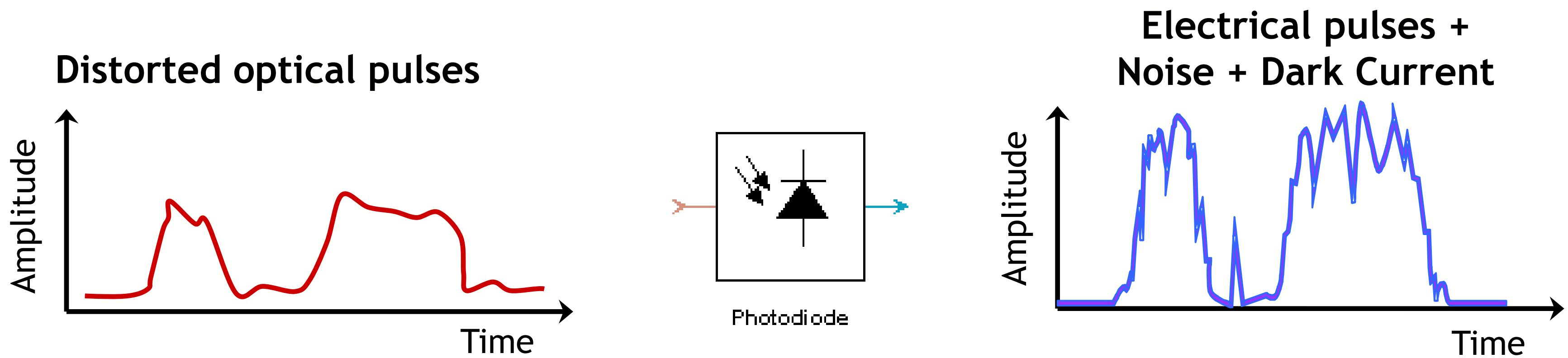
- Lasers are usually modeled using laser rate equations
- Time dynamics (like overshoots) and other detailed laser characteristics that can distort the optical pulses and add noise are taken into account
- These characteristics depend on material and geometric parameters of the laser (more on this in another module)

Computer Model: Optical Fiber



- Optical fiber propagation can be modeled using the Nonlinear Schrödinger (NLS) Equation
- The following effects, which distort optical pulses, are taken into account:
  - fiber loss (or attenuation)
  - first and second order Group Velocity Dispersion (GVD)
  - nonlinear effects (SPM, XPM, FWM, SRS)

Computer Model: PIN Diode



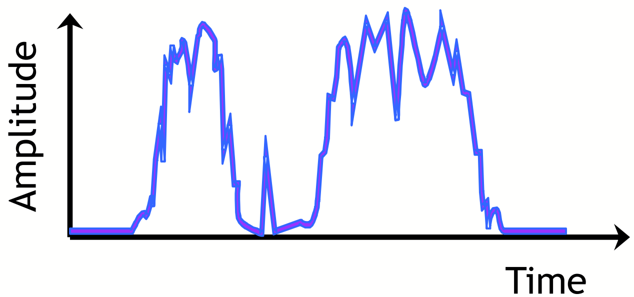
- Converts incident optical field into electrical signal
- Electrical signal is calculated by:

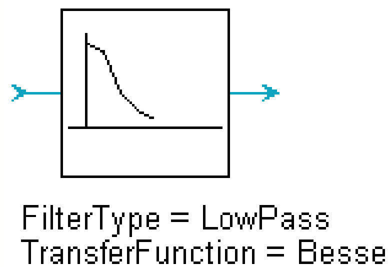
$$i(t) = i_s(t) + n_{sh}(t) + n_{th}(t) + i_d$$

Signal current Shot noise Thermal noise Dark current

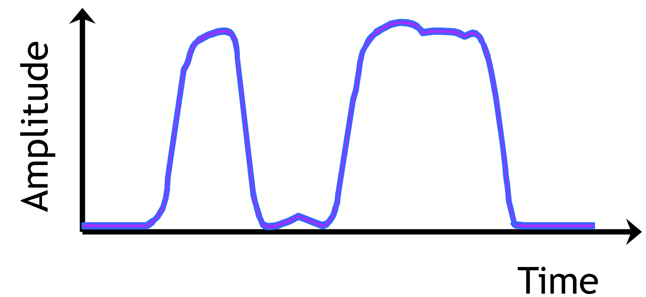
Computer Model: Electrical Filter

Noisy electrical pulses





Filtered electrical pulses

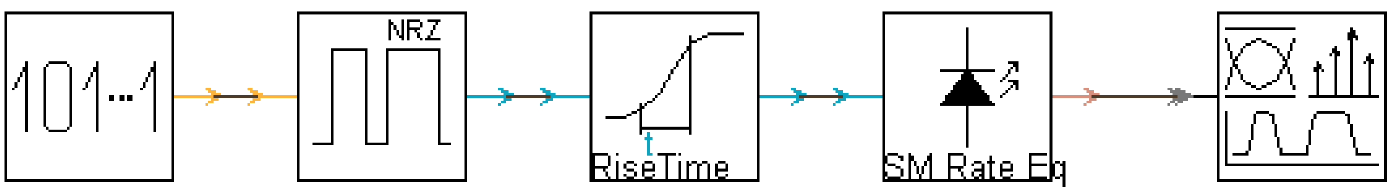


- In this case represents an analog Bessel low pass filter
- Main parameters: CutoffFrequency, FilterOrder
- Typical application: noise suppression after photodiode
- Generally, further processing of the electrical pulses is required to recover the original binary data bit stream

The Transmitter

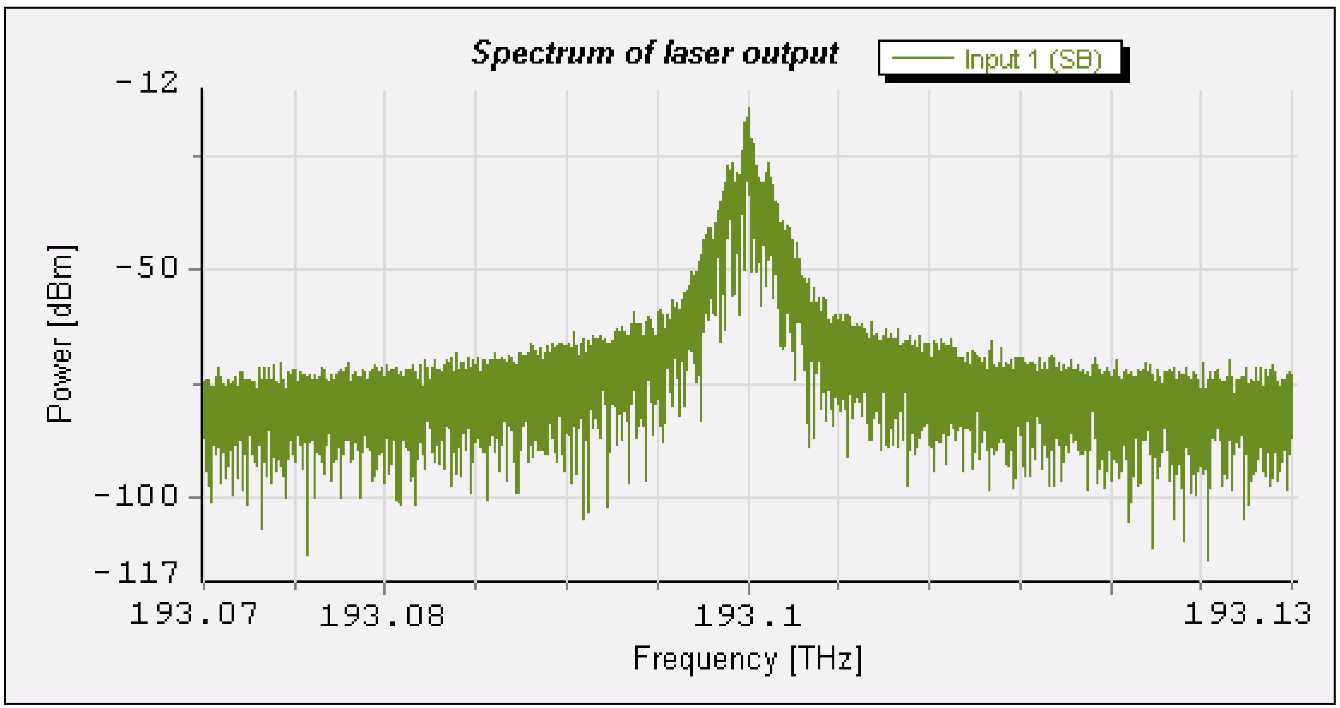
Once ***VPItransmissionMaker***^{TM} *Optical Systems* has started and you are in the correct project directory, click and drag the setup FOC1_1 into the work space.

- A schematic of the transmitter section of the fiber-optic transmission link appears. It consists of a PRBS generator, a Non-Return to Zero (NRZ) coder, a rise time adjuster and a laser (see below).
- A *SignalAnalyzer* is connected to the output of the laser so the optical spectrum of the laser can be seen in the *VPIphotonicsAnalyzer*.



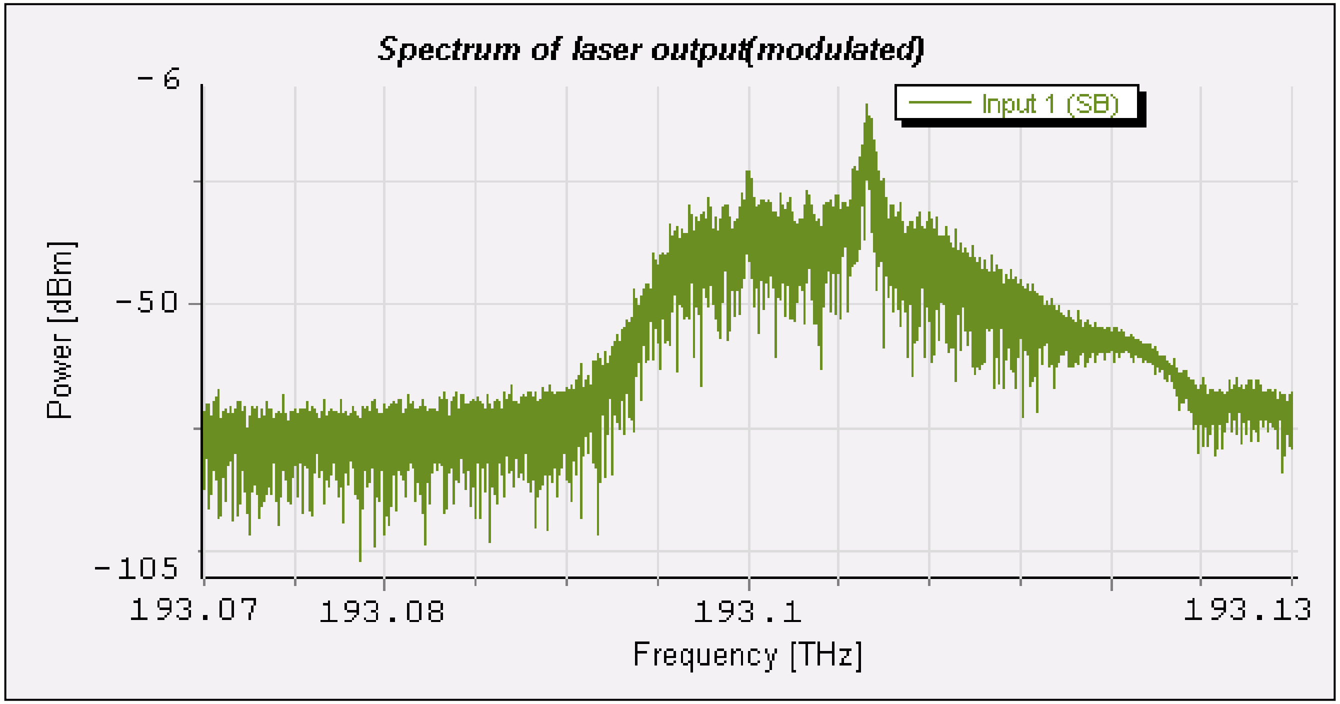
The Transmitter

- The PRBS in the setup is currently set to produce a string of ‘0’s. The laser is biased so that it operates in the linear regime.
- Run the setup as it is. The spectrum of the laser output is generated (see below). Since the PRBS is generating a string of ‘0’s, the laser is unmodulated.



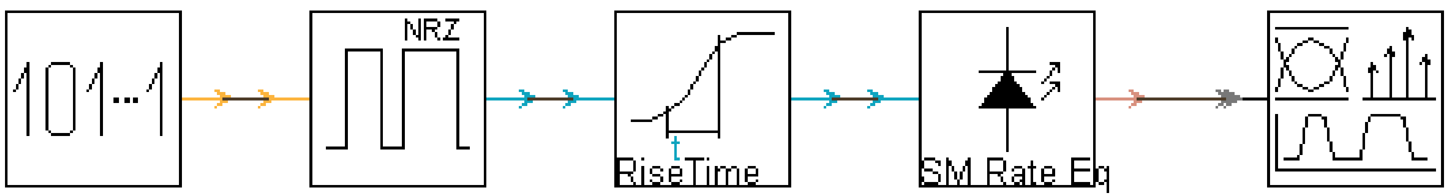
The Transmitter

- Double-click on the icon of the ***PRBS***, and modify its parameter ***PRBS_Type*** from '**Zero**' to '**PRBS**', and run the modified setup.
- With the ***PRBS*** generating a string of random '0's and '1's, the laser is now modulated.
- **Question 1**: What is the difference between this and the unmodulated laser spectrum?



The Transmitter

- The *SignalAnalyzer* **(OSA)** is a frequency domain analyzer that is used to examine the frequency content of a signal. The signal may also be examined in the time domain, by using a *SignalAnalyzer* **(Scope)**.
- Close the current setup. Open the setup FOC1_2. The setup that appears is exactly the same as the previous setup.

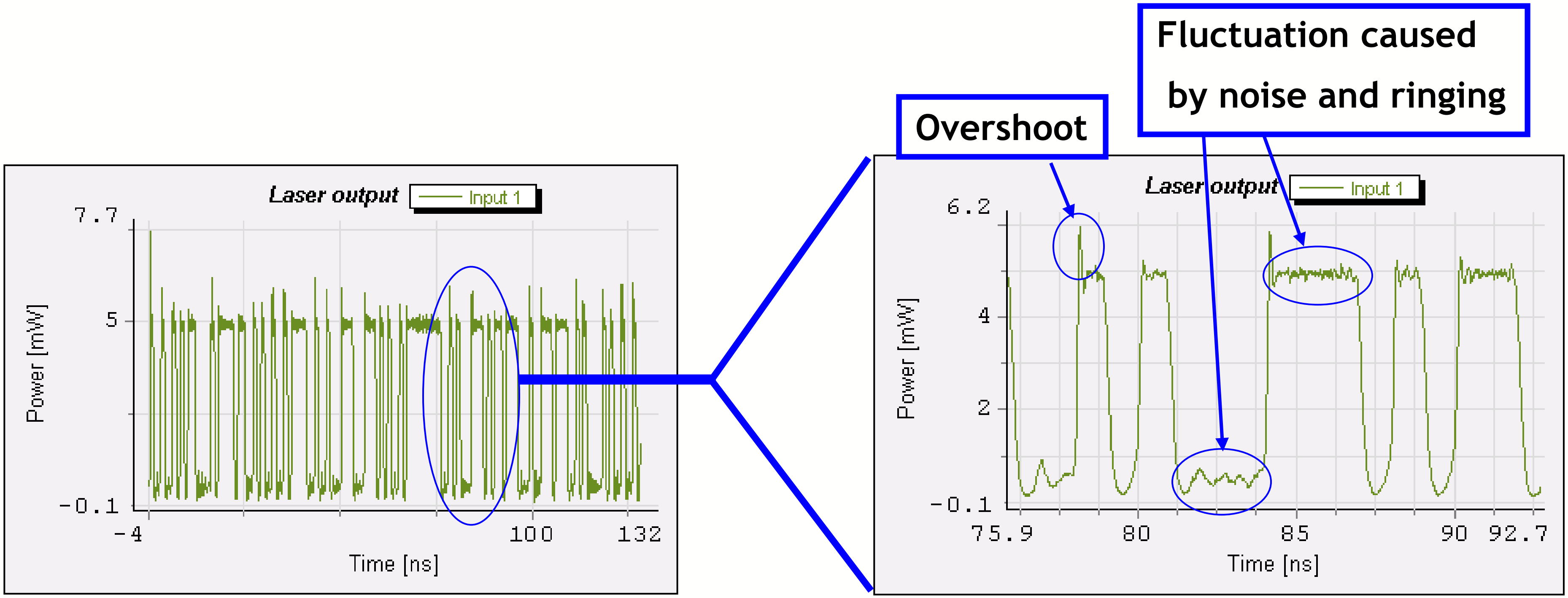


- Run the setup. A scope trace* in the time domain appears, showing the optical waveform produced by the laser.

* Note that in real scopes, any optical waveform that is displayed has to be converted into an electrical waveform by a photodetector first.

The Transmitter

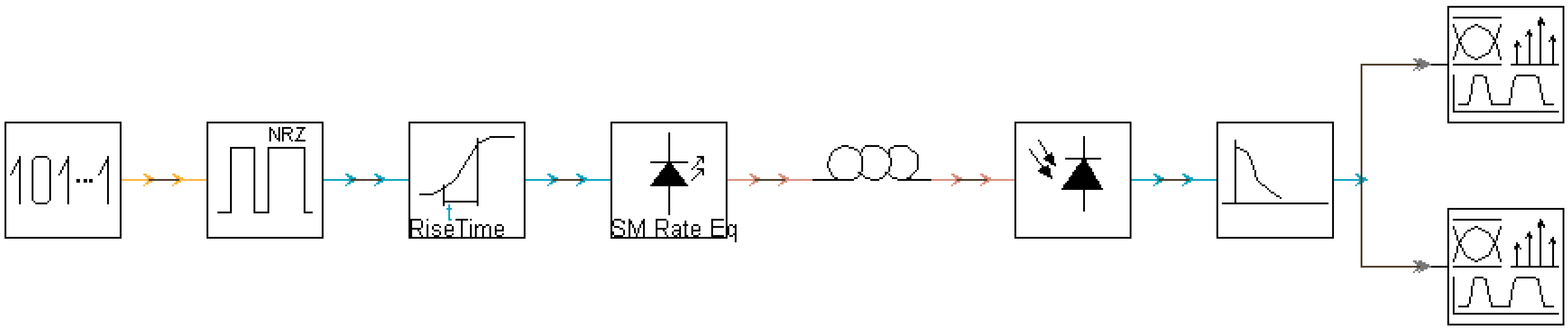
- Play around with the various features of the scope (e.g. rescaling the axes, magnifying a portion of the trace, etc).
- **Question 2**: From the scope trace of the laser output, can you estimate the speed of the optical signal? The speed of a signal is given by the number of bits per second.



The Complete Fiber-Optic Link

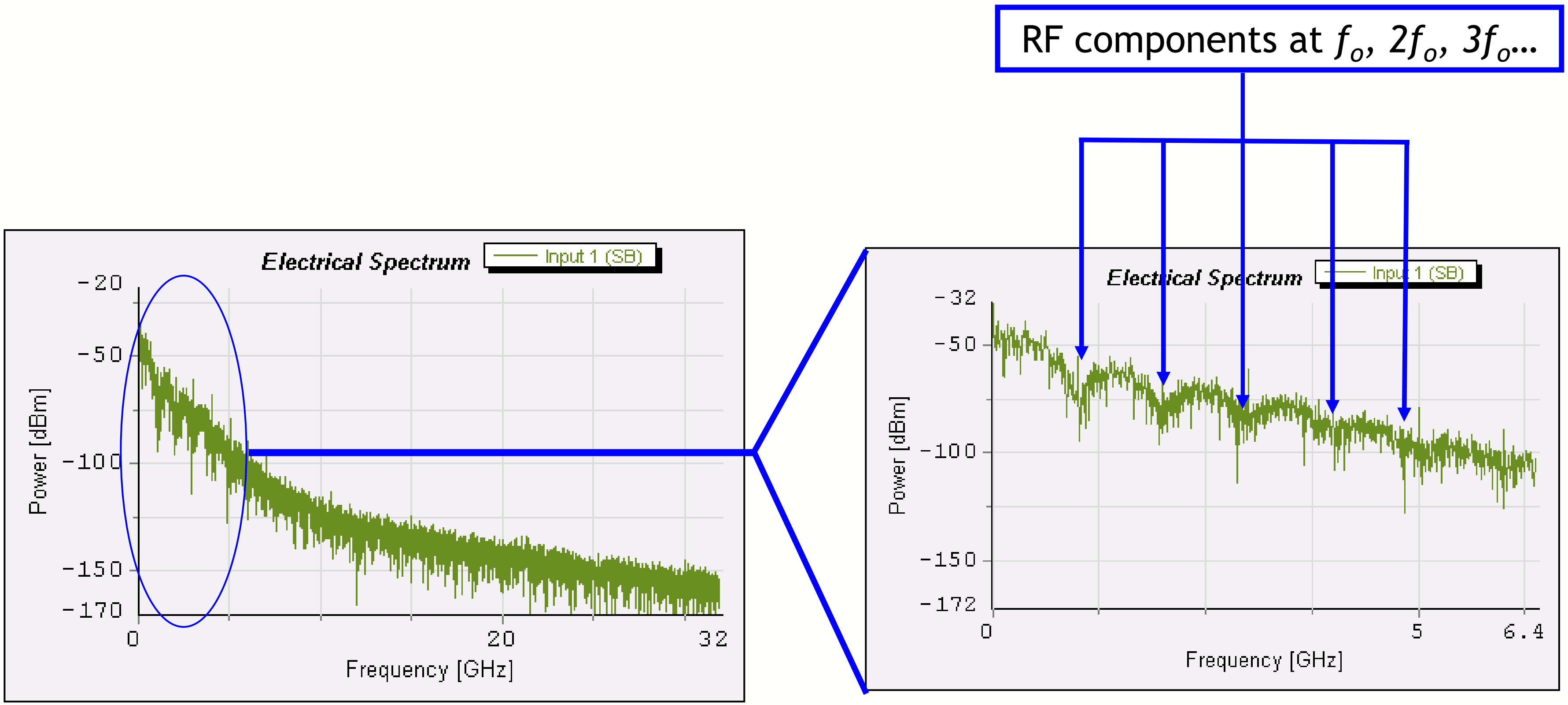
- Close the current setup and open the setup FOC1_3.
- A schematic of the complete fiber-optic link appears.
- The transmitter section of the setup is the same as the previous setups. The output of the laser is now connected to a 10 km length of optical fiber, then a PIN photodetector followed by a electrical low pass (LP) filter. The detected signal is displayed in two *SignalAnalyzers* (in **Scope** and **RFSA*** mode).

*Radio-Frequency Spectrum Analyzer



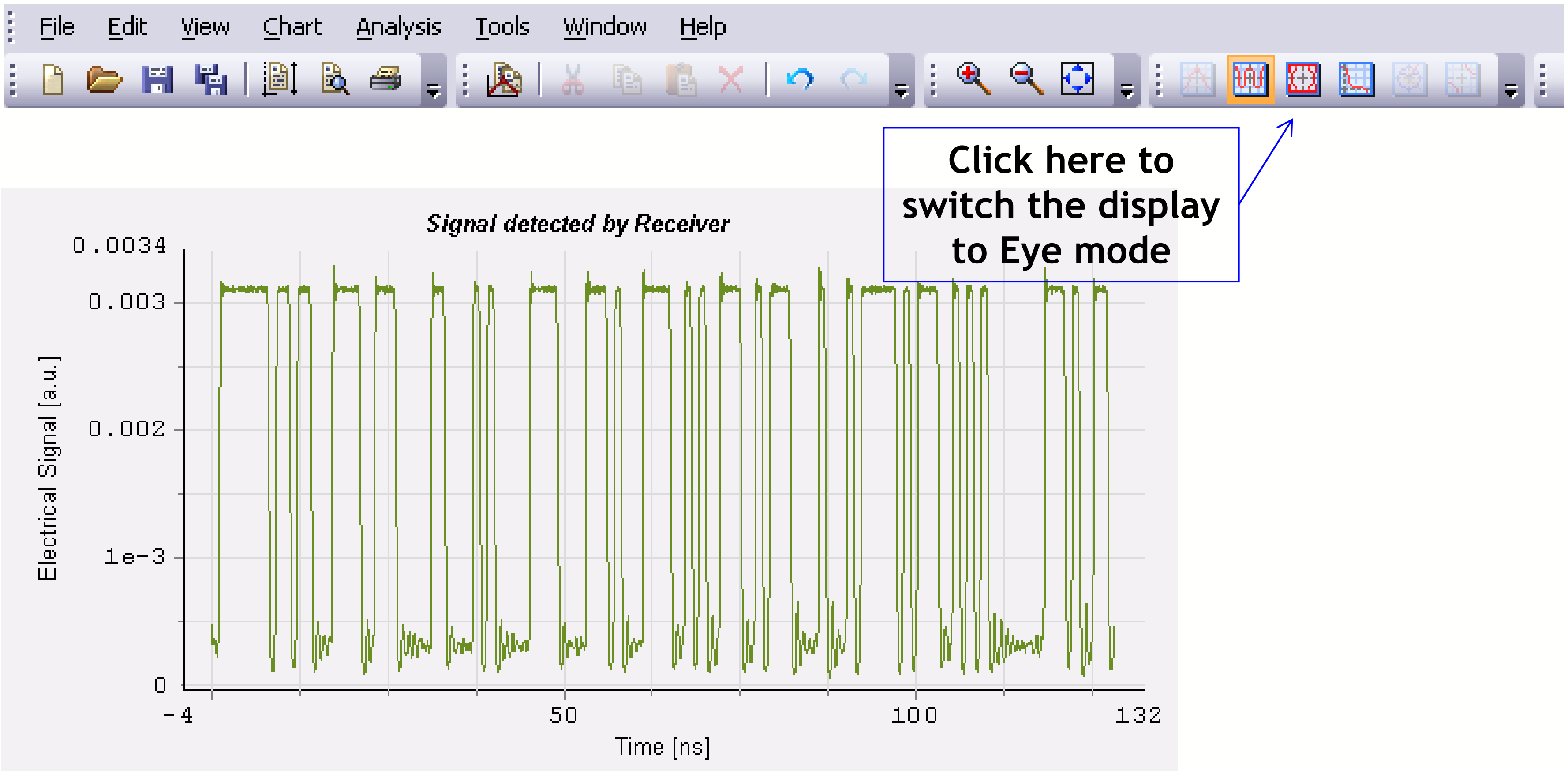
The Complete Fiber-Optic Link

- Run the setup FOC1_3 as it is. When the simulation is finished, two analyzer windows open to display the received electrical signal in the frequency domain (shown below) and the time domain (next page).



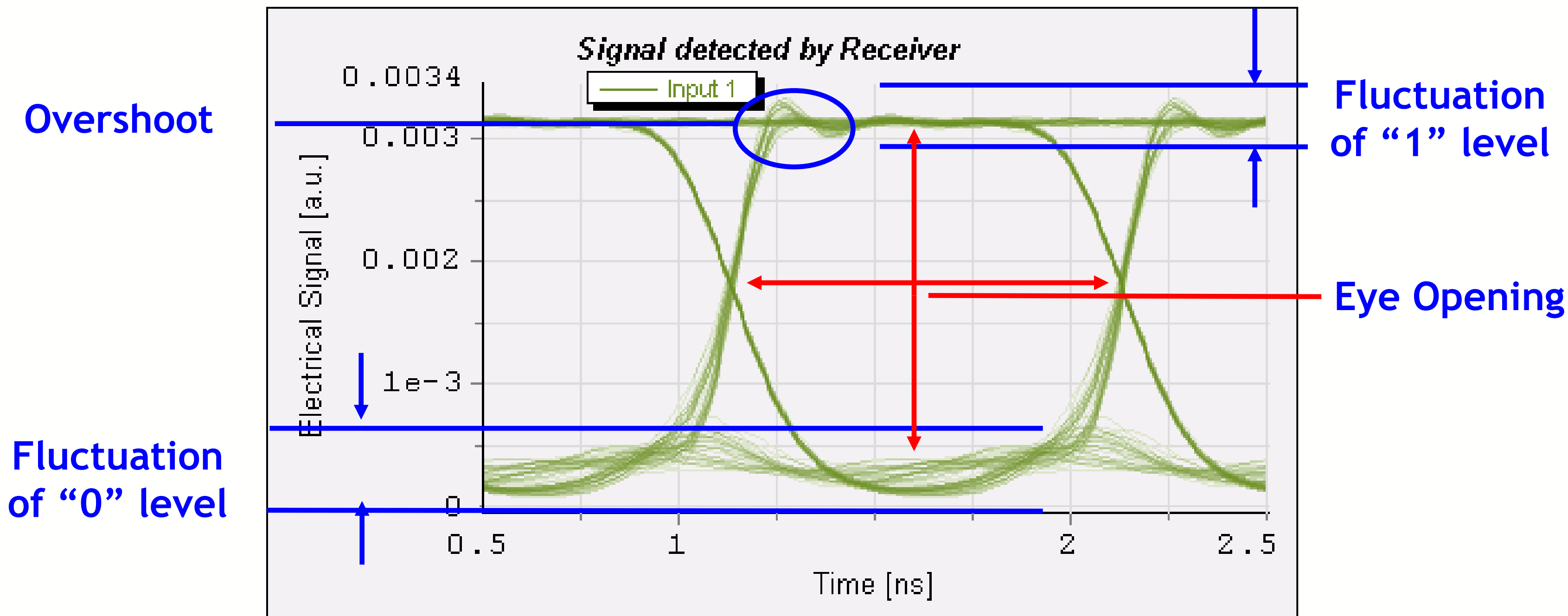
The Complete Fiber-Optic Link

- When analyzing the waveforms of a signal, it is useful to overlap the received pulses. The resultant diagram is known as an Eye diagram.
- Click the Eye mode button and the maximize display button (as shown below).



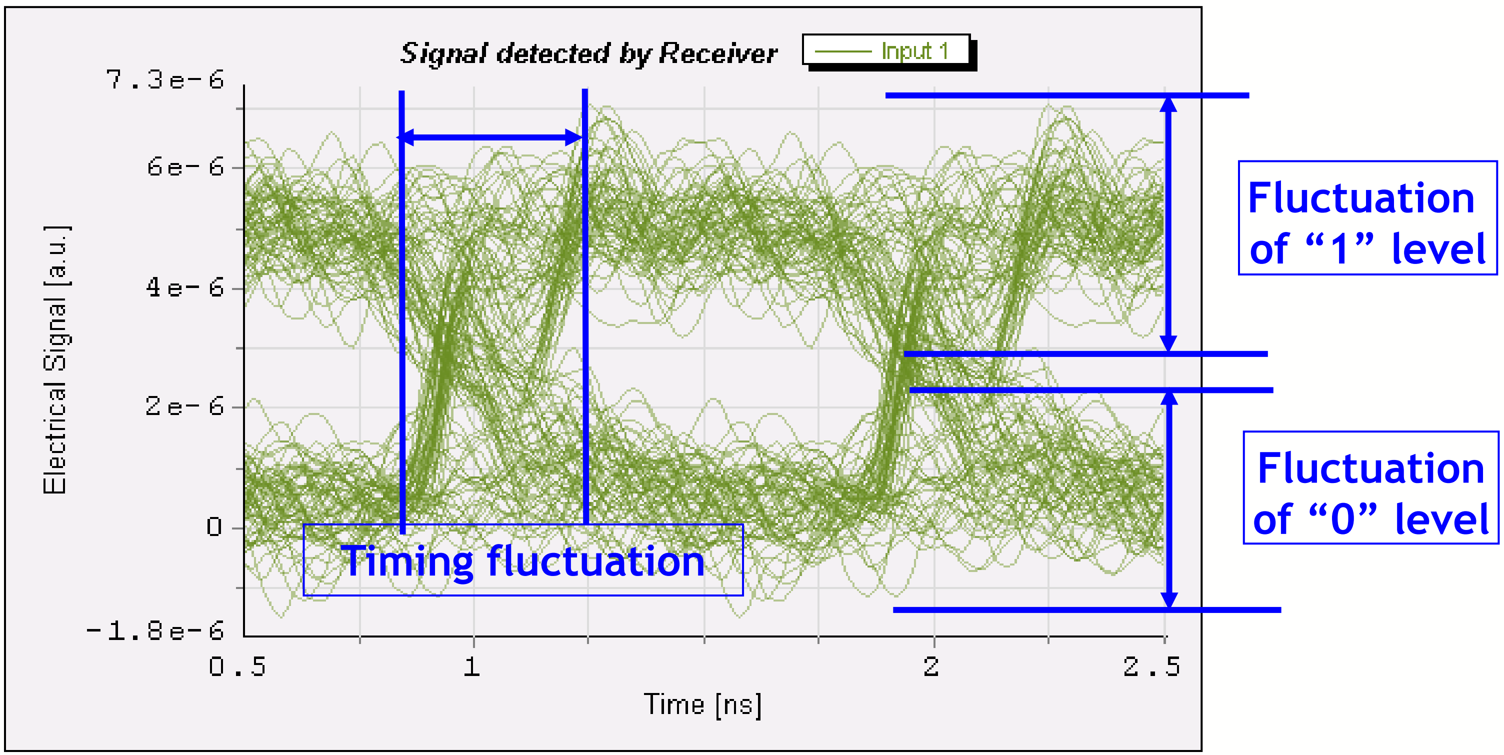
Eye Diagrams

- The Eye diagram is a useful tool for visualizing the performance of communication systems. The maximized Eye diagram of the received pulses is shown below.
- The Eye below is wide open. This shows that the digital '1' and '0' levels of the received bits are easy to distinguish, and implying a very good quality received signal. The other features of the Eye diagram also tell us something about the signal (and thus the system), as we shall see later.



Eye Diagrams

- Double-click on the fiber icon in the schematic, and modify its parameter *Length* from actual **10.0e3** (10km) to **150.0e3** (150 km). Run the modified setup, and display the Eye diagram.
- The Eye shown below indicates that the received pulses are severely distorted compared to the previous simulation. The deterioration is caused by higher optical attenuation experienced by the pulses propagating over the longer fiber.



Eye Diagrams

- Note that the received optical power is significantly smaller (by about three orders of magnitude). As a result, the thermal noise in the detector has a more severe effect on the weaker received signal pulses.
- This is reflected by the fuzziness of the Eye diagram in the previous page, as the digital ‘1’ and ‘0’ level are corrupted by receiver noise. Such an Eye diagram is said to be ‘closed’, and indicates a received signal of a poor quality.
- A fiber-optic communication system in this state is said to be ‘loss-limited’.

Bit Error Ratio (BER)

The Eye diagram introduced previously provides an immediate, graphical/visual feel for the performance of the system.

A more objective measure of the performance of a system is the Bit Error Ratio (BER) (also known as Bit Error Rate). This is the number of bits detected incorrectly (i.e. bit errors) over a certain time interval, divided by the total number of bits transmitted during the same time interval.

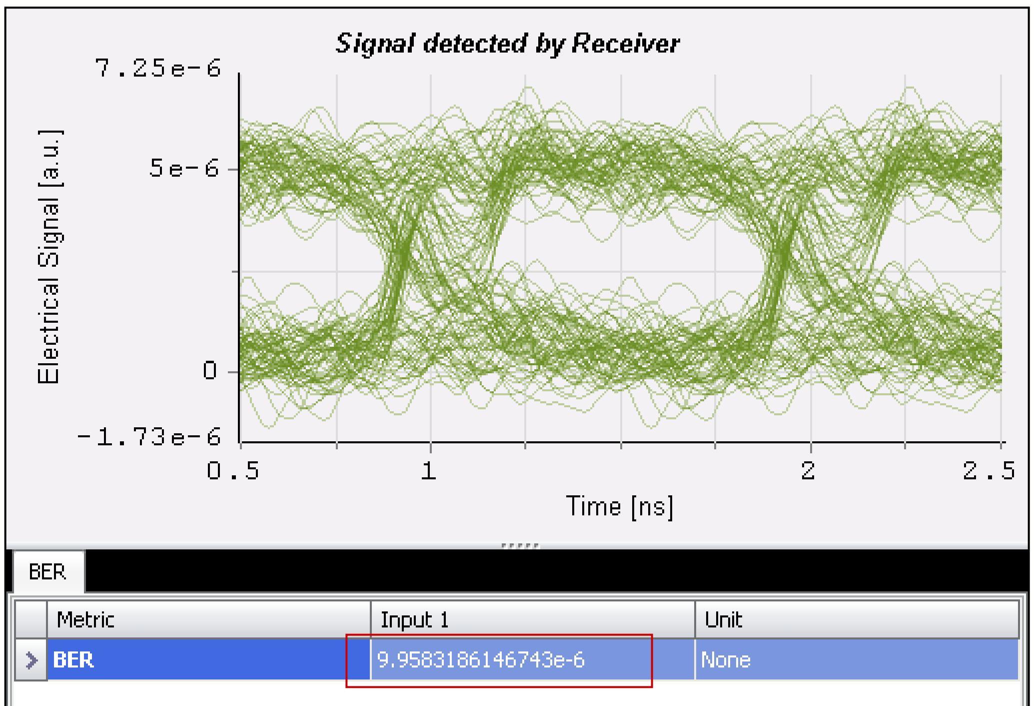
The scope used to display the received pulses as an eye diagram has a built-in function that can estimate the BER. It works by making certain statistical assumptions about the distribution of the digital '1' and '0' levels of the pulses in the received signal. The theory of BER estimation will be covered in greater detail in another module.

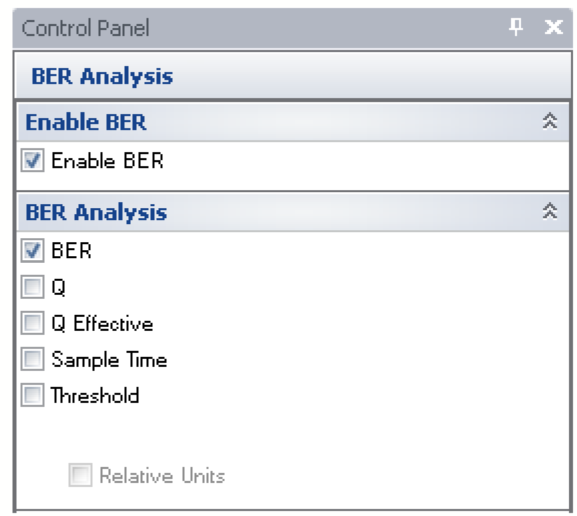
Determine the BER of the signal in the Eye diagram that was shown in the previous page.

- Click in the menu on **Control Panel,** look for **BER Analysis** and box mark **Enable BER** and **BER**.

Estimating BER from an Eye Diagram

- The estimated BER is displayed below the Eye diagram. It is found to be of the order 10^{-6}, which is not satisfactory in practical fiber-optic communication systems (should be below 10^{-9} for systems without Forward Error Correction (FEC)).





Introduction to Fiber-Optics Communications II
FOC 2

Interactive learning module

University Program
Photonics Curriculum Version 8.0

Preface

In this module, a simple but complete fiber-optic transmission link will be studied. The setup consists of the three basic elements common to all fiber-optic communication systems:

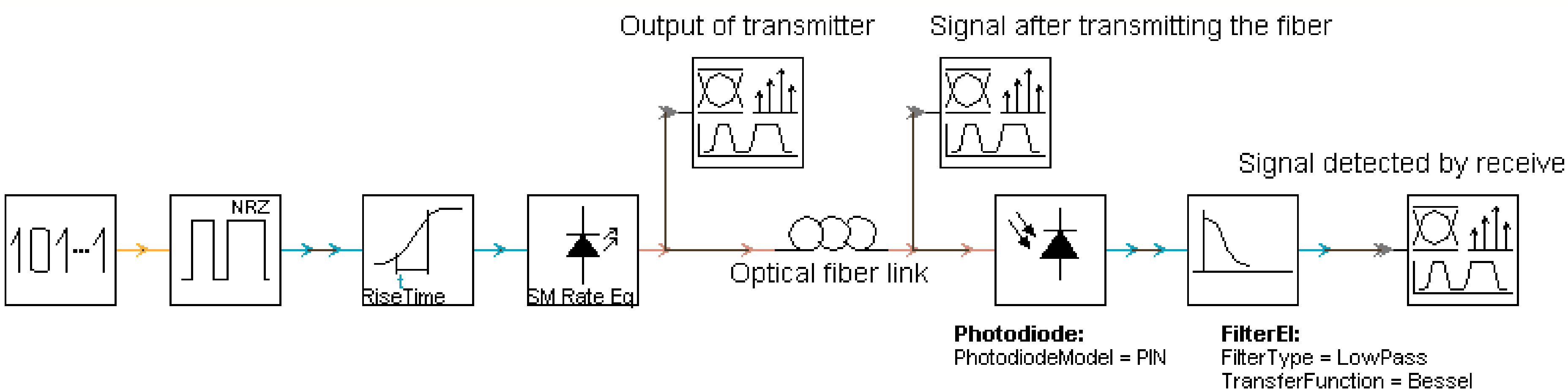
- An *optical transmitter* converts an electrical signal into optical pulses. In the simulation setup, a single longitudinal mode semiconductor laser is directly modulated with a pseudo random bit sequence (PRBS).
- The optical pulses are transmitted over the *fiber-optic channel*, which in this case consists of one section of optical fiber.
- The transmitted pulse stream is converted back into the electrical domain by the *optical receiver*. In the system under consideration, it consists of a photodetector followed by an electrical filter to enhance the signal quality. *SignalAnalyzer* (Time and frequency) are used to evaluate the simulation results.

Note:
For details on the handling of VPItransmissionMaker / VPIcomponentMaker please read the *Simulation Guide* before starting this unit.

Limitation of transmission length

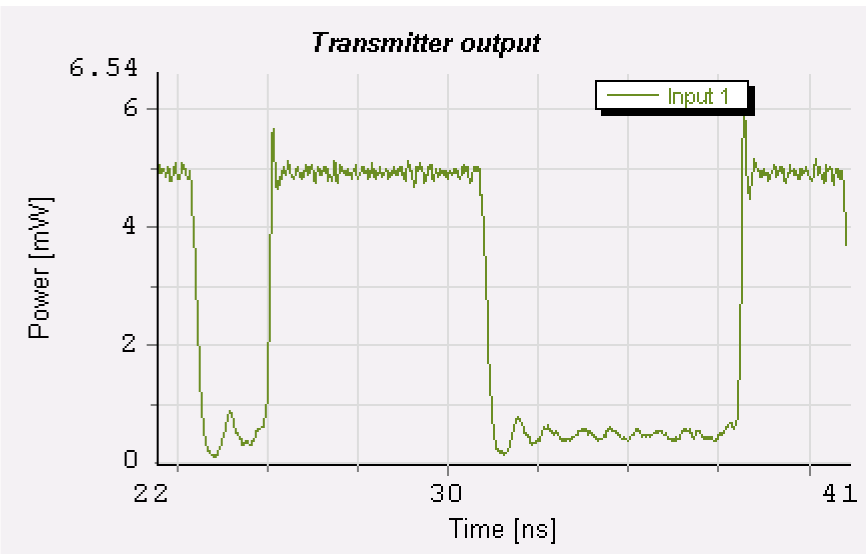
Open the setup FOC2_1.

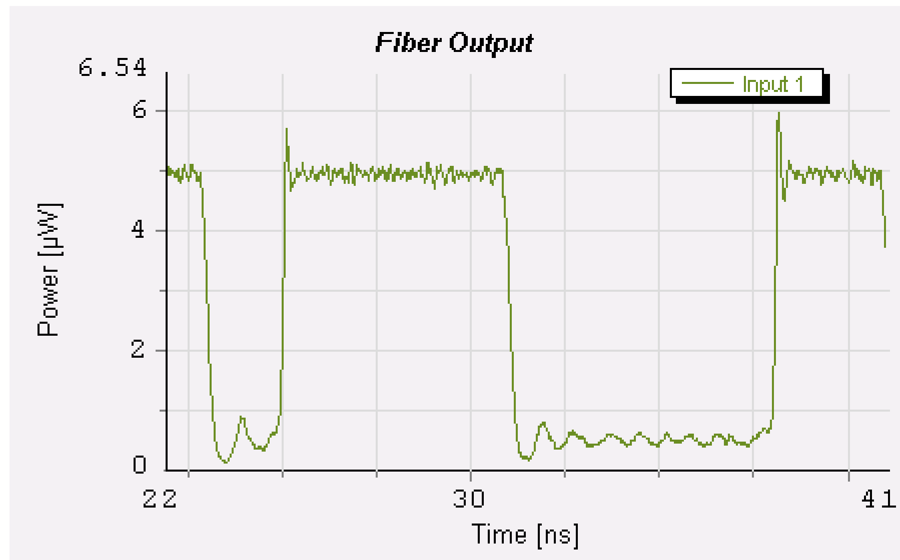
- A schematic of the complete fiber-optic link appears, as shown below.
- The transmitter and receiver sections of the setup are the same as in module FOC1. However, the length of the optical fiber has been set to 150 km.
- The parameters of the optical fiber have also been modified so that the effects of fiber dispersion and nonlinearities are turned off. Thus, optical signal pulses propagating through the fiber are affected only by fiber attenuation.
- *SignalAnalyzer* modules are placed at the output of the transmitter, the input to the photo detector and at the output of the receiver.



Fiber Attenuation

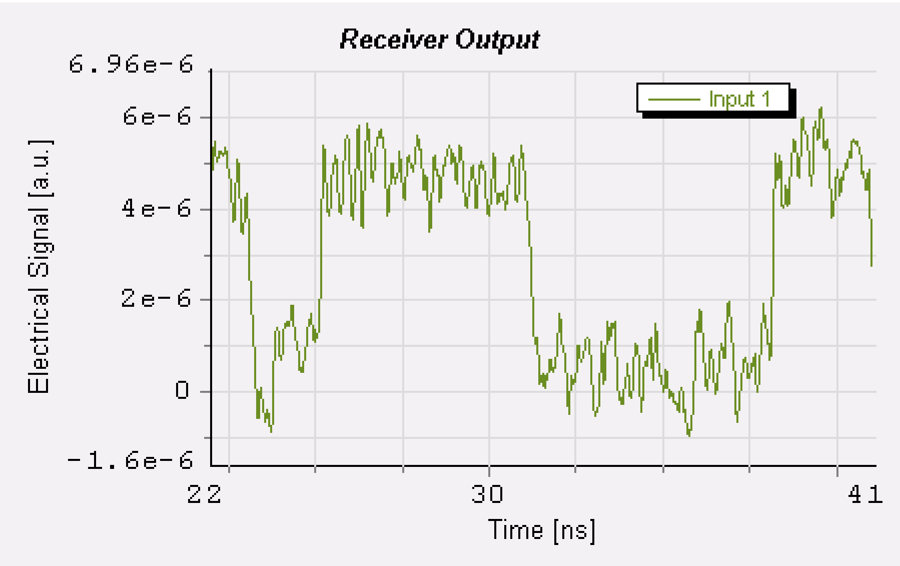
- Run the setup FOC2_1 as it is.
- Three scope traces appear. They should look like those shown below and on the next page.
- **Question 1**: What is the difference between the two scope traces shown below?

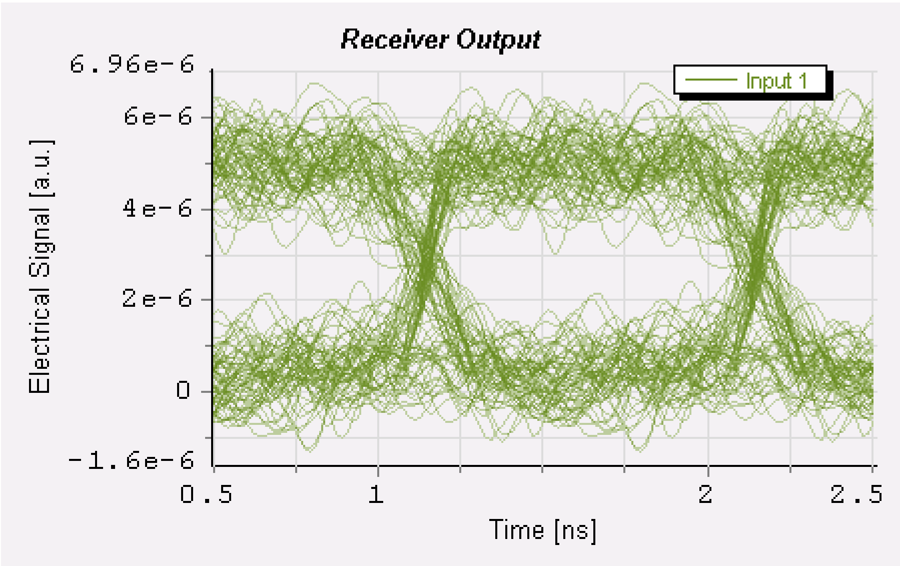




Fiber Attenuation

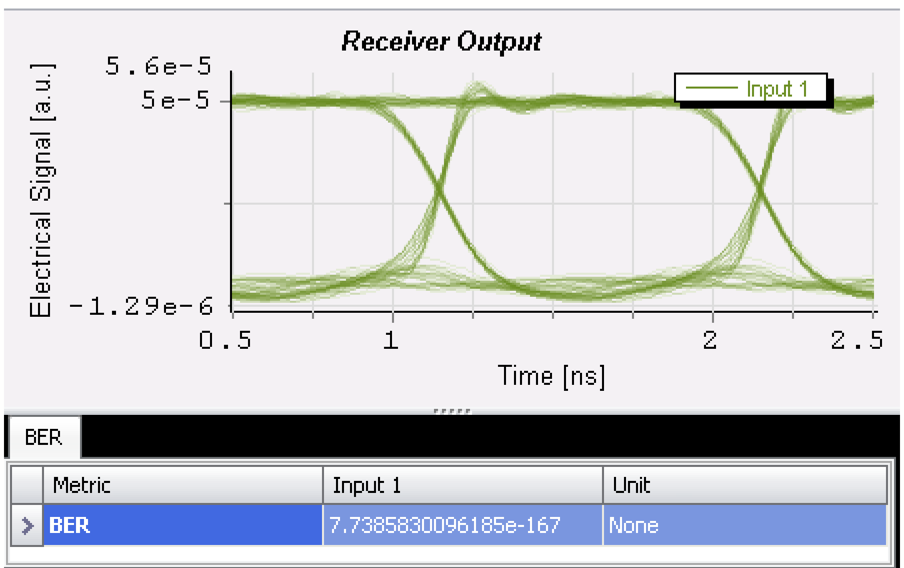
- Shown below are the scope traces of the electrical signal detected by the receiver, and the associated eye diagram. To switch to Eye mode, select **Eye** in the **Analysis** menu or click the eye toolbar button.
- **Question 2**: Why is the electrical signal so severely distorted, given that the optical signal arriving at the receiver is virtually undistorted?

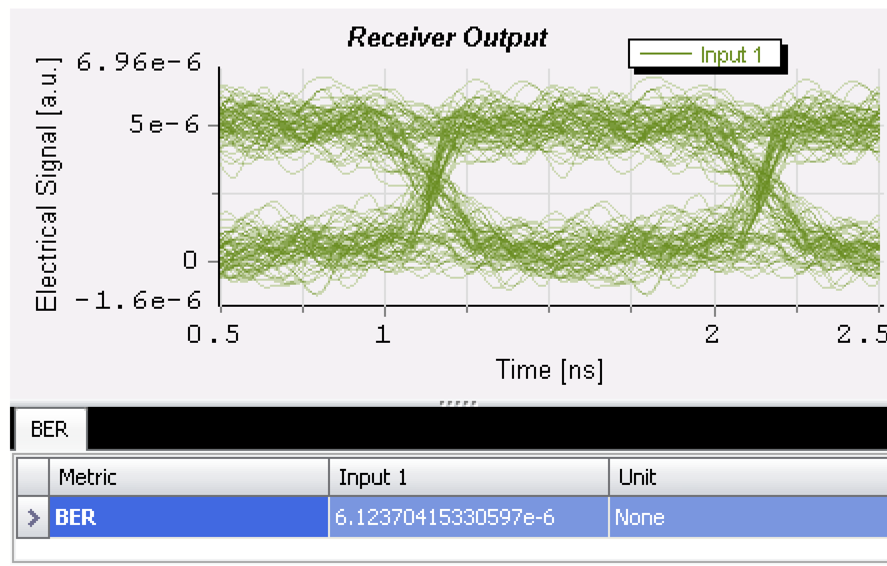




Loss Limited System

- *Set the FiberNLS—Length* = 100.0e3. Rerun, and obtain the eye diagram of the received electrical signal (shown below in the figure on the left). Use the **BER Analysis** of the **Control Panel** to estimate the BER.
- Repeat the step above, increasing the fiber length by 10 km each time, until the fiber length is 150 km. Make a plot of the BER vs fiber length (transmission distance).
- **Question 3**: What is the transmission distance at which the system becomes loss limited? Assume that the maximum acceptable BER for the system is 10^{-9}.
  Hint: use the plot of BER vs fiber length that you obtained above.

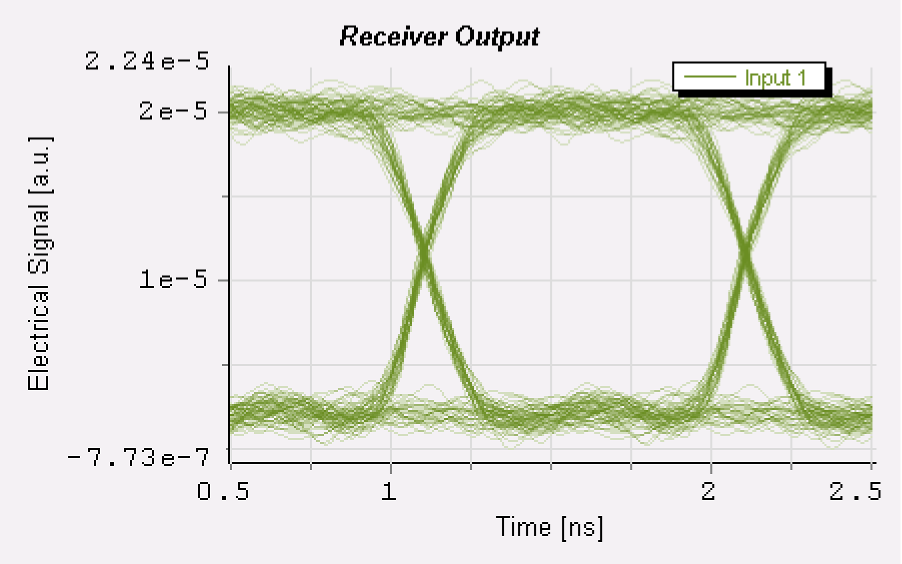




Fiber length = 100 km

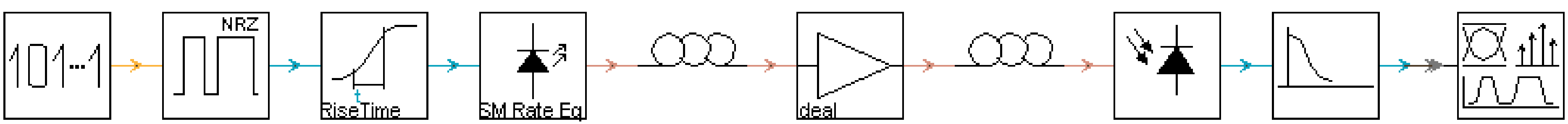
Loss Limited System: Solution 1

- To overcome the loss limit, a simple solution is to increase the output power of the transmitter.
- Change the parameter *LaserRateEqSM*—***PowerNorm*** from 5.0e-3 W to 20.0 e-3 W. Make sure that the fiber length is set to 150 km, and then rerun the simulation. The resultant eye diagram is shown below.
- **Question 4**: Can we arbitrarily increase the transmission distance of the system by simply increasing the transmitter output power? If not, why not?



Loss Limited System: Solution 2

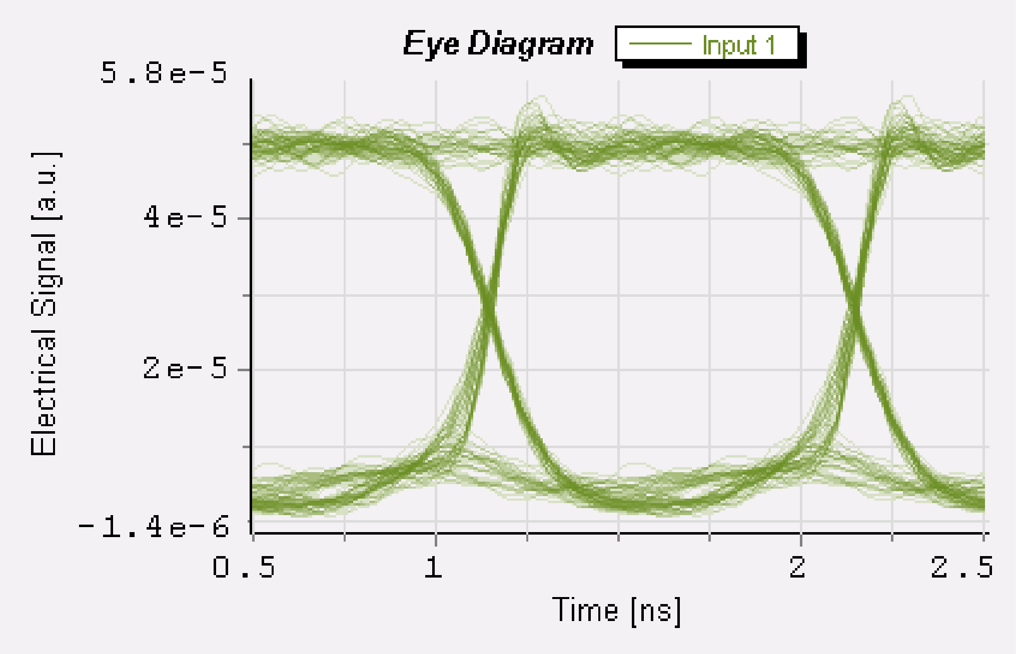
- Another method for compensating the fiber attenuation is to use an optical amplifier (such as an Erbium-Doped Fiber Amplifier, EDFA) to boost the power of transmitted optical signal. The schematic FOC2_2 of such a system is shown below.
- Although fiber attenuation can be fully compensated by putting optical amplifiers in an optical fiber link, the cost of transmission will increase, depending on the number of optical amplifiers used. One design issue is to find the optimum number of amplifiers needed to compensate for fiber attenuation over a given transmission distance, while maintaining the required BER performance (usually 10^{-9} or less).



FilterEl:
FilterType = LowPass
TransferFunction = Bessel

Loss Limited System: Solution 2

- Run FOC2_2. In this case the amplifier is at the end of the fiber increasing the optical power just before the photodiode in what is known as pre amplification. Although in the schematic there is a fiber after the amplifier this is setup to have 0 km (check its characteristics). The eye diagram for the signal after 150 km of transmission is shown below. There is definite improvement in this case, compared to the case (shown earlier) where no optical amplifier was used.

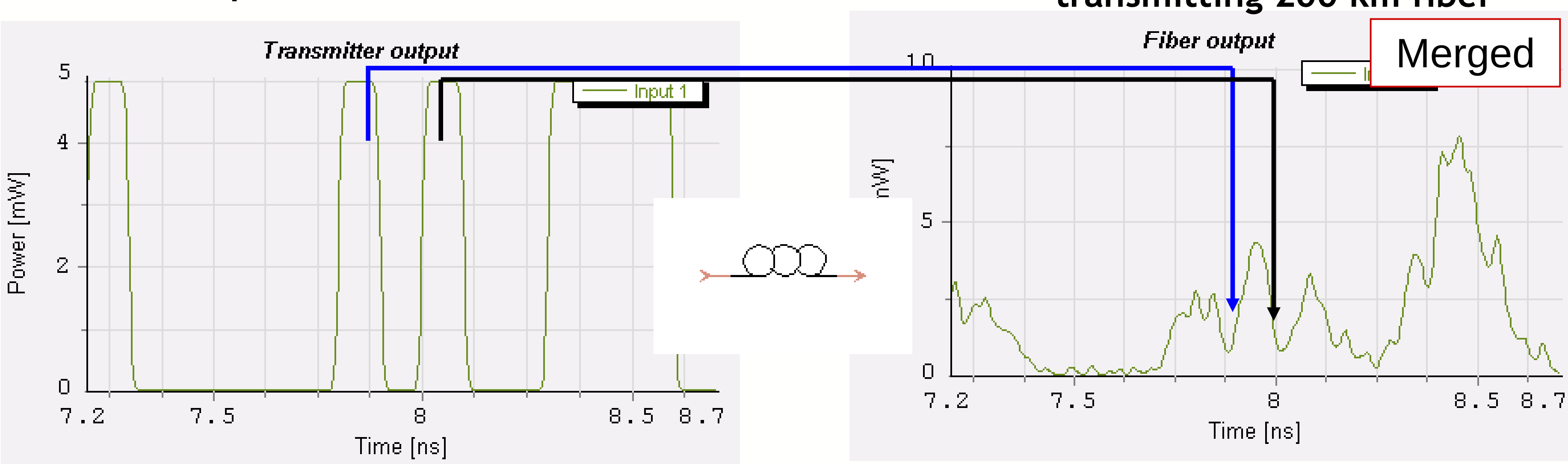


Fiber Dispersion

- Open FOC2_3. Turn the fiber attenuation off (set *FiberNLS*-***Attenuation*** to 0) and set *FiberNLS*-***Length*** to 200e3 m. Run the simulation.
- The signal at the output of transmitter and after 200 km of transmission through a standard single mode fiber (SMF) are shown below on the left and right respectively.
- Fiber group velocity dispersion (GVD) causes the pulse to spread during transmission. After 200 km, the pulses have broadened, and the two pulses (highlighted in the middle of diagram) have merged together. So the “0” in the middle of those two pulses will be erroneously detected as “1”, leading to increased bit errors.

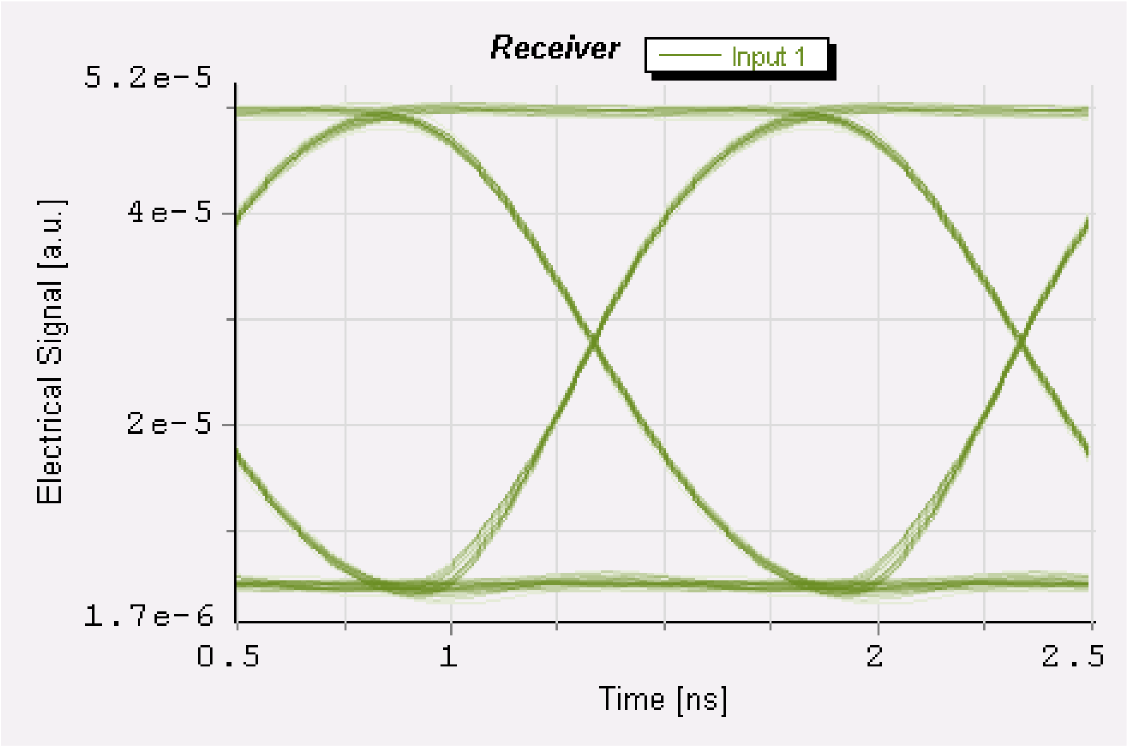
Output of transmitter

Optical signal after transmitting 200 km fiber



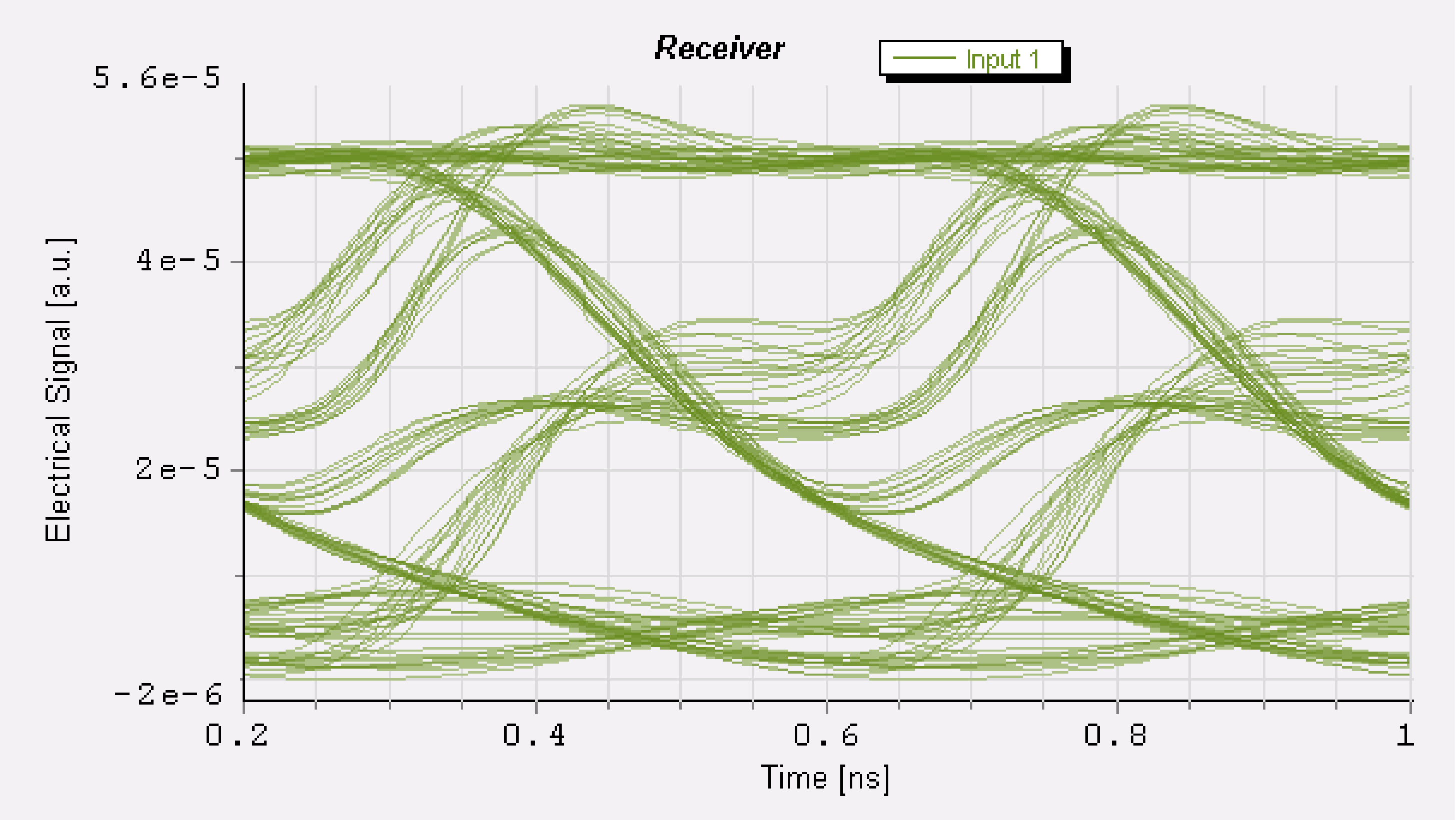
Bit rate limitation due to Dispersion

- To study the limitation of the transmitted bit rate due to dispersion, we start with FOC2_4. The bit rate of the system in that schematic has been set to 1 Gbit/s.
- Run the simulation. Press the **eye-**button in the toolbar of the VPIphotonicsAnalyzer window for the *SignalAnalyzer* after the electrical filter. The eye diagram is shown below, and the eye is wide open, indicating almost error free transmission.



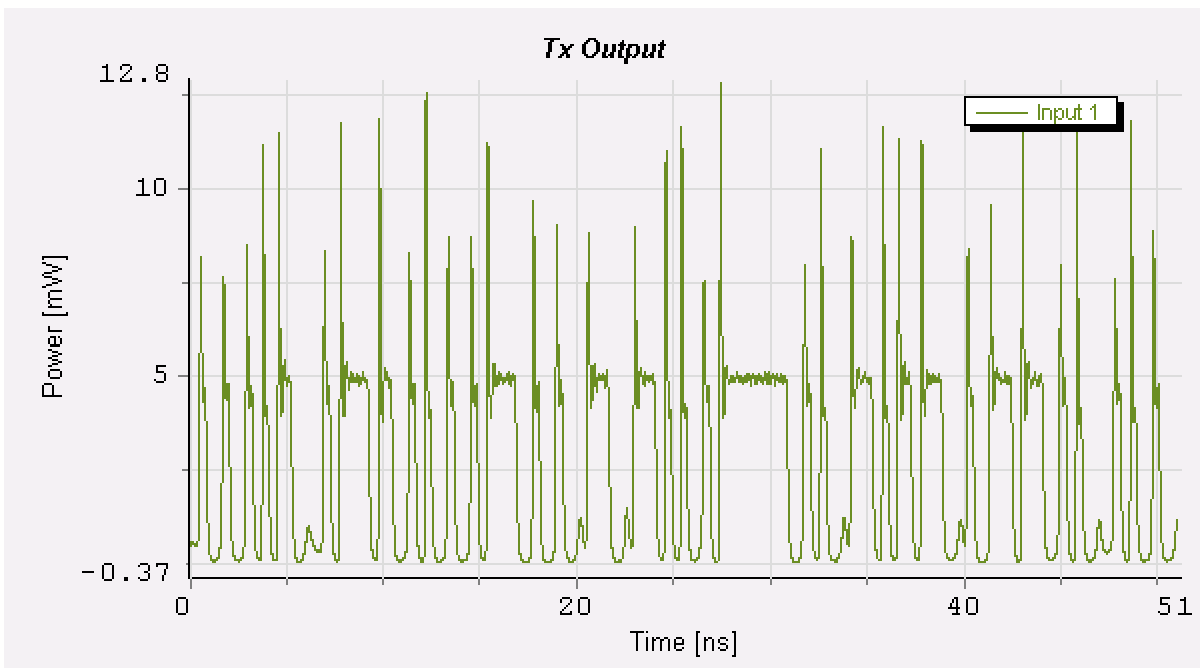
Bit rate limitation due to Dispersion

- Next, open FOC2_5. This is the same system as before, but now the bit rate is increased to 2.5 Gbit/s and fiber length reduced to 100 km. The resulting eye diagram is shown below.
- The received pulses are distorted, leading to a closing of the eye and the BER of the system has increased above the acceptable level of 10^{-9}.



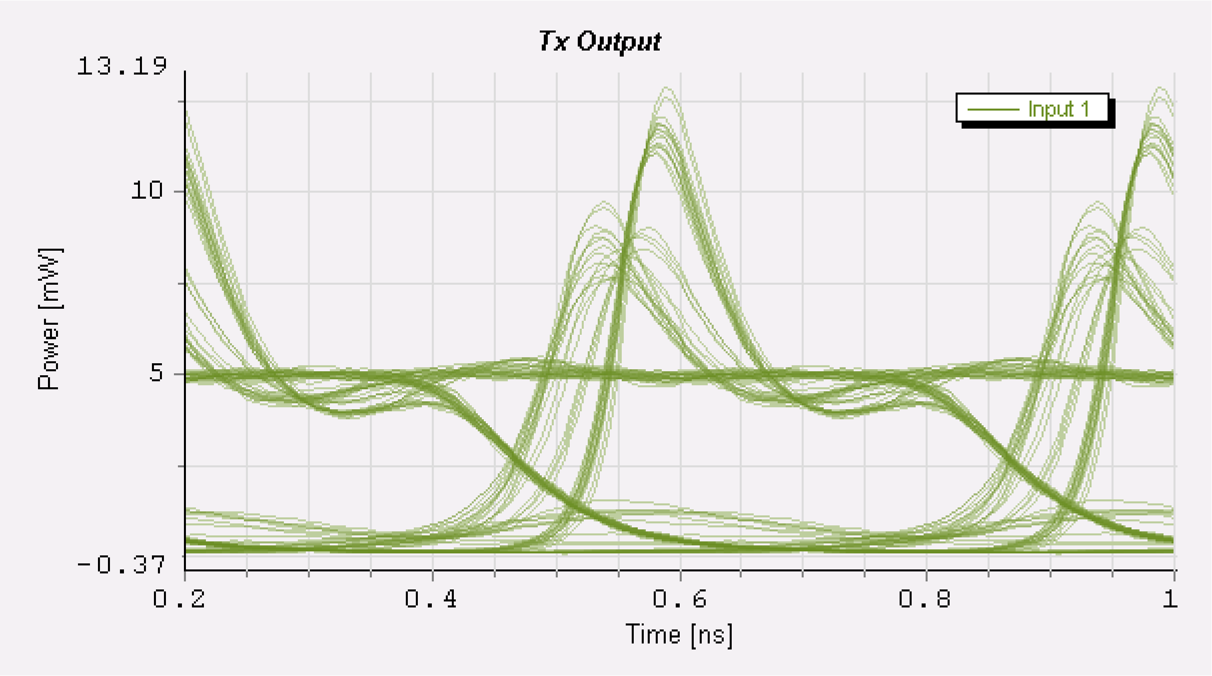
Bit rate limitation due to Dispersion

- To find the cause of the distortion, we first look at the output of the transmitter in the schematic of FOC2_5 to make sure that the pulses are generated properly.
- The *SignalAnalyzer* **(Scope)**, affixed to the transmitter, reveals that the optical pulses are generated with considerable initial overshoot near the leading edge. This effect is caused by relaxation oscillations, and is typical in directly-modulated lasers (which will be studied in greater detail in another module).



Bit rate limitation due to Dispersion

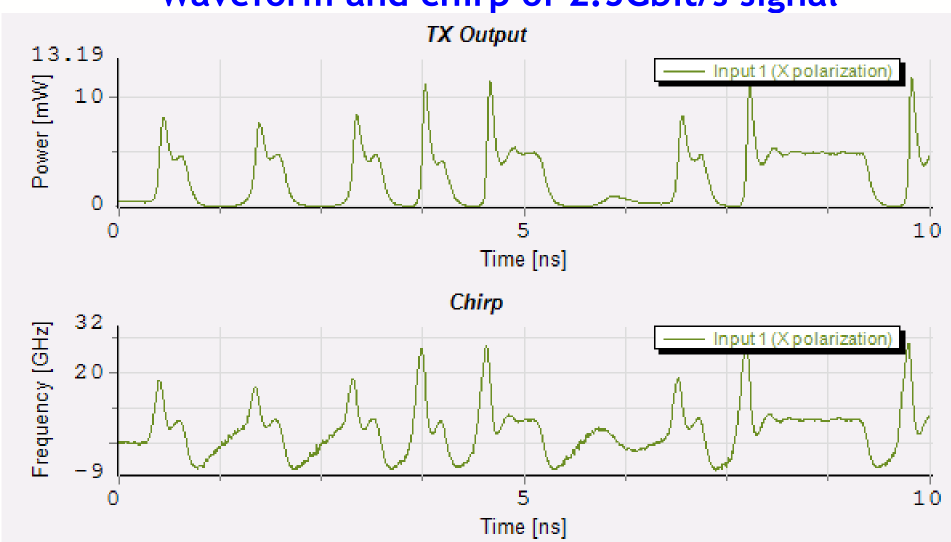
- Press the **eye**-button in the toolbar of the VPIphotonicsAnalyzer window for the *SignalAnalyzer* corresponding to the output of the transmitter.
- The evaluation of the eye-diagram shows that the optical pulses still produce a fairly wide open eye, despite the overshoots. Thus, the observed degradation of the pulses at the receiver must be caused by something else.



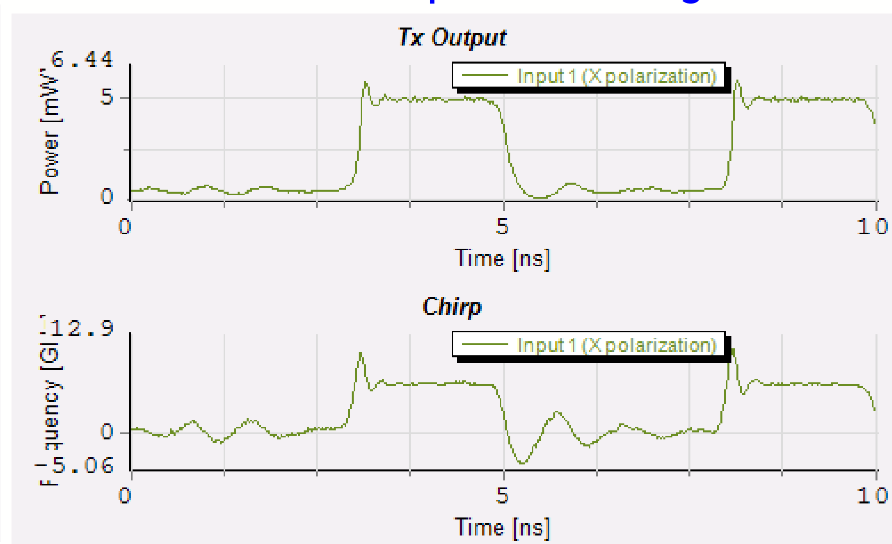
Bit rate limitation due to Dispersion

- Display the signal frequency chirp at the transmitter output for FOC2_5 and FOC2_4. For this, click on the transmitter window in the VPIphotonicsAnalyzer (it should be in **Scope** mode) and select the *X polarization* in the **Control Panel** under **Common Settings** once. Then, click on **Scope Settings** and select the option *Chirp* in the checkbox. The waveform and chirp for 1 Gbit/s and 2.5 Gbit/s signal are shown below.
- Note that the 2.5 Gbit/s pulses are considerably more chirped than the 1 Gbit/s pulses. The chirp is particularly large at the leading edge of the pulses, exceeding 20 GHz, where that of 1 Gbit/s is only 12 GHz.

Waveform and chirp of 2.5Gbit/s signal



Waveform and chirp of 1 Gbit/s signal



Bit rate limitation due to Dispersion

- It is well known that amplitude modulation in semiconductor lasers is accompanied by phase modulation. The mode frequency differs from its steady-state value. Pulses experiencing such a phase modulation are called *chirped*.
- The frequency chirp broadens the spectrum of the optical signal considerably. Due to fiber dispersion, different frequencies propagate with different velocities, which in turn leads to pulse distortion.
- With increased signal bit rates, the tolerable dispersion decreases, since the bit durations become shorter. For a given transmission distance, pulse broadening, the overlap of broadened pulses and hence bit-errors are more likely to occur in systems with higher bit rates. An alternative way of looking at it, is that the effect of fiber dispersion on chirped pulses becomes significant over shorter transmission distances, for systems with a bit rate of 2.5 Gbit/s compared to systems the operate at a bit rate of 1 Gbit/s.
- The chirp in the optical signal pulses have thus limited how much the bit rate of a system can be increased due to fiber dispersion. Therefore, optical sources that produce chirped optical pulses should be avoided.

Fiber Dispersion: Solution 1

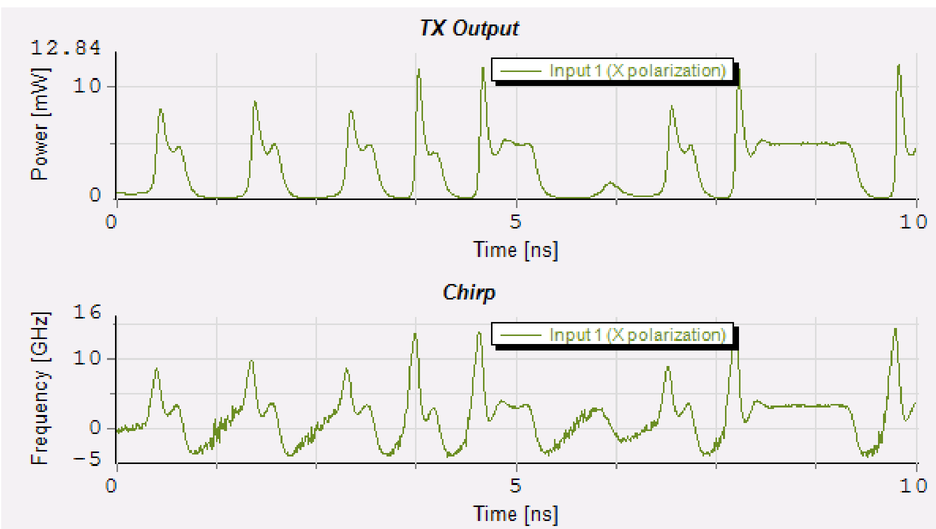
- One obvious solution is to reduce the chirp in the signal pulses by using a better laser.
- There are lasers with special internal structures that can be optimized so that they produce less chirp when directly modulated.
- Such a laser can be simulated simply by altering the value of one of the key parameters in the laser model used in the transmitter.

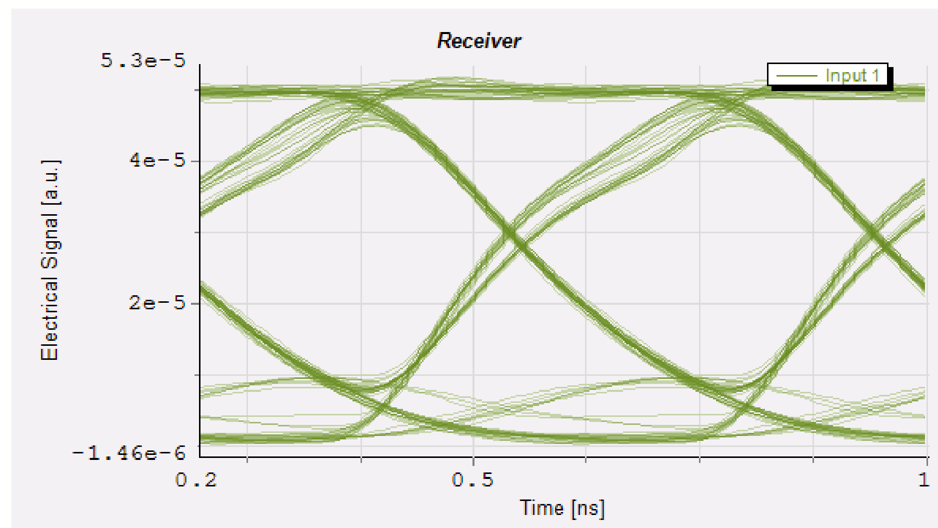
- This parameter is the *LaserRateEqSM*—***IndexToGainCoupl*** parameter. Set it to 3.0 in FOC2_5 and repeat the simulation.

Fiber Dispersion: Solution 1

- The waveform and chirp of the laser output are shown below on the left and the eye diagram of the received signal is shown on right.
- The frequency chirp of the pulses at the laser output is significantly reduced.
- The received pulses produce a wider opened eye-diagram.
- This verifies that the frequency chirp was the limiting factor in the previous system.

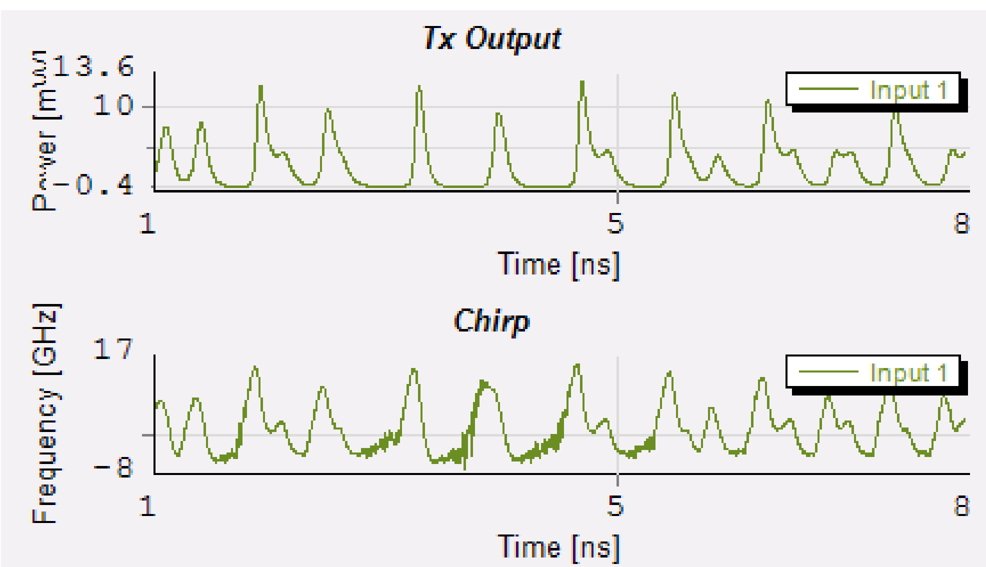
2.5Gbit/s signal

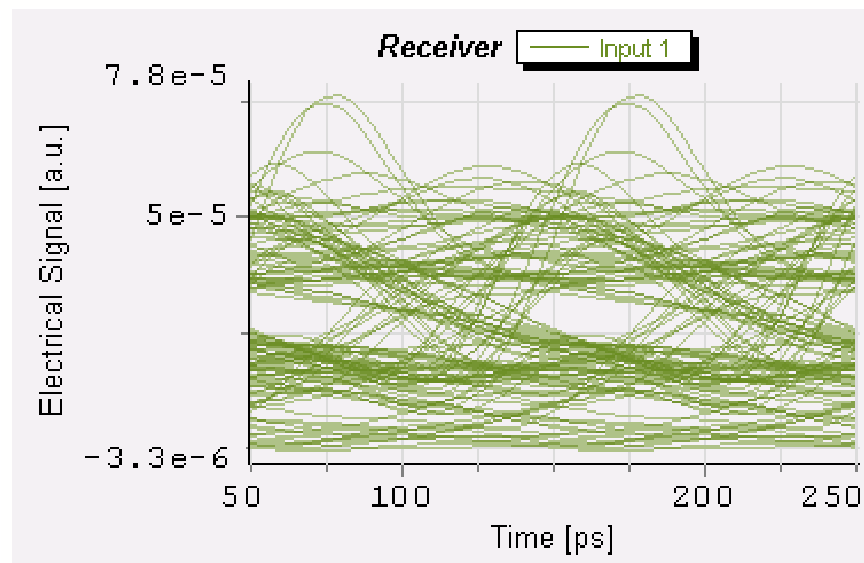




Limitation of Solution 1

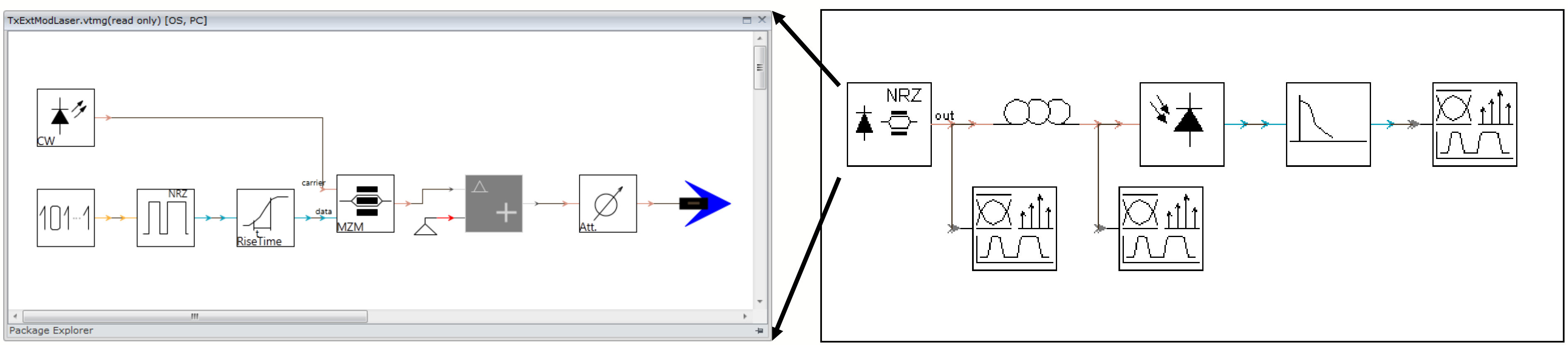
- Improved lasers still exhibit a some of chirp (albeit much less) under direct modulation. At bit rates above 2.5 Gbit/s, even a low level of chirp is unacceptable. In fact, there will be a certain bit rate, above which the laser cannot produce pulses that are acceptable for transmission.
- To investigate this, increase the bit rate of the system in the previous schematic to 10 Gbit/s and run it (or use FOC2_6). The analyzer screens that will appear are shown below. Obviously, the laser under consideration is not able to follow the modulation at 10 Gbit/s. The eye is already totally closed at the transmitter end, as shown below in the figure on the right.





Fiber Dispersion: Solution 2

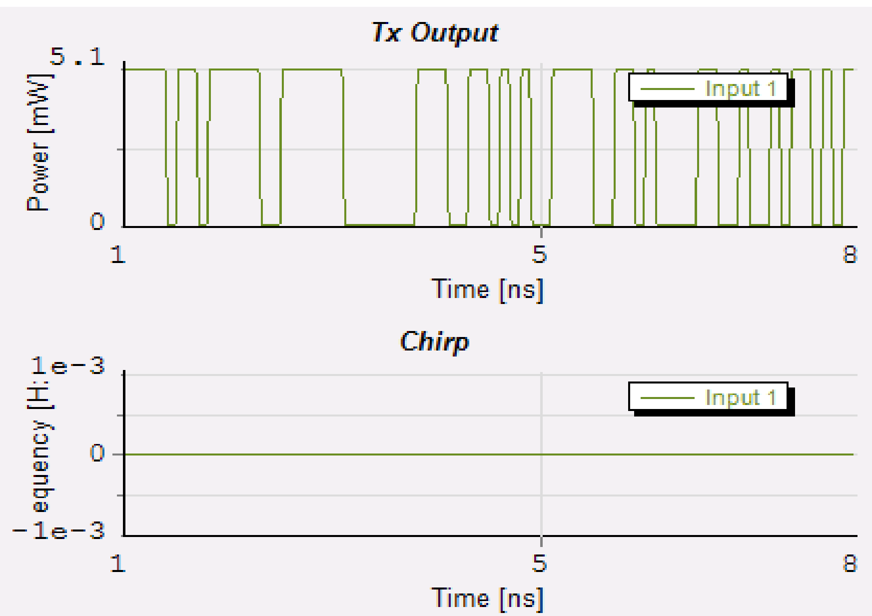
- Another technique for avoiding the limits arising from frequency chirp and limited laser dynamics is external modulation, where an external modulator is used to modulate the continuous wave (CW) output of an unmodulated laser.
- Open FOC2_7. The schematic is shown below in the figure on the right. Note that the transmitter is replaced by a module *TxExtModLaser*. This transmitter module consists of submodules. You can look inside the transmitter module by right clicking it and selecting the "Look Inside" option. The internal architecture of the module is shown below in the schematic on the left.



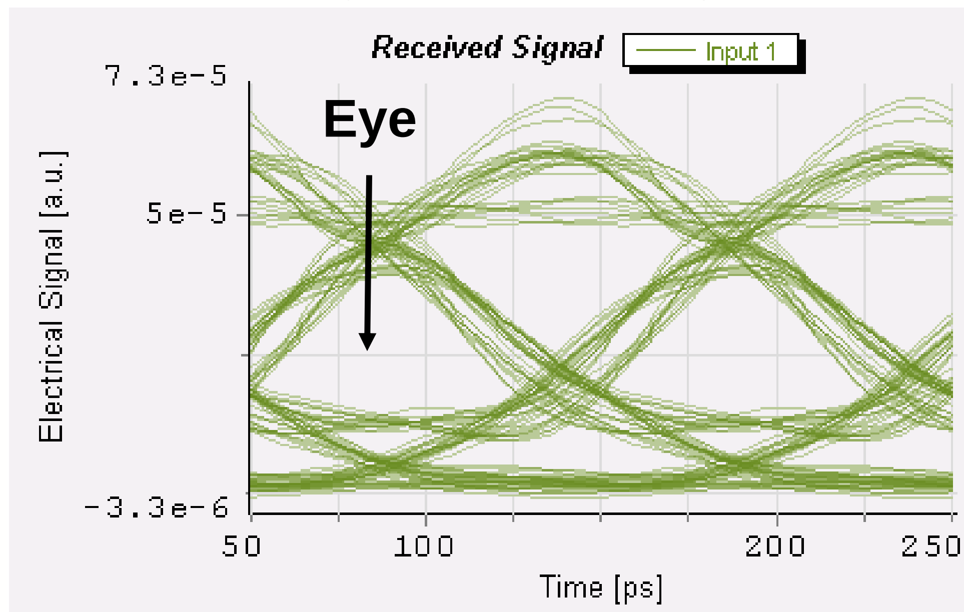
Fiber Dispersion: Solution 2

- Check that the bit rate is set to 10 Gbit/s, the fiber length to 100 km and the fiber attenuation to 0.2 dB/km.
- Run the simulation.
- The output of transmitter and the eye diagram of the received signal are shown below.
- Compared with the results discussed in solution 1, the externally modulated transmitter generates clear and chirp free pulses, and the eye of the received signal is improved.

Output of transmitter

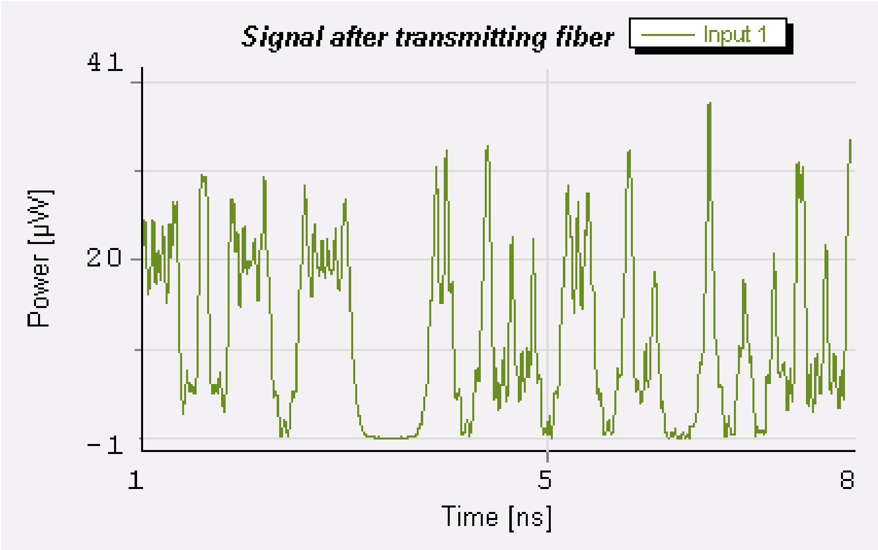


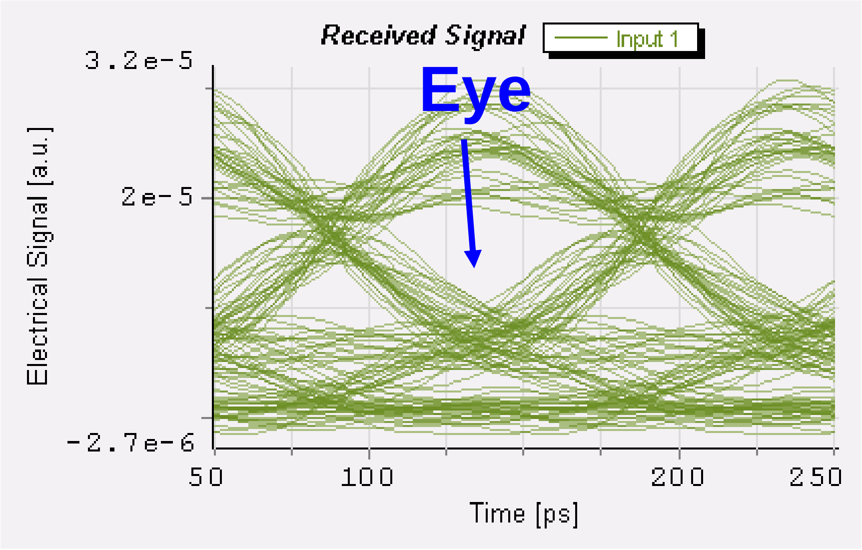
Eye of received signal



Limitation of Solution 2

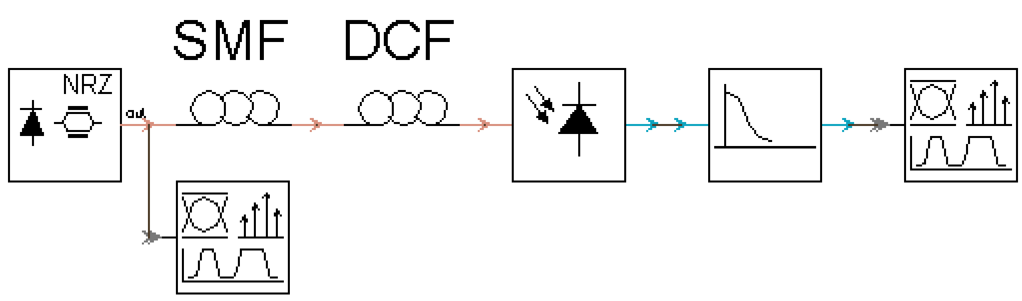
- Increase the length of the SMF fiber to 120 km and repeat the simulation. The pulses at the receiver end are distorted (see figure below on the left), resulting in large eye closure as shown in the figure below on the right.
- The observed impairments of the system performance are caused by pulse spreading due to group-velocity dispersion (GVD) in the fiber. The system is ***dispersion-limited***.
- It is observed that the received signals degrade quickly as the fiber length is increased (increase again the fiber length to further highlight this effect).
- However, as dispersion is a linear pulse propagation effect, the resulting signal distortions can be overcome by using simple dispersion compensating techniques.





Fiber Dispersion: Solution 3

- A third solution is to apply dispersion compensating fibers (DCFs) to counter the effects of fiber dispersion.
- This is achieved by inserting spans of DCFs, which are specially designed optical fibers that reverse the effects of fiber dispersion. How DCFs actually work to undo the effects of dispersion will be covered in another module. Here, we simply demonstrate that there are other methods of getting around the limitations of fiber dispersion other than by improving the laser design.
- Open FOC2_8. The schematic is shown below. Another module *FiberNLS*, used to model a DCF, is placed after the standard SMF fiber.



Fiber Dispersion: Solution 3

- Before proceeding, make sure that the length of the SMF-fiber is set to 120 km and set:

FiberNLS (DCF)—***Length***	= 16.0/90.0*120e3
FiberNLS (DCF)—***Dispersion***	= -90e-6
FiberNLS (DCF)—***Attenuation***	= 0

- Run FOC2_8. As can be seen in the figure below, the eye diagram is wide open, suggesting that the dispersion compensated system operates at acceptably low BER values.