

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.

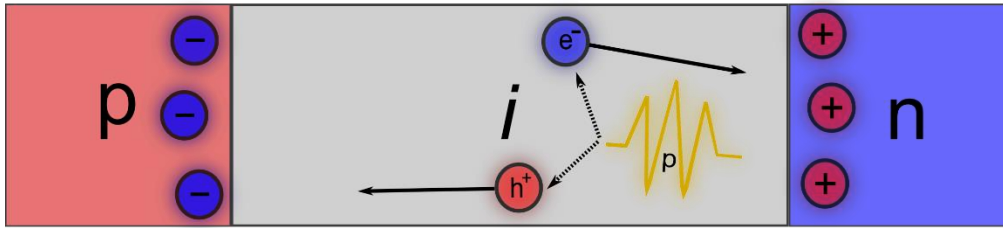


Figure 1: Structure of a PIN photodetector.

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.

Answer: $\eta = 1 - e^{-\alpha L} = \frac{qR_D}{hf}$

$$e^{-\alpha L} = 1 - \frac{1.24 \times 0.85}{1.55}$$

$$\alpha = 0.456 \mu\text{m}^{-1}$$

$$\eta = 0.68$$

- 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.

Answer: $\tau_{tr} = \frac{T_r}{\ln 9} - \tau_{RC}$

$$\tau_{tr} = 8.1 \text{ ps}$$

$$v_{drift} = \frac{1.75 \mu\text{m}}{8.1 \text{ ps}} = 2.16 \times 10^5 \text{ m/s}$$

$$\Delta f = \frac{1}{2\pi(8.1 \text{ ps} + 1 \text{ ps})} = 17.5 \text{ GHz}$$

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?

Answer: $\sigma_s^2 = 2q(I_p + I_d)\Delta f$
 $= 2 \times 1.602 \times 10^{-19} \times (10 + 0.008) \times 15 \times 10^9$
 $\sigma_s = 6.94 \times 10^{-5} \mu\text{A}$

- 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.

Answer: $\sigma_T^2 = (4k_B T/R_L)\Delta f$
 $= (4 \times 1.3806 \times 10^{-23} \times \frac{294.15}{45}) \times 1.5 \times 10^9$
 $\sigma_T = 0.736 \mu\text{A}$

- 2.2.3 Now calculate the SNR of the photodetector.

Answer: $SNR = I_p^2/(\sigma_s^2 + \sigma_T^2)$
 $= 10^2/((6.94 \times 10^{-5})^2 + (0.736)^2)$
184.6 or 22.67 dB

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

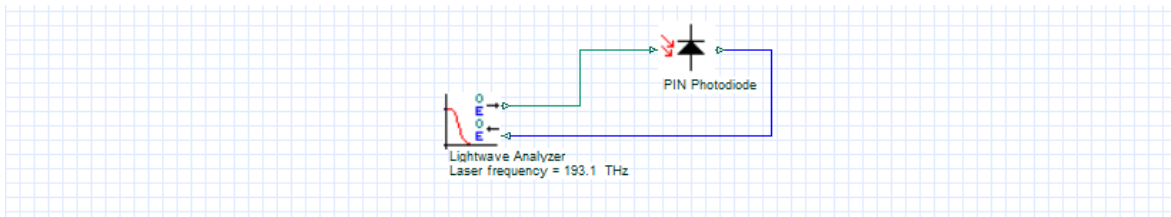


Figure 2: Layout using the Lightwave Analyzer.

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.

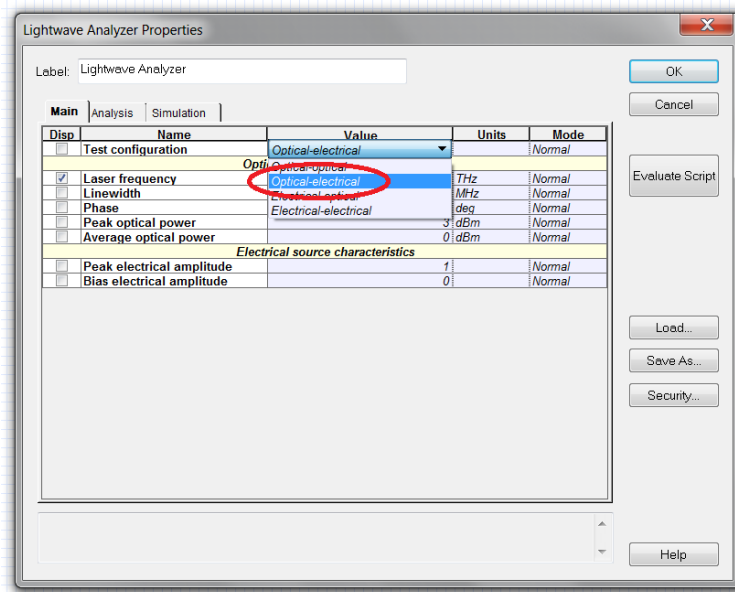


Figure 3: Lightwave Analyzer component properties.

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.

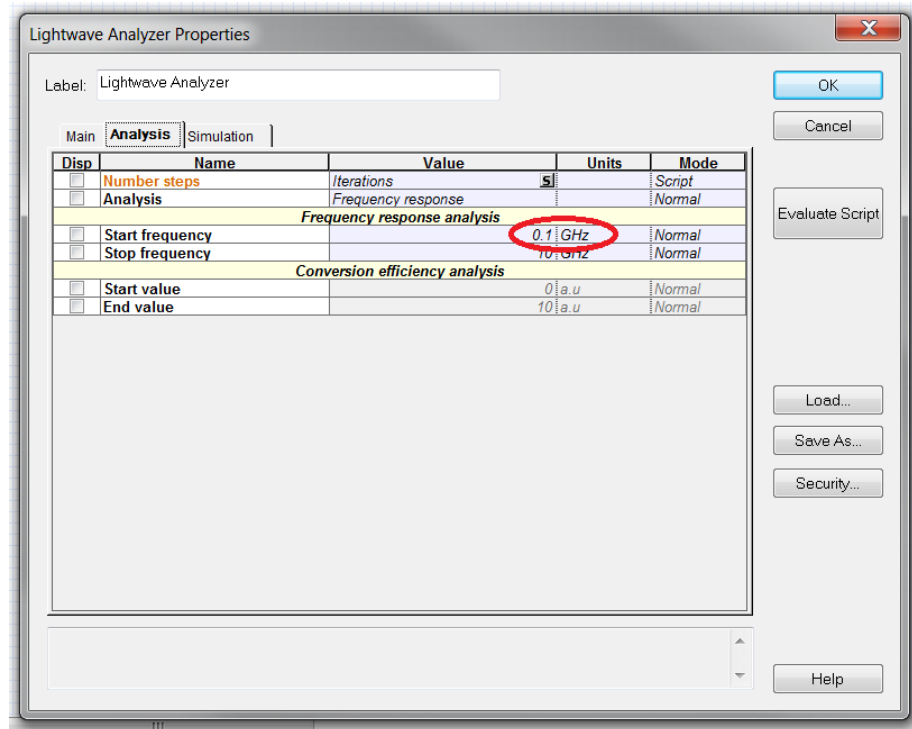


Figure 4: Setting parameters on the Analysis tab.

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.

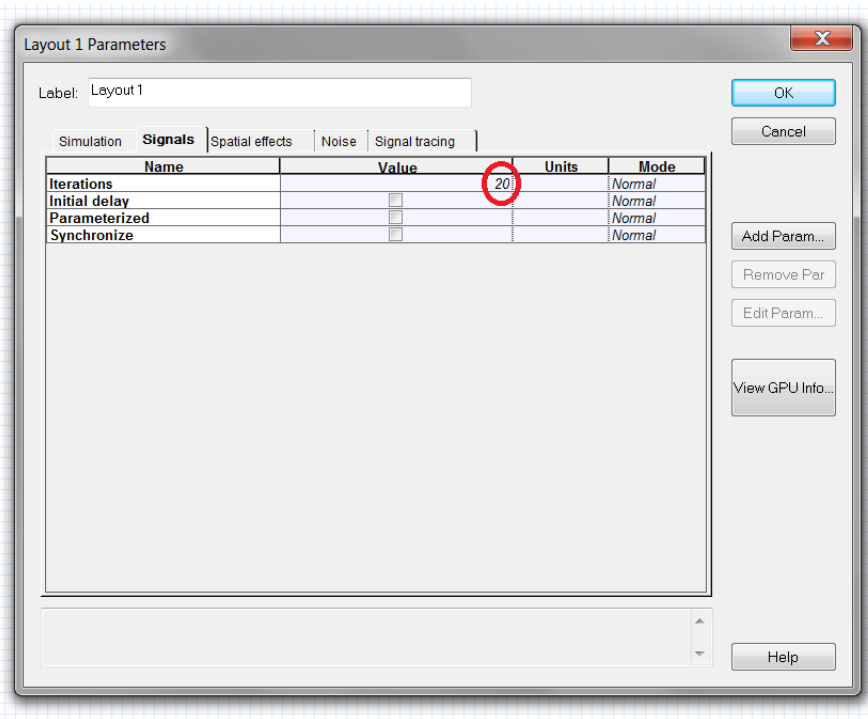


Figure 5: Layout parameters window.

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

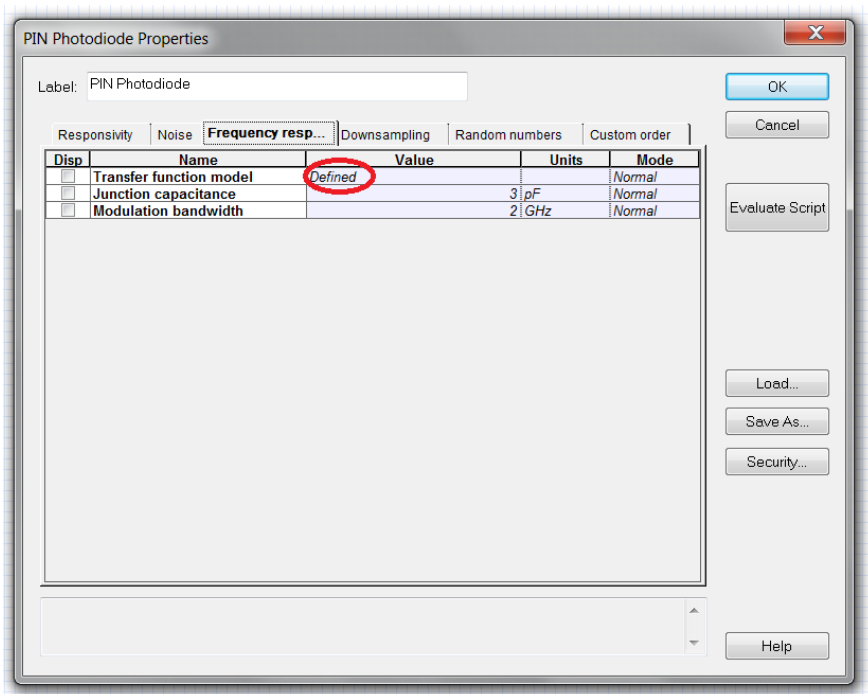


Figure 6: PIN Photodiode properties window.

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.

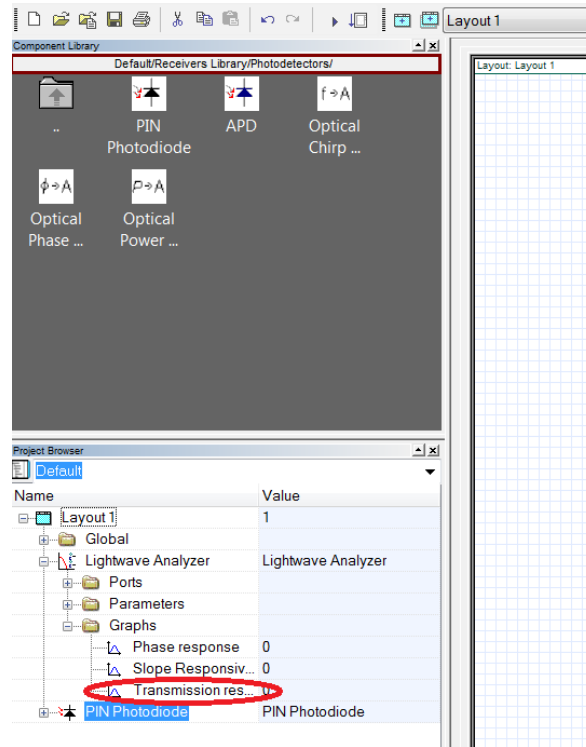


Figure 7: Finding the Transmission response graph in the Project Browser.

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.

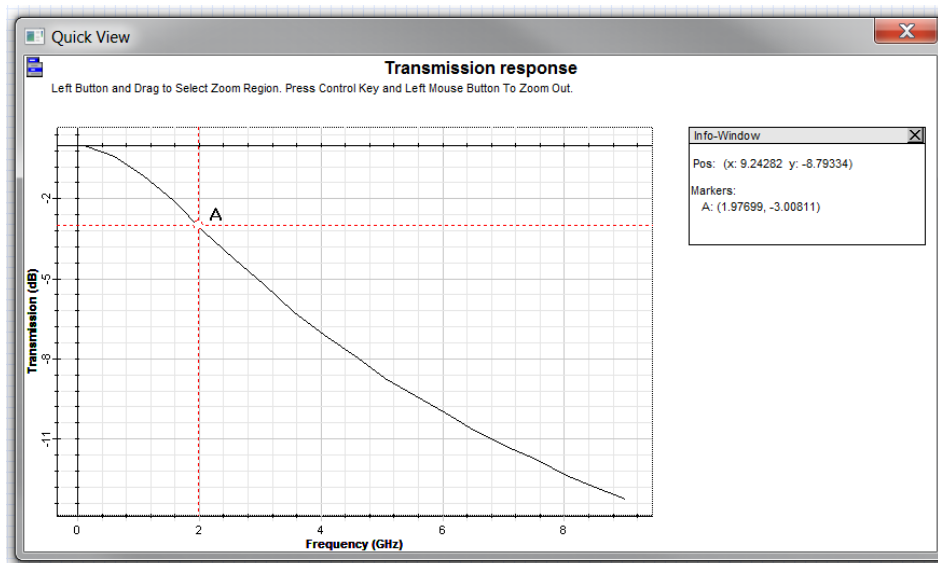


Figure 8: Frequency response of the PIN photodiode.

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”.

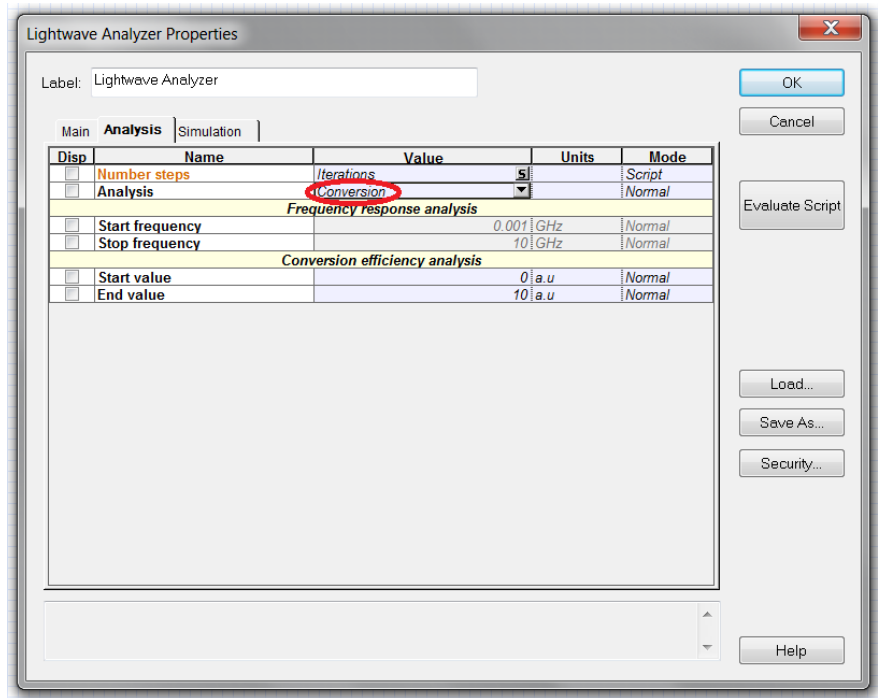


Figure 9: Changing the operation of the Lightwave Analyzer.

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:

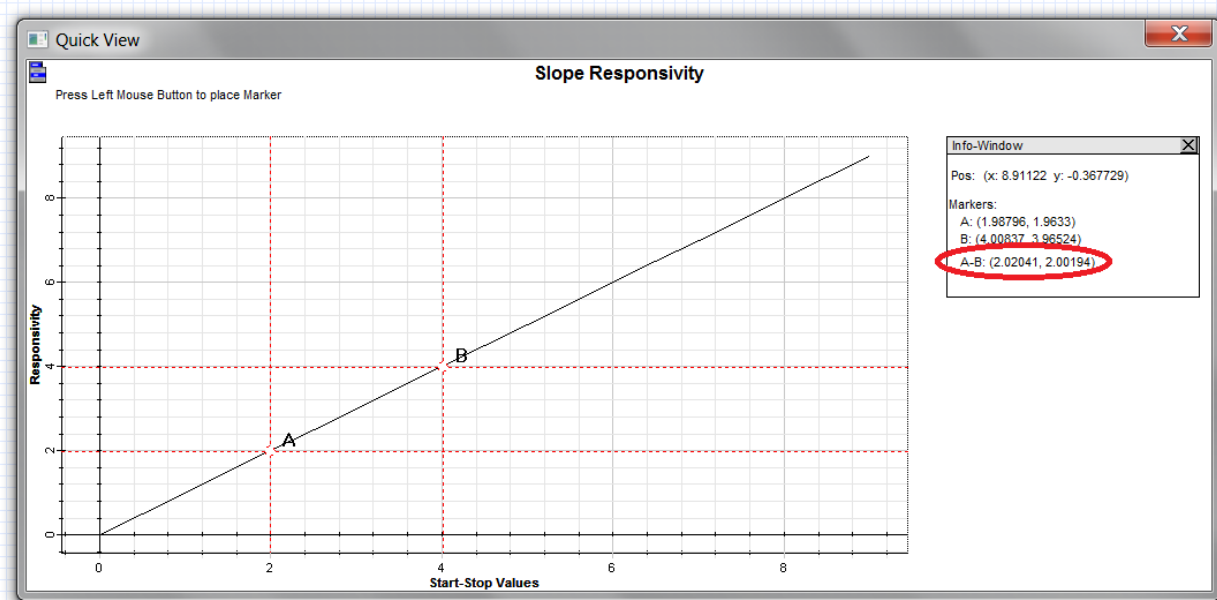


Figure 10: Plotting the conversion efficiency.

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 $\sim 1\text{A/W}$.

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.

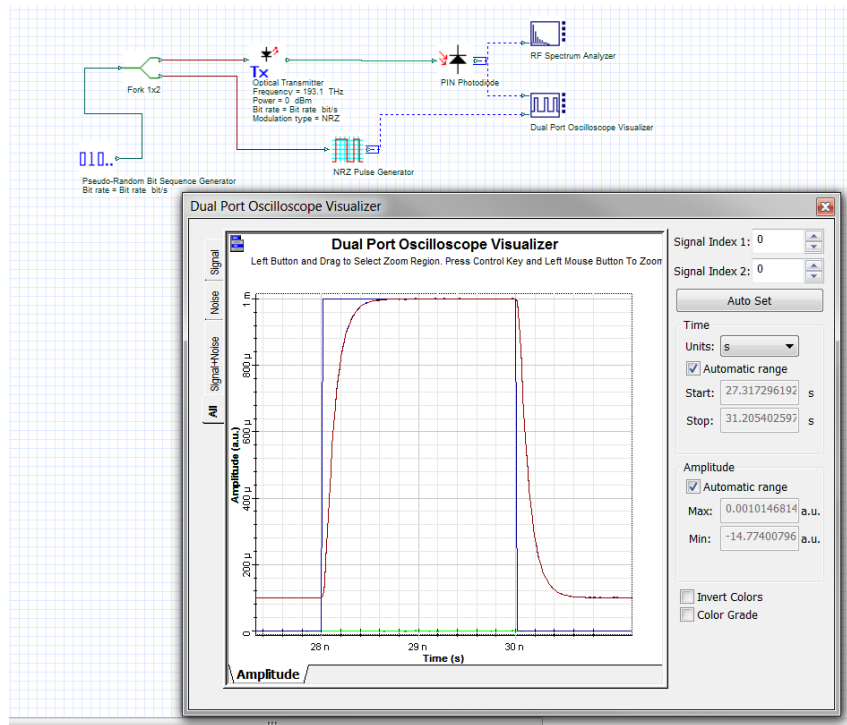


Figure 11: Calculating the bandwidth from the rise and fall time.

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?

Answer: InGaAs bandwidth: 1.608 GHz

InGaAs responsivity: 0.967 A/W

3.2.2 What are the bandwidth and responsivity of the Ge Photodiode?

Answer: Ge bandwidth: 7.92 GHz

Ge responsivity: 0.4303 A/W

3.2.3 Compare the responsivity of the two photodiodes and the semiconductors respective band gap energies. Explain the differences.

Answer: The Ge photodiode has a smaller responsivity at this particular wavelength because its band gap is centered at a lower energy.

3.2.4 Determine the rise times of both photodiodes. Calculate the bandwidth again from this value.

Answer: InGaAs rise time: 219.9 ps

InGaAs bandwidth: 1.59 GHz

Ge rise time: 43.8 ps

Ge bandwidth: 7.99 GHz

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.