Data transmission tests of the ATLAS Inner Tracker Detector opto-electrical conversion system.

Time-domain Reflectometer
Measurements of The Optosystem Data
Transmission Chain

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ATLAS ITk

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The Optosystem

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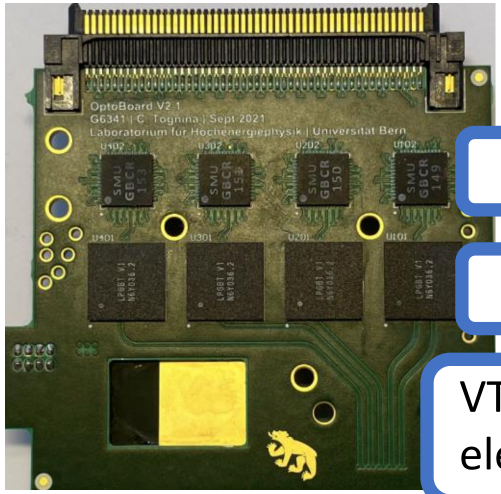
➢ For the HL-LHC, the ATLAS Inner Detector will be replaced with the Inner Tracker (ITk)

➢ The new ATLAS ITk will require a new optical to electrical conversion system (Optosystem)! *(see: "Tests and results of the power components of the ATLAS Inner Tracker detector readout system." Lucas Mollier, "Performance tests of the ATLAS Inner Tracker Pixel detector opto-electrical conversion system" Marianna Glazewska)*

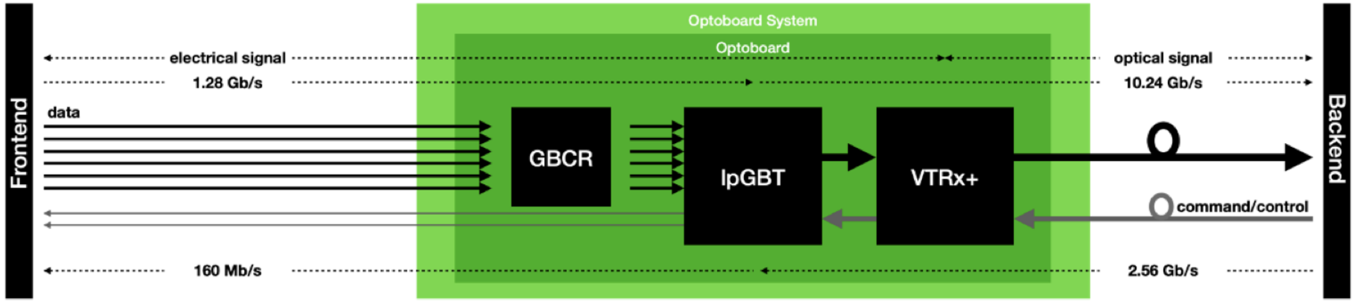
➢ Electrical signal from the pixel modules is converted to optical signal via the Optoboard. This presentation will focus on testing the quality of data transmission!



GBCR: equalization

lpGBT: multiplexing

VTRx+(on reverse side) electro-optical conversion

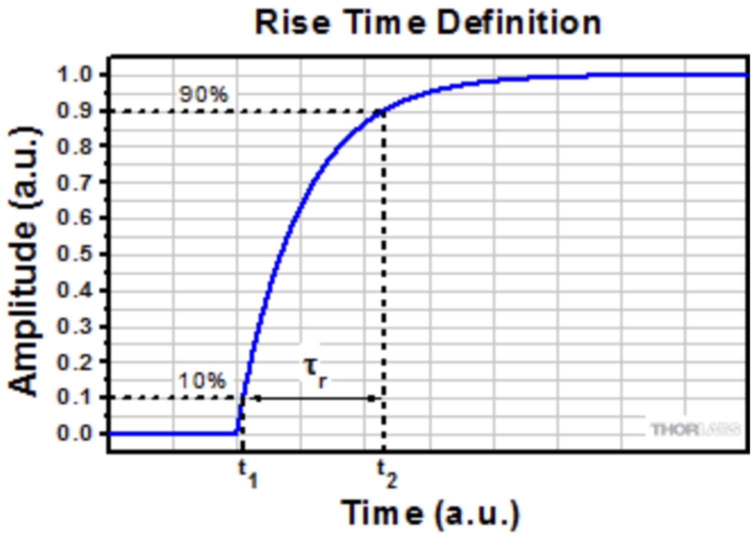


The TDR

TDR: Time-domain reflectometer

How does it work?

- Sends a pulse signal (with a specified rise time) down the transmission chain under test
- Measures the reflected signals from this pulse
- Calculates impedance and scattering parameter values at each point in the transmission chain



Rise time: Time taken for amplitude of signal to rise for 10% to 90%

1 . Impedance Measurements

What is Impedance?

- The measure of the opposition that a circuit or a part of a circuit presents to electric alternating current.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Resistance

Inductive reactance

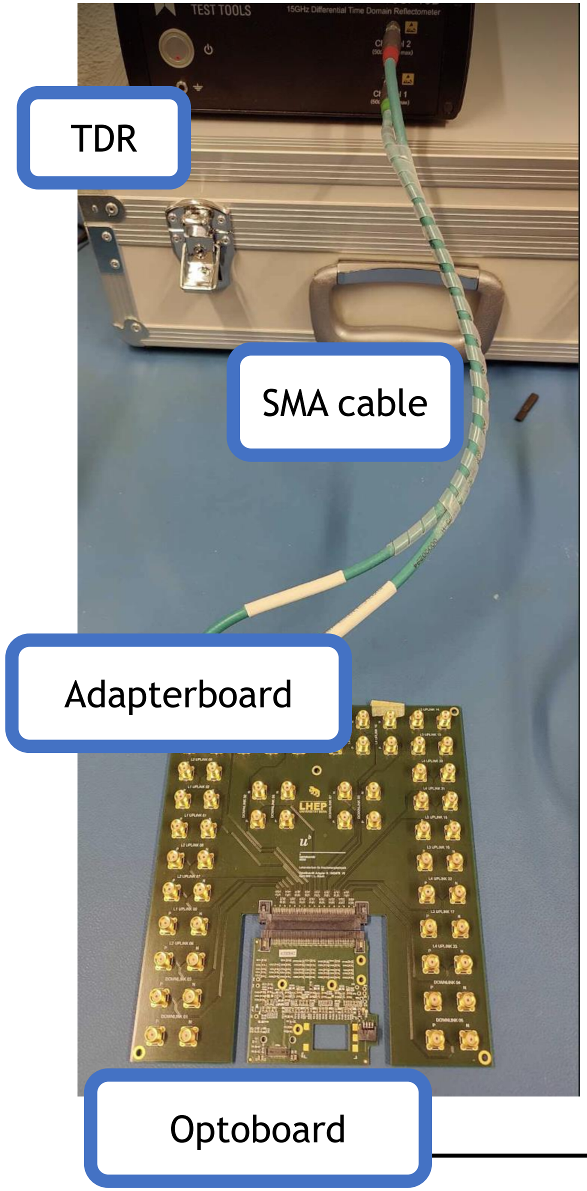
$$X_L = 2\pi \boldsymbol{f} L$$

Capacitive reactance

$$X_C = \frac{1}{2\pi \boldsymbol{f} C}$$

- Frequency dependent
- Parasitic: unwanted caused by lagging or leading of current from naturally occurring capacitors and inductors

Impedance Measurements



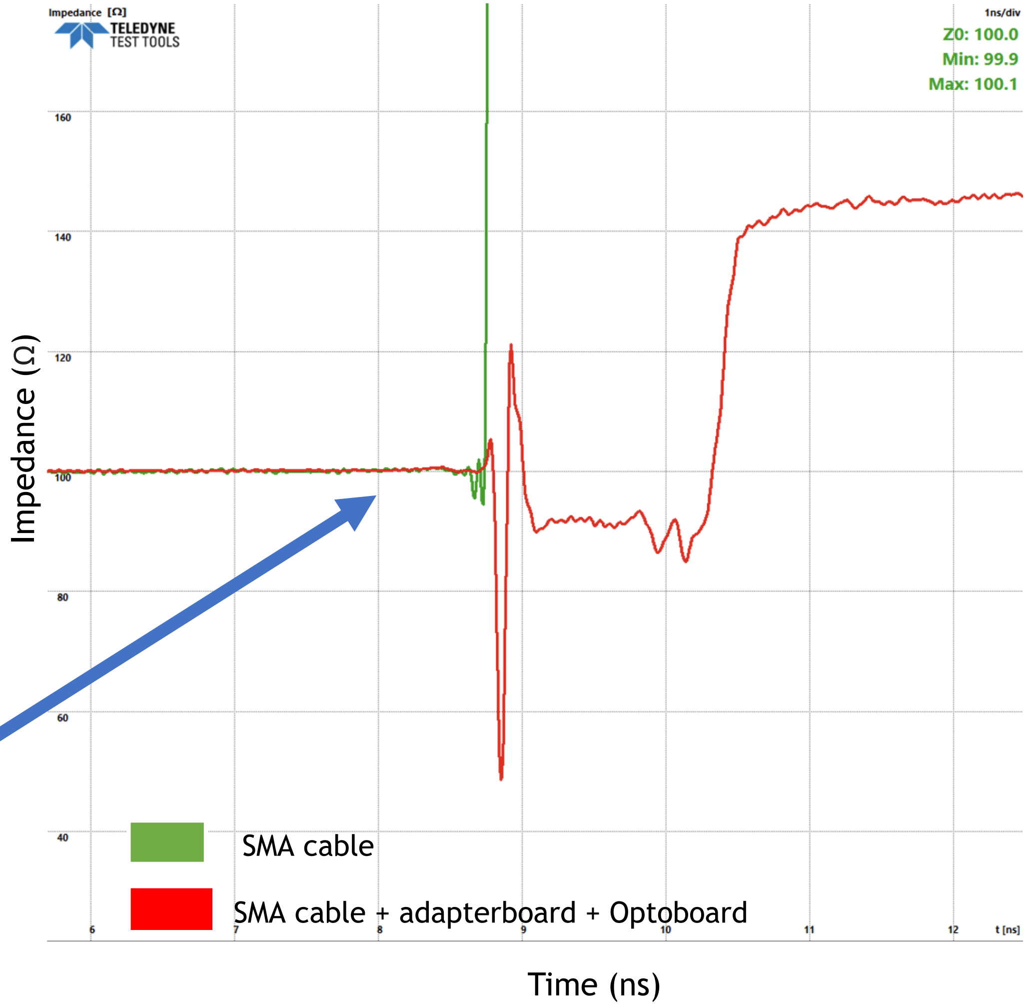
- Signal is sent from the TDR down the transmission chain at test
- We plot impedance as a function of time taken for the signal to propagate down the chain
- When signal reaches a boundary between materials (interconnect) with different impedance, the signal reflects

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad [1]$$

- We want to match the impedance across the transmission chain

$$R = 0 \quad \Rightarrow Z_2 = Z_1$$

- In this talk we explore these features



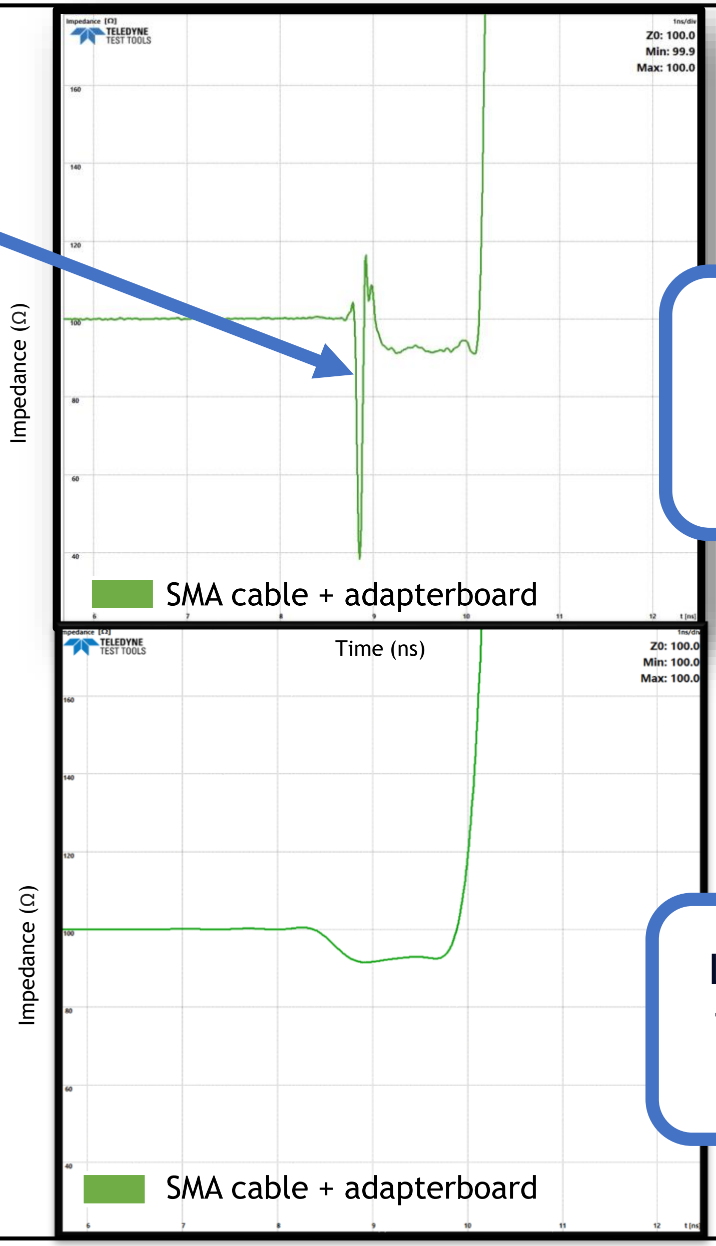
Discontinuities

- "Discontinues" arise when there is a change in impedance which we cannot resolve.
- Spatial resolution is determined by the rise time of the TDR pulse
  - We can resolve a time between two structures of roughly half the rise time of the signal
  - To see impedance:

$$\mathit{Time} < \frac{1}{2}\ \mathit{Rise\ Time}\ (\mathit{RT})$$

- When we test our system, we use the same rise time of ATLAS module (1.28Gb/s : rise time of ≈ 500ps)

Note: longer rise time means lower frequency. Reactance component of impedance is frequency dependant. This can also change the shape of the discontinuity!



Impedance not resolved. Shorter rise time needed!

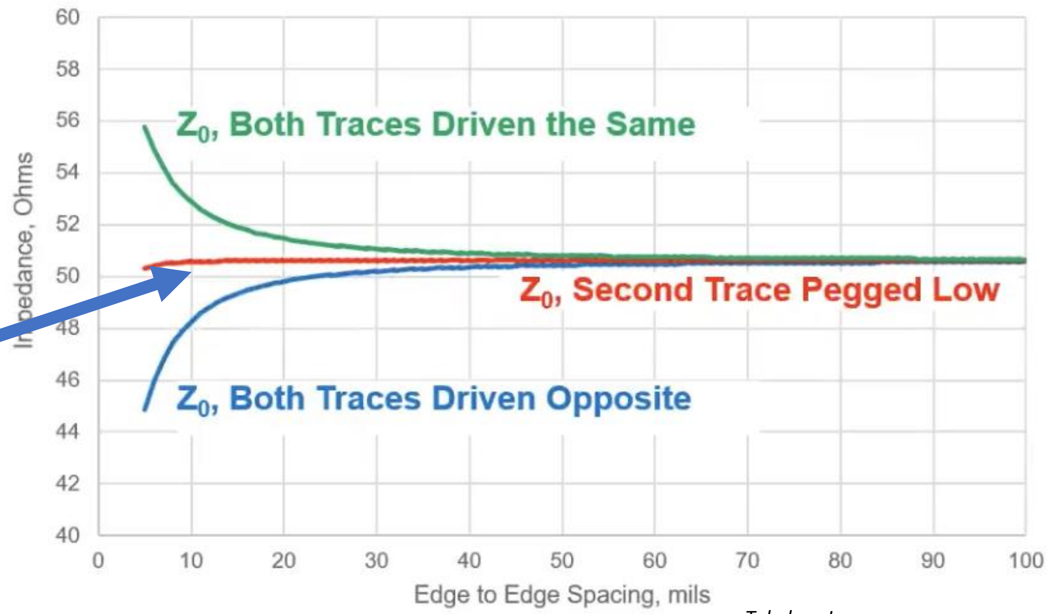
Increase rise time

Longer rise time: features are less resolved.

Differential Impedance and Coupling

- Optosystem signal is differential: signal on positive and negative lines measured with respect to each other
- If transmission lines are close to each other, differential signal susceptible to coupling
- Coupling affects differential impedance value!

Can test for coupling!



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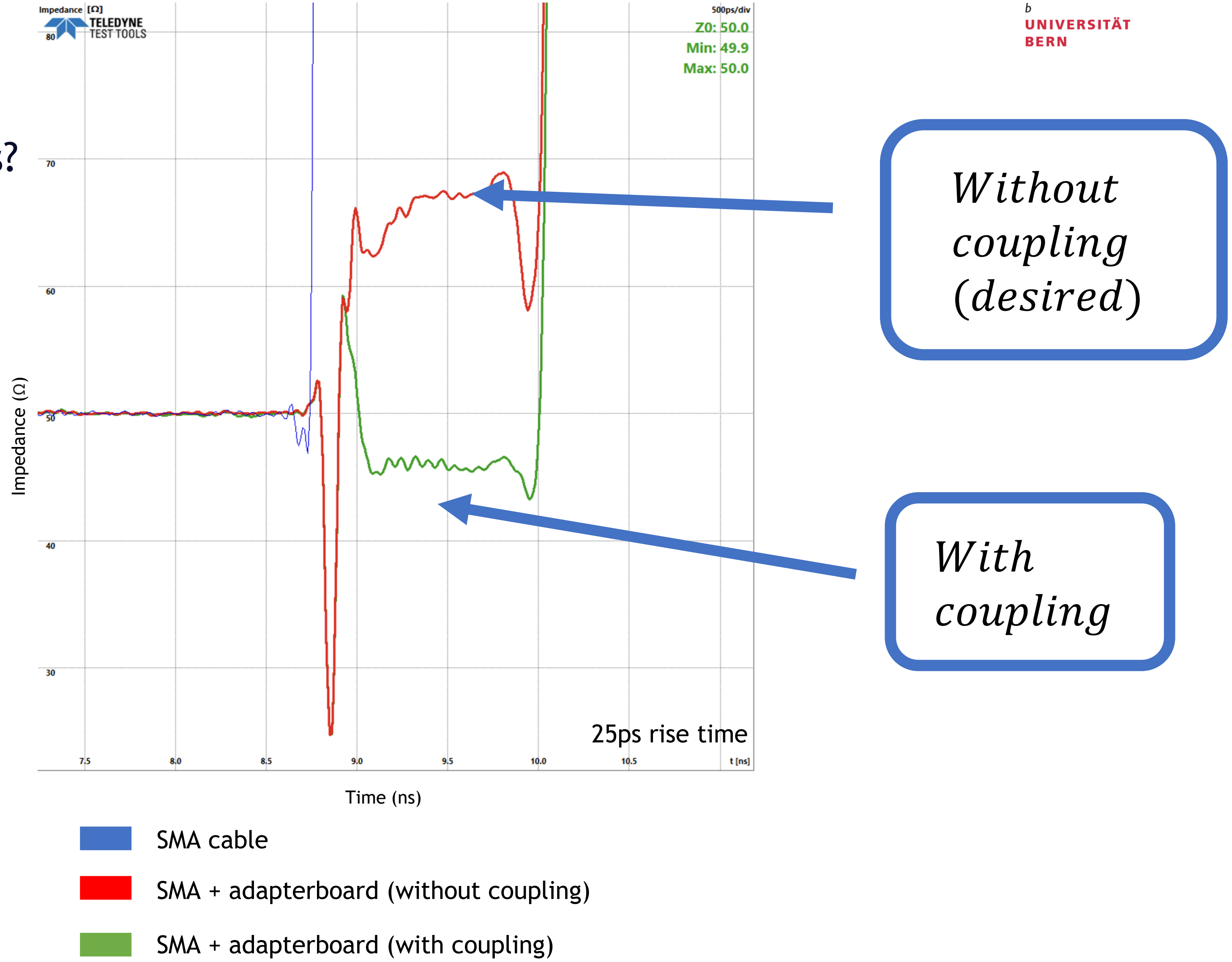
Coupling Example

- Can we see this effect in our testing PCBs?

- Coupling present!
- Must account for this this when designing boards and PCBs



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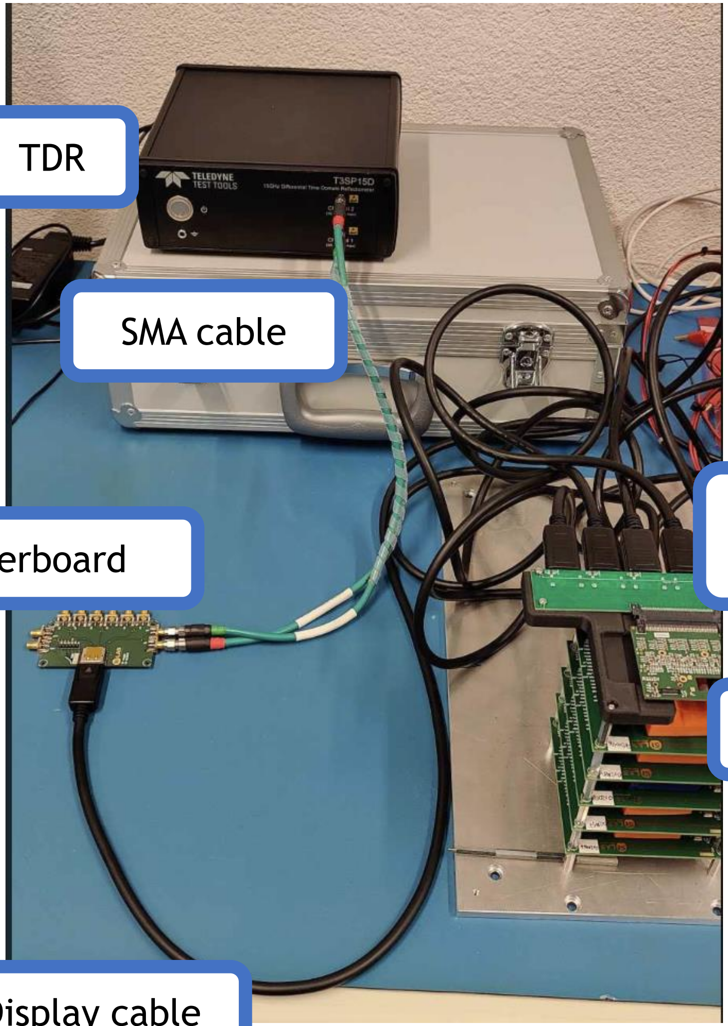
Impedance of Optoboard testing set-up

- Setup will be used to test Optoboards *("Performance tests of the ATLAS Inner Tracker Pixel detector opto-electrical conversion system" Marianna Glazewska, slide 18)*

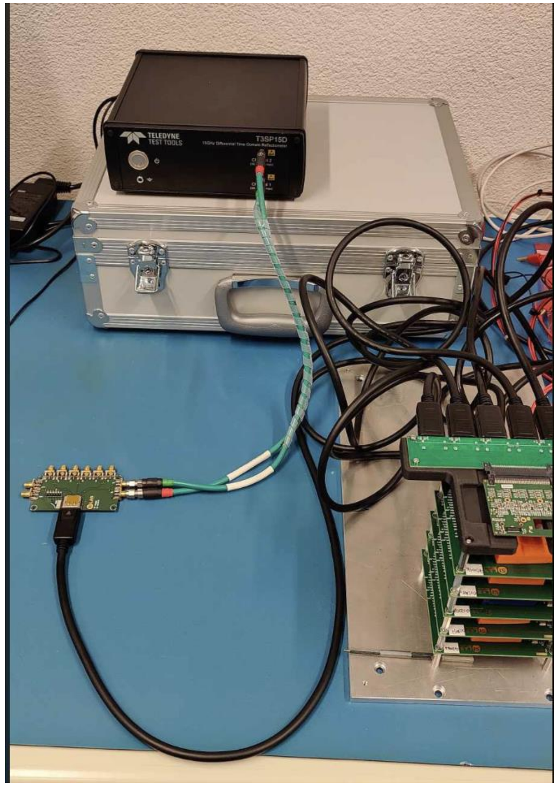
- Aim: Differential impedance of 100 Ω (be within 10%)

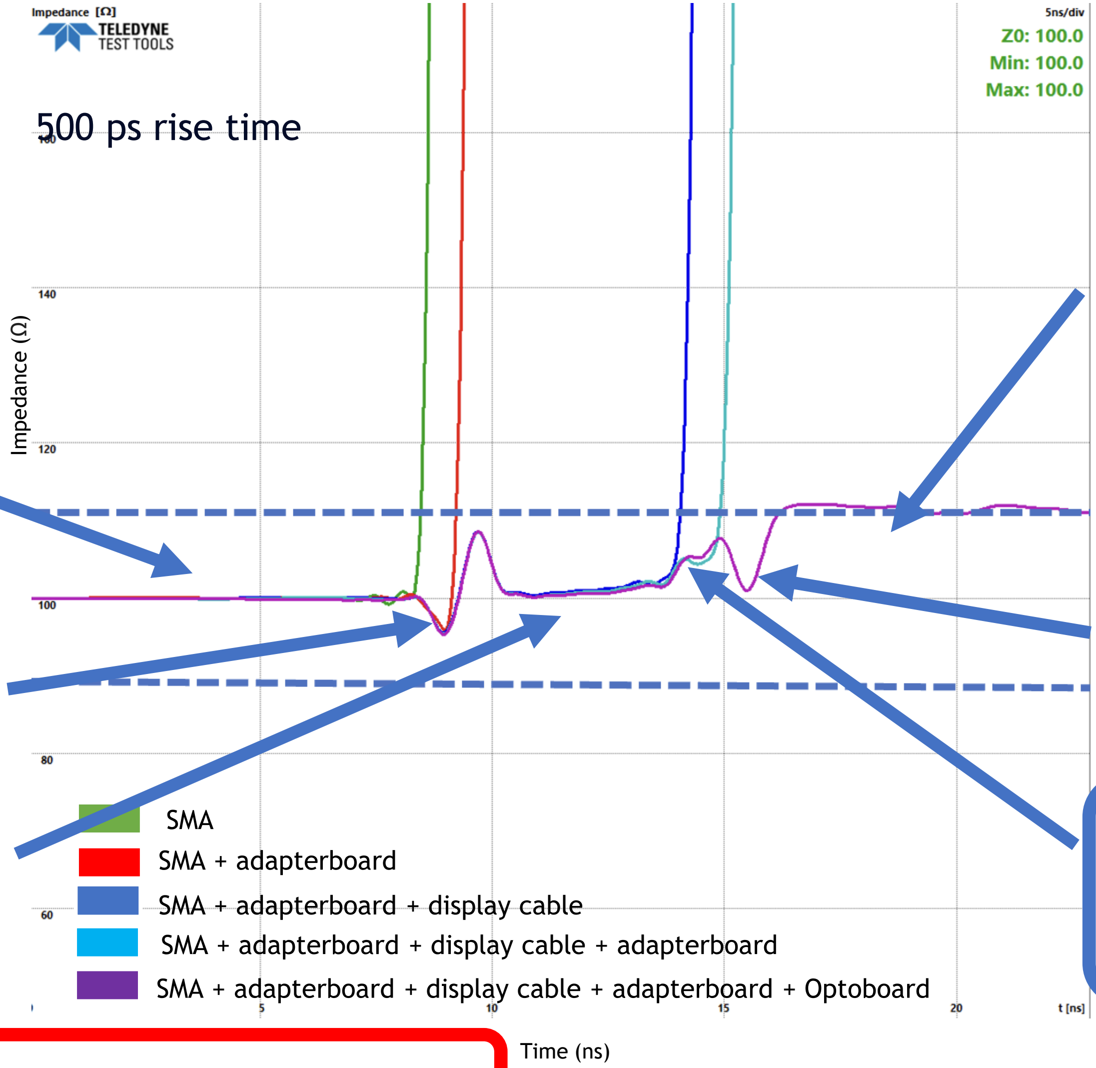
- When we test our system, we use the same rise time as ATLAS module (1.28Gb/s : rise time of ≈ 500ps)



Impedance of Optoboard testing set-up

Aim: Differential impedance of 100 Ω
(Usually aim is to be within 10%)





SMA (constant impedance; no signal reflections)

Adapterboard (coupling present but impedance still within 10% limit)

Display cable (good impedance match to 100 Ω)

GBCR (slight high impedance)

Optoboard

Adapterboard (6DP to ERF) (within 10% limit)

Most of the chain is within 10% of desired impedance (apart from GBCR)

2 . Scattering Parameters

Scattering parameters

- Scattering parameter (reflection coefficient) is defined by the ratio of the amplitude of the sine waves from the different ports

$$s_{jk} = \frac{Sine\ wave\ from\ port\ j}{Sine\ wave\ from\ port\ k}$$

- Measure of frequency dependent loss as signal travels from one material to another (through an interconnect)
- S parameters are measured in decibel (dB)
- dB value is always a ratio of powers, but we convert this to ratio of voltages

$$A_{dB} = 10 * \log\left(\frac{P_{out}}{P_{in}}\right) = 10 * \log\left(\frac{P_{out}^2}{c}\right) = 2 * 10 * \log\left(\frac{V_{out}}{V_{in}}\right)$$

For a good transmission line:

- Small reflection coefficient (S_{21})= large negative dB
- Transmission coefficient (S_{11})close to 1 = small negative dB

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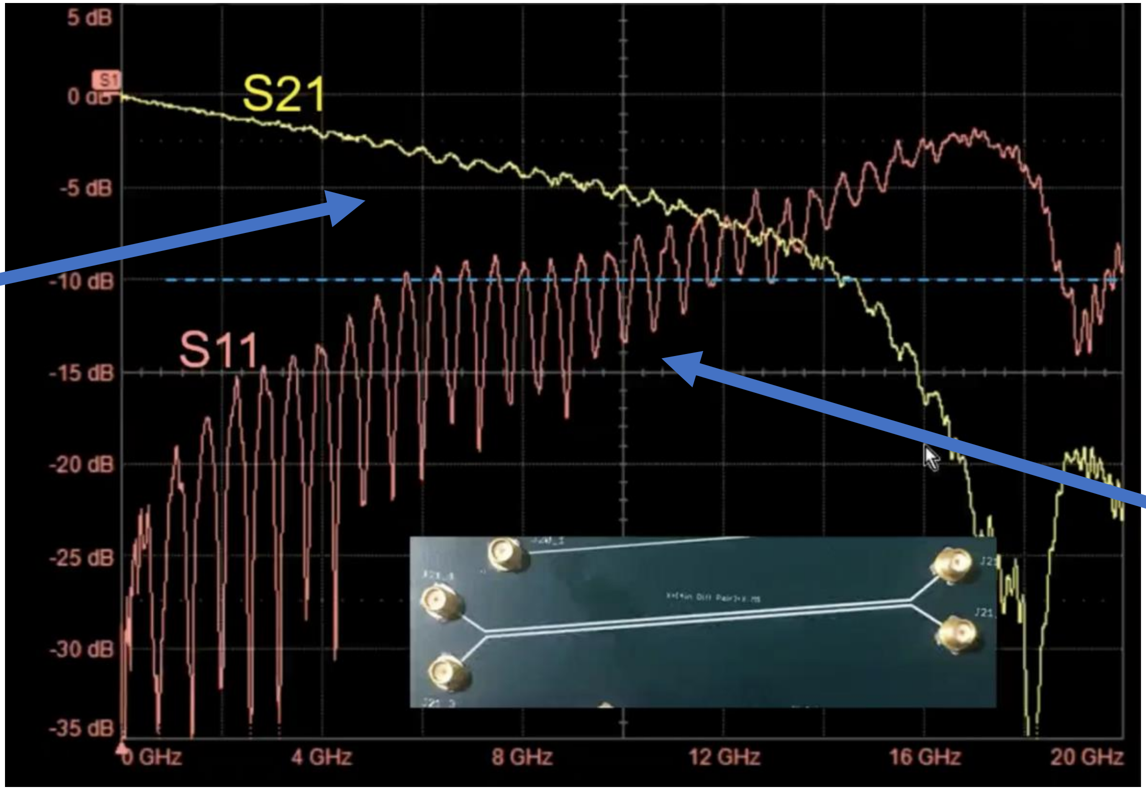
Scattering parameters

Exampe: Simple transmission line

Monotonic drop in transmission coefficient(S_{21}) caused by attenuation. Frequency dependent loss!



Ripples caused by reflections at boundaries

Our module signal is 1.28Gb/s – Our signal is affected!

Frequency dependent loss

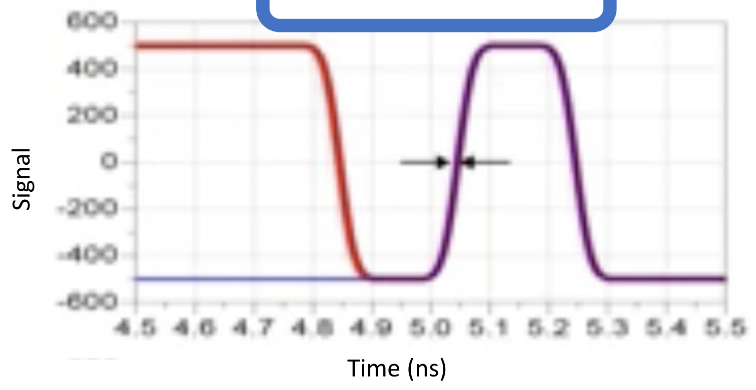
How do frequency dependent losses affect our signal?

- Rise time is degraded -> Jitter!

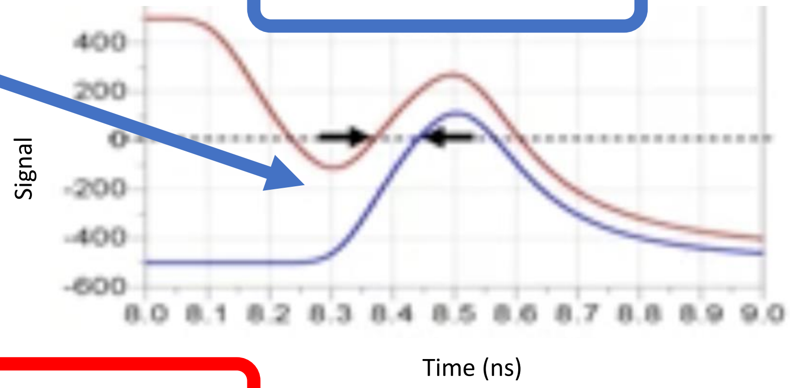
Example:
- 111110100000000 (red)
- 000000100000000 (blue)

- When passed through interconnect red signal does not fully drop and crosses 0 ahead of time
- Variation in the arrival time of the edge = jitter!
- Negative contributions to tests such as BERT scan. *"Performance tests of the ATLAS Inner Tracker Pixel detector opto-electrical conversion system" Marianna Glazewska, slide 10*

No interconnect



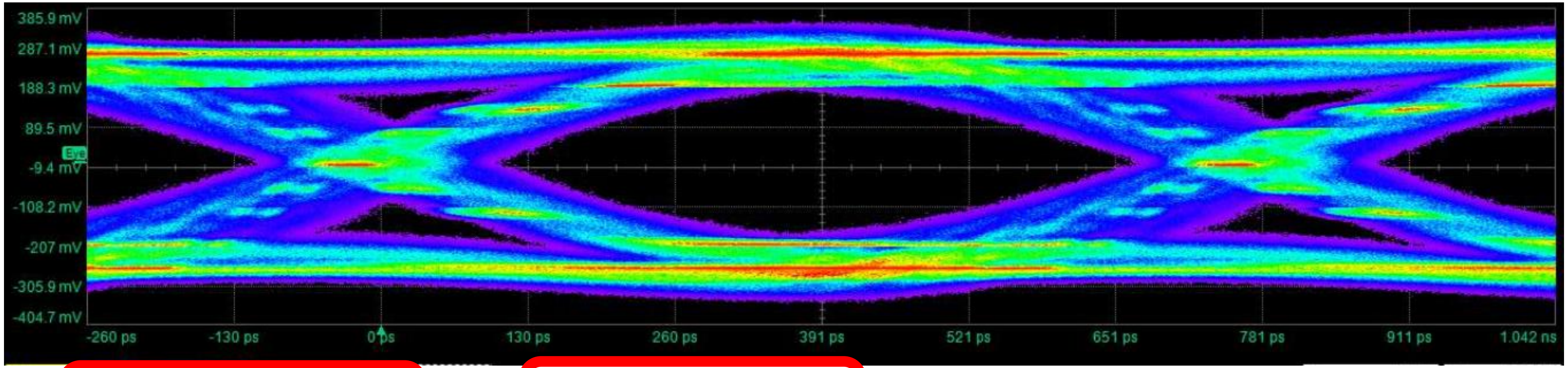
With interconnect



Can create eye diagram (overlay of signal pulses) to study effect of jitter

Eye diagram

- Optoboard production testing set-up eye diagram (uplink)



Eye width: 512 ps

Eye BER: 4.49^{-13}

- Data coming from ITk is at 1.28 Gb/s -> a width of 781.35 ps -> signal slightly attenuated
- We aim for our BER limit to be O(10^{-12}) (*"Performance tests of the ATLAS Inner Tracker Pixel detector opto-electrical conversion system" Marianna Glazewska, slide 10)*
  -> BER criteria satisfied

Summary

- It is vital to test the quality of data transmission in testing set-ups
- Impedance matching is very important in order to minimise losses which can cause jitter
- The TDR is a vital apparatus in determining and minimizing losses in optosystem data transmission

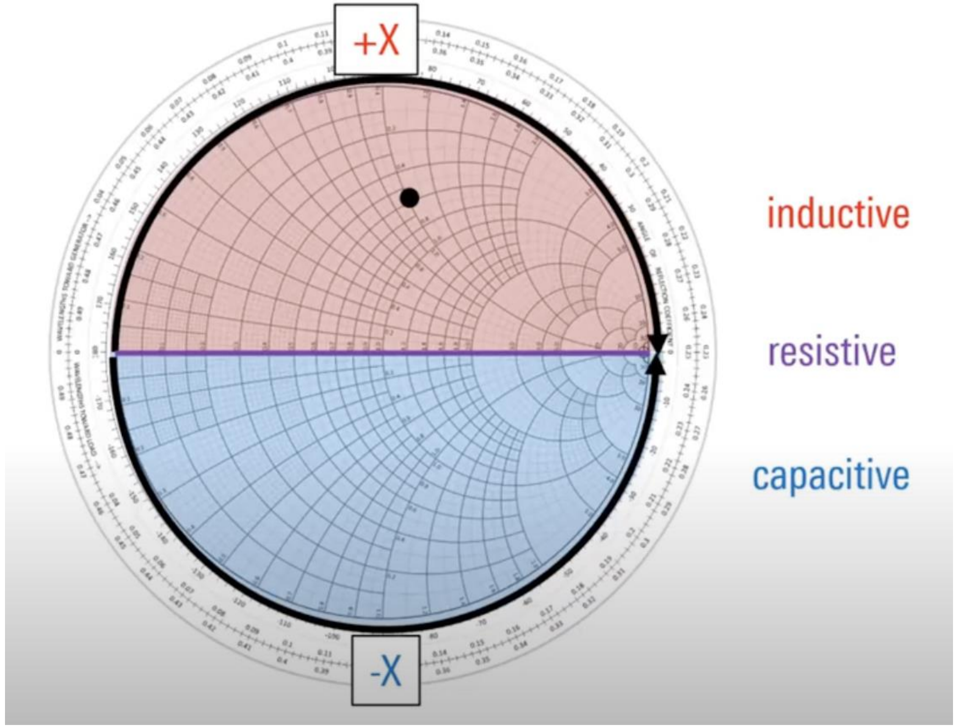
Thank you
Any Questions?

Smith Chart

Complex form: $Z = R + iX$

Resistance

Reactance



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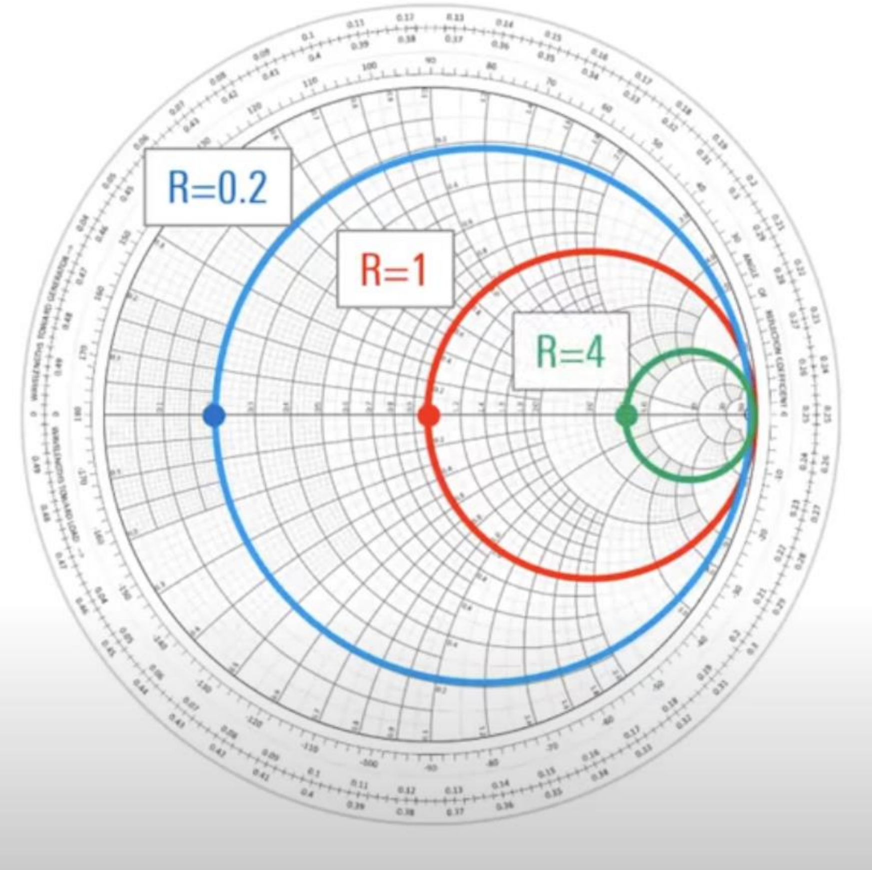
- An impedance at a given frequency is represented as a point on the smith chart
- All points on resistance line have no reactance contribution
- Points above line have inductive reactance contribution (below have capacitive)

Smith Chart



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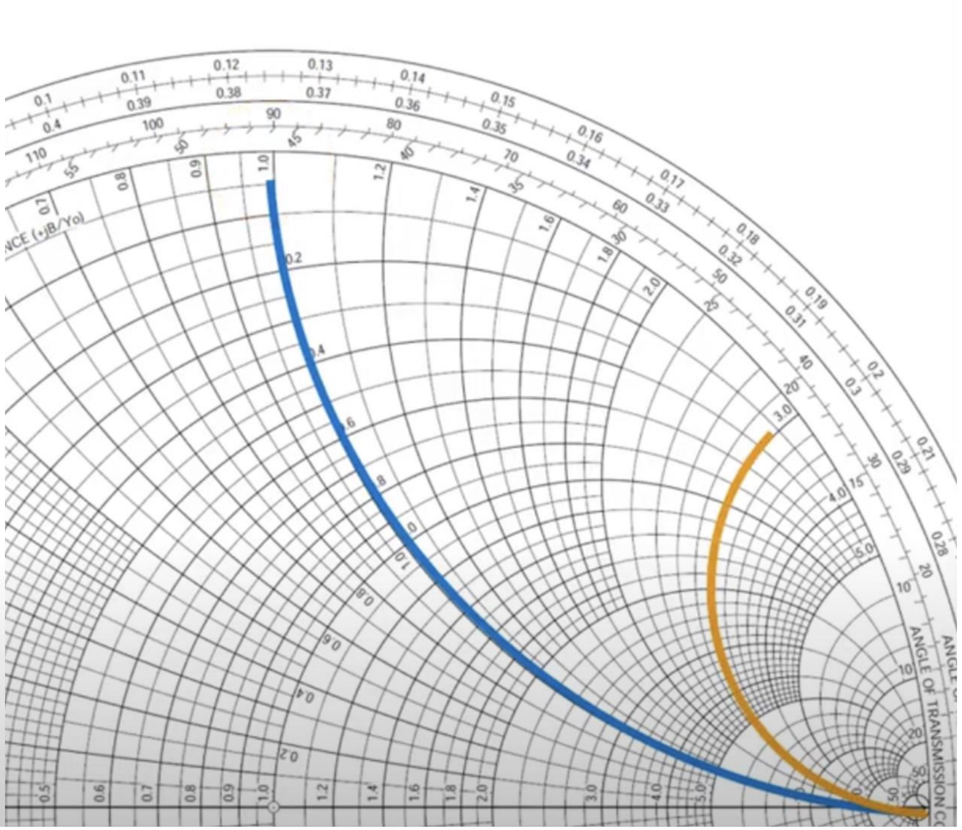

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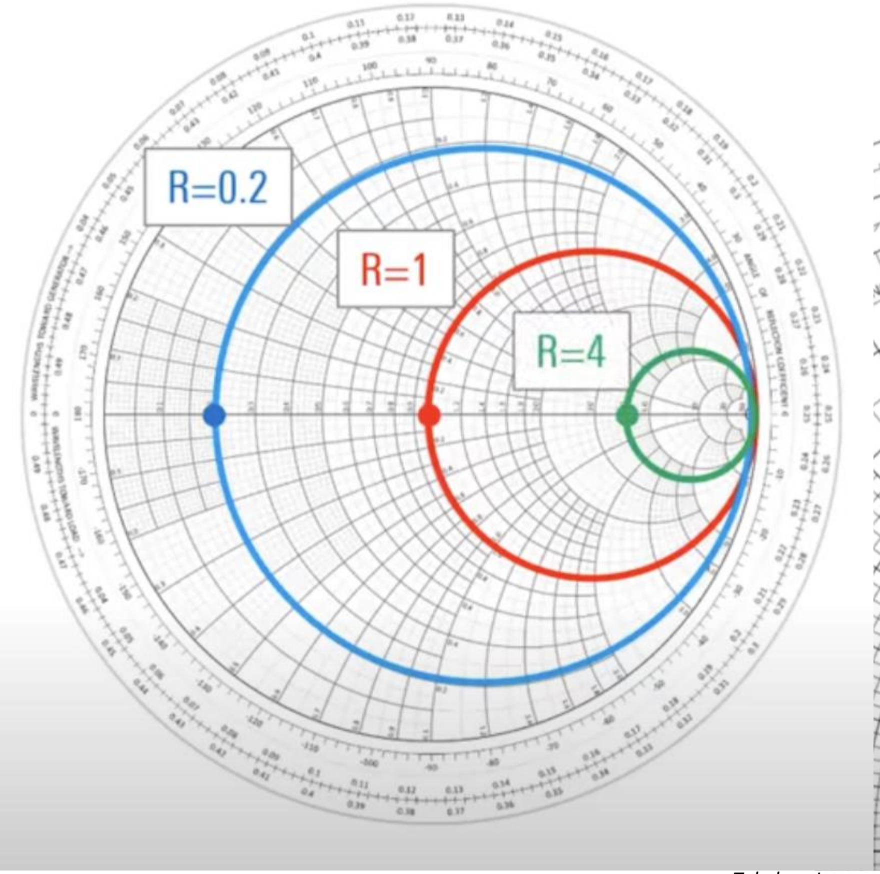
Curves of constant resistance

Curves of constant reactance

Smith Chart



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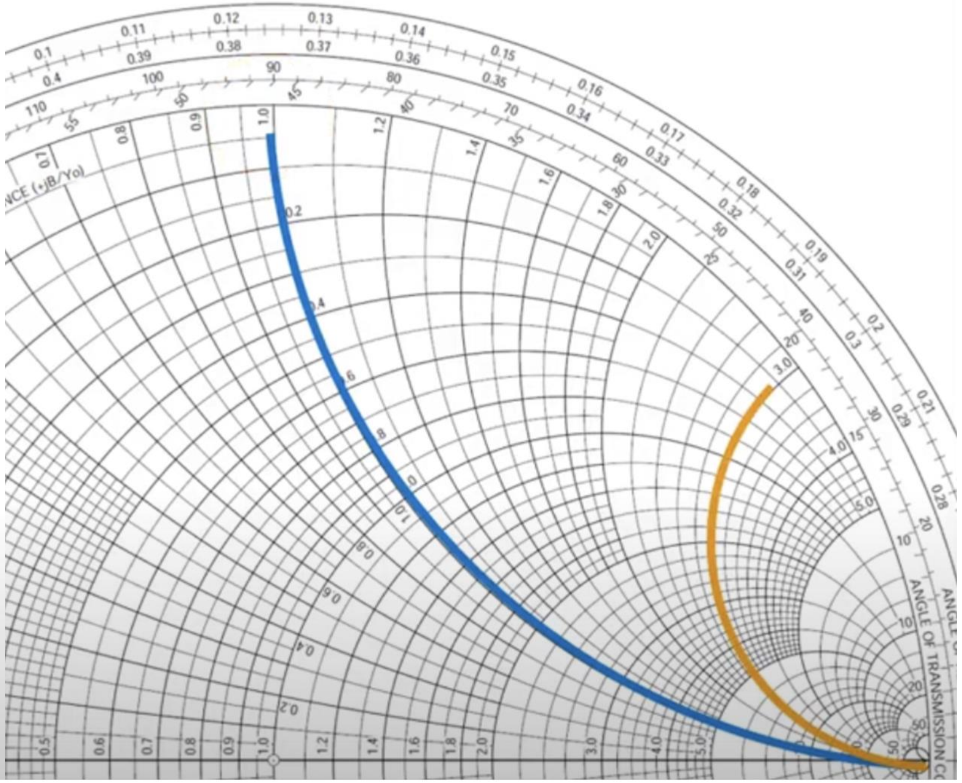
Curves of constant resistance



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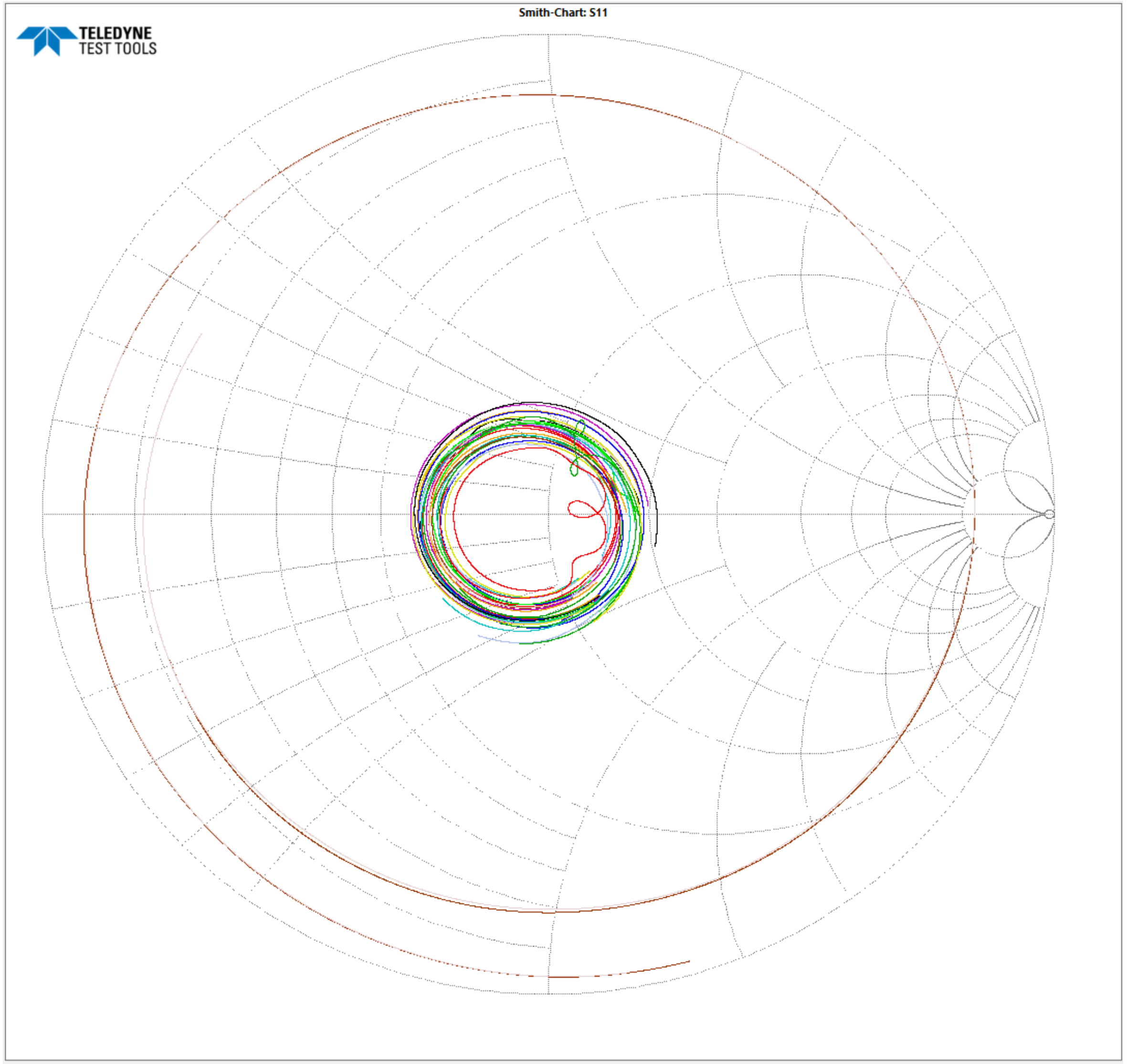
Curves of constant reactance

Important in order to illustrate which components the impedance is coming from

In many systems we want to minimize the the parasitic reactance contribution

Smith Chart



- Set-up: Sma+connector+optoboard
- For all uplinks
- Smith chart shows impedance as a function of frequency
- Constant resistance for all frequencies
- Reactance contribution is changing with frequency

Back-up

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- Nyquist-Shannon Theorem: sampling rate must be at least twice the band width
  - Uplink frequency = 1.38 Gb/s
  - Bandwidth = 0.64 Gb/s

- Rise Time = 0.35/BW
  - Rise Time ≈ 550

Coupling Example

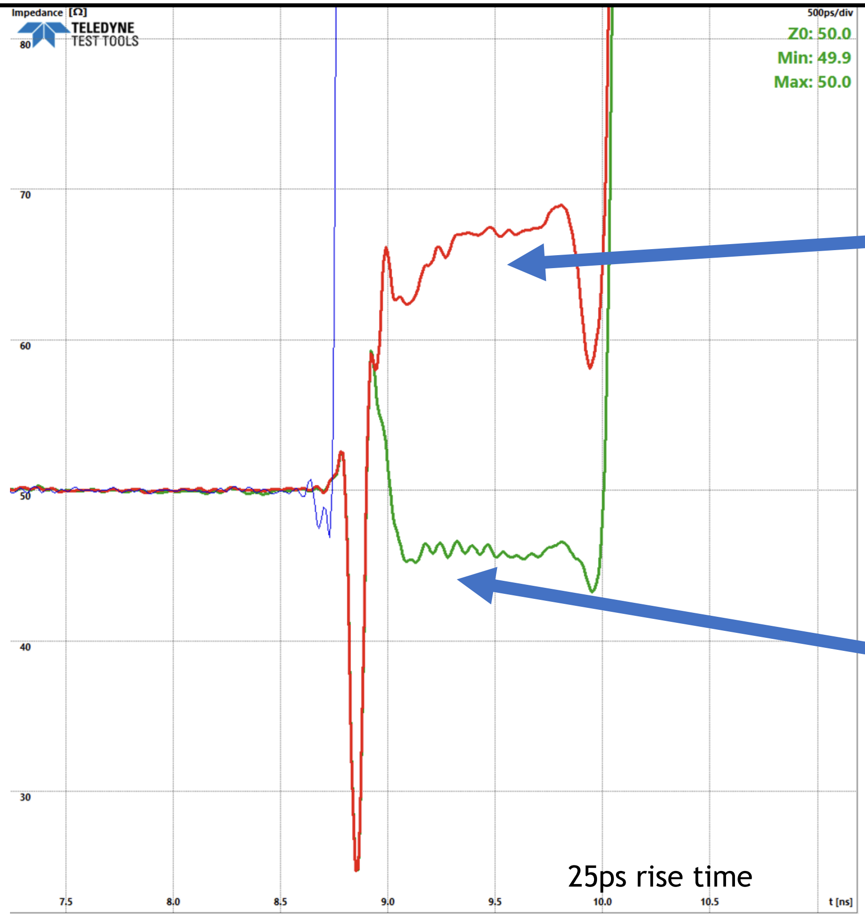
$$Z_{diff} = 2 * Z_{odd}$$

Z_{odd} = impedance of single transmission line when two lines in a pair are driven differential (like a single ended impedance but with effect of coupling)

Z_{odd} = $Z_{single\ ended}$ if no coupling occurs between transmission lines

Single ended and odd impedance is **not** the same -> coupling occurs in the board

$Z_{odd} \neq Z_{single}$



Time (ns)

Z_{single}

Z_{odd}

SMA cable

SMA + adapterboard (single ended)

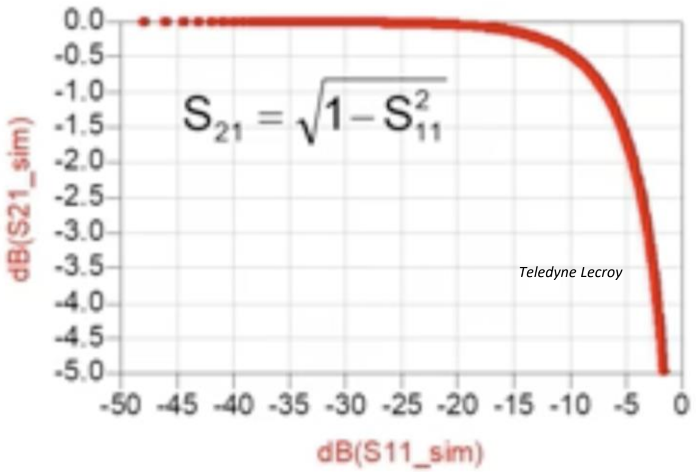
SMA + adapterboard (differential)

How much loss is acceptable?

- How does S_{11} affect S_{21}
- Conservation of energy!
  $1 = S_{11}{}^2 + S_{21}{}^2 +$ losses
- S_{21}= 0dB for perfect interconnect
- Only when S_{11} > -13 , S_{21} is affected!
- Typically S_{11} < -13 to have little impact on S_{21} and is allowed

If no other losses :

$$S_{21} = \sqrt{1 - S_{11}{}^2}$$



Impedance of Optoboard setup

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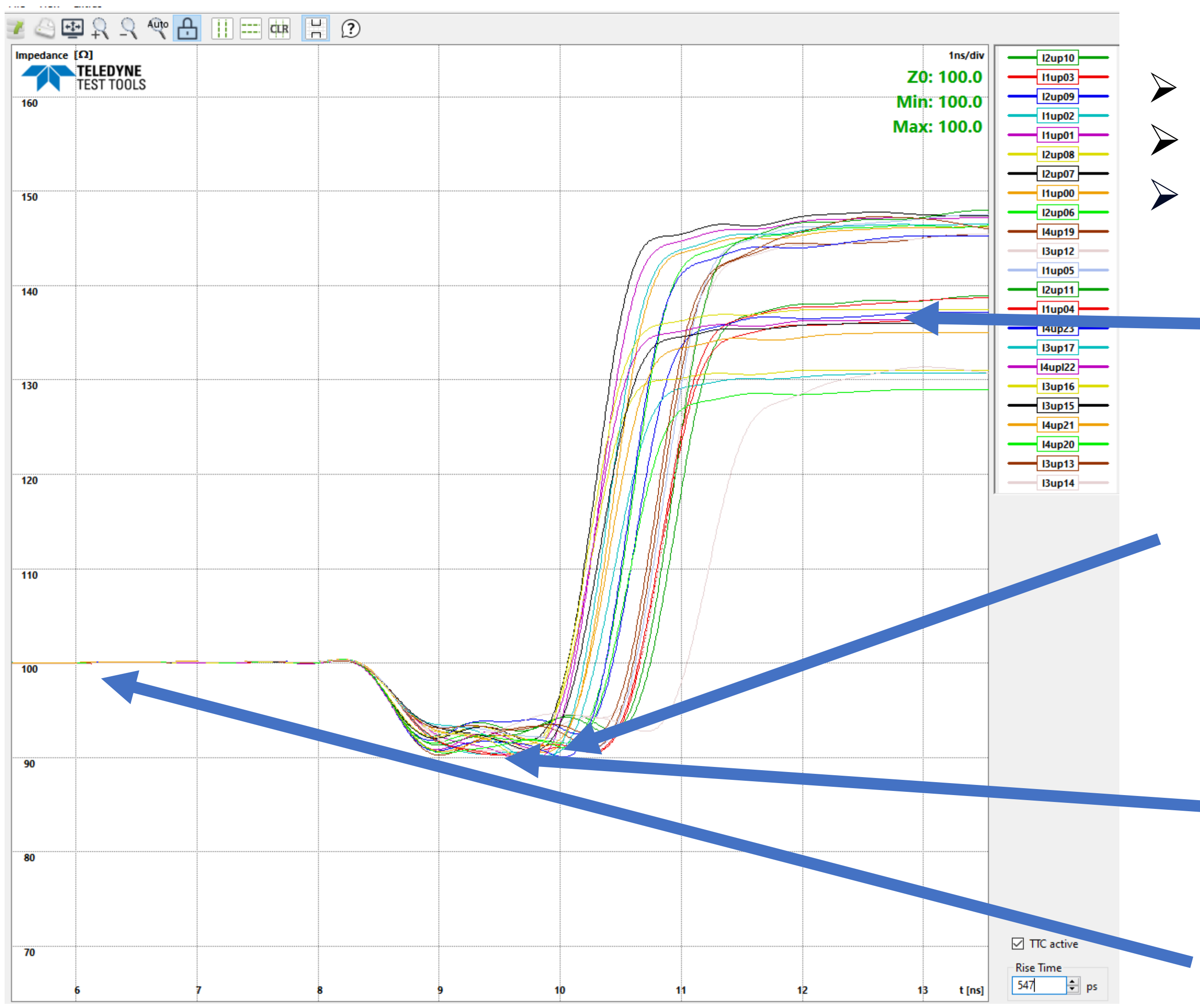
- Set-up: Sma+connector+optobaord
- All uplinks!
- Aim: Differential impedance of 100 Ω (within 10%)



GBCR (unknown reason for high impedance)

Optoboard (impedance cannot be resolved)

Connector Board (drop due to coupling)

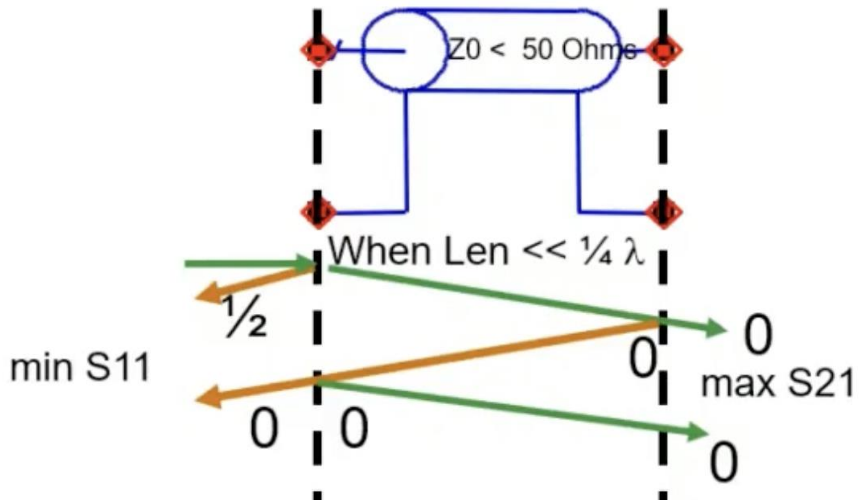
SMA (good SMA cable! Instantaneous impedance)

Common Trends: Ripples

Low to high $R = \frac{Z_2 - Z_1}{Z_2 + Z_1} > 0$

High to low $R = \frac{Z_2 - Z_1}{Z_2 + Z_1} < 0$

- 50 Ω material → < 50 Ω → 50 Ω
- Signal of low frequency Len << 1/4 **λ**
- High to low : reflecting wave out of phase
- Low to high: reflecting wave in phase
- S_{11} destructive and S_{21}constructive
- So… S_{11} = minimum and S_{21} maximum



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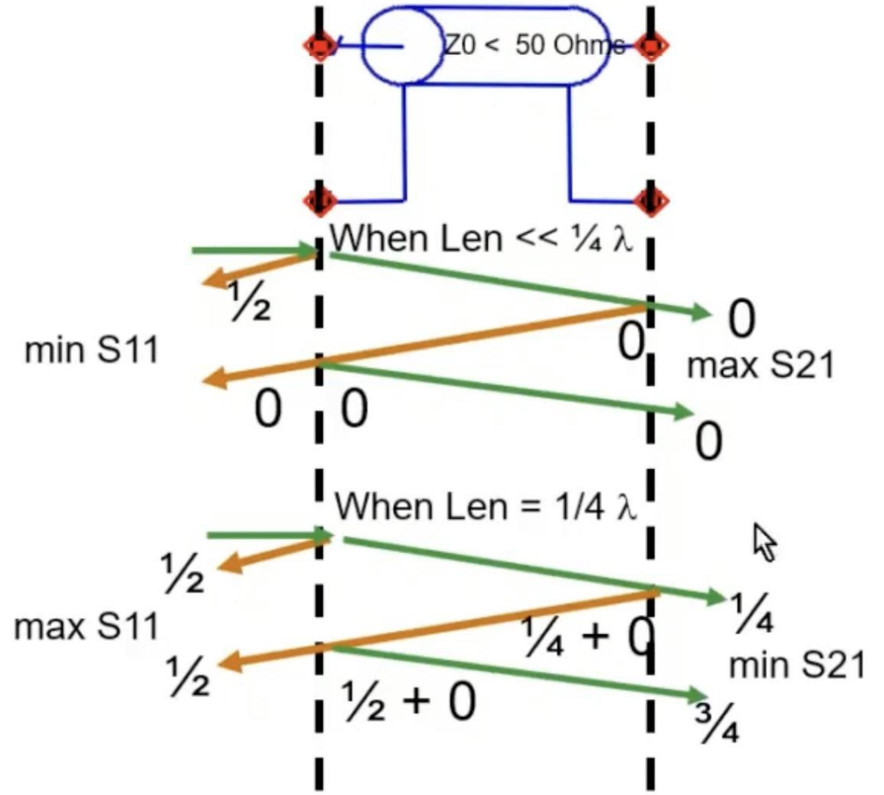
Common Trends: Ripples

- Now increase frequency such that Len =1/4 λ
- Following the same principle but now wave travels 1/4λ
- S_{11} constructive and S_{21}destructive
- … S_{11} = maximum and S_{21} minimum



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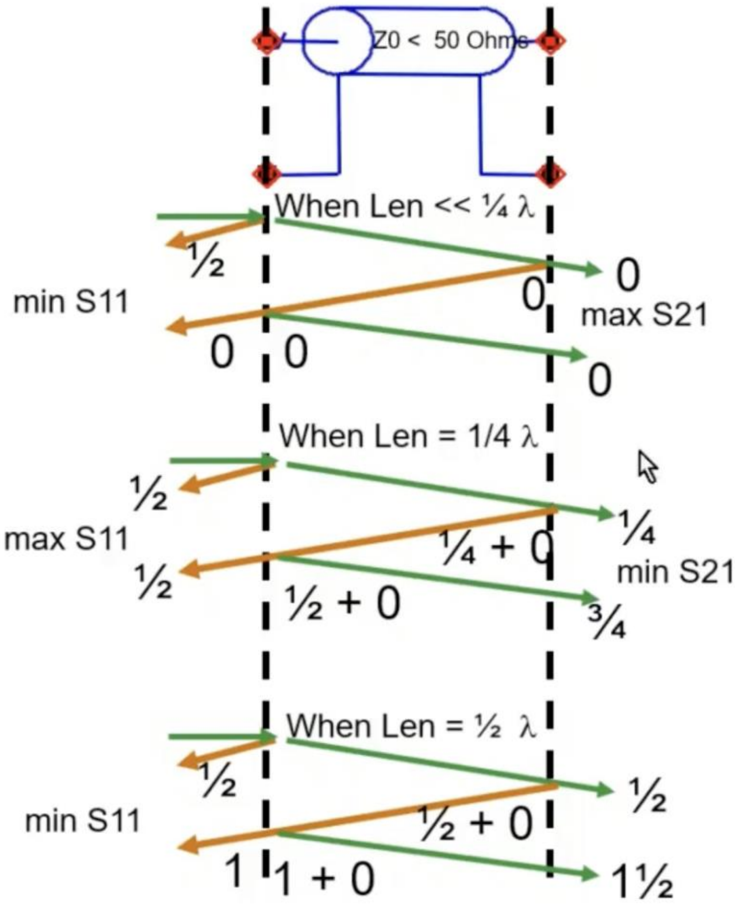
Common Trends: Ripples

- Now increase frequency such that Len =1/2 λ
- Following the same principle but now wave travels 1/2λ

- S_{11} destructive and S_{21}constructive
- … S_{11} = minimum and S_{21} maximum



Common Trends: Ripples

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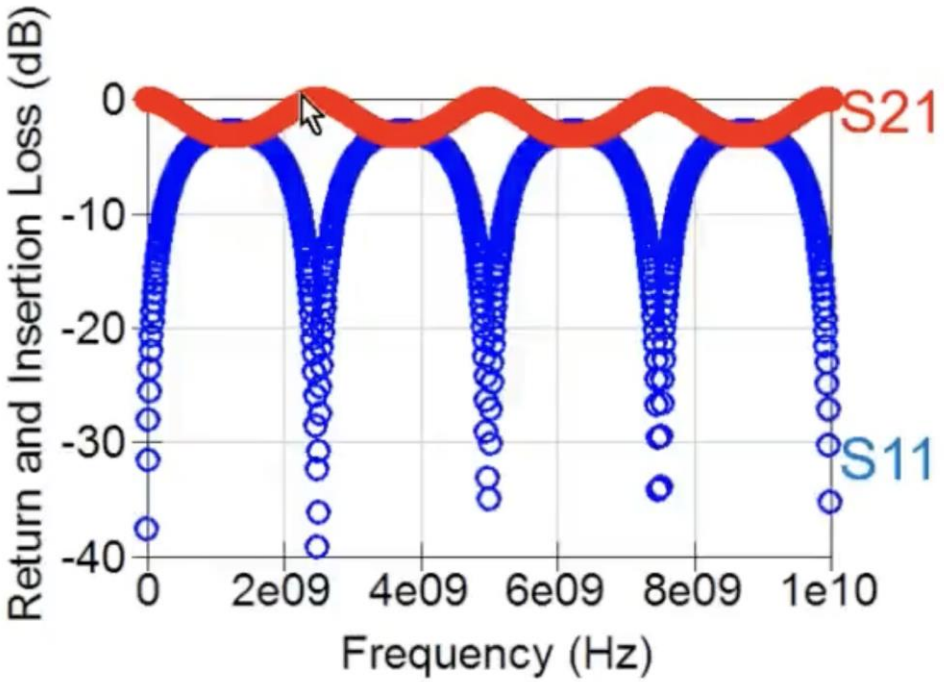
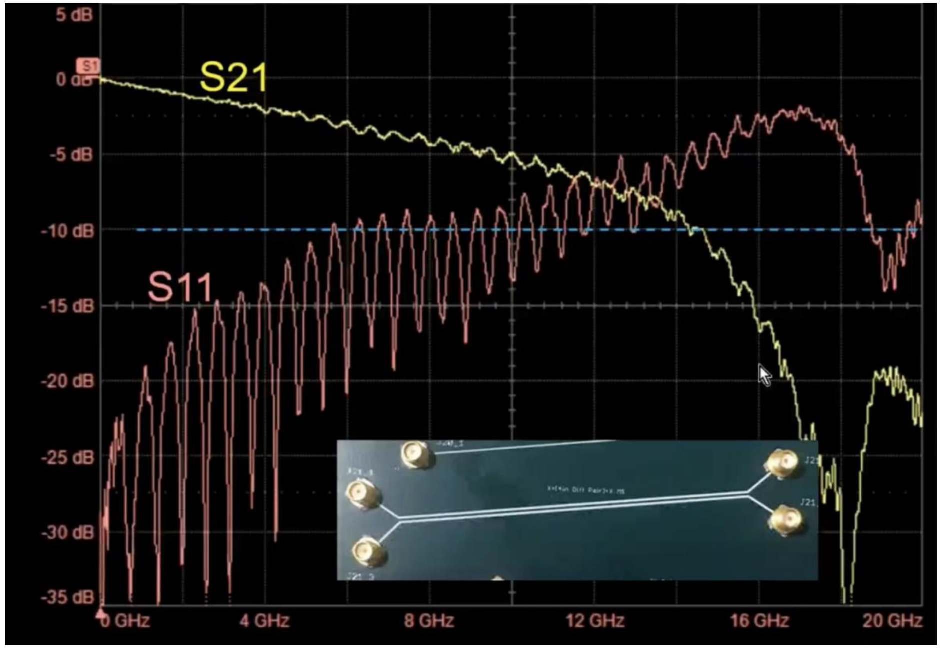
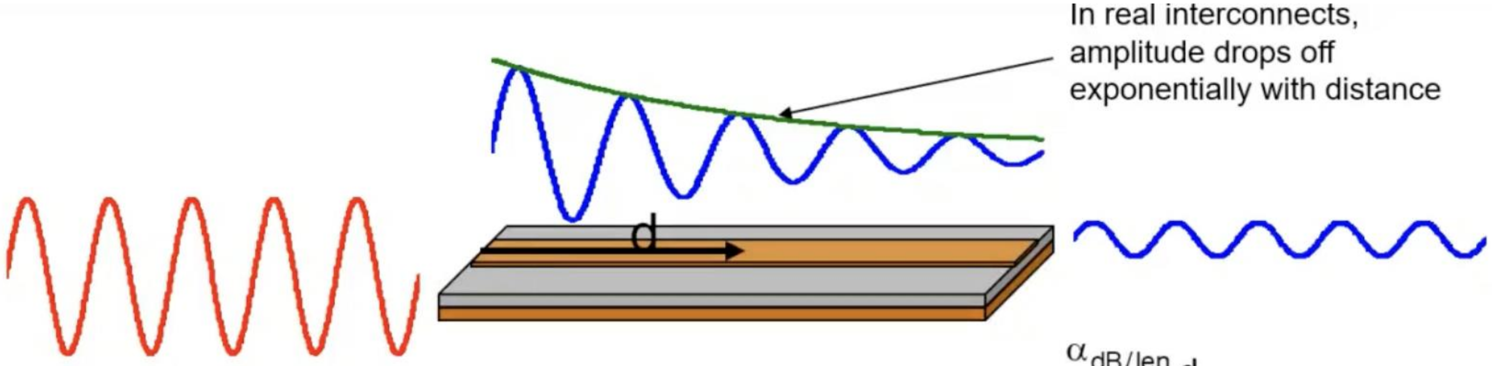
As frequency increases, ripples arise from construction and destruction of reflected waves!





S parameters and Attenuation



$$V_{out}(d) = V_{in} 10^{-\frac{\alpha_{dB/len}}{20} d}$$

$$20 \times \log\left(\frac{V_{out}}{V_{in}}\right) = -\alpha[dB/in] \times d$$

$$S21[in\ dB] = 20 \times \log\left(\frac{V_{out}}{V_{in}}\right) = -\alpha[dB/in] \times d = attenuation$$

S parameters and Attenuation

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$$S_{21}\ has\ 2\ main\ losses:\ dielectric\ loss + conductor\ loss$$

- Dielectric loss:
  - Periodic rotation of dipoles
  - Higher frequency -> more power dispatched -> attenuation increased

- Conductor loss:
  - Higher frequency-> more inductance contribution

- The loss is **frequency dependent**

- High frequency signals attenuate more than low frequency