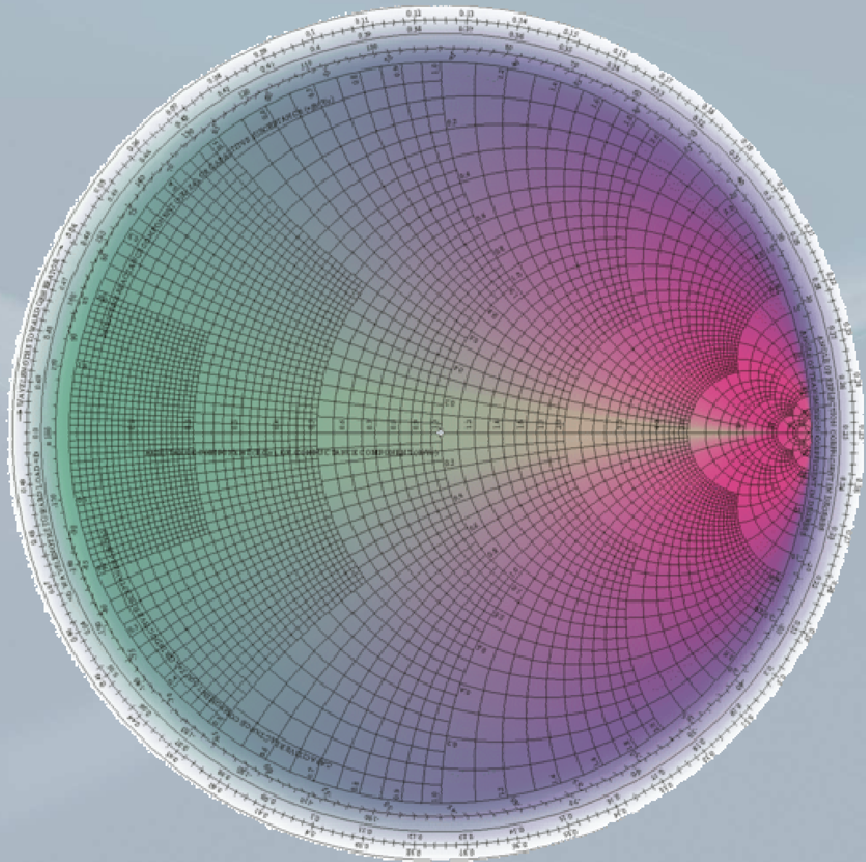
Evaluating signal integrity with a Vector Network Analyzer



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ROHDE & SCHWARZ

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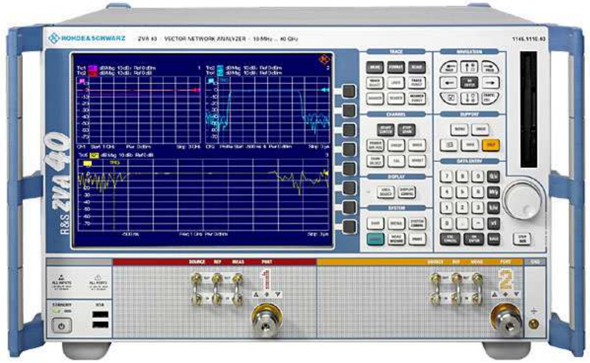
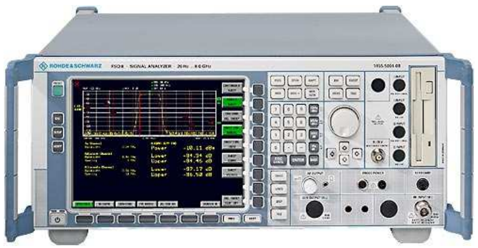
Agenda



- **Scalar vs. Vector analysis**
  - **Uses for each**
- **Transmission Lines**
- **S-Parameters**
  - **Wave quantities and wave ratios**
  - **How S-Parameters are derived from wave quantities**
- **Network Analyzer Architecture**
  - **Block diagram of ZVA**
- **Calibration**
  - **Importance of calibration**
  - **Use of calibration manager on the ZVA**
- **Signal Integrity measurements**
  - ***Time domain***
  - ***Balanced devices***

Spectrum Analyzers vs. Vector Network Analyzers



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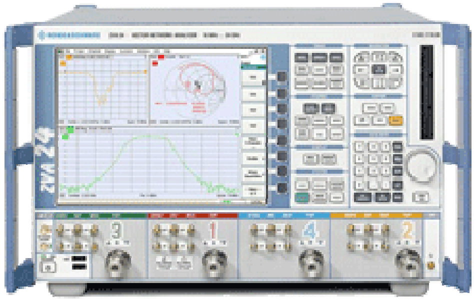


Measures Signals

Measures Devices

Spectrum Analyzers:

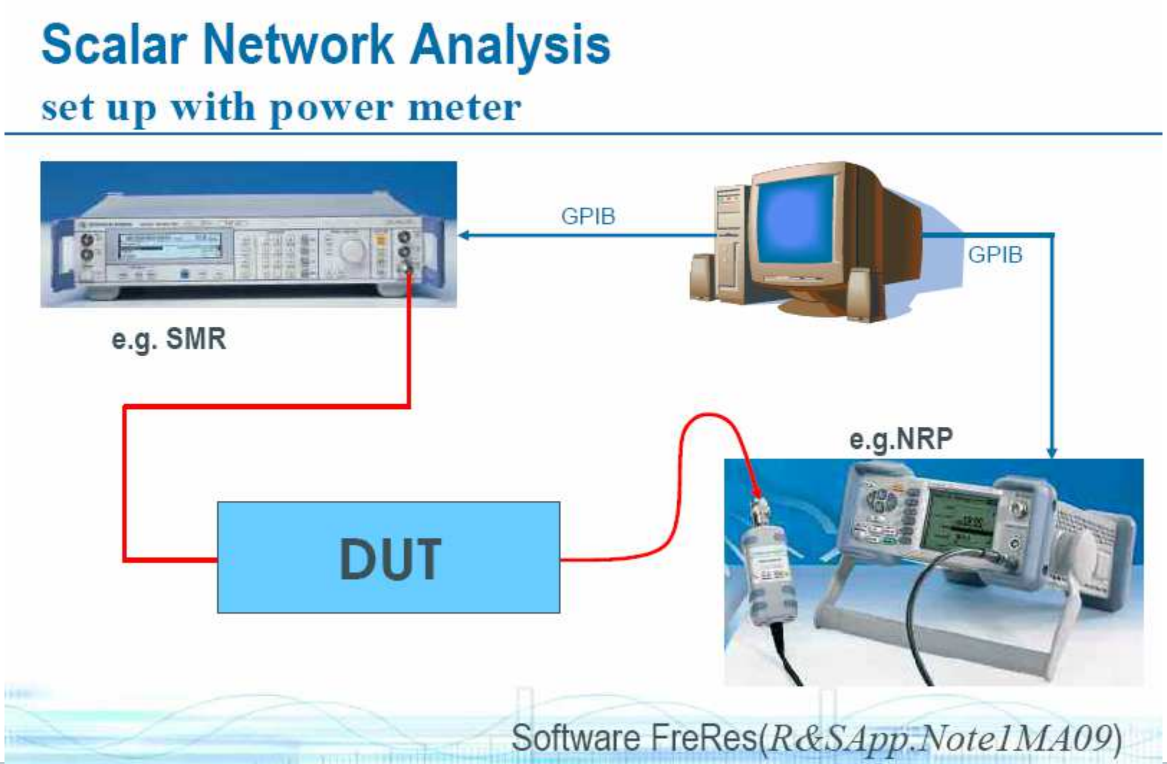
- Measure signal amplitude characteristics, carrier level, sidebands, harmonics..
- Can demodulate (+ measure) complex signals
- Spec Ans are receivers only (single channel)
- Can be used for scalar component test (no phase) with tracking gen. or external source

Network Analyzers:

- Measure components, devices, circuits, sub-assemblies
- Contains sources and receivers
- Display ratioed amplitude and phase (frequency, power or time sweeps)
- Offers advanced error correction.

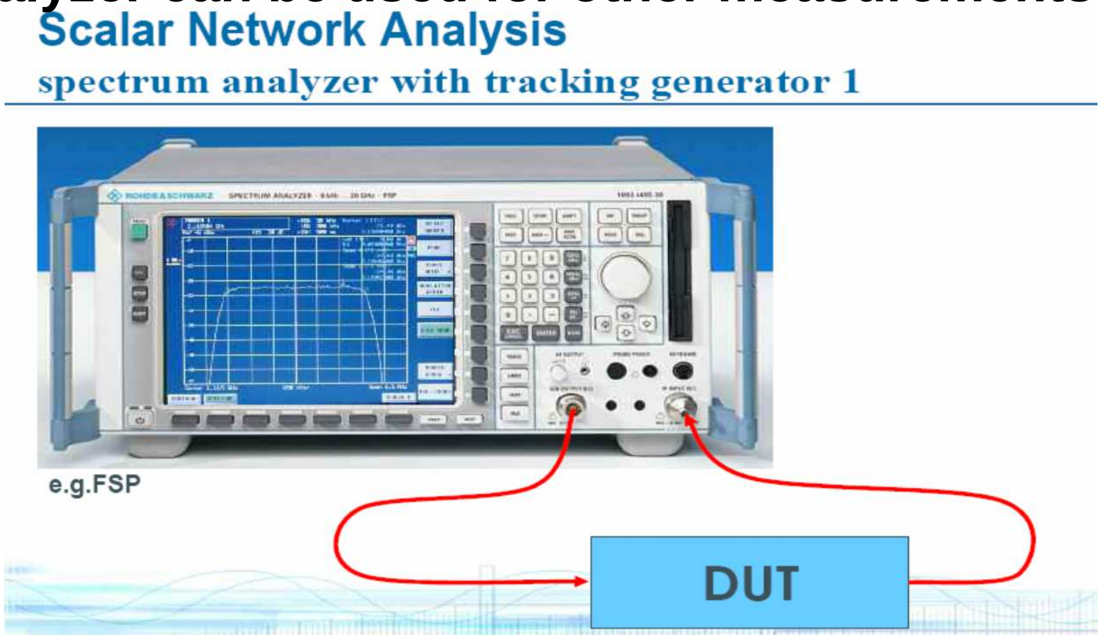
Scalar Network Analysis

- **Basic scalar analyzer can be a signal generator and a power meter**
- **Drawbacks are speed, dynamic range and no phase information**
- **Advantage is cost**



Scalar Network Analysis

- **Basic scalar analysis can be done with a spectrum analyzer, tracking generator or external generator**
- **Drawback is cost compared to signal generator and sensor**
- **Still no phase information**
- **Advantages are speed, dynamic range and spectrum analyzer can be used for other measurements**



What Devices do Vector Network Analyzers Test?

Filters

RF Switches

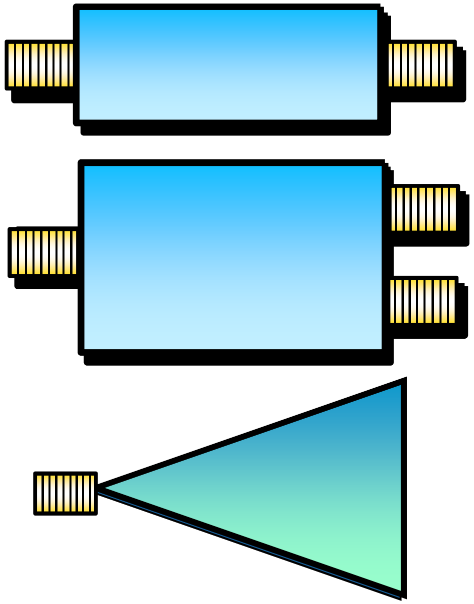
Couplers

Cables

Amplifiers

Antennas

Isolators



Mixers (upconverters, downconverters, also sometimes referred to as transmitters and receivers)

…Most 2 (or more) port devices (and some 1 port devices)

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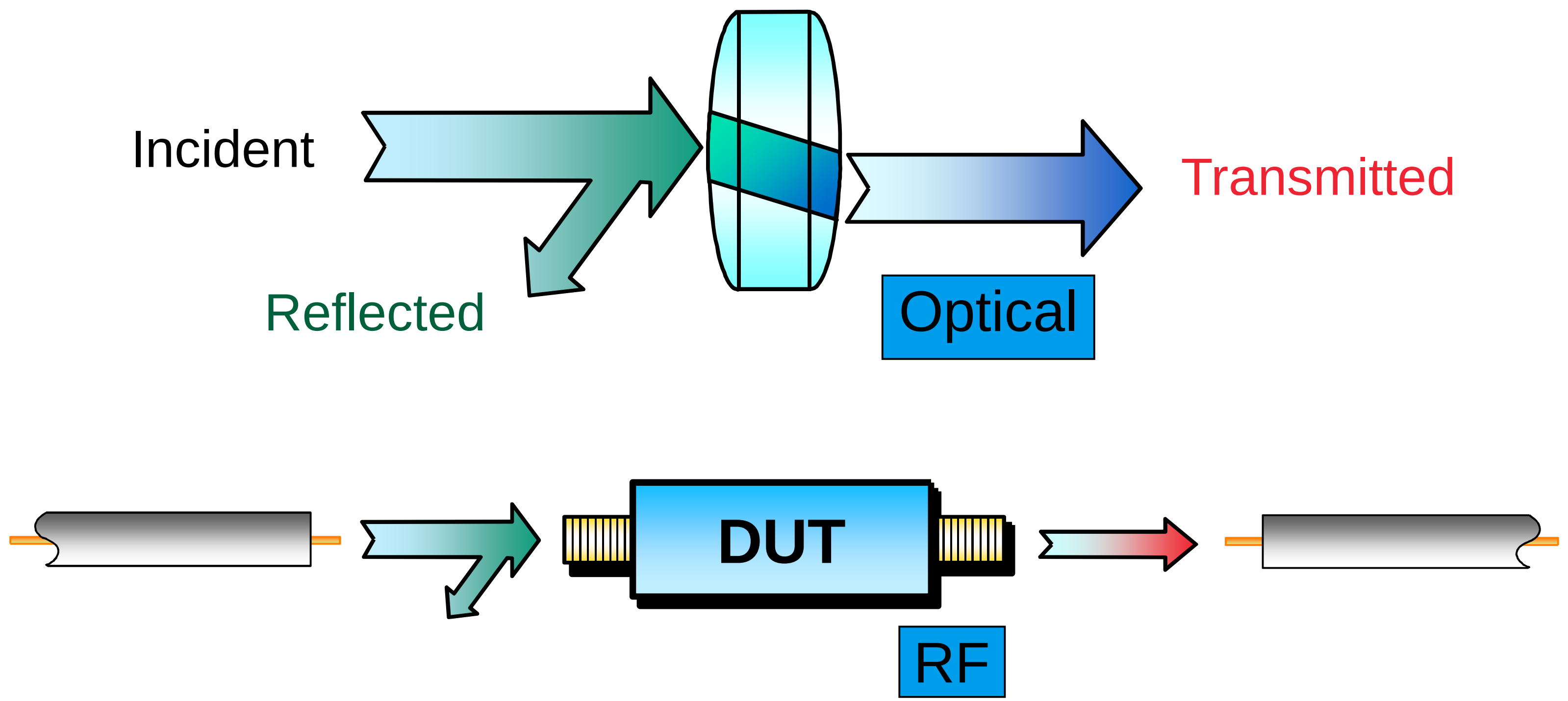
Optical Analogy to RF Transmission

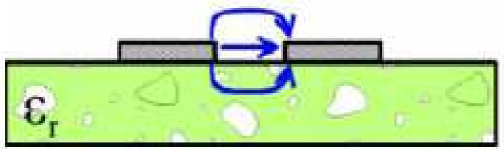
- **Network analyzers measure transmitted and reflected signals relative to the incident signal**
- **Scalar analyzers measure magnitude only, vector analyzers measure magnitude and phase of these signals**



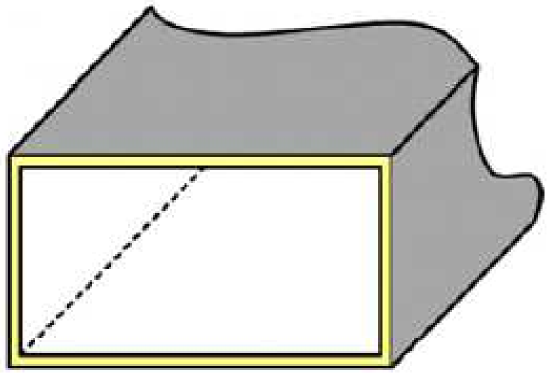
Transmission Lines

Parallel Lines

Coax Cable

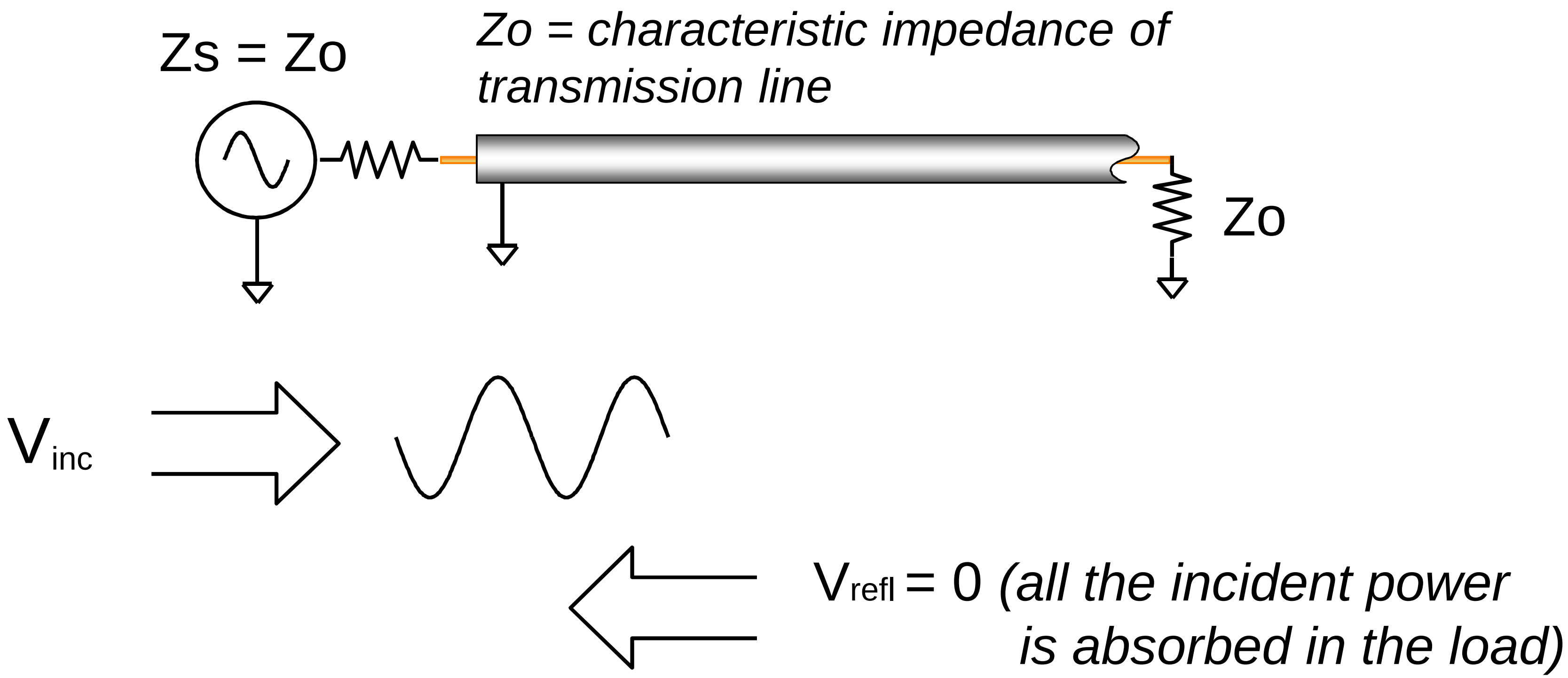


Microstrip Line



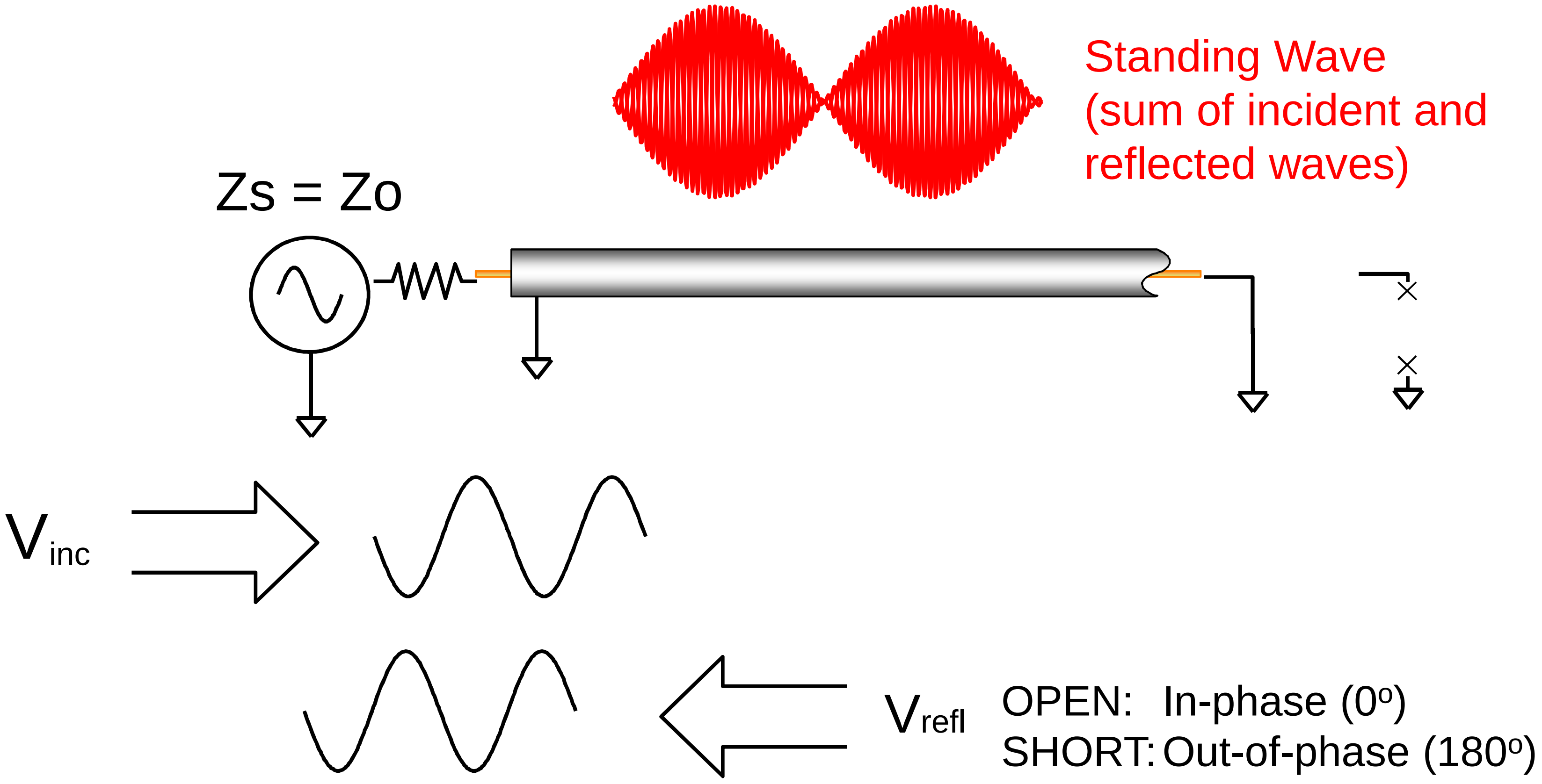
Waveguide

Transmission Line Terminated with Zo



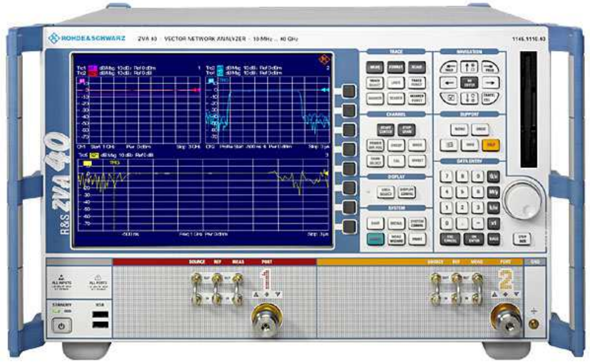
A transmission line terminated in Zo behaves like an infinitely long transmission line

Transmission Line Terminated with Short, Open



A transmission line terminated in a short or open reflects all power back to source

Agenda



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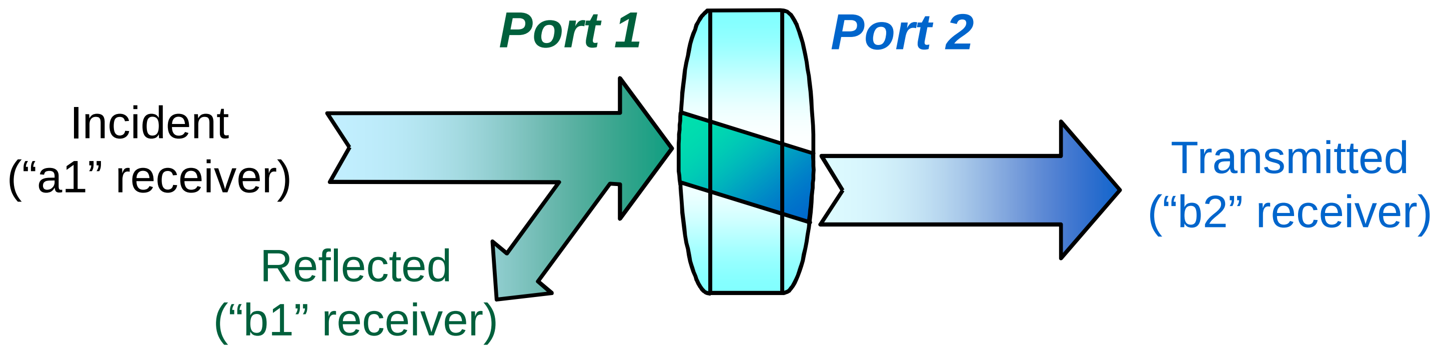
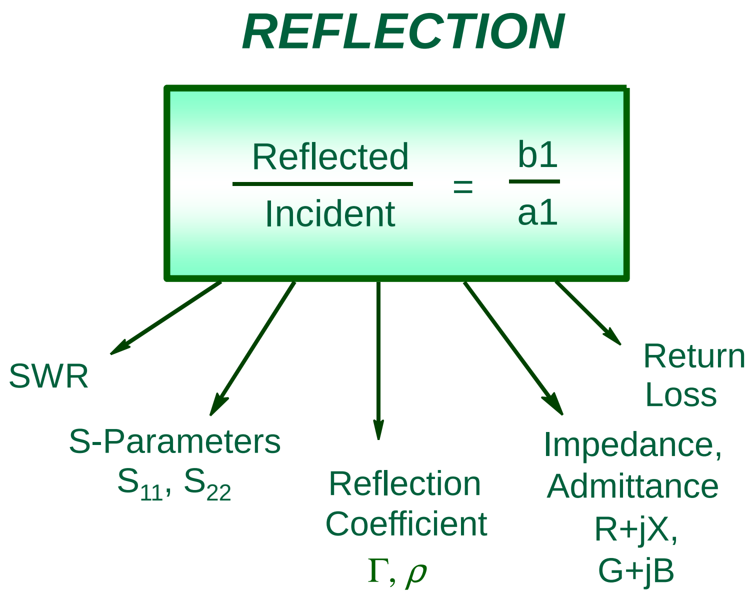
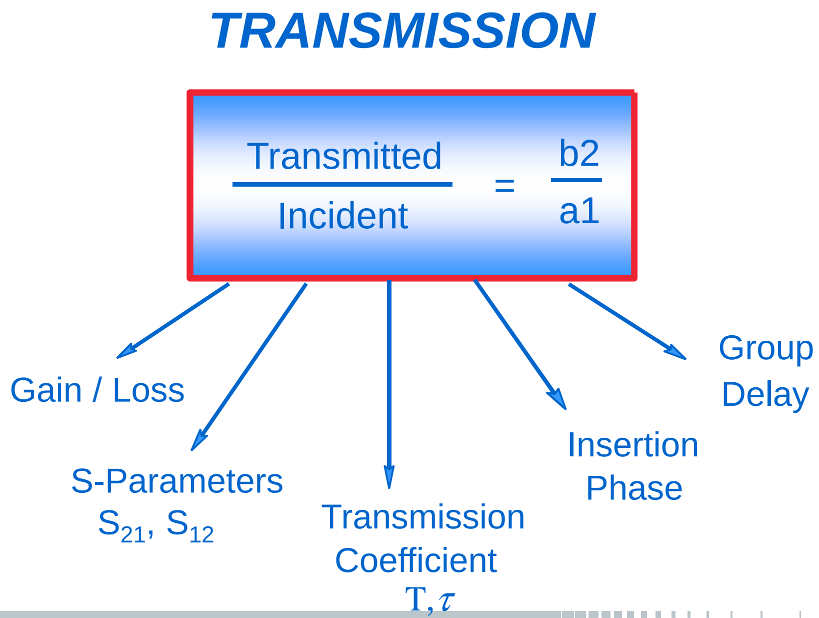
High-Frequency Device Characterization

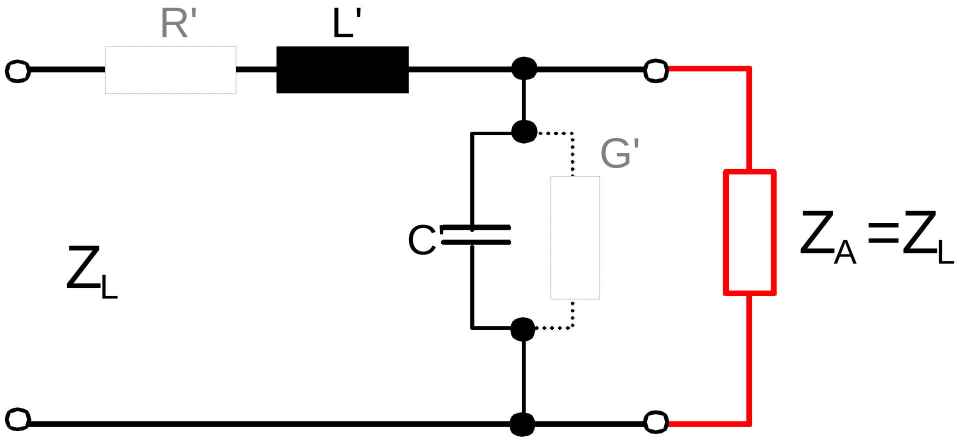


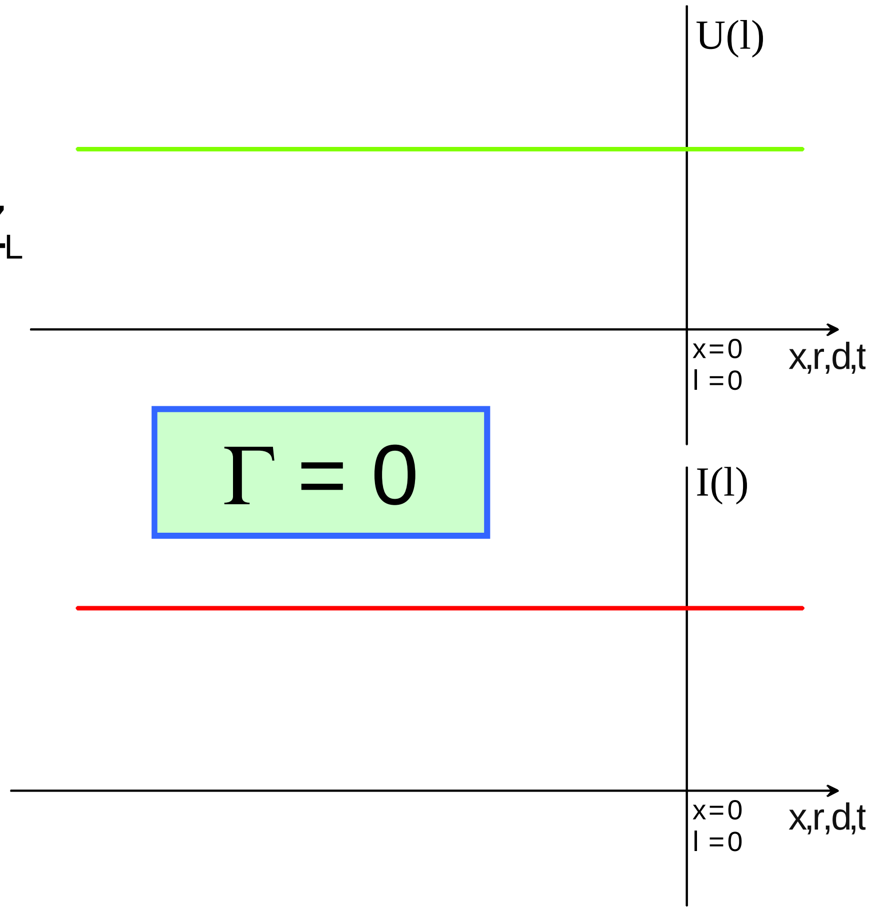




Reflection and transmission

Termination with line impedance (MATCH)

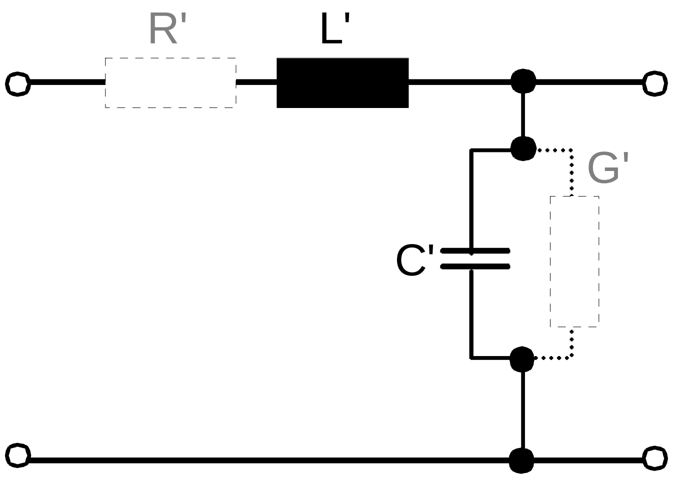


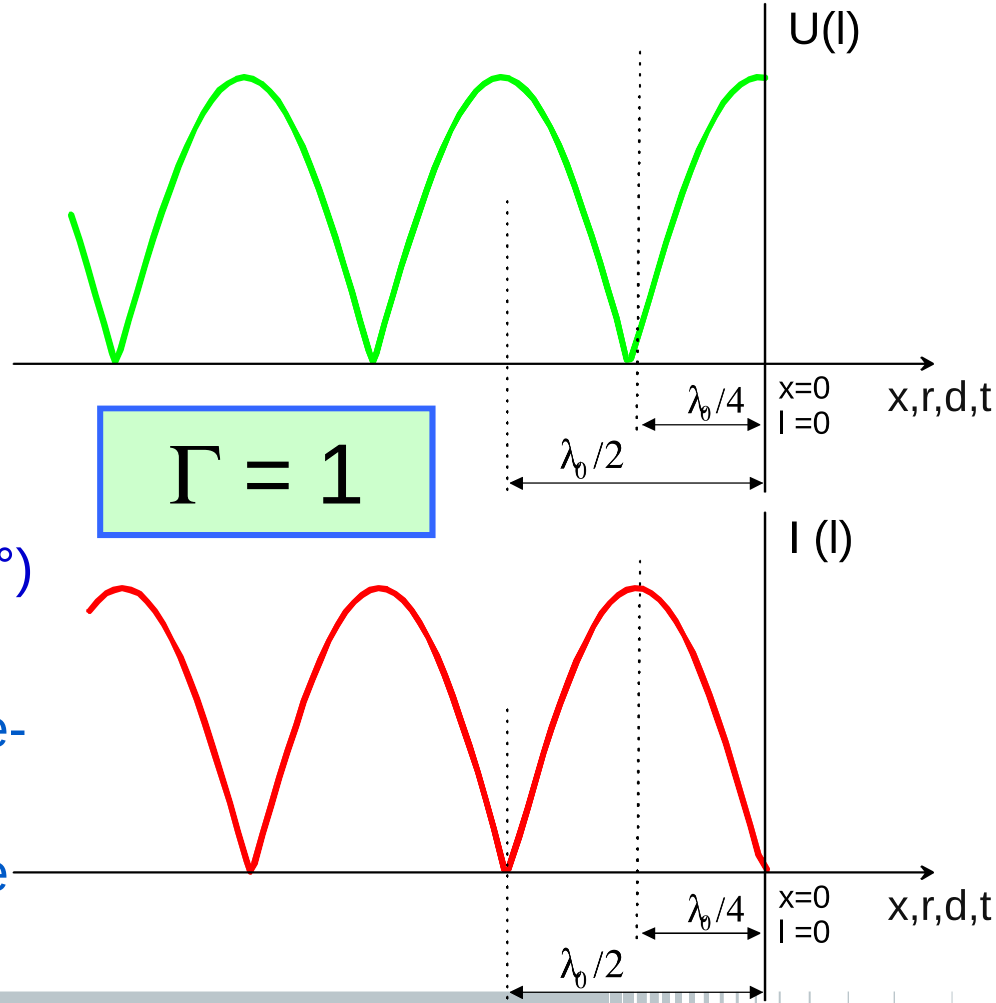


- Current and voltage in phase
- Perfect traveling wave
- No space dependence
- Perfect power transmission from source to drain

Reflection and transmission

Open line: (OPEN) $Z_a = \infty$

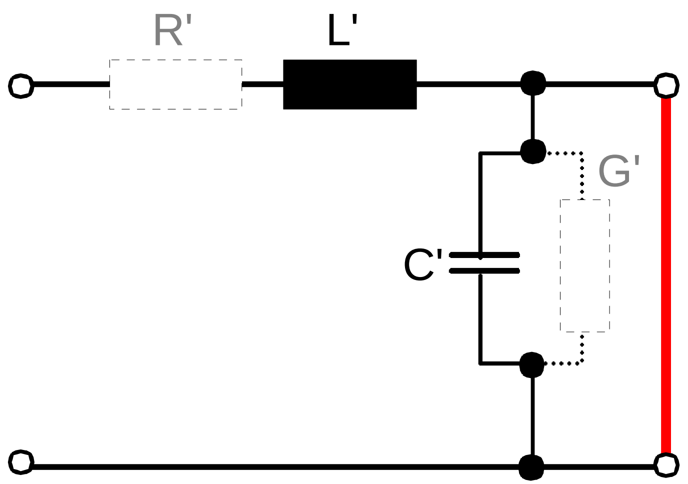


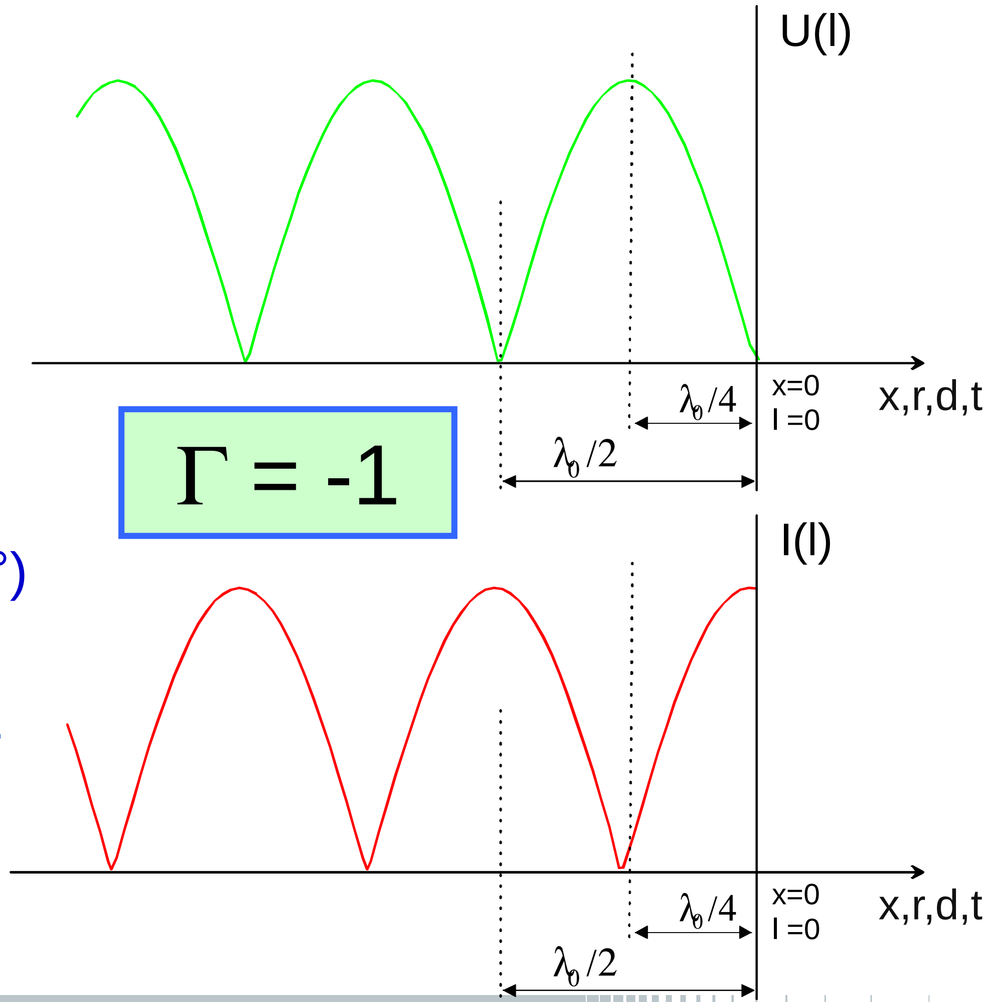


- Reactive behavior ($\Delta\varphi_{U,I} = -90°$)
- Standing wave
- Current and voltage are space-dependent
- Power oscillates along the line

Reflection and transmission

short-circuited line: (SHORT) $Z_a = 0$

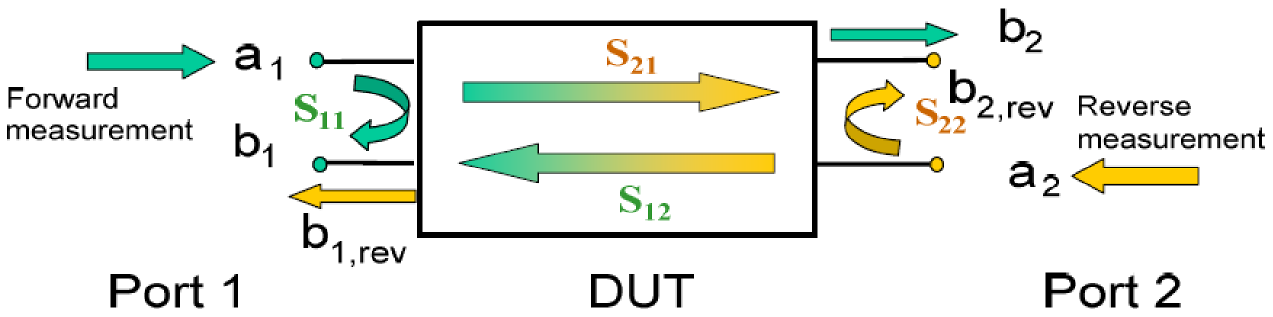




- Reactive behavior ($\Delta\varphi_{U,I} = +90°$)
- Standing wave
- Current and voltage are space-dependent
- Power oscillates along the line

S-Parameters, wave quantities and their relationship

S-parameters are the basic measured quantities of a network analyzer. They describe how the DUT modifies a signal that is transmitted or reflected in forward or reverse direction. For a 2-port measurement the signal flow is as follows:

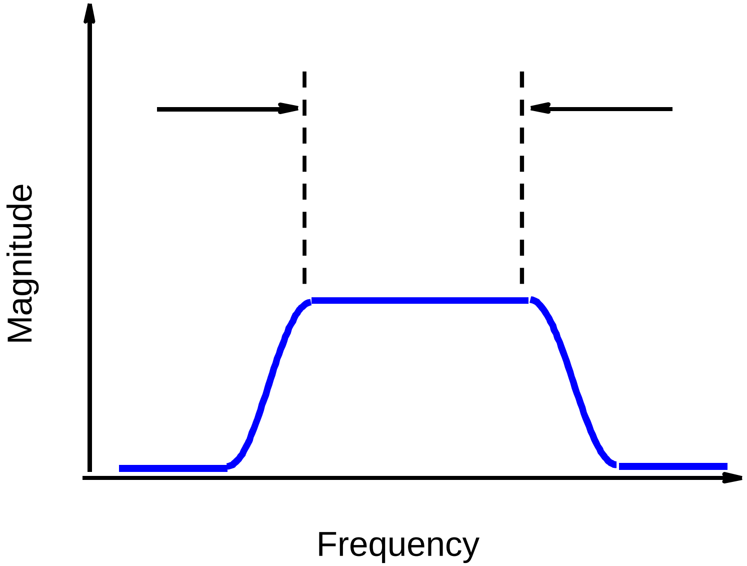


- S_{11} isthe input reflection coefficient, defined as the ratio of the wave quantities b_1/a_1, measured at PORT 1 (forward measurement with matched output and $a_2 = 0$).
- S_{21} is the forward transmission coefficient, defined as the ratio of the wave quantities b_2/a_1 (forward measurement with matched output and $a_2 = 0$).
- S_{12} is the reverse transmission coefficient, defined as the ratio of the wave quantities b_1 (reverse measurement with matched input, $b_{1,rev}$ in the figure above and $a_1 = 0$) to a_2.
- S_{22} is the output reflection coefficient, defined as the ratio of the wave quantities b_2 (reverse measurement with matched input, $b_{2,rev}$ in the figure above and $a_1 = 0$) to a_2, measured at PORT 2.

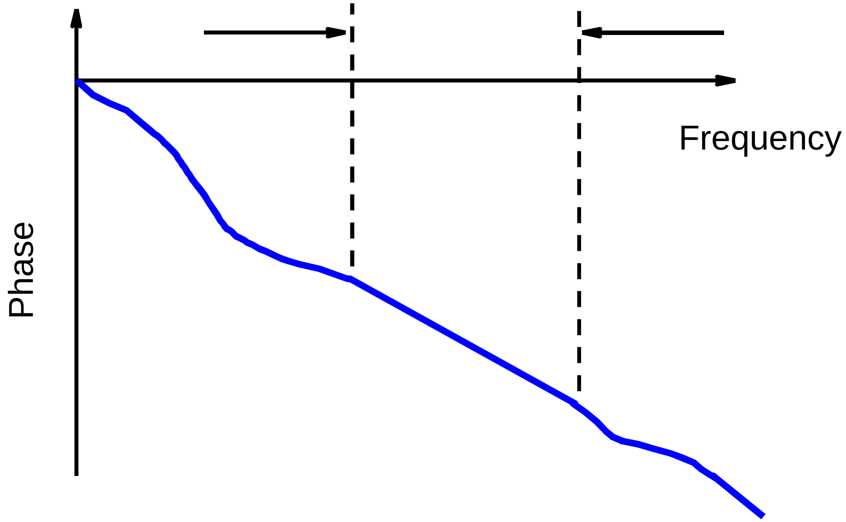
See page 59 of the ZVA user manual

Criteria for Distortionless Transmission

Constant amplitude over bandwidth of interest



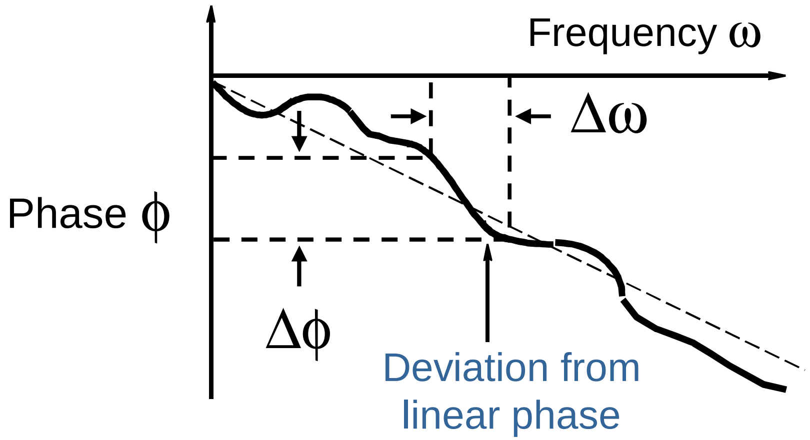
Linear phase over bandwidth of interest

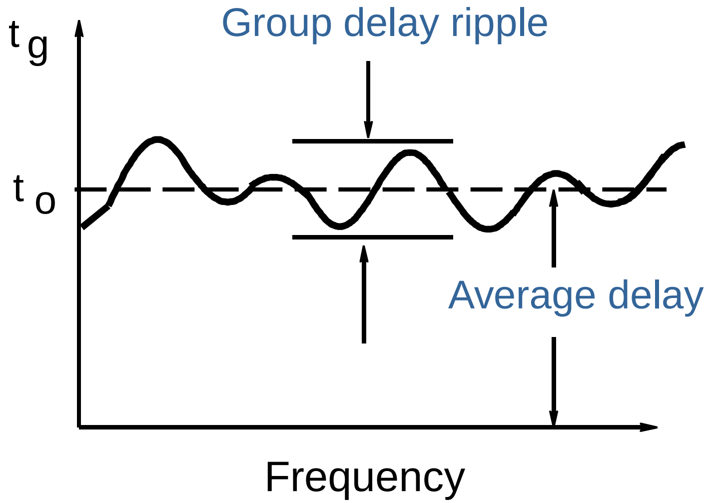


Distortion is indicated by:

- **Deviation from constant amplitude**
- **Deviation from linear phase (or stated another way...)**
- **Non-constant group delay**

Group Delay





Group Delay =

$$\frac{-d\varphi}{d\omega} = \frac{-1}{360^\circ} * \frac{d\phi}{df}$$

φ in radians

ω in radians/sec

ϕ in degrees

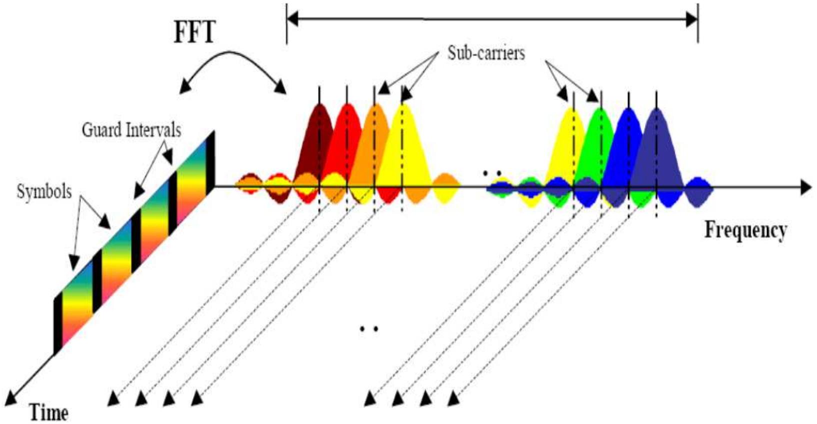
f in Hertz ($\omega = 2\pi f$)

- VNAs calculate group delay from phase measurement across frequency
- Group-delay ripple indicates phase distortion (deviation from linear phase)
- Average delay indicates electrical length of DUT
- Aperture of group delay measurement is very important

Real world example of distortion: OFDMA and EVM

- Consider an OFDMA signal that is 20 MHz wide, 1201 sub-carriers
- With “nearly flat” amplitude and phase response…

  - **EVM is ~ 55 dBc; a fairly low value.**



Real world example of distortion: OFDMA and EVM

- Introduce "linear" amplitude and phase distortion via a channel filter, which primarily impacts the band edges…
  - **Approximately 0.5 dB of amplitude response**
  - **Approximately 2.5 nS of group delay response**
- EVM is now 35 dBc at the band edges
- Poor EVM can result in lost data, which means retransmission of data, which means lost $$$$$

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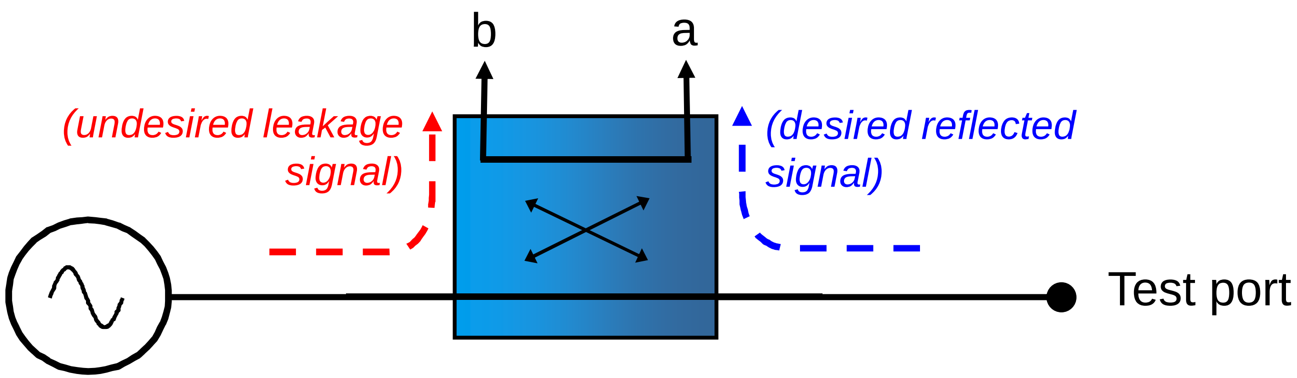
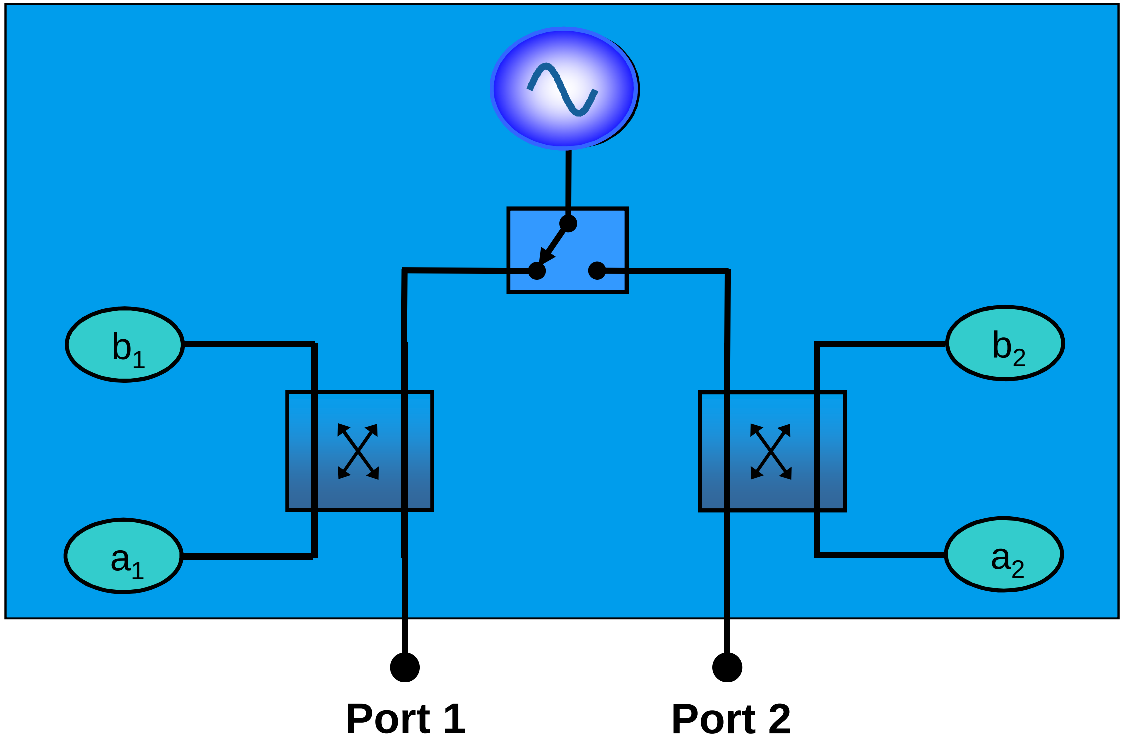
Directional Coupler – Directivity

- **Directivity is a measure of how well a coupler can separate signals moving in opposite directions**
- **A termination at the test port should result in no signal at the b receiver**
- **The difference between the coupled signal and the leakage signal is the directivity of the coupler (typical values: 15-25dB)**



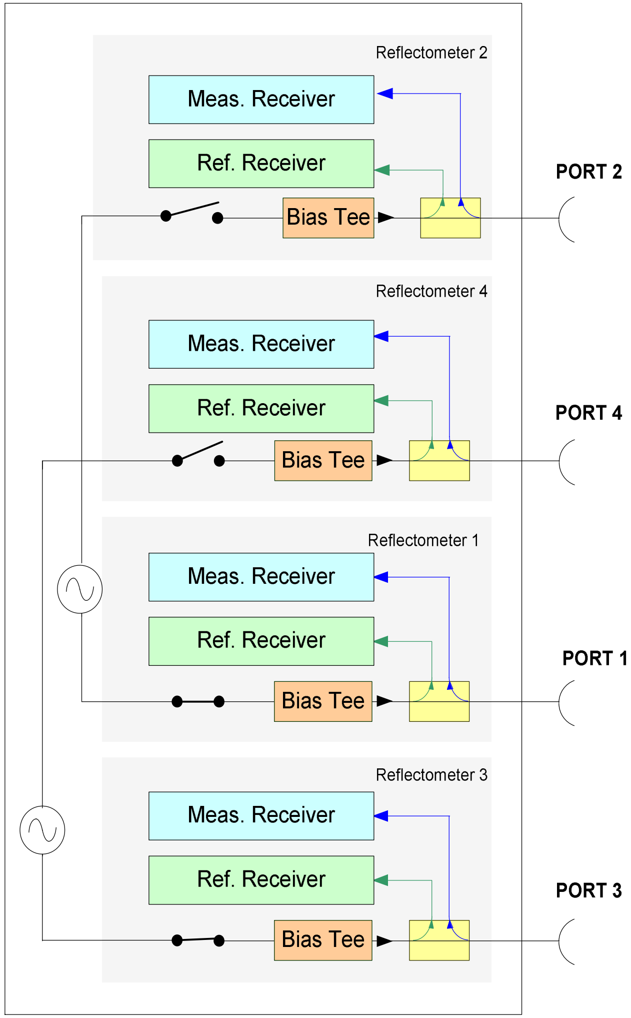
Directional Coupler

Vector Network Analyzer Block Diagram

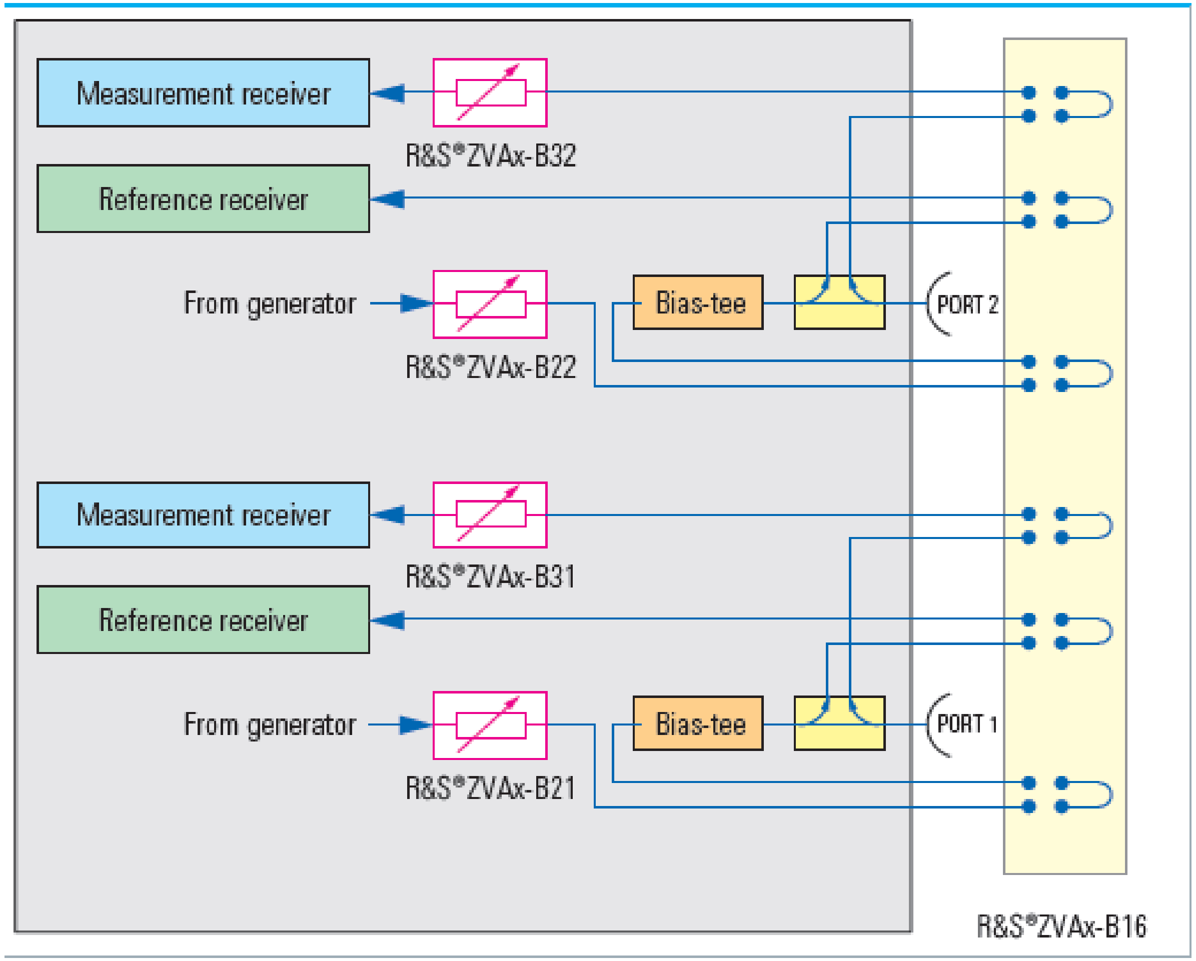


“a” receiver is also known as reference receiver
“b” receiver is also known as measure receiver

ZVA 4-Port Test Set



ZVA 2-Port Test Set with direct receiver access (B16)



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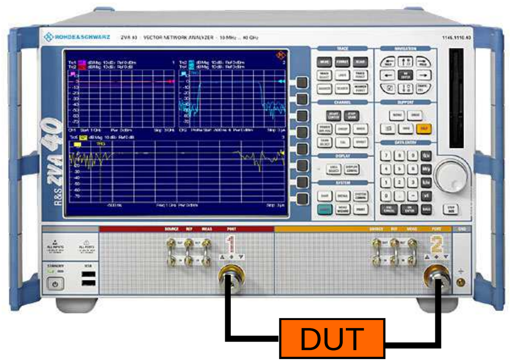
Measurement Errors (Calibration)



<u>Drift Errors</u>

- Caused by changes in environment after calibration (temperature, humidity)
- Minimized by controlling test environment

<u>Random Errors</u>

- Caused by instrument noise, switch and connector repeatability
- Not repeatable
- Minimized by high quality equipment and ***good measurement practices***

cannot be removed – only minimized

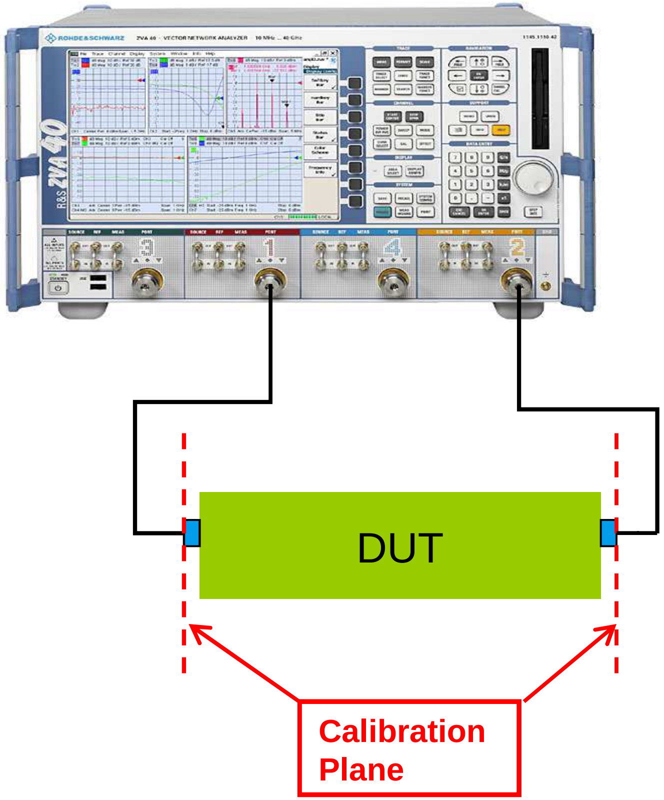
<u>Systematic Errors</u>

- Due to non-ideal components in the VNA and test setup
- Assumed to be repeatable
- **Calibration** is used to correct for these errors
- Residual error limited by quality of calibration standards

removed (nearly) with calibration

Calibration

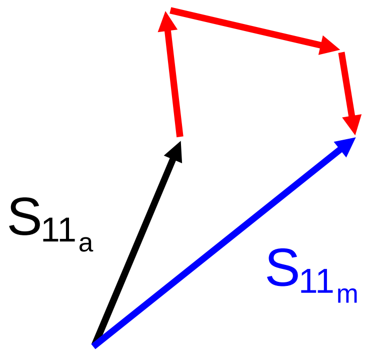
- We only want to measure our DUT (device under test) and nothing else!
- Need to remove the phase and amplitude response of our test setup
- Connect known standard (something we know) to the "calibration plane"

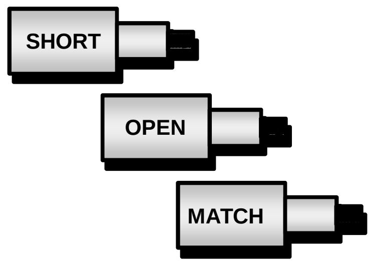


Types of Error Correction

- **Response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- **Vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error





Vector Error Correction

- Process of characterizing systematic error terms
  - Measure known standards
  - Remove effects from subsequent measurements

- 1-port calibration *(reflection measurements)*
  - Only 3 systematic error terms measured
  - Directivity, source match, and reflection tracking

- Full 2-port calibration *(reflection and transmission measurements)*
  - 10 systematic error terms measured (crosstalk assumed to be zero)
  - Usually requires 7 measurements on four known standards (TOSM)
  - Thru need not be characterized (unknown thru calibration)

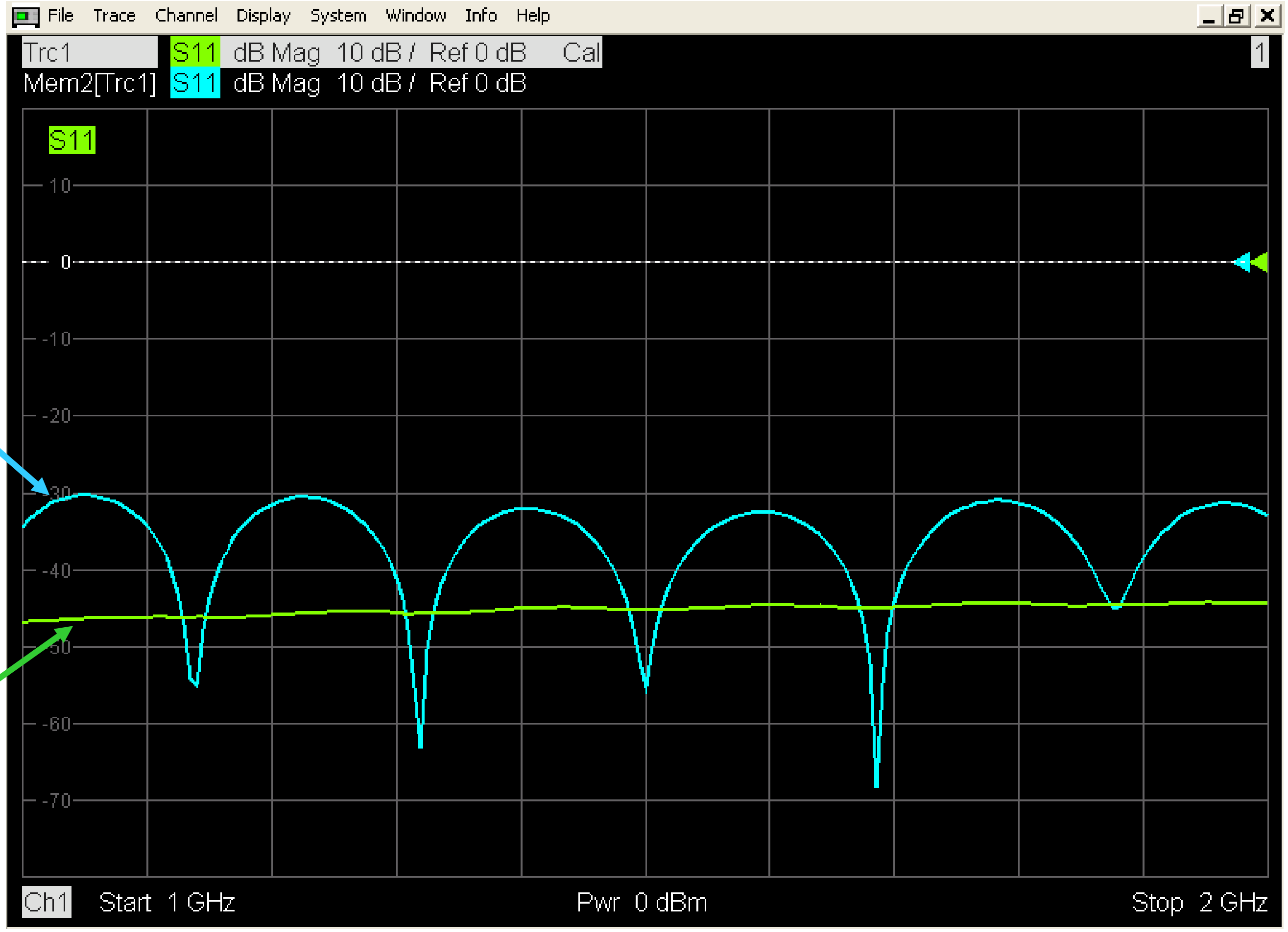
- Standards defined in cal kit definition file
  - Network analyzer contains standard cal kit definitions
  - CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!
  - User-built standards must be characterized and entered into user cal kit

Improvement from a One-Port Calibration

Measurement of match at the end of a 2ft cable

uncalibrated

1-port cal



Methods of De-embedding

- Simple delay (port extension)
  - Simply moves reference plane (mathematically)
  - Assumes fixture is ideal transmission line with fixed delay
  - Simple loss model can optionally be included
  - Delay can be entered explicitly or measured with an open or short

- Fixture Compensation
  - Models fixture vs. frequency (delay and loss)
  - Does not assume fixture is simple ideal transmission line
  - Compensation can be measured with open, short, or both
  - AFR can also be done

- De-Embedding
  - Models fixture as lumped element network or…
  - Uses measured S-parameters of fixture to de-embed
  - Most accurate, but S-parameters can be difficult to measure for some fixtures

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Introduction – Signal Integrity

- Signal Integrity is a set of measures of the quality of an electrical signal

- Two Key Aspects of SI:
  - Timing which can be quantified as Jitter
  - Signal Quality which can be described with parameters such as ringing, crosstalk, etc.

- Jitter can be measured directly in the time-domain using an oscilloscope or in the frequency-domain using a phase noise analyzer

- Signal Quality can be measured in the time-domain using a high-speed TDR technique or in the frequency-domain using a vector network analyzer (s-parameters).

- IEEE P802.3ap Task Force uses S-parameters as test cases for proposed solutions to the problem of 10 Gbit/s ethernet over backplanes.

Measurement Techniques for Balanced Devices

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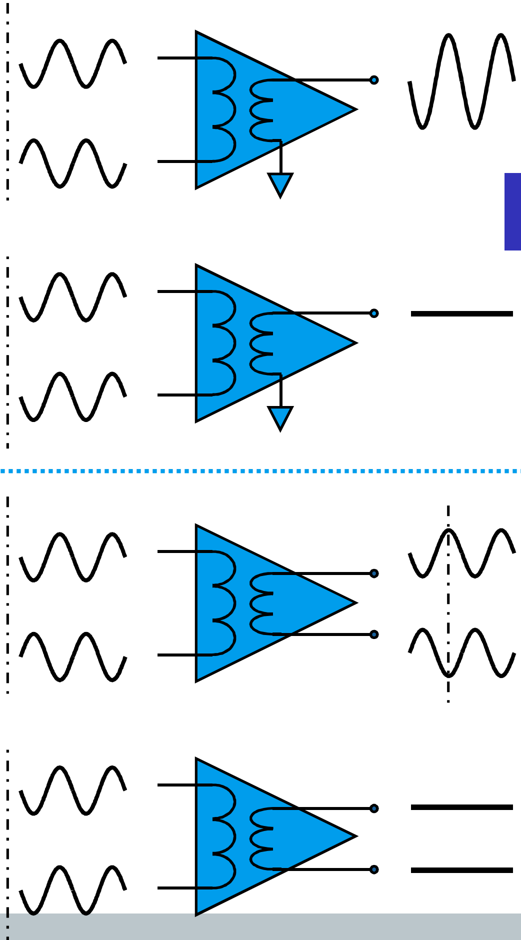
Balanced Devices

Ideal device responds to differential input signals and rejects common-mode input signals

Differential-mode signal

Common-mode signal

(EMI or ground noise)



Balanced to single-ended

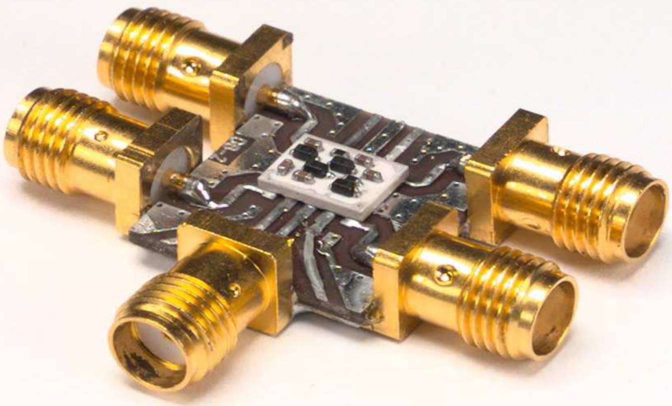
Differential-mode signal

Common-mode signal

(EMI or ground noise)

Fully balanced

Balanced devices – Why Balanced Design?

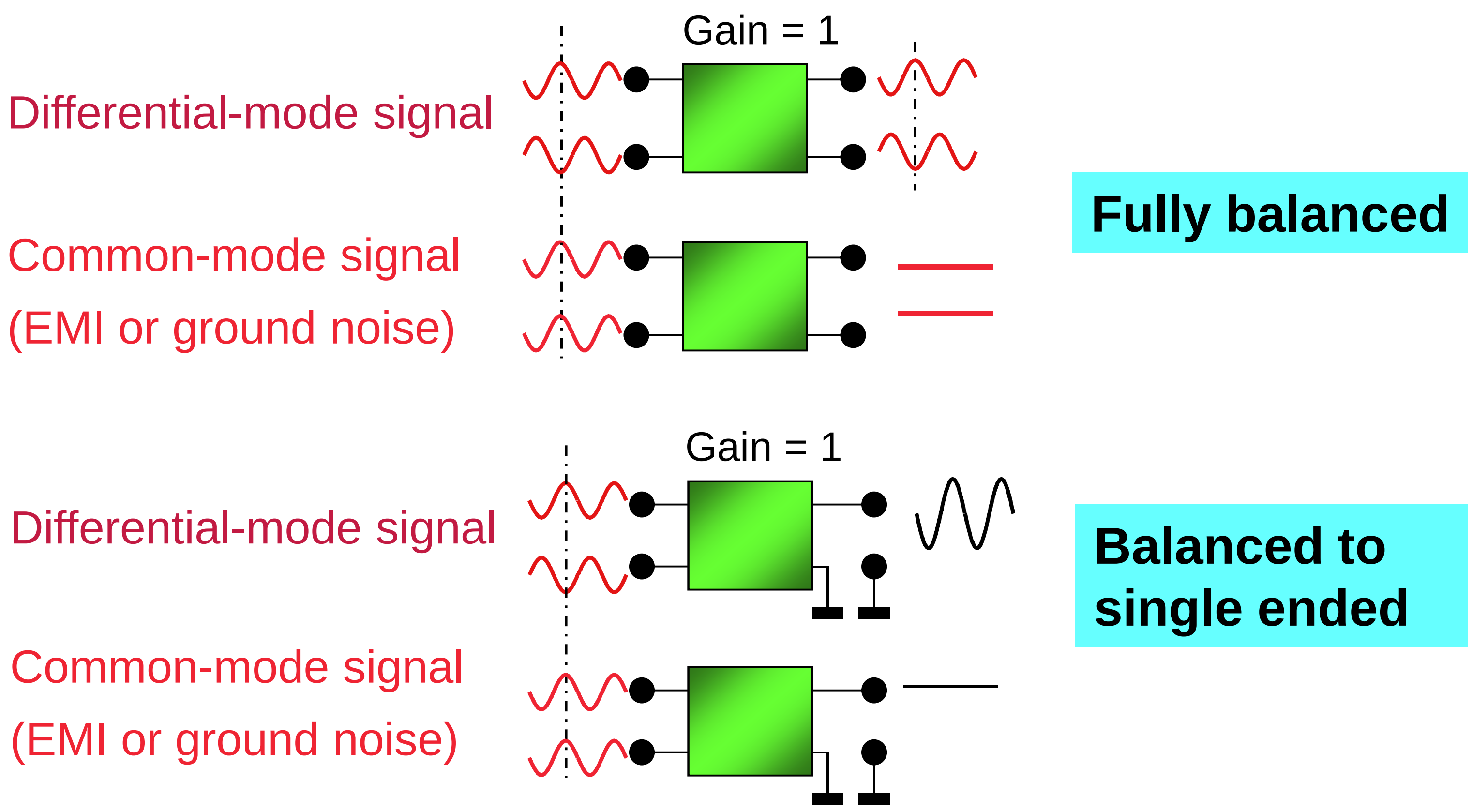


Components with balanced design:

- Amplifiers
- Mixers
- Filters (e.g. SAW filters)
- PCB layout in mobile phones
- LAN adapters, converters, filters
- PC components (HDD control, etc)
- Almost all signals high-speed serial data signals

- Advantages:
- High noise immunity
  - Minimizes Power and ground plane noise
  - Minimizes EMI susceptibility
  - Minimizes Cross talk
- Low radiated noise
- High integration density
- Lower power consumption

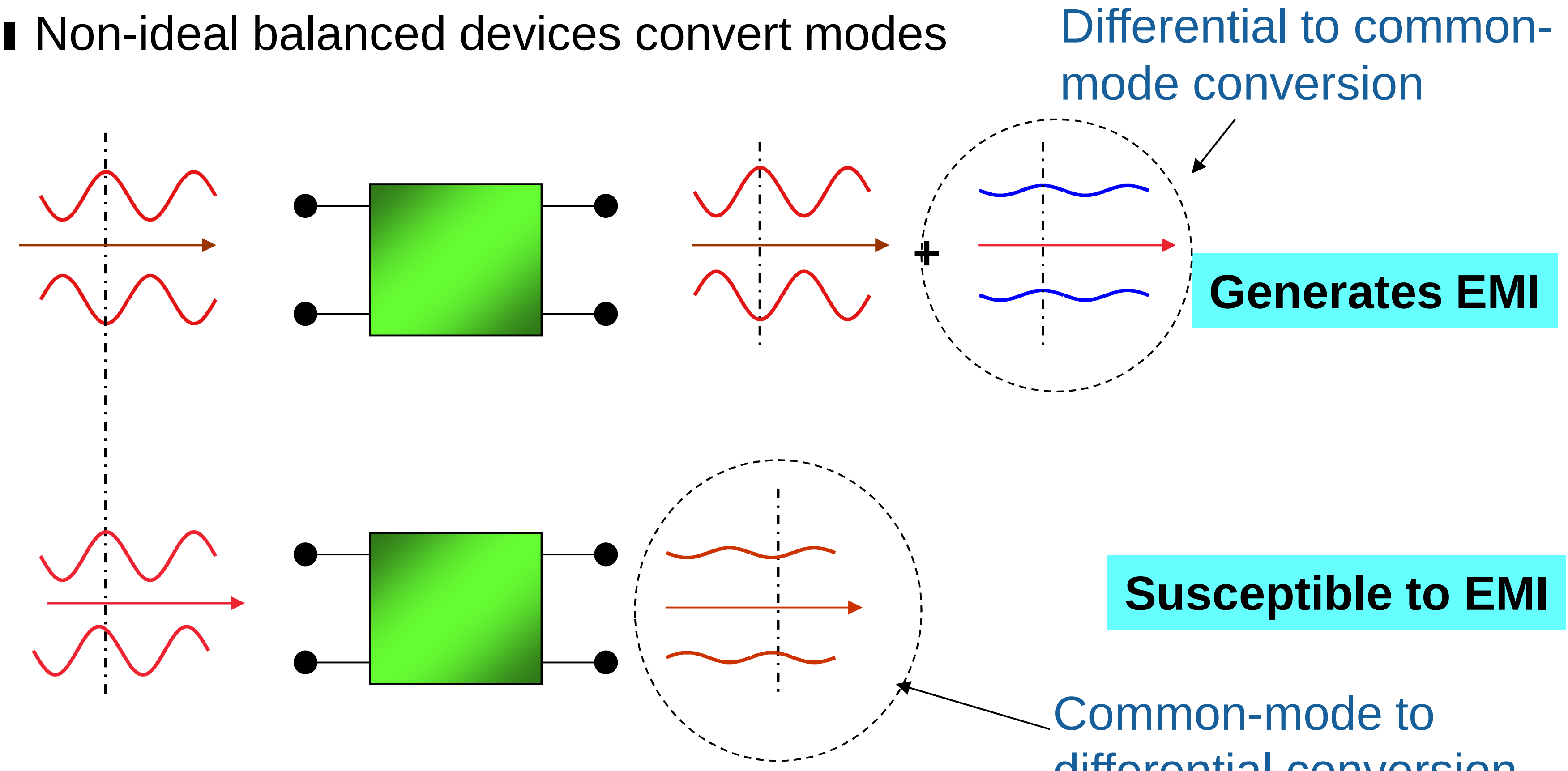
Ideal Balanced Device Characteristics



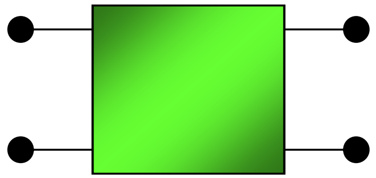
Ideally, balanced devices transmit differential and reject common-mode signals

Non-Ideal Balanced Device Characteristics

- Non-ideal balanced devices convert modes



Parameters to Test for a Balanced Device



- Performance in pure differential mode
- Performance in pure common mode
- Conversion from differential mode to common mode (in both directions)
- Conversion from common mode to differential mode (in both directions)

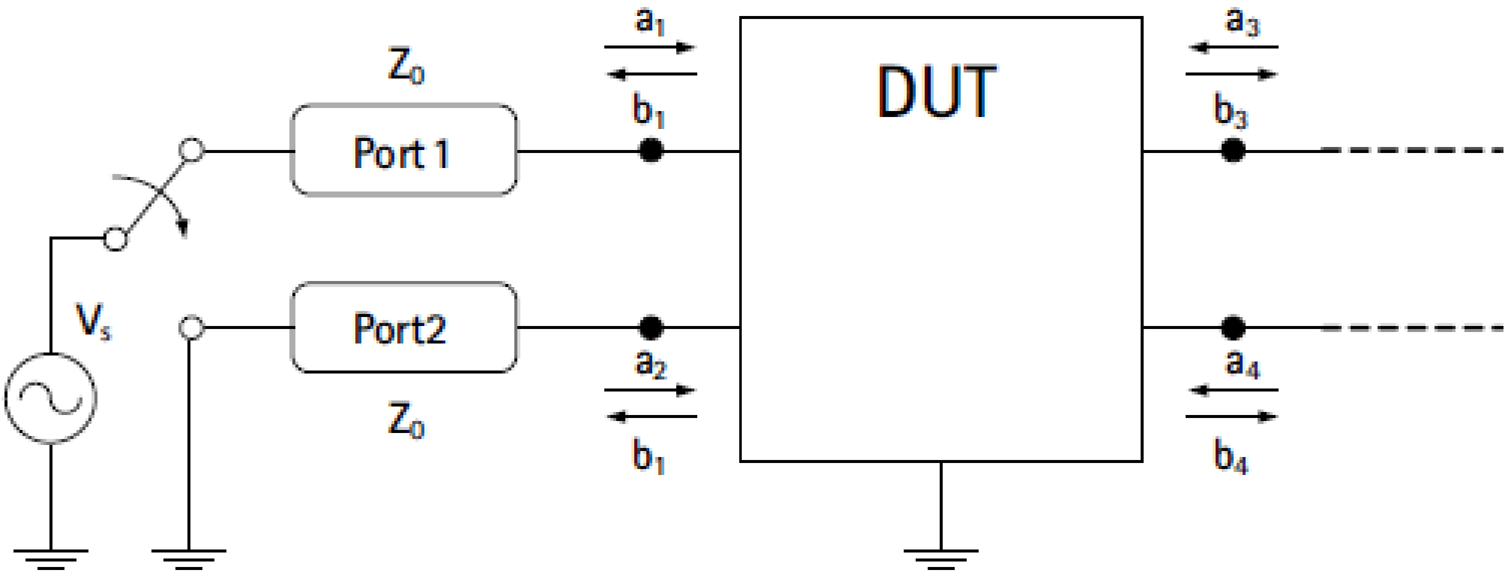
Basic Architecture: Definition of Differential Measurements

Measurement Principle

- VirDi = Virtual differential Mode
  - Characterization of balanced DUT as single ended DUT with mathematical calculation of mixed-mode S-Parameters from single ended S-Parameters

- TruDi = True differential Mode
  - Stimulation of DUT with true differential and common mode signals with calculation of mixed-mode S-Parameters from error corrected mixed mode wave quantities

Virtual Differential Measurement



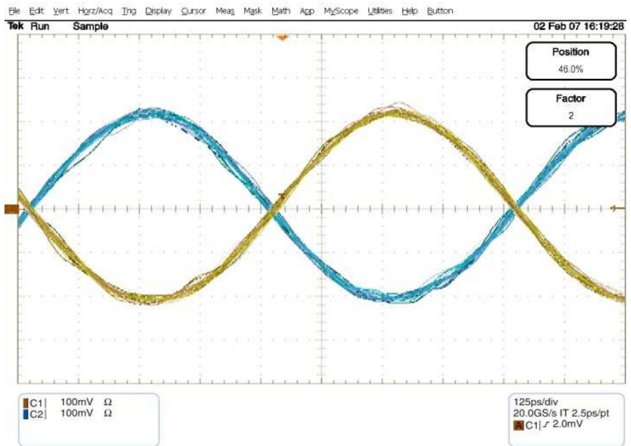
- Single ended measurements with post processing using linear superposition
- Applicable for all passive devices and active devices operating in their linear region
- Large deviations compared to True Differential in large signal operation, especially in terms of compression curve characteristics
  - Nonlinear behavior of the DUT prohibits linear superposition

ZVA – True Differential Mode

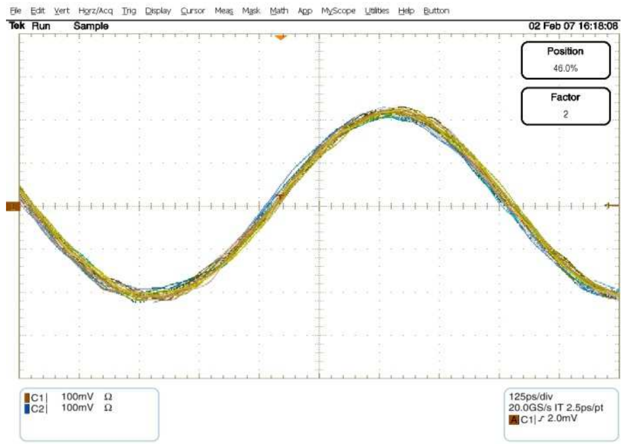
- Coherent sources
  - Generation of true differential and common mode stimulus signals
  - At least one signal output can be adjusted in amplitude and phase with respect to the other
- Simultaneous measurement of two reference signals (a waves) and two measurement signals (b waves)
- Four-port calibration in the reference plane
  - Vector-corrected measurement of single ended waves or voltages
- Calculation of true differential S-Parameters from vector corrected wave quantities

Sweep modes (R&S ZVA-K6)

differential mode 180°



common mode 0°



Coherent signals of arbitrary phase and amplitude imbalance are possible

- Sweep Modes:
  - Frequency
  - Phase (Phase of the stimulating signal can be swept from 0° to 180°)
  - Magnitude (Variation of the relative magnitude of the differential signals)
  - “Classical” VNA calibration techniques sufficient (full two port)

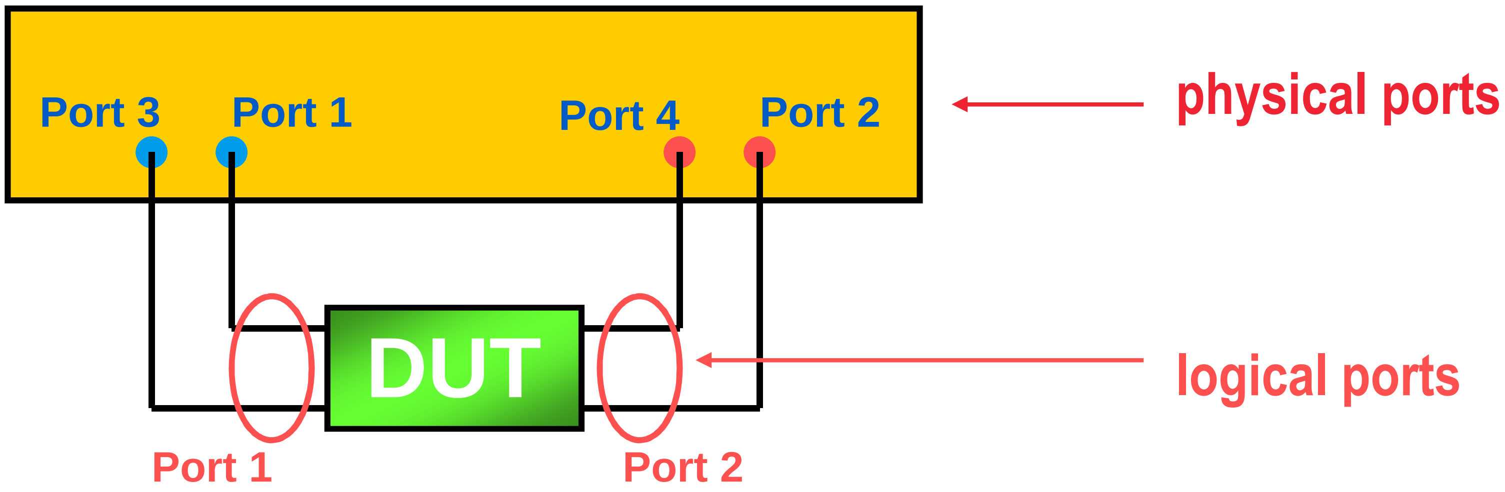
⇒ Investigation of the DUT under real conditions

Typical measurements quality parameters

- Differential and common mode insertion loss
- Differential and common mode return loss
- NEXT-Measurements (Near End Crosstalk)
- FEXT-Measurements (Far End Crosstalk)
- Amplitude-Imbalance
- Phase-Imbalance
- Common-Mode Rejection Ratio (CMRR)

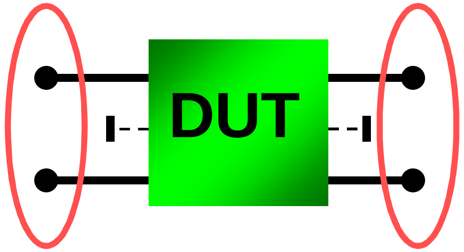
Port Configurations for Differential DUT

- Physical single ending ports → logical balanced ports



- Different impedances for common-mode and differential-mode
  - differential-mode (ideally matched) → 100 Ω (=2*Z0)
  - common-mode (ideally matched) → 25 Ω (= 1/2*Z0)

Modal Decomposition Method
Mixed Mode S-Parameter Matrix



Logical Port 1 Logical Port 2

		Differential-Mode stimulus		Common-Mode stimulus	
		Port 1	Port 2	Port 1	Port 2
Differential-mode Response	Port 1	S_{dd11}	S_{dd12}	S_{dc11}	S_{dc12}
	Port 2	S_{dd21}	S_{dd22}	S_{dc21}	S_{dc22}
Common-mode Response	Port 1	S_{cd11}	S_{cd12}	S_{cc11}	S_{cc12}
	Port 2	S_{cd21}	S_{cd22}	S_{cc21}	S_{cc22}

Naming Convention: $S_{\text{mode meas., mode stim., port meas., port stim.}}$

Mixed Mode S-Matrix: DD Quadrant

input reflection

reverse transmission

$$\begin{bmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd22} & S_{cc21} & S_{cc22} \end{bmatrix}$$

forward transmission

output reflection

- Describes fundamental performance in pure differential-mode operation

Mixed Mode S-Matrix: CC Quadrant

input reflection

reverse transmission

$$\begin{bmatrix} S_{dd\,11} & S_{dd\,12} & S_{dc\,11} & S_{dc\,12} \\ S_{dd\,21} & S_{dd\,22} & S_{dc\,21} & S_{dc\,22} \\ S_{cd\,11} & S_{cd\,12} & S_{cc\,11} & S_{cc\,12} \\ S_{cd\,21} & S_{cd\,22} & S_{cc\,21} & S_{cc\,22} \end{bmatrix}$$

forward transmission

output reflection

- Describes fundamental performance in pure common-mode operation

Mixed Mode S-Matrix: DC Quadrant

input reflection — reverse transmission

$$\begin{bmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd22} & S_{cc21} & S_{cc22} \end{bmatrix}$$

forward transmission — output reflection

- Describes conversion of a common-mode stimulus to a differential-mode response
- Terms are ideally equal to zero with perfect symmetry
- Related to the generation to EMI

Mixed Mode S-Matrix: CD Quadrant

input reflection

reverse transmission

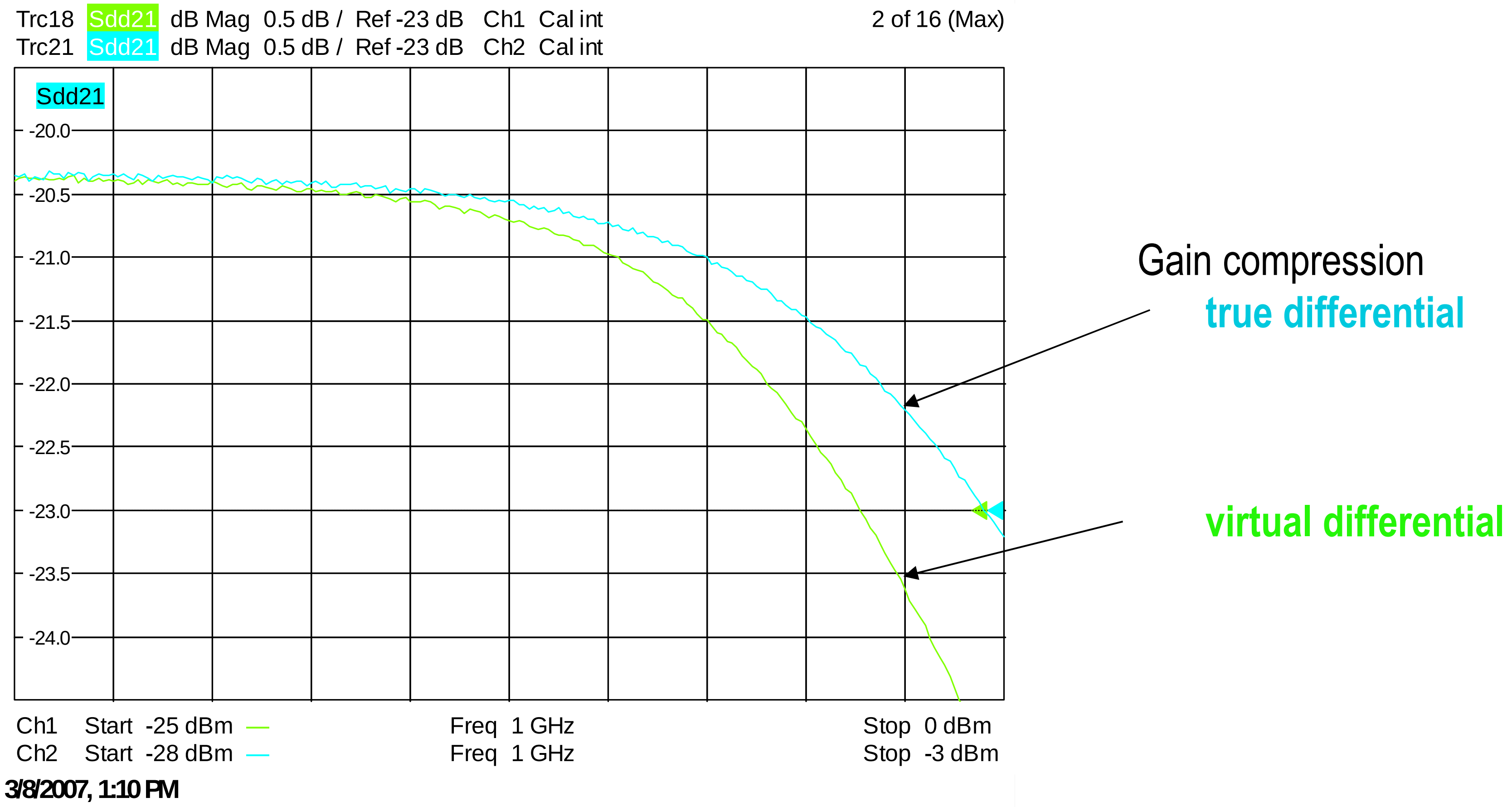
$$\begin{bmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd22} & S_{cc21} & S_{cc22} \end{bmatrix}$$

forward transmission

output reflection

- Describes conversion of a differential-mode stimulus to a common-mode response
- Terms are ideally equal to zero with perfect symmetry
- Related to the susceptibility of EMI

Example 1: Tunable Active Filter



True differential power axis has been shifted by -3 dB to equalize voltage amplitudes

Summary: TruDi vs. VirDi

- Passive Devices/Linear operation
  - TruDi and VirDi give exactly the same results

- Active Devices/Non-linear operation
  - Significant difference between TruDi and VirDi
  - TruDi represents the real operating conditions of a device

- TruDi Measurements
  - Requires two phase coherent sources
  - Ability to set amplitude and phase independently
  - Relative phase stability of VNA sources is crucial for reproducible results

Measurement Techniques for TDR

ROHDE&SCHWARZ

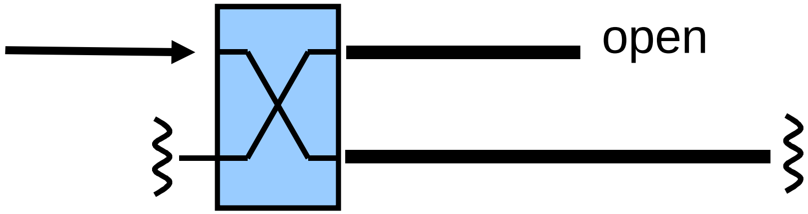
Applications of TDR

Localization of Faults in Transmission Lines

- This is the 1st application that I think of for TDR measurements
- Examples include localizing a fault on an underground cable or a cable running up a tower
- Test to see if an antenna is properly connected
- Check if an amplifier or filter is presenting the expected impedance

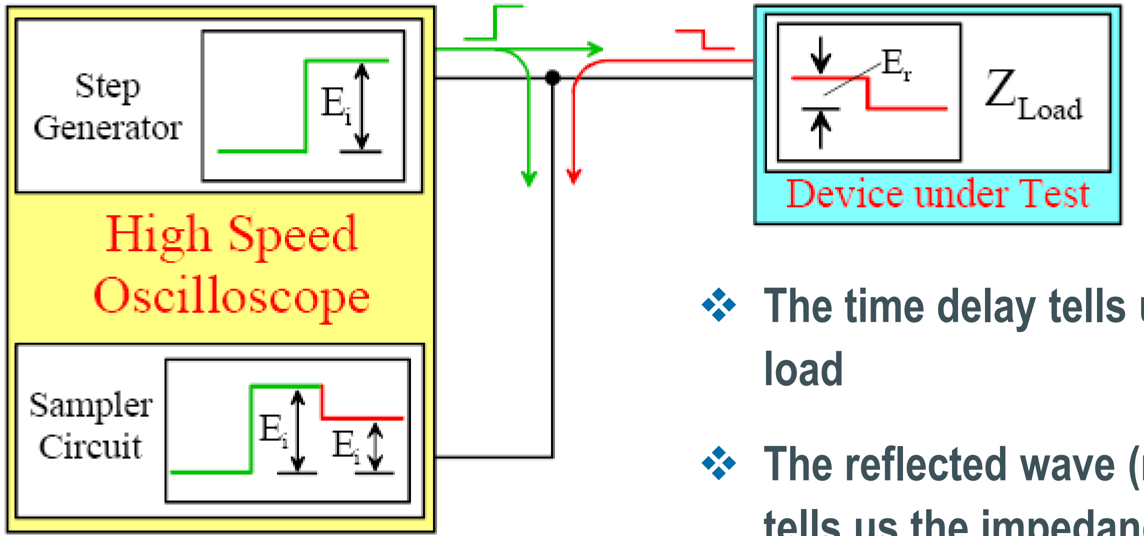
Applications of TDR

- Moving the Reference Plane of RL measurements
  - This is the second most common use for TDR
  - In the frequency domain we see “all” the reflected signals. By separating the results in the time domain, we can determine the source of the reflections.



But what is a TDR measurement?

- In a TDR measurement, we send a pulse down a transmission line, and then we record (in time) the reflections that come back out of the transmission line.
- This can be done with a “fast” power supply and a “fast” oscilloscope.
- The goal is to measure the transient traveling waves on the transmission line leading to the device under test



- The time delay tells us the distance to the load
- The reflected wave (magnitude and phase) tells us the impedance of the load

And what are the challenges

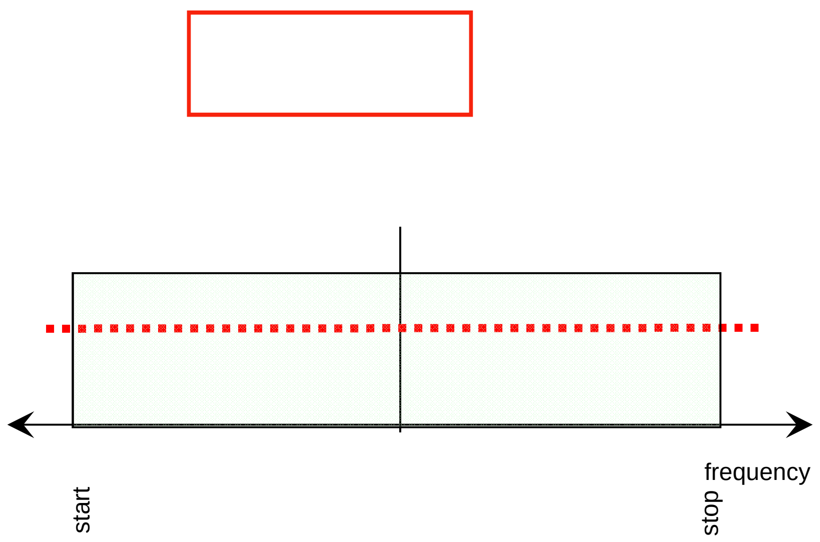
- Generating a very clean and fast pulse

1. **A stepped pulse in the time domain generates *all* frequencies in the frequency domain.**
2. **The pulse generator needs to be matched to the transmission line. Mismatches need to be “calibrated” out of the measurement.**
3. **The oscilloscope needs to sample at a very high frequency. These pulses are traveling at the speed of light if the transmission line has an air dielectric.**
4. **The oscilloscope also needs to be matched to the transmission line.**

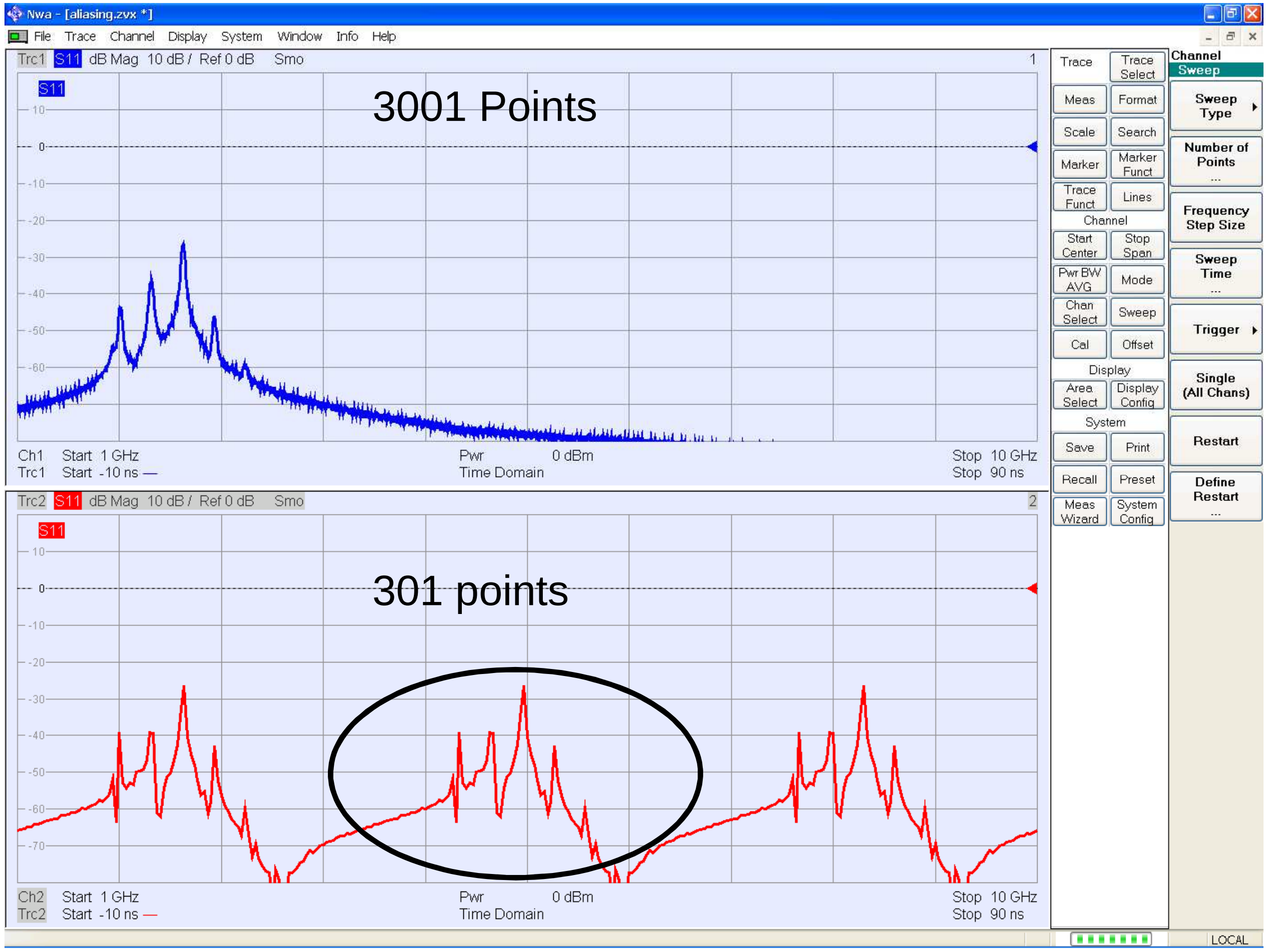
- These challenges match up well with the features of modern vector network analyzers.

Aliasing in the time domain

- Aliasing results from the fact that the Network Analyzer measures the spectrum at a finite number of discrete measurement points
- In the time domain, this results in the time response being copied at regular intervals (Fourier transform of a comb spectrum is a comb spectrum)
- Ambiguity range: $\Delta t = 1 / \Delta f$
  where Δf = spacing of measurement points

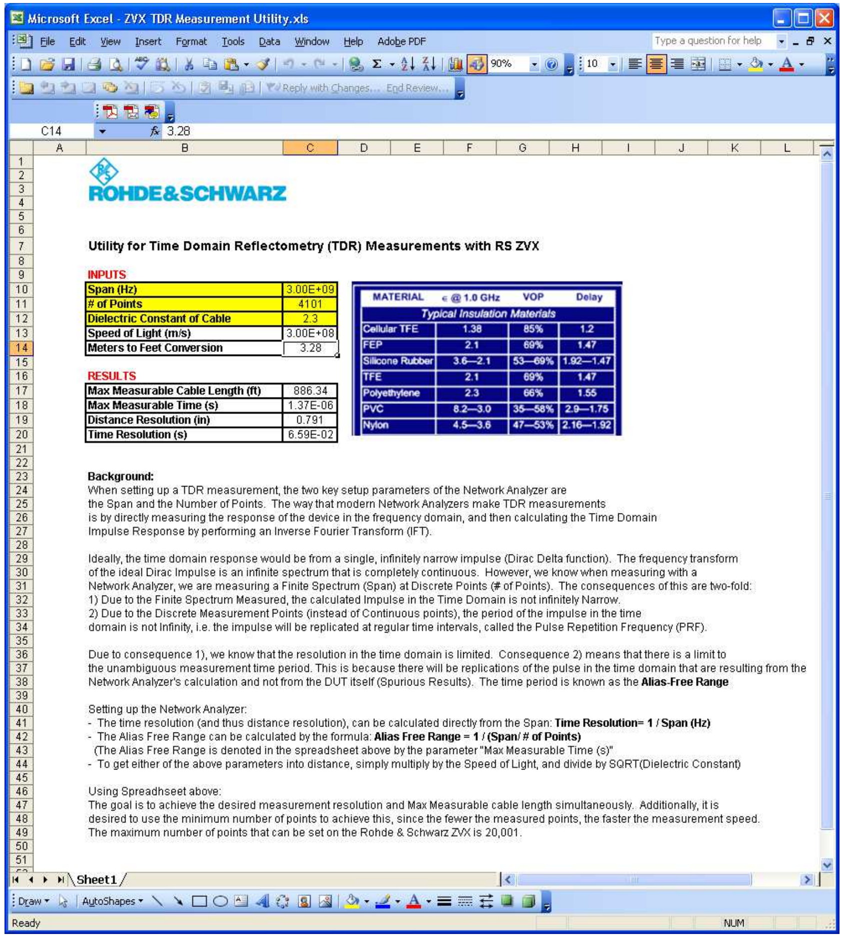


Aliasing in the time domain

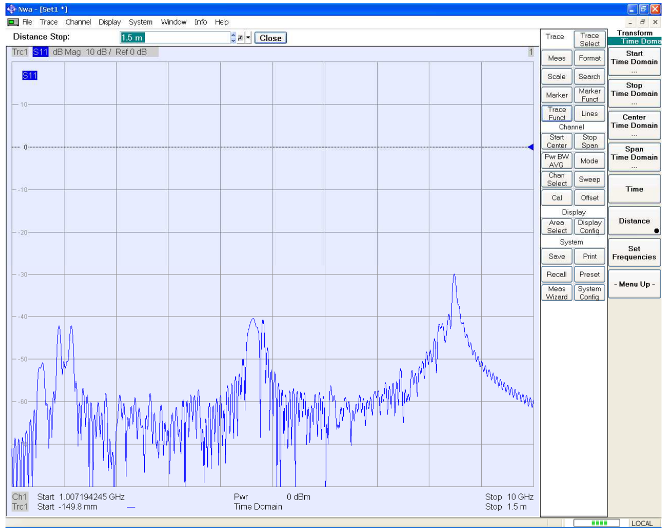


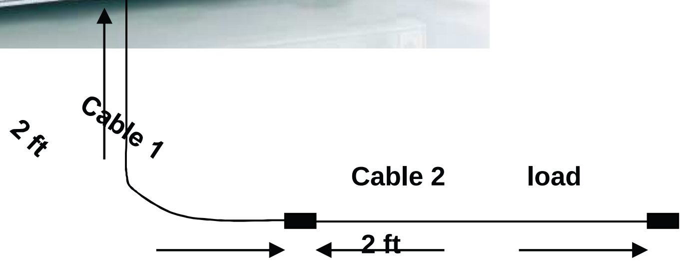
Tradeoffs and settings

- We need to pick a frequency span and number of points
  - We will end up with an alias free range, and a time resolution.
  - A spreadsheet can help us with this.
- We then pick a window function in the frequency domain
  - We end up with a minimum pulse width, and a certain amount of side lobe suppression or ringing.
  - What are we trying to measure, high dynamic range, or a high amount of precision on the distance or time axis.



Example: Distance to Fault (DTF)





SETTINGS and CONSTANTS

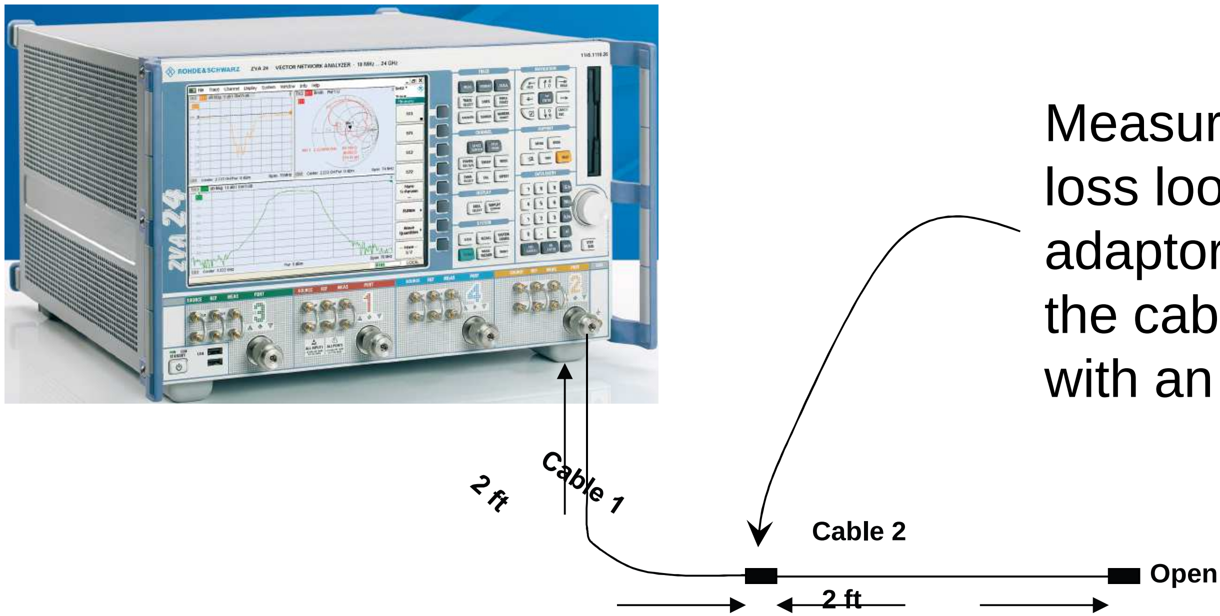
Span (Hz)	9.99E+09
# of Points	1001
Dielectric Constant of Cable	2
Lowpass Mode=2, Bandpass Mode = 1	1
Speed of Light (m/s)	3.00E+08
Meters to Feet Conversion	3.28

LIMITATIONS

Max Measurable Cable Length (ft)	69.72
Max Measurable Time (s)	1.00E-07
Distance Resolution (in)	0.255
Time Resolution (s)	4.25E-02

Time Gating

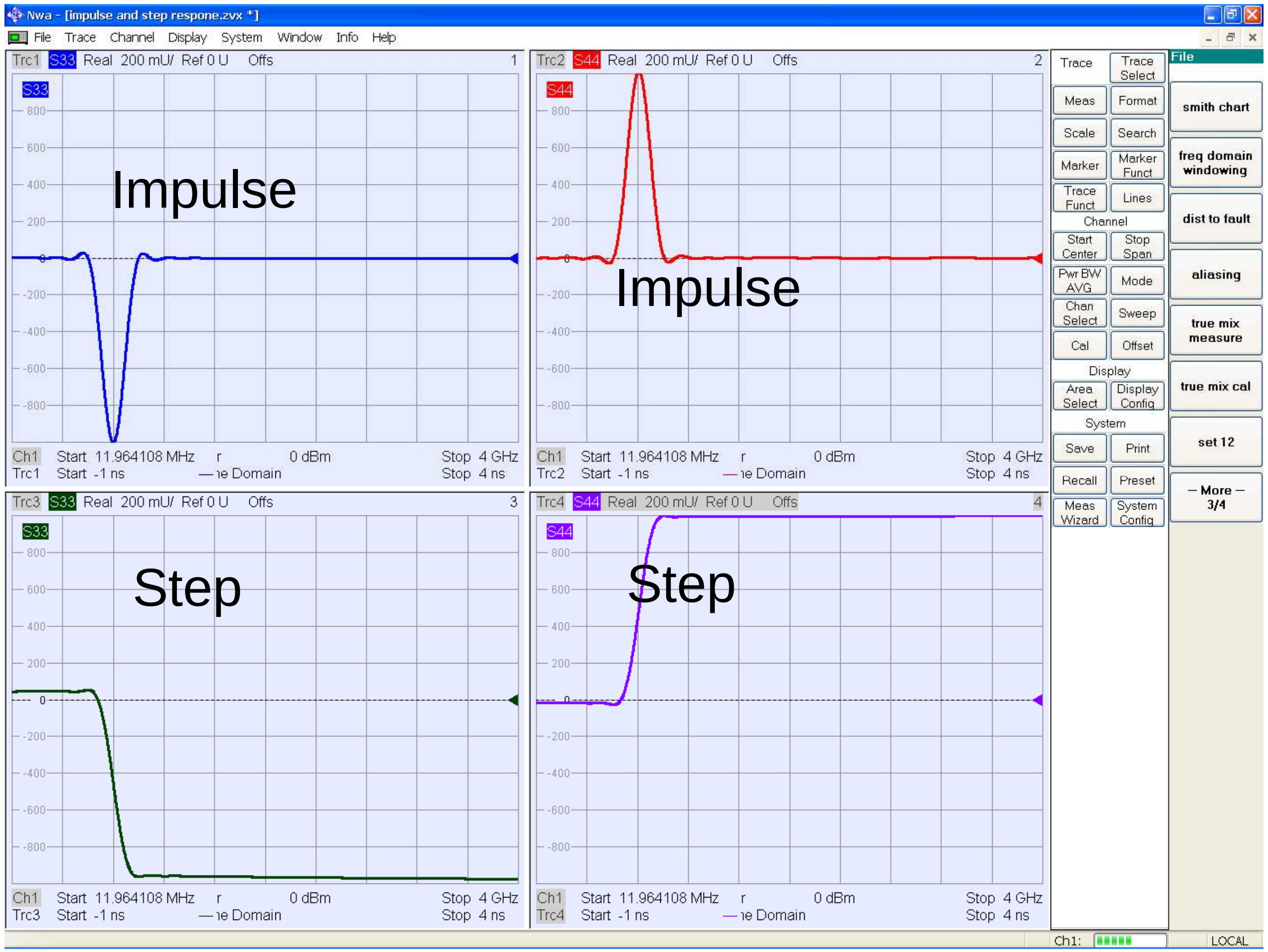
- Time Gating opens up a whole new range of applications for the Time Domain option of a Network Analyzer
- Typical application is to filter out certain parts of the response and display back into the Frequency Domain.



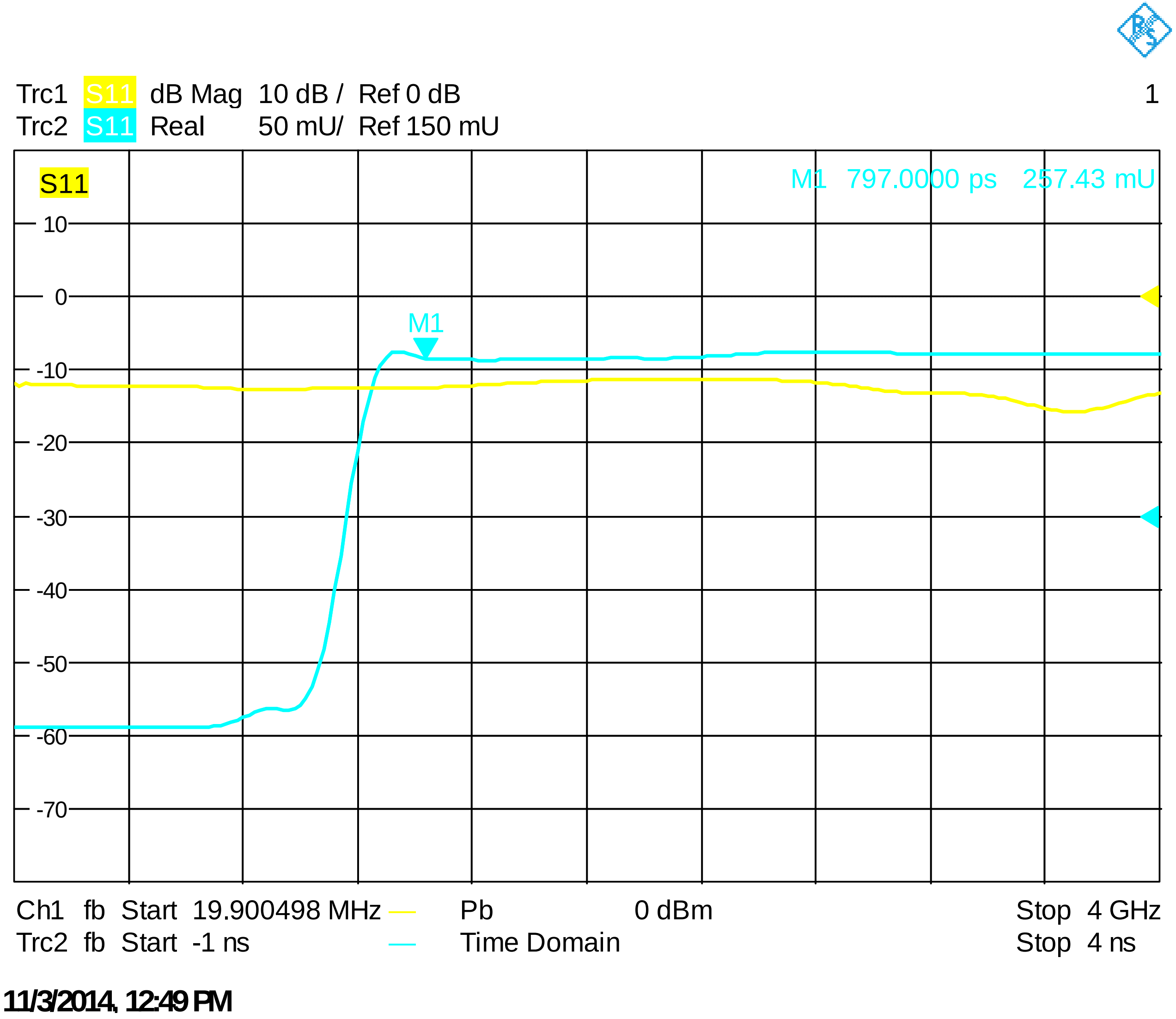
Measure the return loss looking into this adaptor, even though the cable is terminated with an open circuit.

Impulse and Step Response Examples

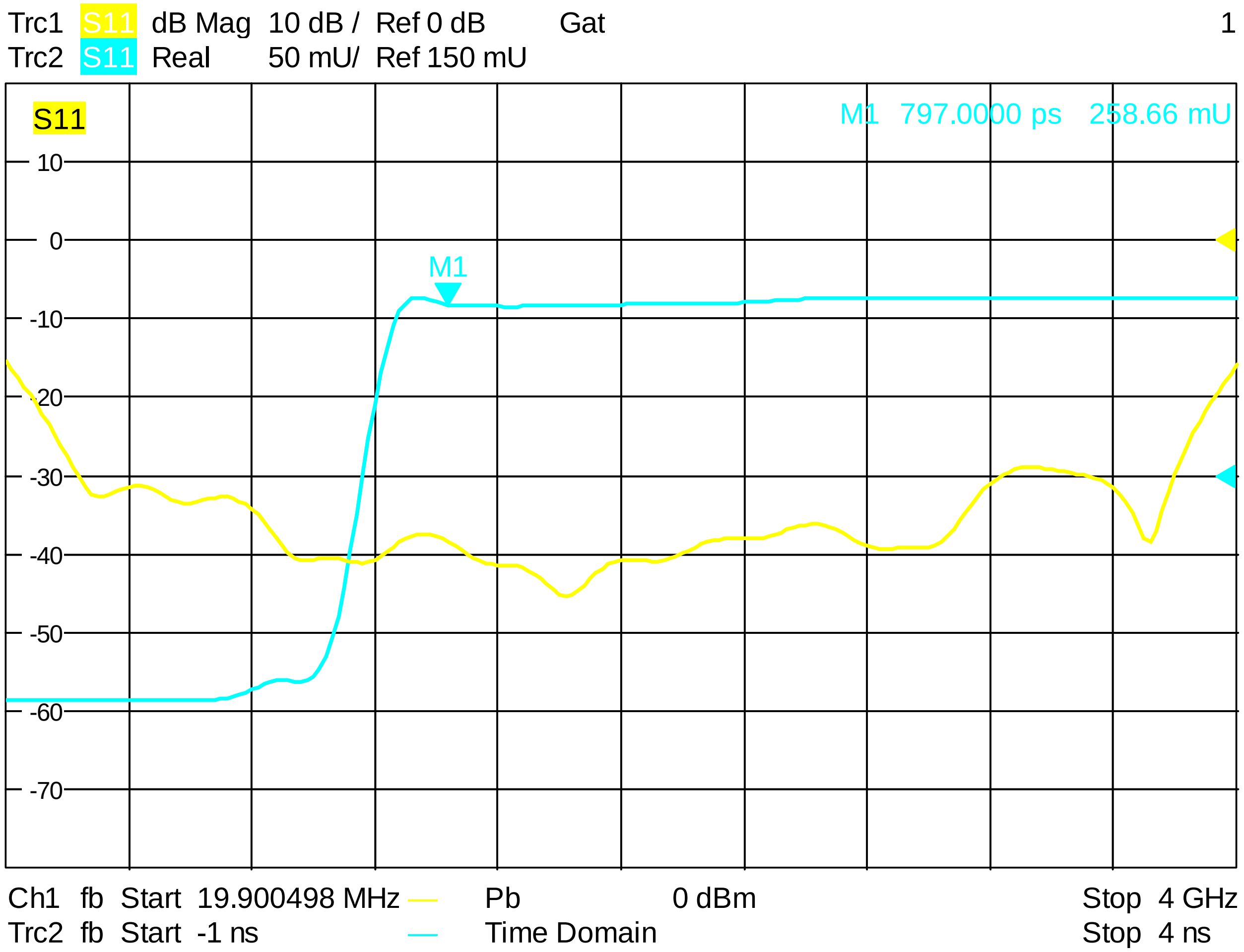
SHORT OPEN



S11 measurement with no gating



S11 measurement with gating



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Summary of VNA Settings

- The Span determines the *Time Resolution* as follows:
  When in Bandpass Mode Resolution = 2 / Span
  When in Lowpass Mode Resolution = 1 / Span
- The # of Points and Span determine the *Ambiguity Range* by the following relation: Range = 1/ Δf = 1 / (Span / # of points)
- Use Lowpass Mode if the sign of the Real Part of Γ is important (e.g. for a Short Circuit Response). Bandpass Mode can be used when only concerned with Magnitude measurements.
- Frequency Windowing affects the shape of the main and side lobe responses in the Time Domain.
- Use Time Gating to filter out undesired discontinuities of the DUT.
- Time Gate Windowing affects the shape of the main and side lobe responses in the Frequency Domain.

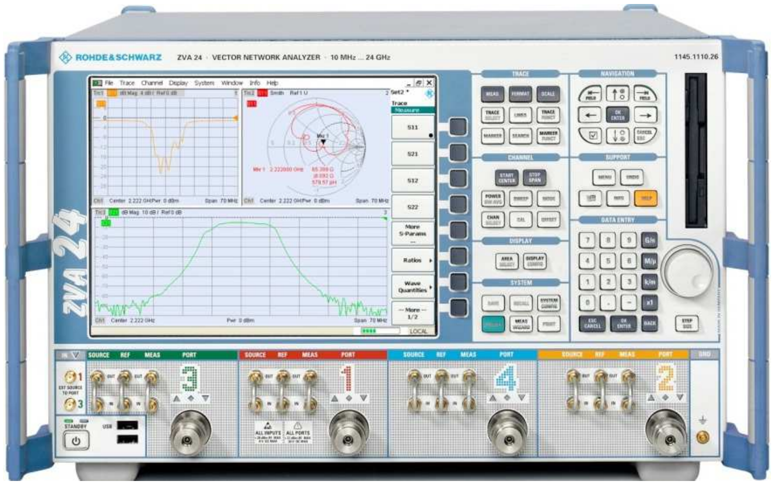
What is the Measurement Frequency?

- The max frequency for the VNA can be calculated from the required rise time of the data.

ZNB8	***8.5 GHz***	***59 ps***
ZVA24	***24 GHz***	***21 ps***
ZVA40	***40GHz***	***13 ps***
ZVA50	***50 GHz***	***10 ps***
ZVA67	***67 GHz***	***7.5 ps***
ZVA110	***110GHz***	***4.5 ps***

Thank you!


ROHDE&SCHWARZ
PASS DynCheck
PASS TransDel
PORT 1
PORT 2


ROHDE&SCHWARZ
ZVA 24 · VECTOR NETWORK ANALYZER · 10 MHz ... 24 GHz
ZVA 24