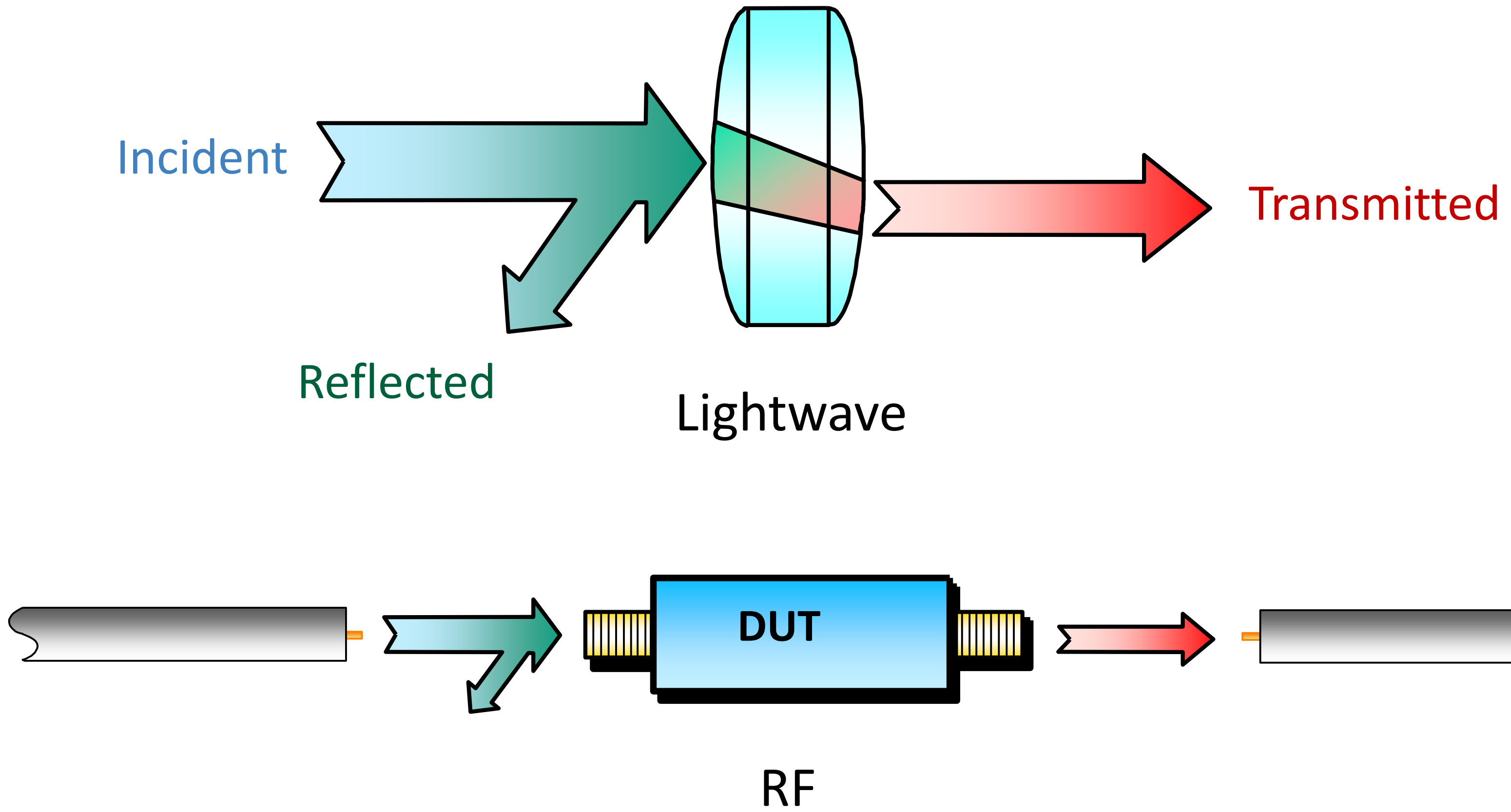
Network Analysis

KEYSIGHT
TECHNOLOGIES

Agenda

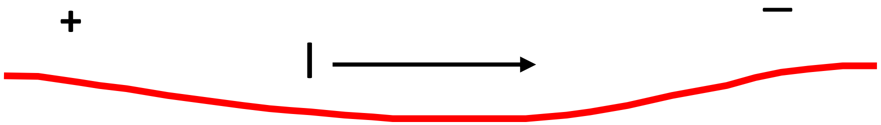
- Transmission Lines
- S-Parameters
- The Smith Chart
- Network Analyzer Block Diagram
- Network Analysis Measurements
- Calibration and Error Correction

RF Energy Transmission



Transmission Line Basics

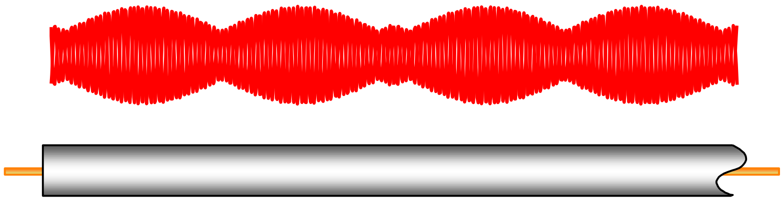
Low frequencies



– Wavelengths >> wire length

– Current (I) travels down wires easily for efficient power transmission

– Measured voltage and current not dependent on position along wire



High frequencies

– Wavelength » or << length of transmission medium

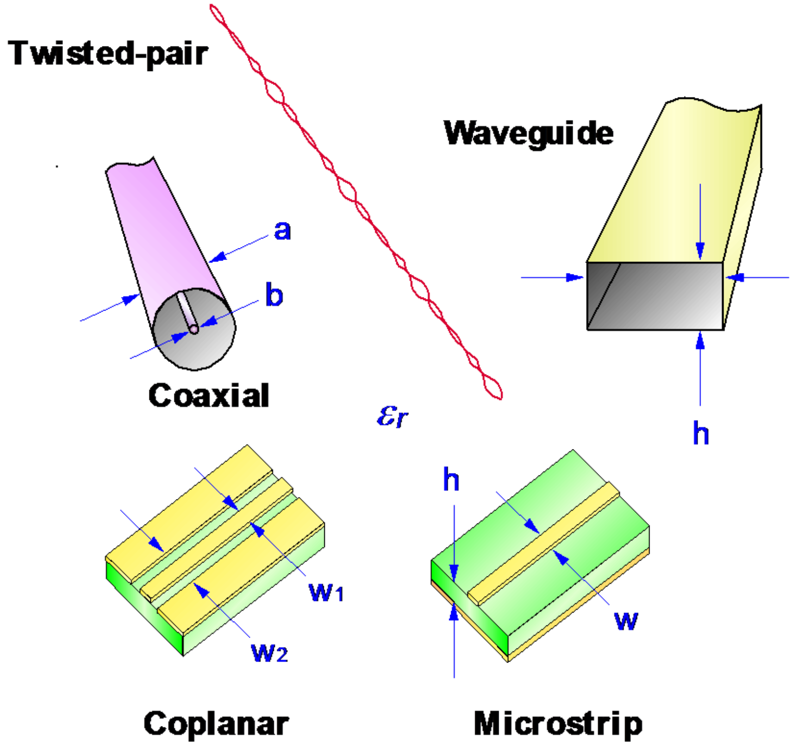
– Need transmission lines for efficient power transmission

– Matching to characteristic impedance (Zo) is very important for low reflection and maximum power transfer

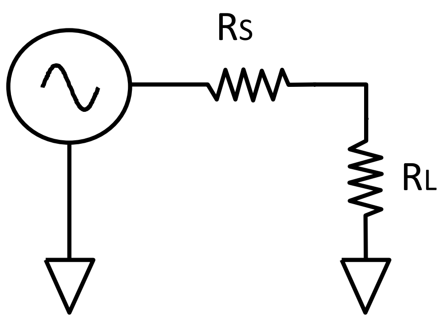
– Measured envelope voltage dependent on position along line

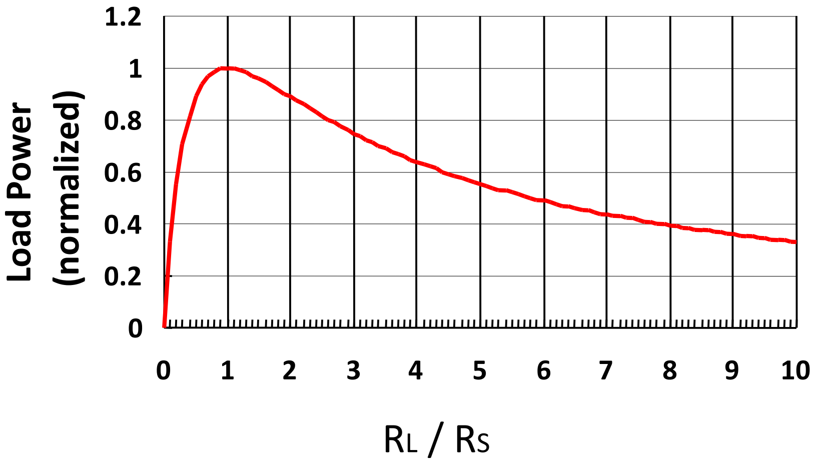
Transmission line Z_o

- Z_o determines relationship between voltage and current waves
- Z_o is a function of physical dimensions and ε_r
- Z_o is usually a real impedance (e.g. 50 or 75 ohms)



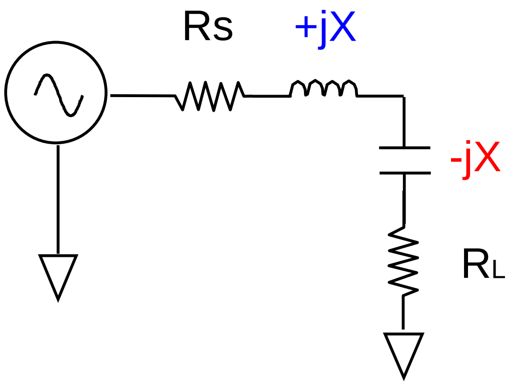
Power Transfer Efficiency



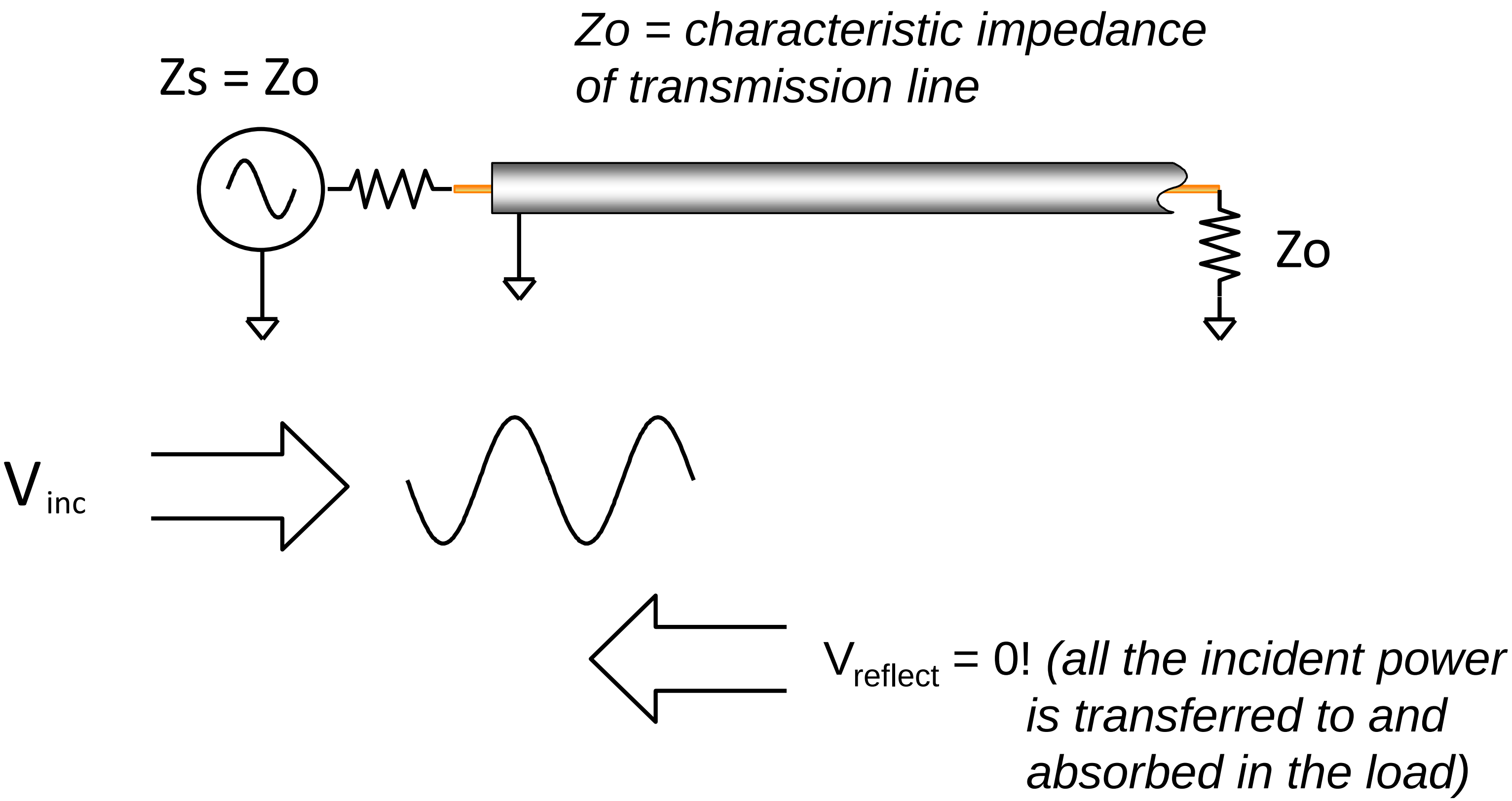


Maximum power is transferred when $R_L = R_S$

For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match)

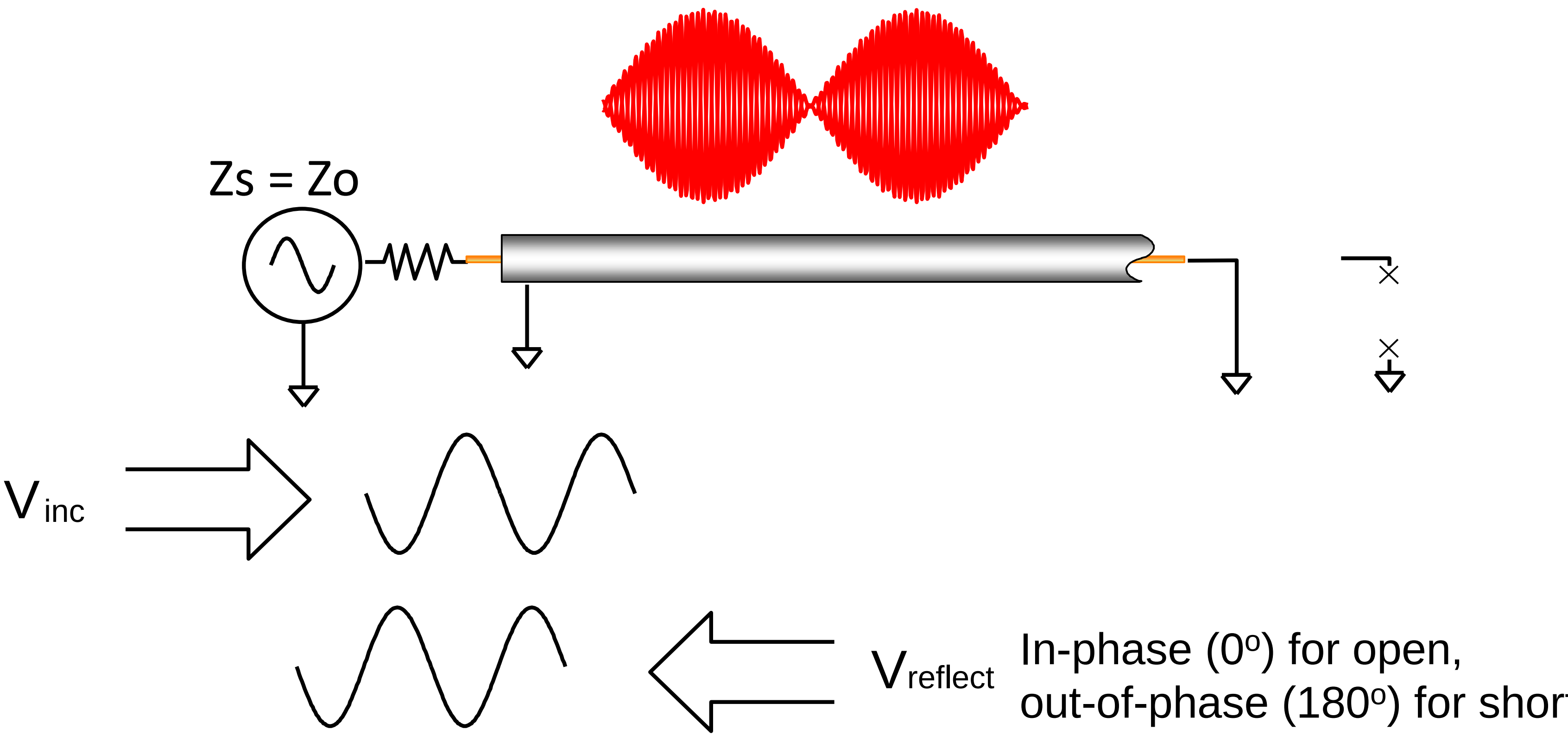


Transmission Line Terminated with Zo



For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

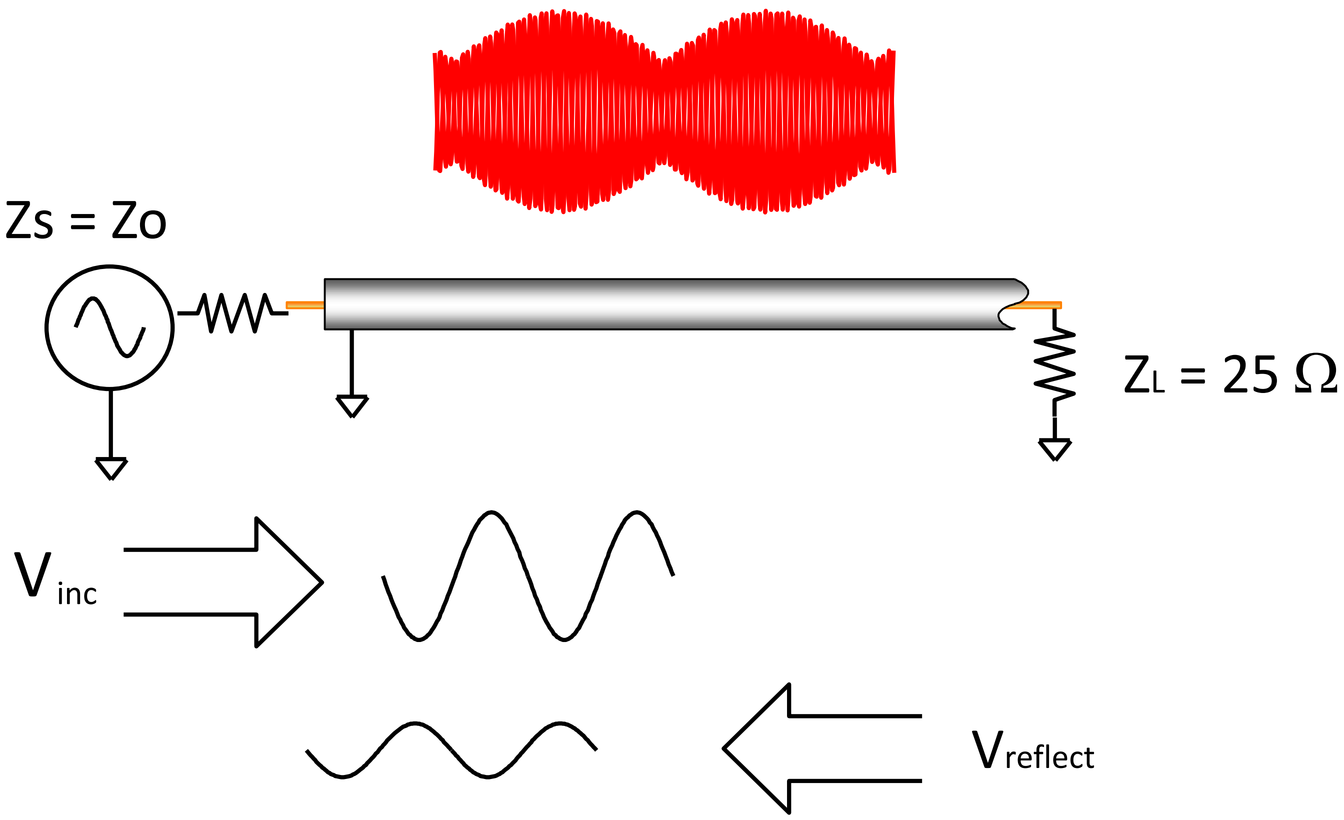
Transmission Line Terminated with Short, Open



For reflection, a transmission line terminated in a short or open reflects all power back to source

KEYSIGHT TECHNOLOGIES

Transmission Line Terminated with 25 Ohms

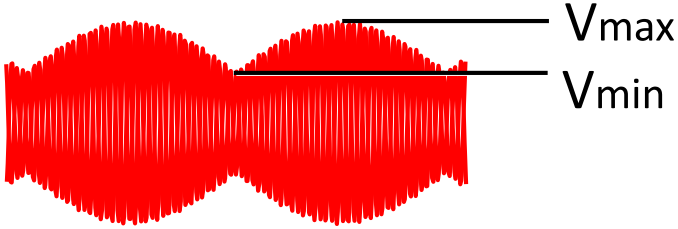


Standing wave pattern does not go to zero as with short or open

Reflection Parameters

Reflection Coefficient [S11] $= \Gamma = \dfrac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \dfrac{Z_L - Z_o}{Z_L + Z_o}$

Return loss = -20 log(ρ), $\rho = |\Gamma|$



Voltage Standing Wave Ratio

VSWR $= \dfrac{V_{max}}{V_{min}} = \dfrac{1+\rho}{1-\rho}$

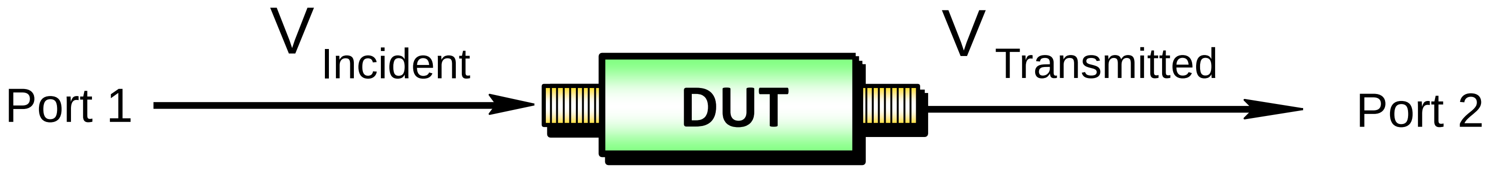
No reflection
(ZL = Zo)

Full reflection
(ZL = open, short)

No reflection		Full reflection
0	ρ	1
∞ dB	**RL**	0 dB
1	**VSWR**	∞

KEYSIGHT TECHNOLOGIES

Transmission Parameters

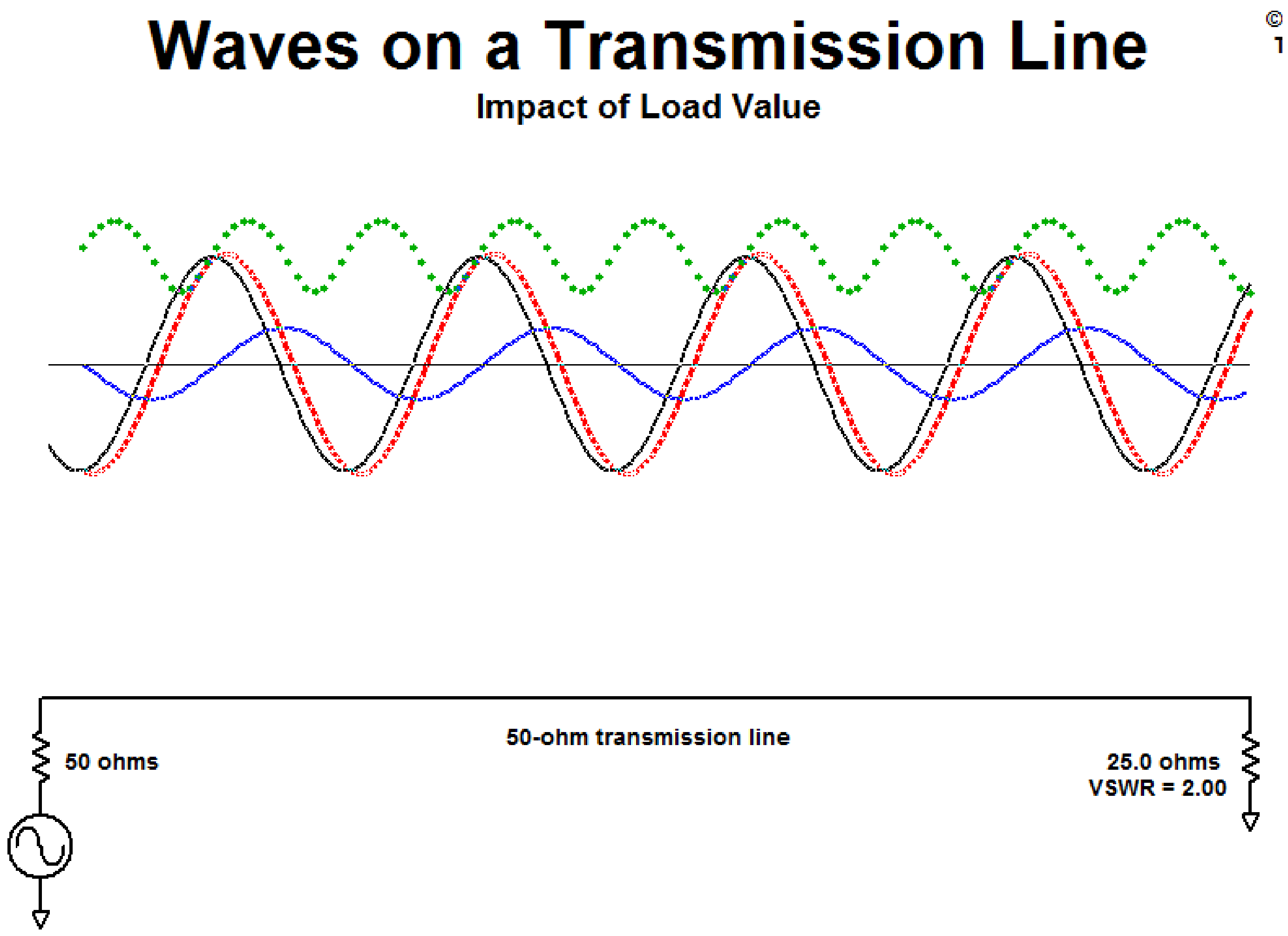


$$\text{Transmission Coefficient [S21]} = T = \frac{V_{Transmitted}}{V_{Incident}} = \tau \angle \phi$$

$$\text{Insertion Loss (dB)} = -20 \text{ Log} \left| \frac{V_{Trans}}{V_{Inc}} \right| = -20 \text{ Log}(\tau)$$

$$\text{Gain (dB)} = 20 \text{ Log} \left| \frac{V_{Trans}}{V_{Inc}} \right| = 20 \text{ Log}(\tau)$$

Demonstration:



Agenda

– Transmission Lines

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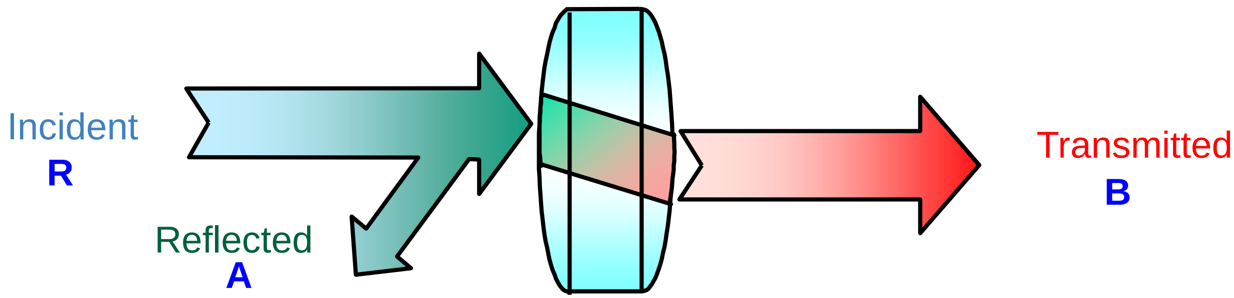
High-Frequency Device Characterization



REFLECTION

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$

- VSWR
- S-Parameters S_{11}, S_{22}
- Reflection Coefficient Γ, ρ
- Impedance, Admittance R+jX, G+jB
- Return Loss

TRANSMISSION

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$

- Gain / Loss
- S-Parameters S_{21}, S_{12}
- Transmission Coefficient T, τ
- Insertion Phase
- Group Delay

KEYSIGHT TECHNOLOGIES

Characterizing Unknown Devices

Using parameters (H, Y, Z, S) to characterize devices:

- Gives linear behavioral model of our device
- Measure parameters (e.g. voltage and current) versus frequency under various source and load conditions (e.g. short and open circuits)
- Compute device parameters from measured data
- Predict circuit performance under any source and load conditions

H-parameters

$V_1 = h_{11}I_1 + h_{12}V_2$

$I_2 = h_{21}I_1 + h_{22}V_2$

Y-parameters

$I_1 = y_{11}V_1 + y_{12}V_2$

$I_2 = y_{21}V_1 + y_{22}V_2$

Z-parameters

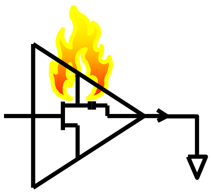
$V_1 = z_{11}I_1 + z_{12}I_2$

$V_2 = z_{21}I_1 + z_{22}I_2$

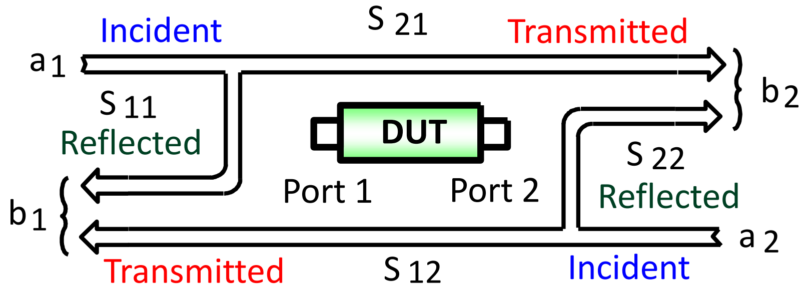
$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit**)*

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$ *(requires **open circuit**)*

Why Use Scattering, S-Parameters?



- Relatively easy to **obtain** at high frequencies
  - Measure voltage traveling waves with a vector network analyzer
  - Don't need shorts/opens (can cause active devices to oscillate or self-destruct)
- Relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- Can **cascade** S-parameters of multiple devices to predict system performance
- Can **compute** H-, Y-, or Z-parameters from S-parameters if desired
- Can easily import and use S-parameter files in **electronic-simulation** tools

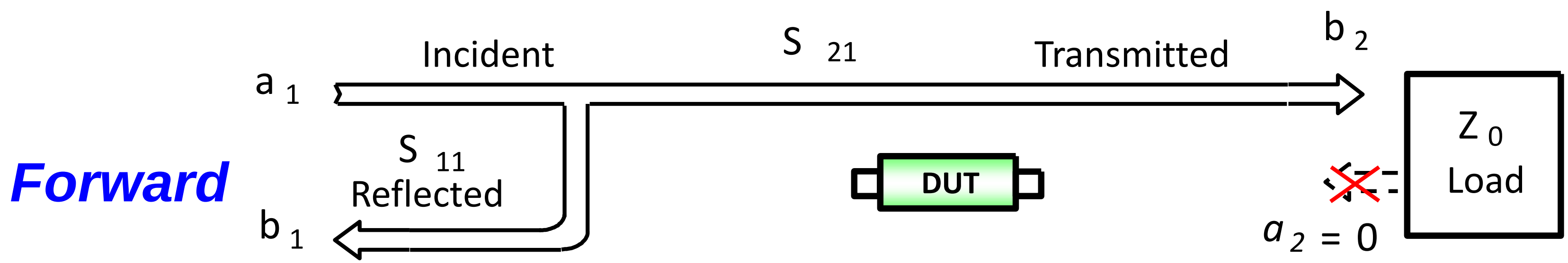


$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

KEYSIGHT TECHNOLOGIES

Measuring S-Parameters

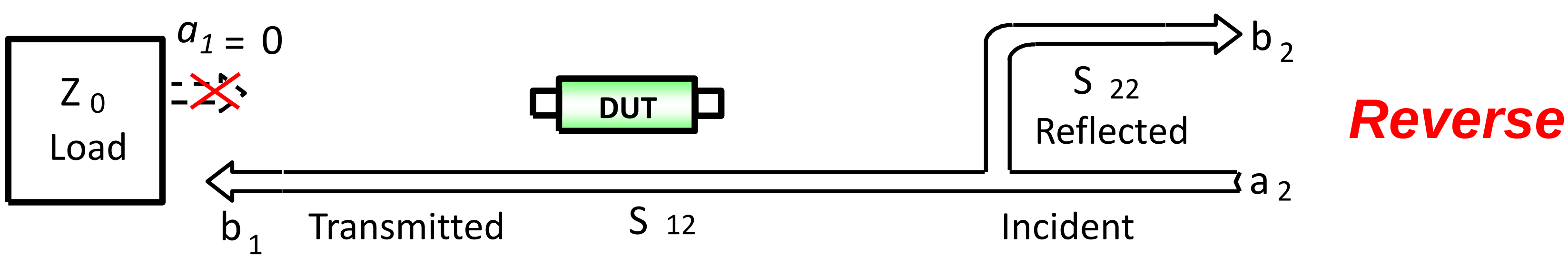


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0}$$

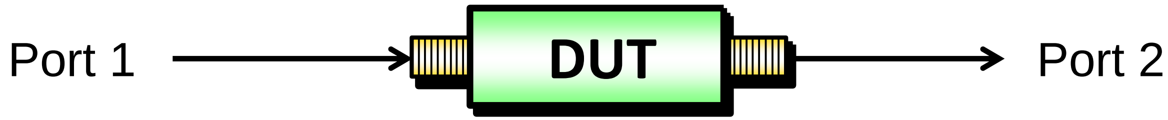
$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0}$$



KEYSIGHT TECHNOLOGIES

Equating S-Parameters With Common Measurement Terms



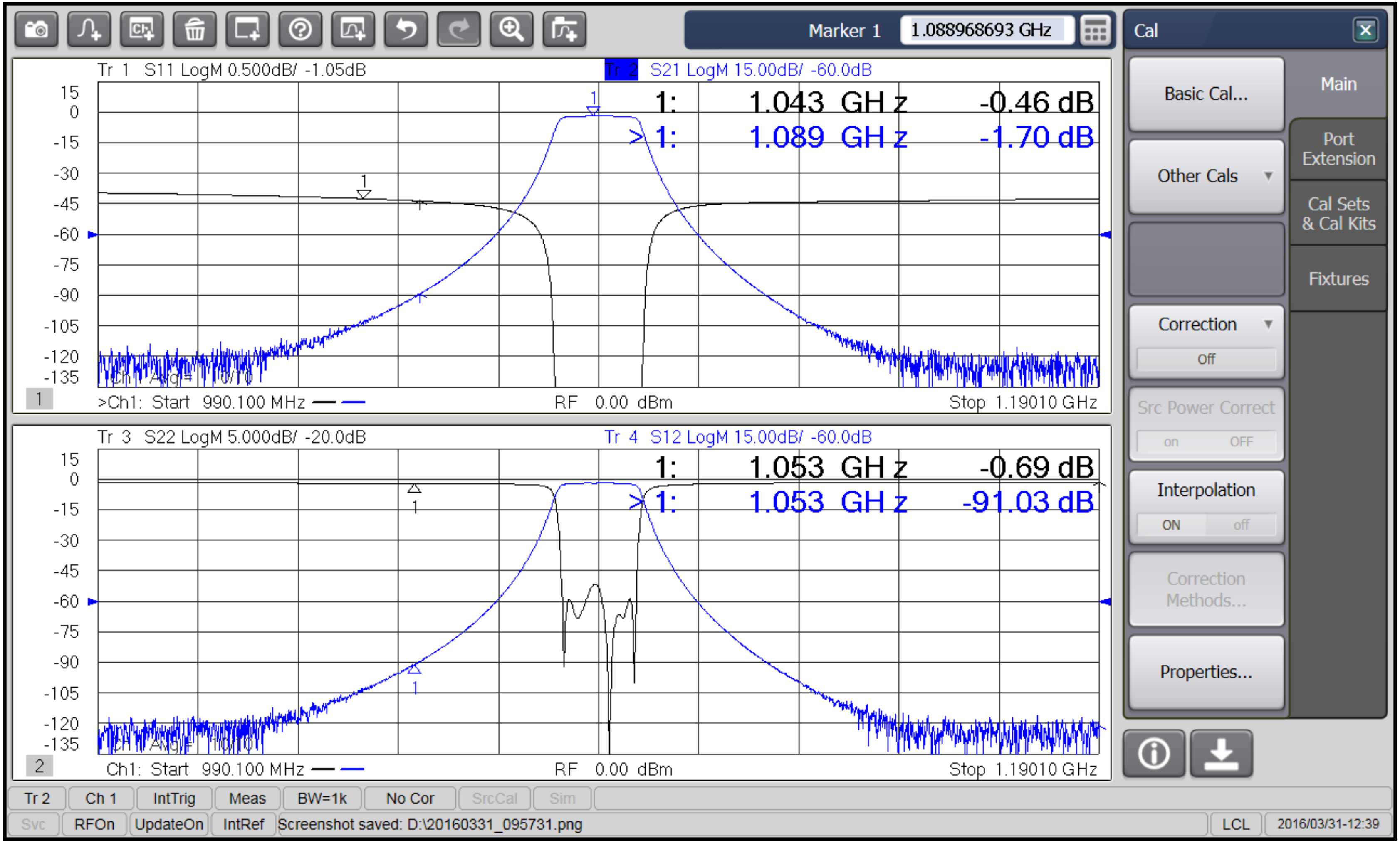
S_{11} = forward reflection coefficient ***(input match)***

S_{22} = reverse reflection coefficient ***(output match)***

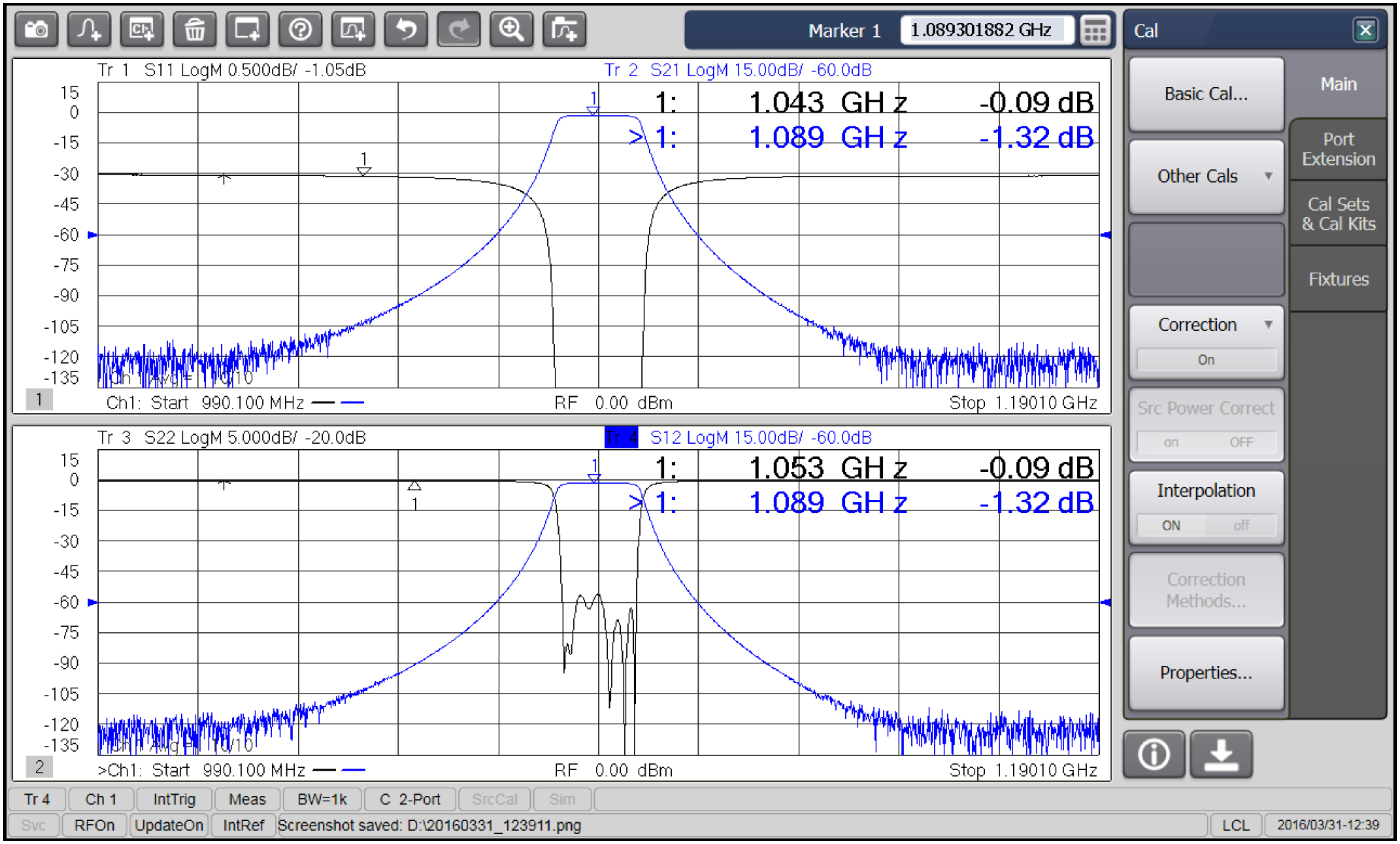
S_{21} = forward transmission coefficient ***(gain or loss)***

S_{12} = reverse transmission coefficient ***(isolation)***

Demonstration
4 S-Parameters with Correction Off



Demonstration
4 S-Parameters with Correction On



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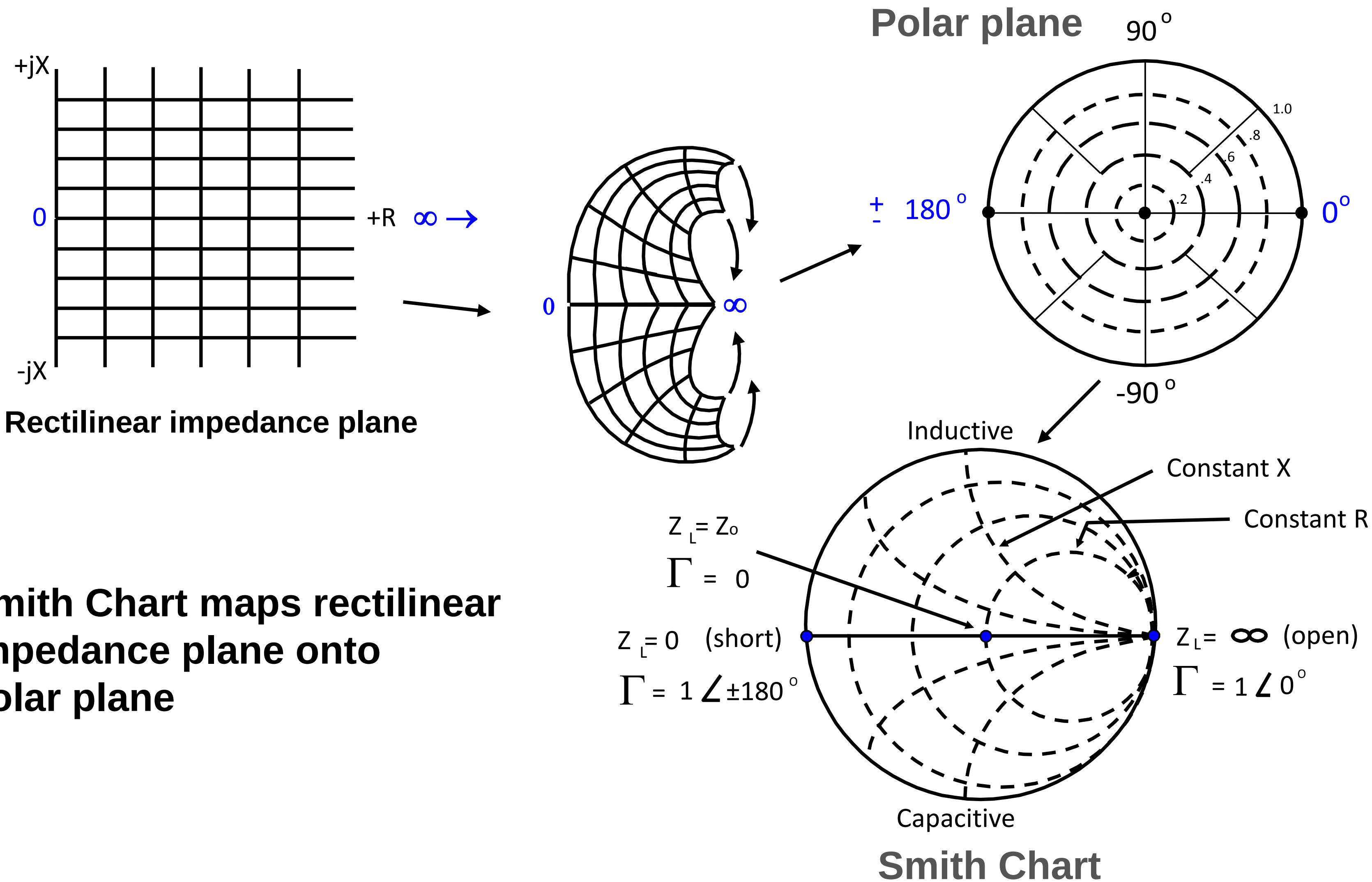
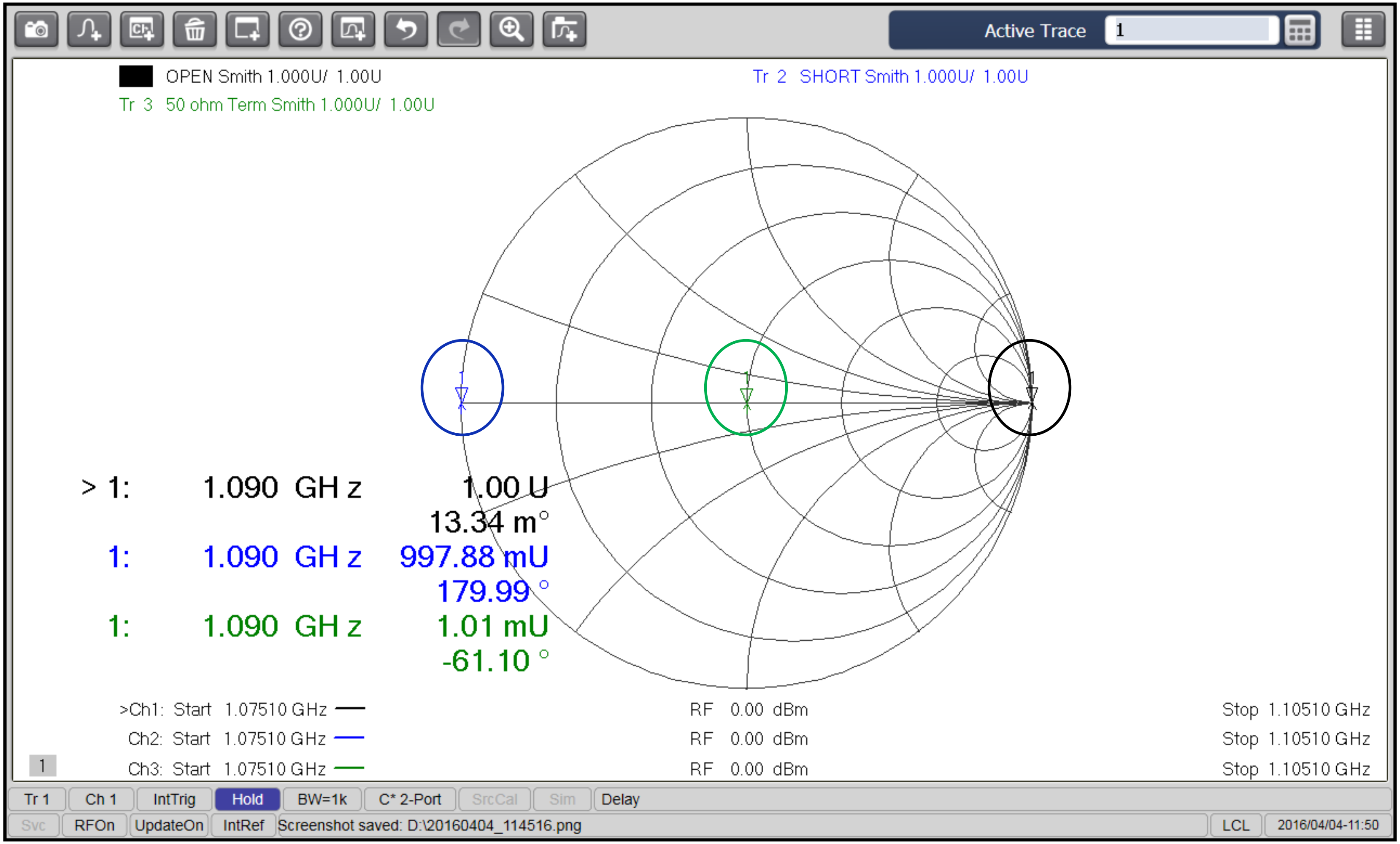
Smith Chart Review



Smith Chart maps rectilinear impedance plane onto polar plane

Demonstration: Smith Chart
Short, and Open, and a Matched Impedance



KEYSIGHT TECHNOLOGIES

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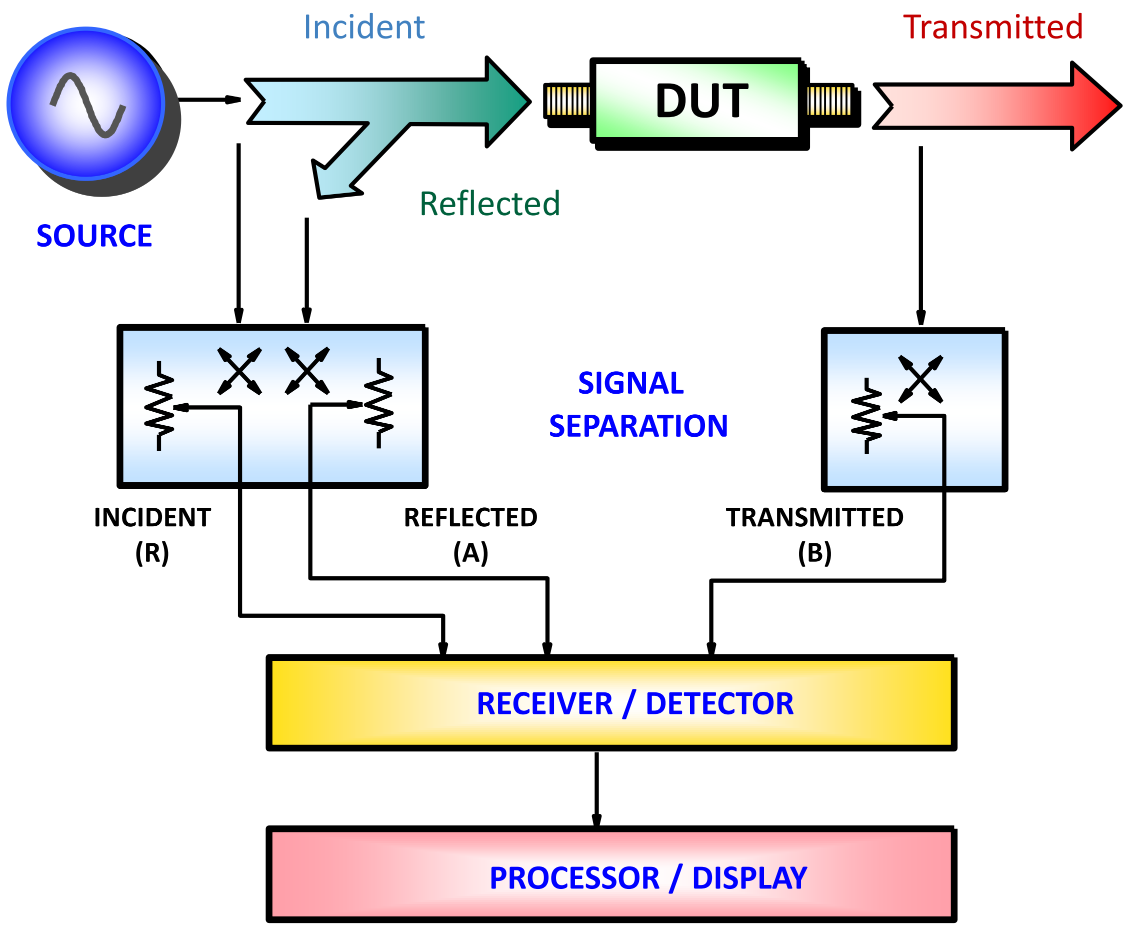
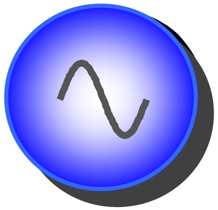
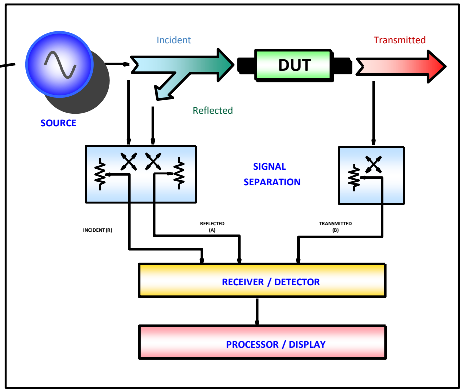
Generalized Network Analyzer Block Diagram (Forward Measurements Shown)



Source





– Supplies stimulus for system

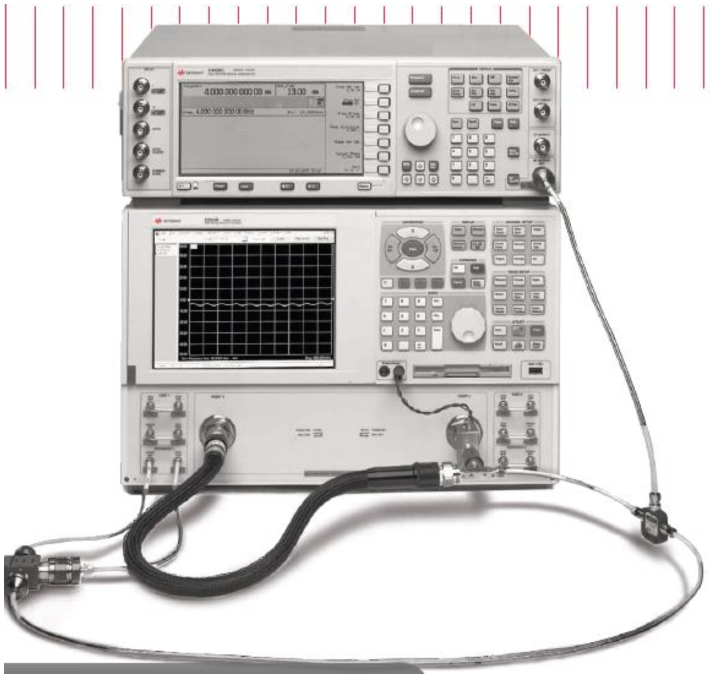
– Can sweep frequency or power

– Traditionally NAs had one signal source

– Modern NAs have the option for a second internal source and/or the ability to control external source

  - Can control an external source as a local oscillator (LO) signal for mixers and converters

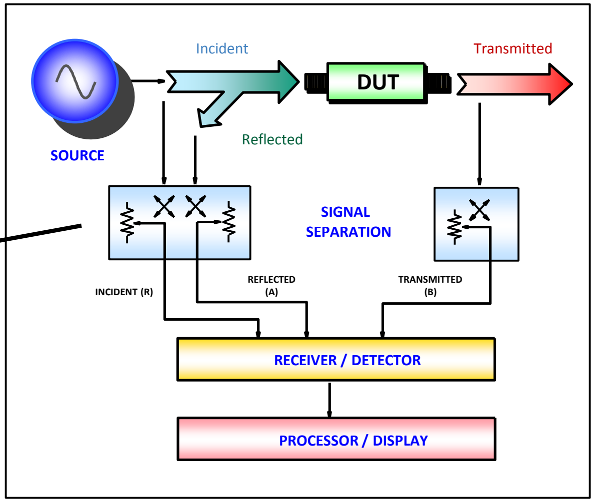
  - Useful for mixer measurements like conversion loss, group delay



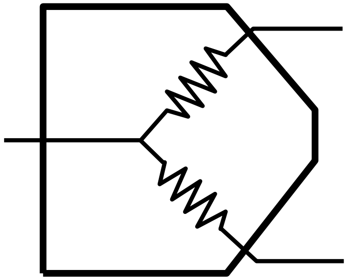
Signal Separation

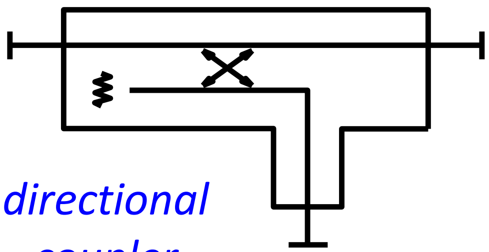
– Measure incident signal for reference

– Separate incident and reflected signals



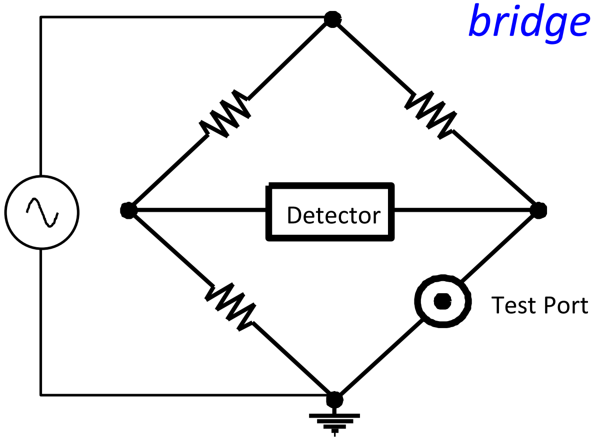
splitter



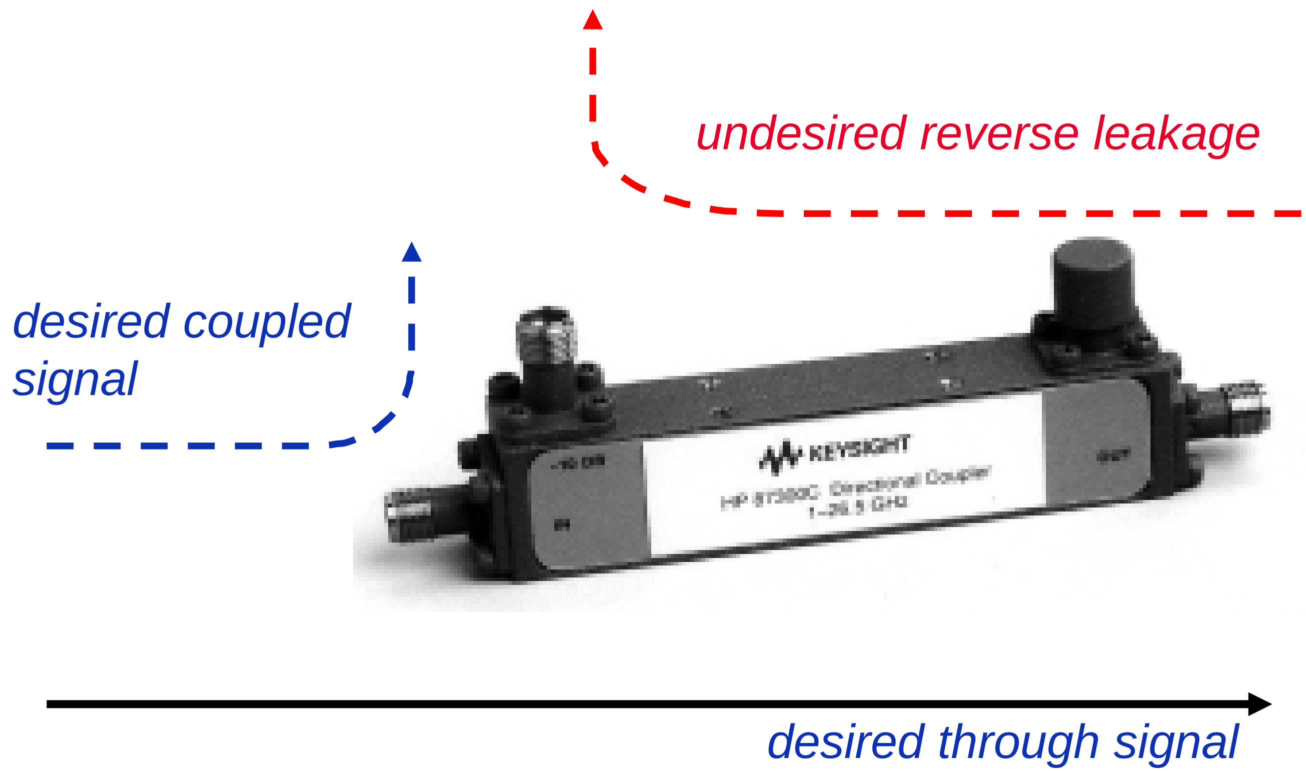


directional coupler

bridge

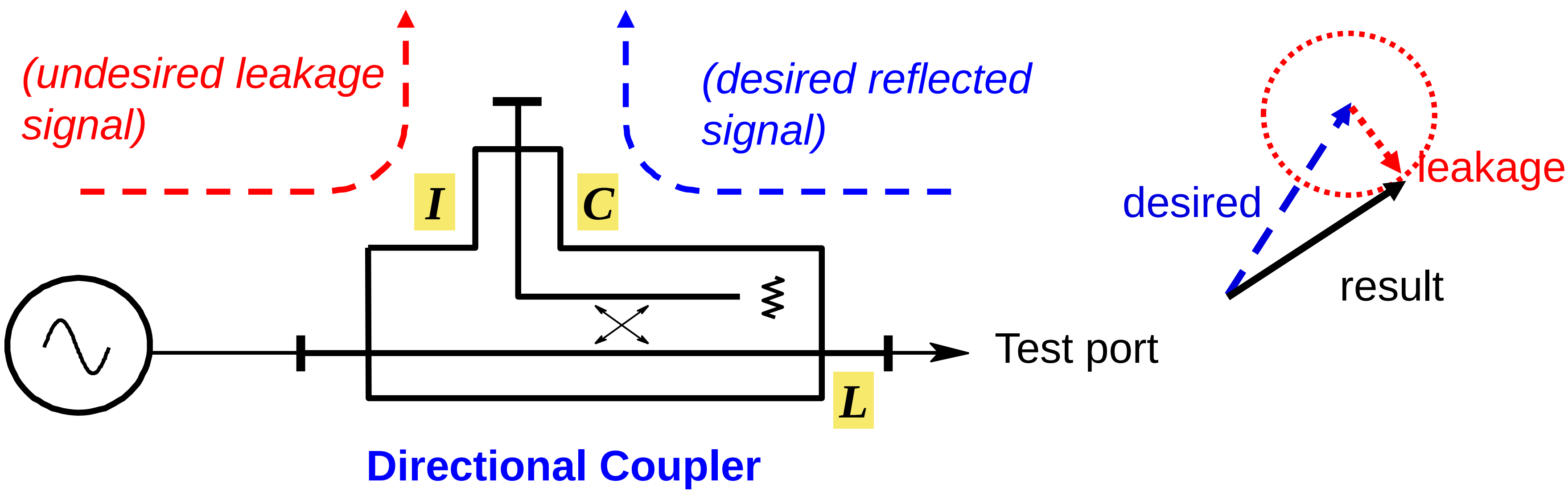


Directional Coupler



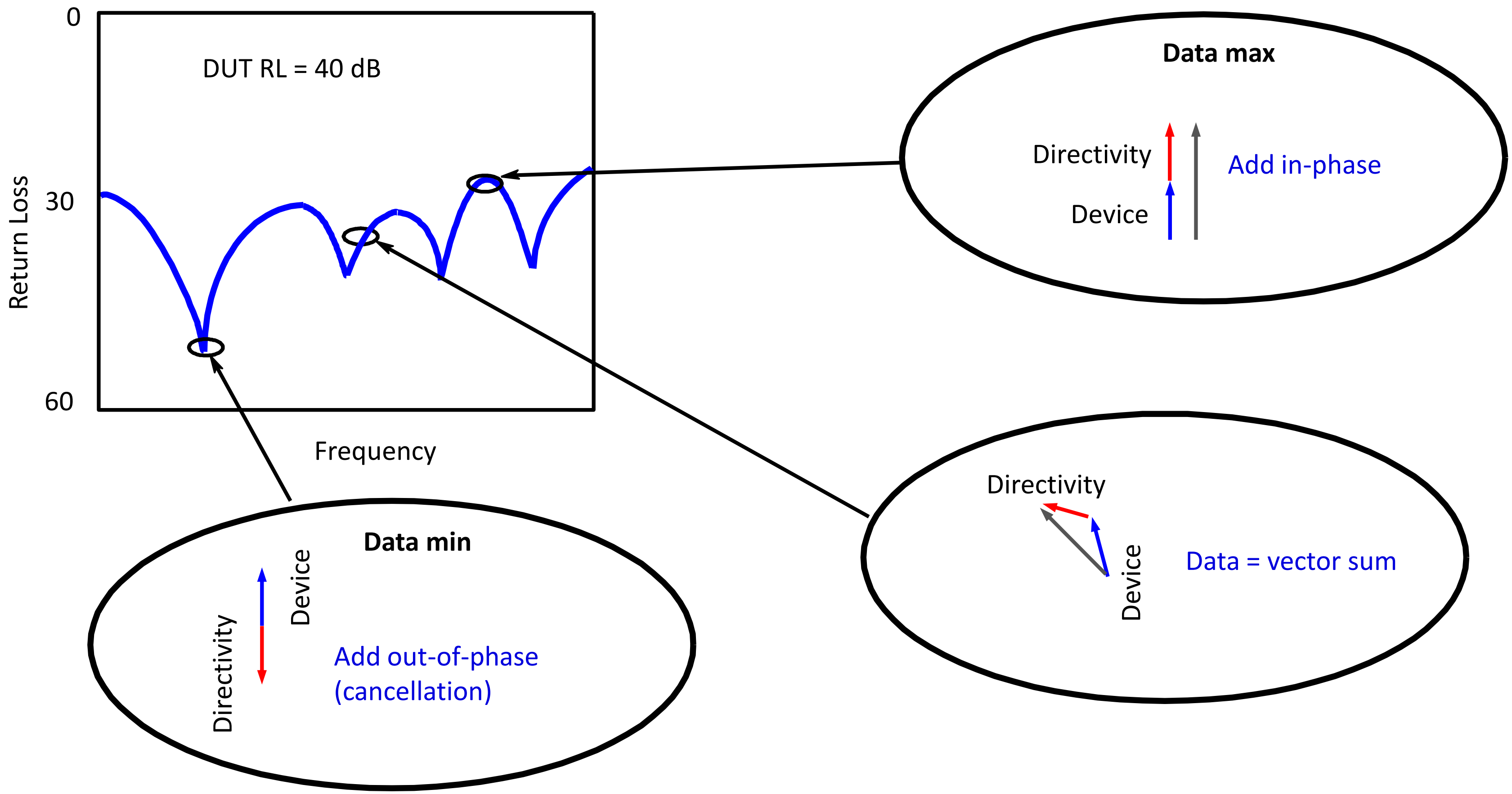
Directivity

Directivity is a measure of how well a directional coupler or bridge can separate signals moving in opposite directions

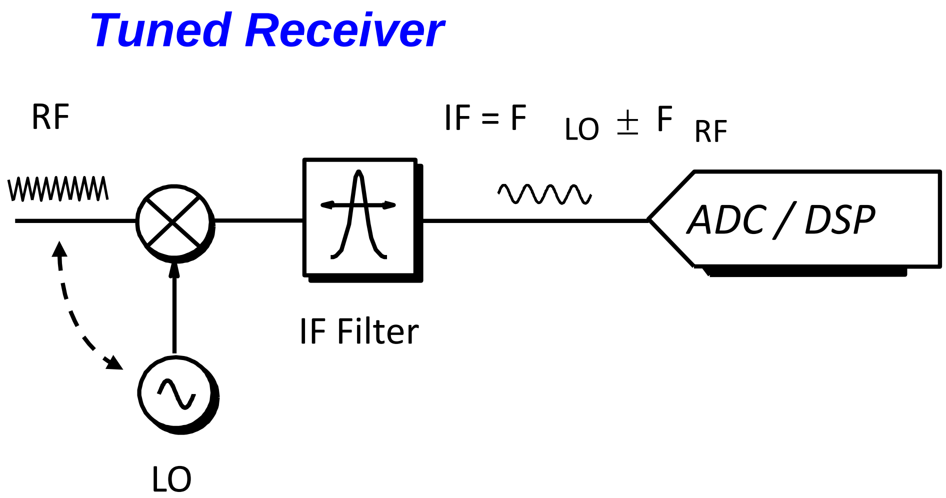


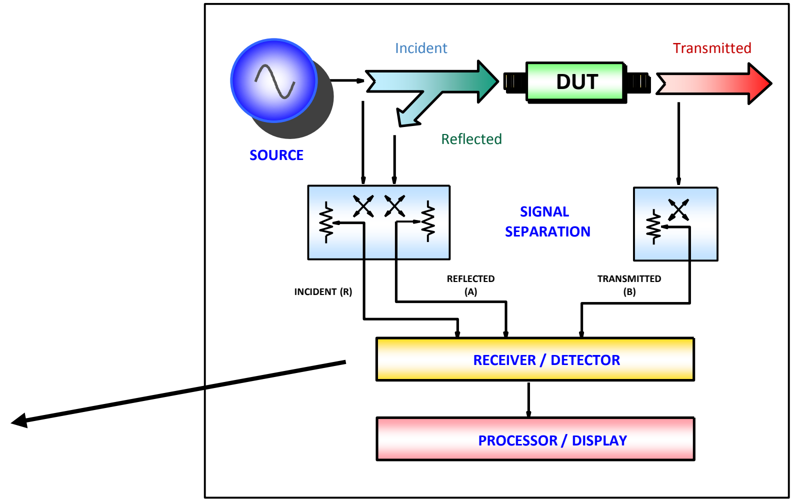
Directivity = Isolation (I) - Fwd Coupling (C) - Main Arm Loss (L)

Interaction of Directivity with the DUT (Without Error Correction)



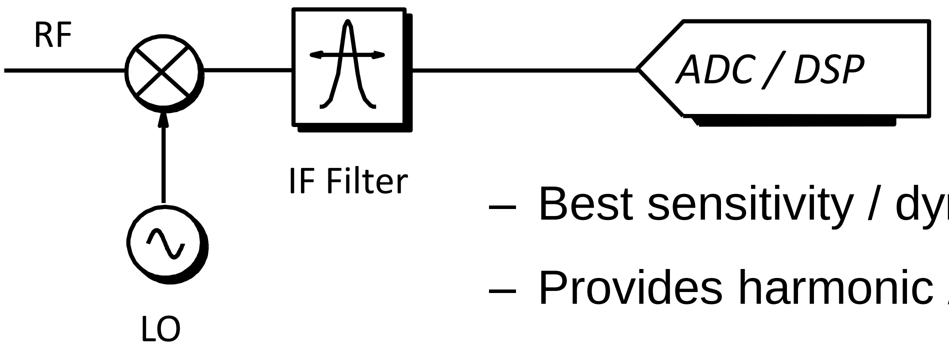
Detector



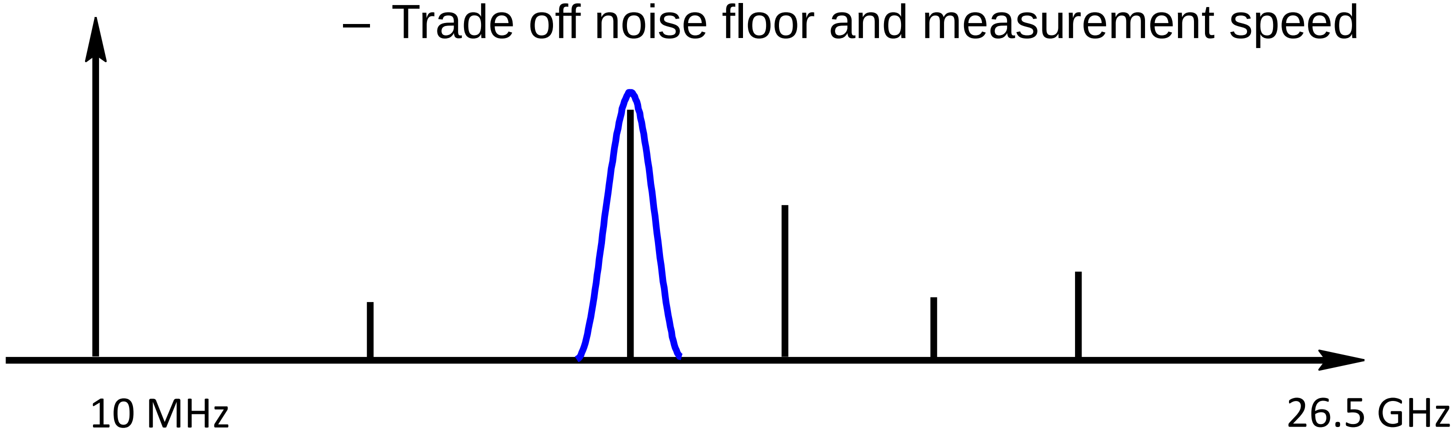


Vector narrowband
(magnitude and phase)

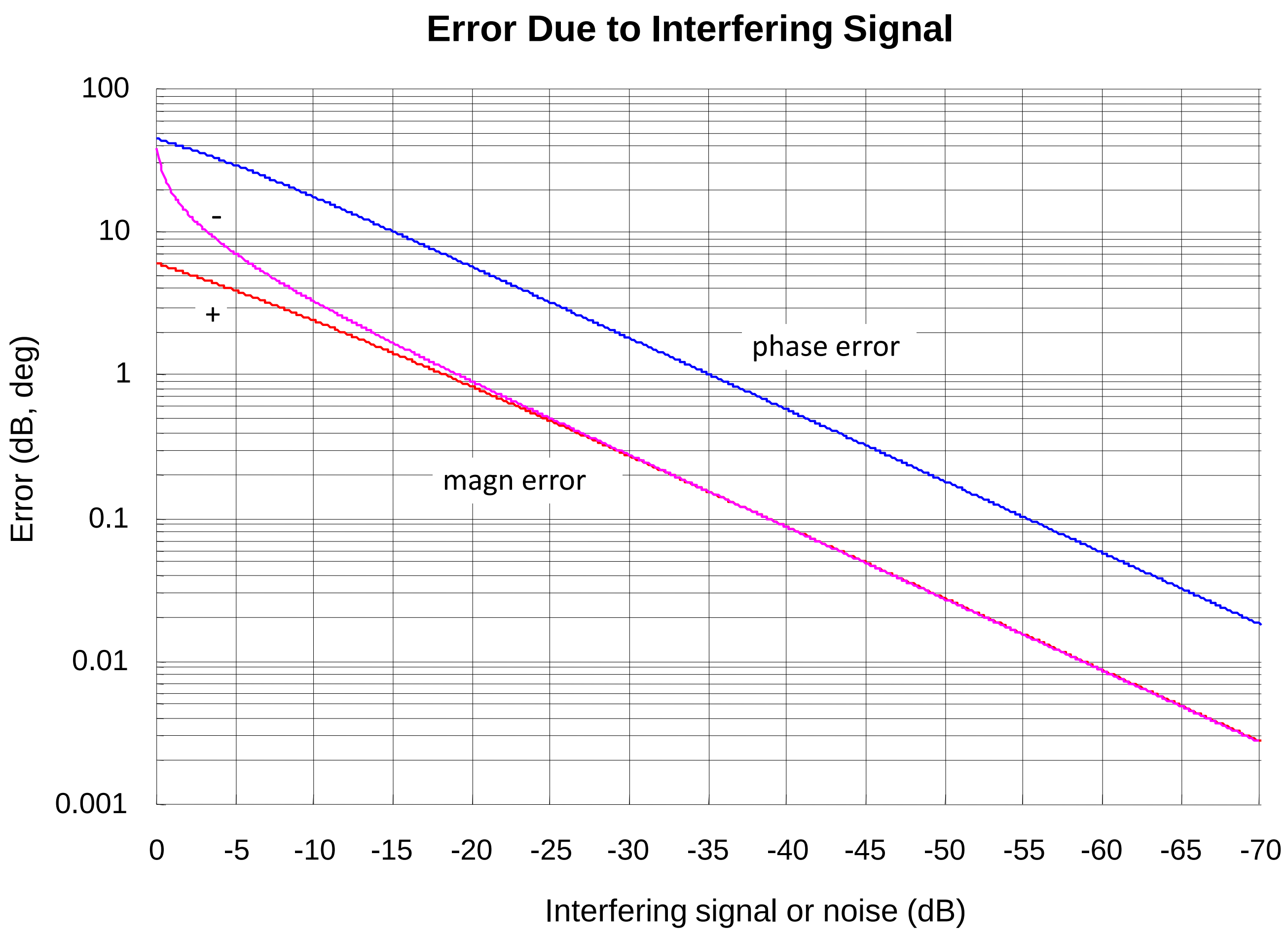
Detector:
Narrowband Detection - Tuned Receiver



- Best sensitivity / dynamic range
- Provides harmonic / spurious signal rejection
- Improve dynamic range by increasing power, decreasing IF bandwidth, or averaging
- Trade off noise floor and measurement speed

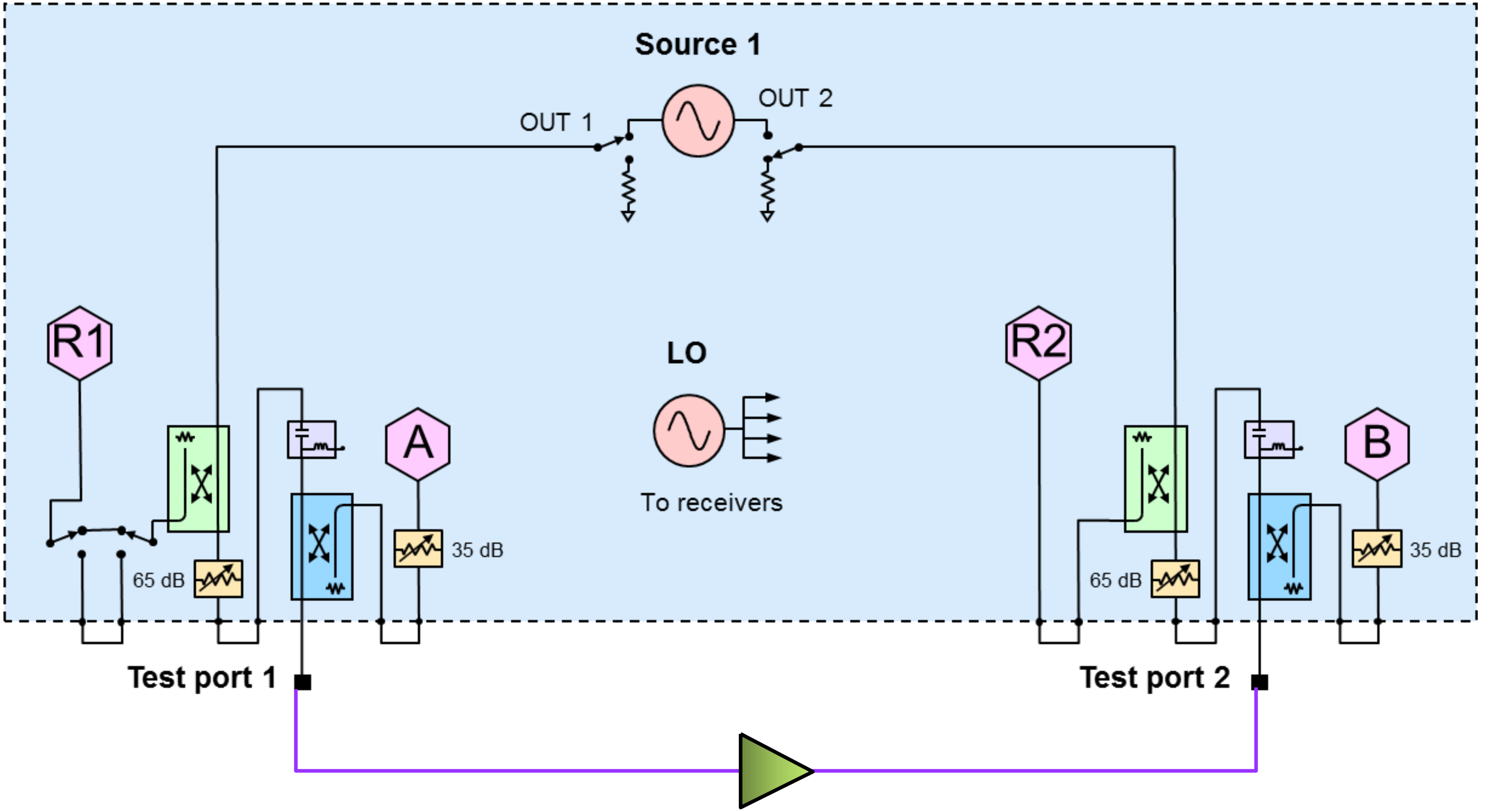


Dynamic Range and Accuracy



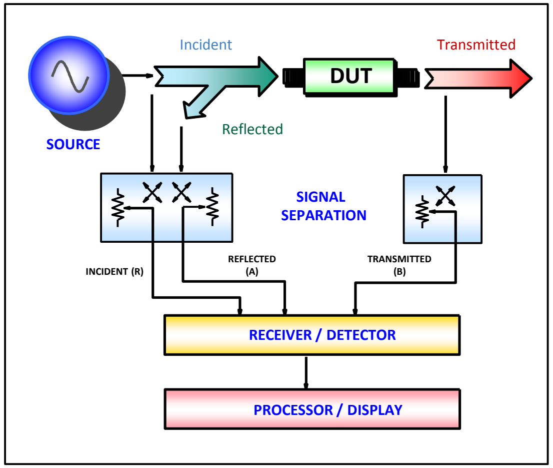
Dynamic range is very important for measurement accuracy!

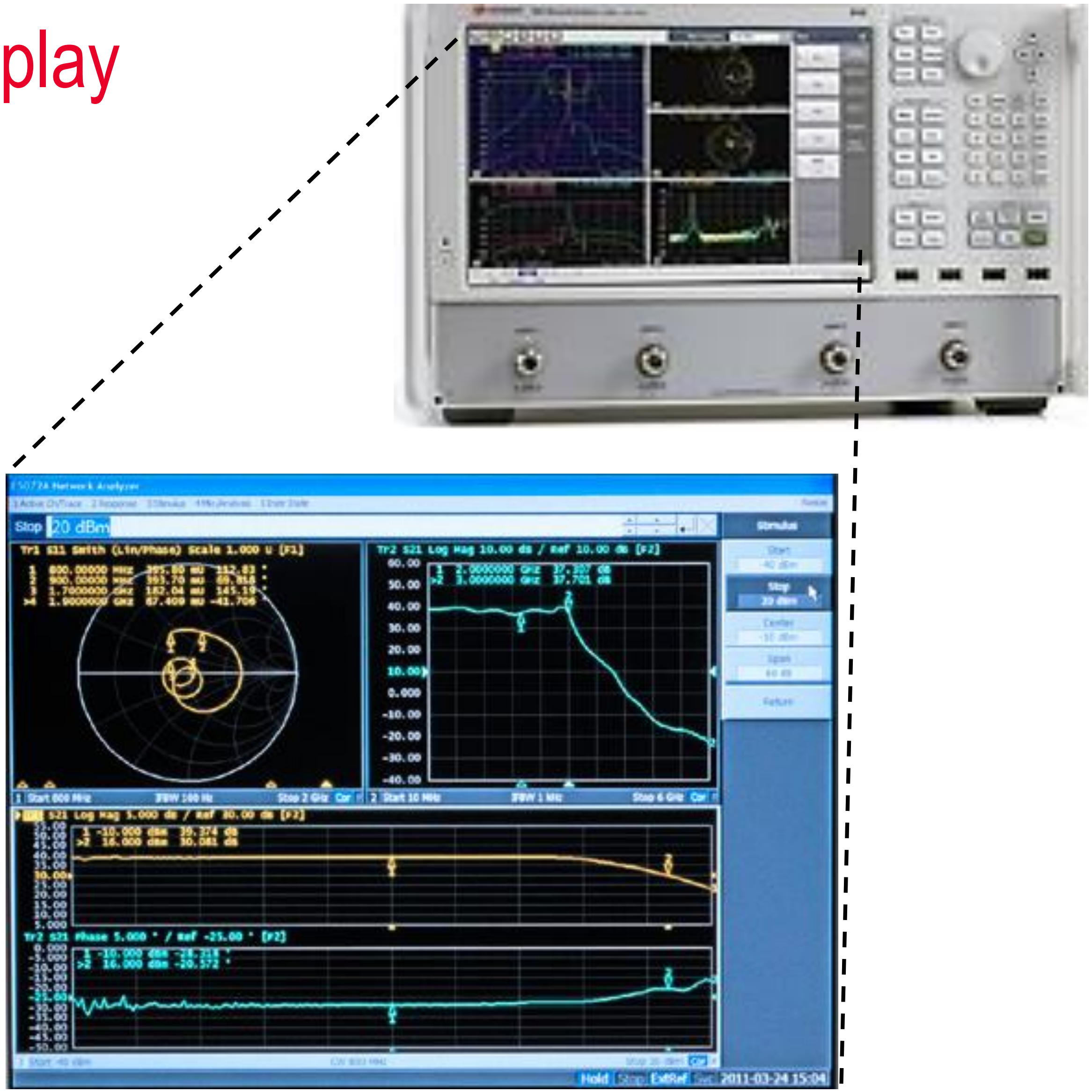
Demonstration
VNA - 2 port Block Diagram



KEYSIGHT TECHNOLOGIES

Processor / Display





- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts
- Time-domain transform
- Trace math

KEYSIGHT TECHNOLOGIES

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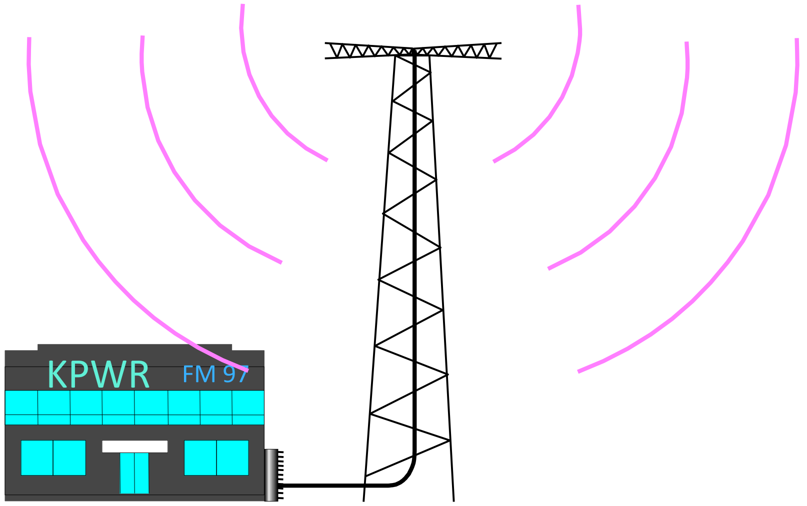
Why Do We Need to Test Components?

– Verify specifications of “building blocks” for more complex RF systems

– Ensure distortion-free transmission of communications signals

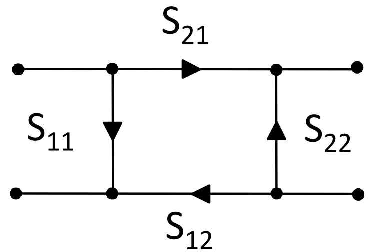
- Linear: constant amplitude, linear phase / constant group delay
- Nonlinear: harmonics, intermodulation, compression, X-parameters

– Ensure good match when absorbing power (e.g., an antenna)

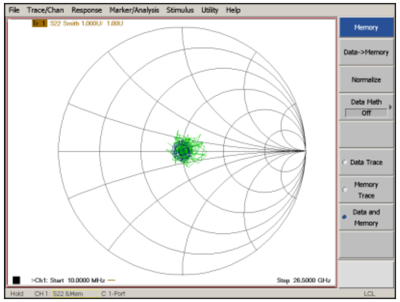


The Need for Both Magnitude and Phase

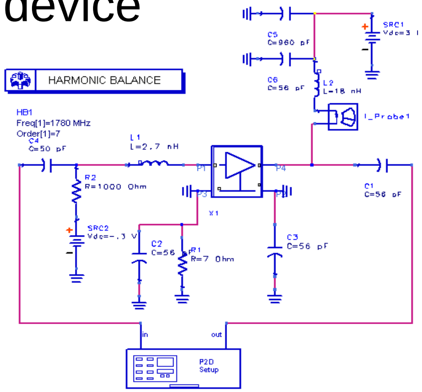
1. Complete characterization of linear networks



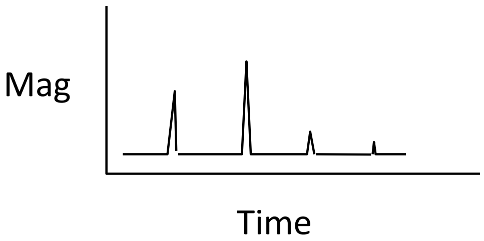
2. Complex impedance needed to design matching circuits



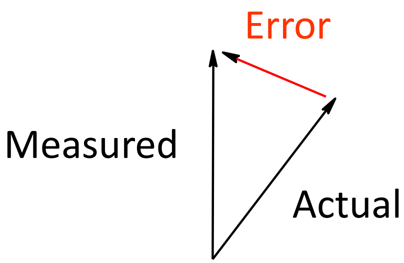
3. Complex values needed for device modeling



4. Time-domain characterization

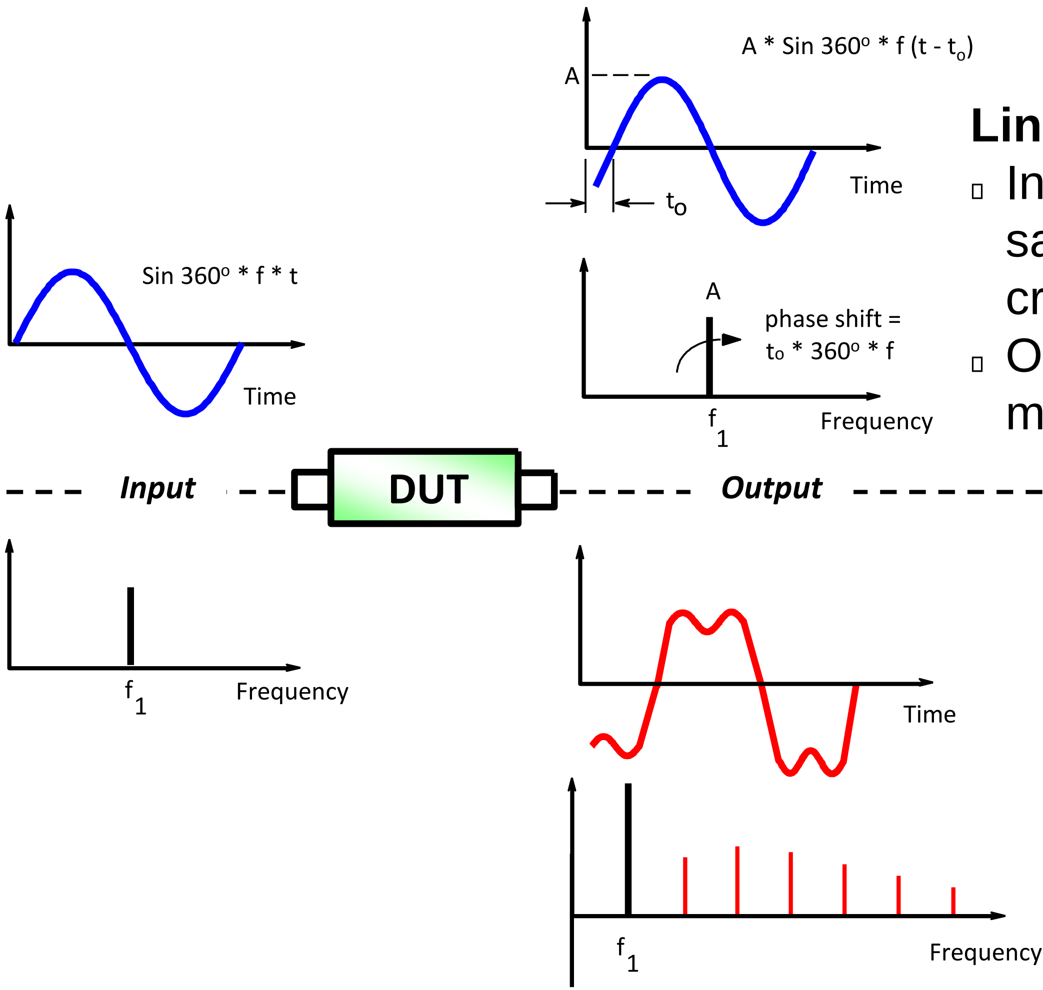


5. Vector-error correction



6. X-parameter (nonlinear) characterization

Linear Versus Nonlinear Behavior



Linear behavior:

- Input and output frequencies are the same (no additional frequencies created)
- Output frequency only undergoes magnitude and phase change

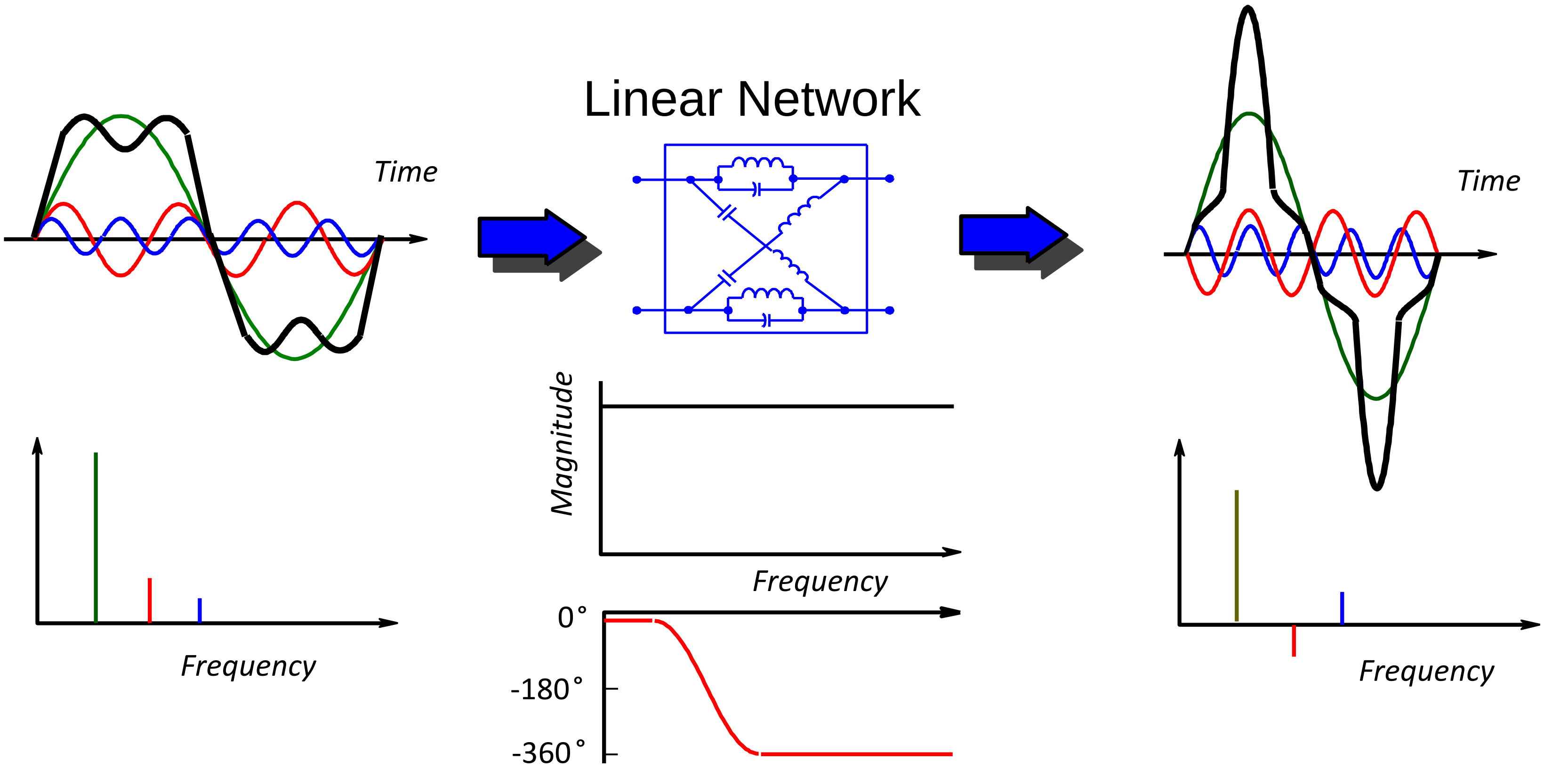
Nonlinear behavior:

- Output frequency may undergo frequency shift (e.g. with mixers)
- Additional frequencies created (harmonics, intermodulation)

KEYSIGHT TECHNOLOGIES

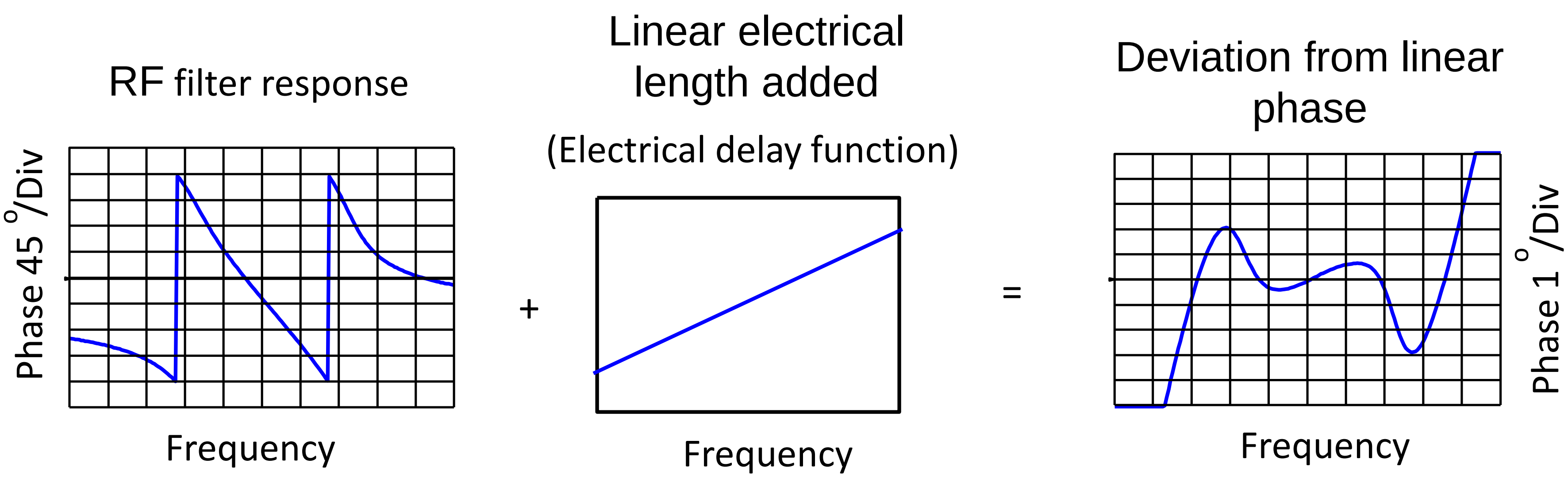
Phase Variation with Frequency

F(t) = sin wt + 1 /3 sin 3wt + 1 /5 sin 5wt



Deviation from Linear Phase

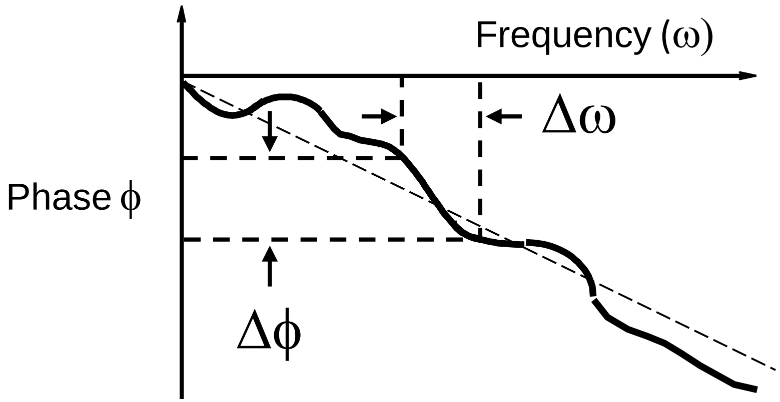
Use electrical delay to remove linear portion of phase response

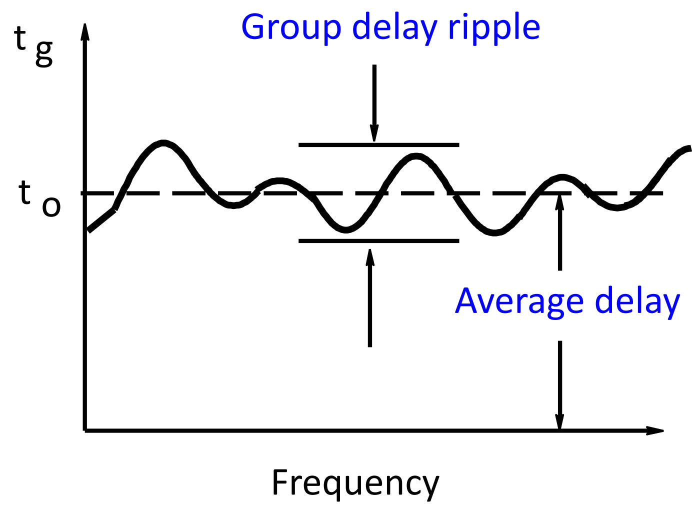


Low resolution

High resolution

Group Delay





Group Delay (t_g)

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

ϕ in radians

ω in radians/sec

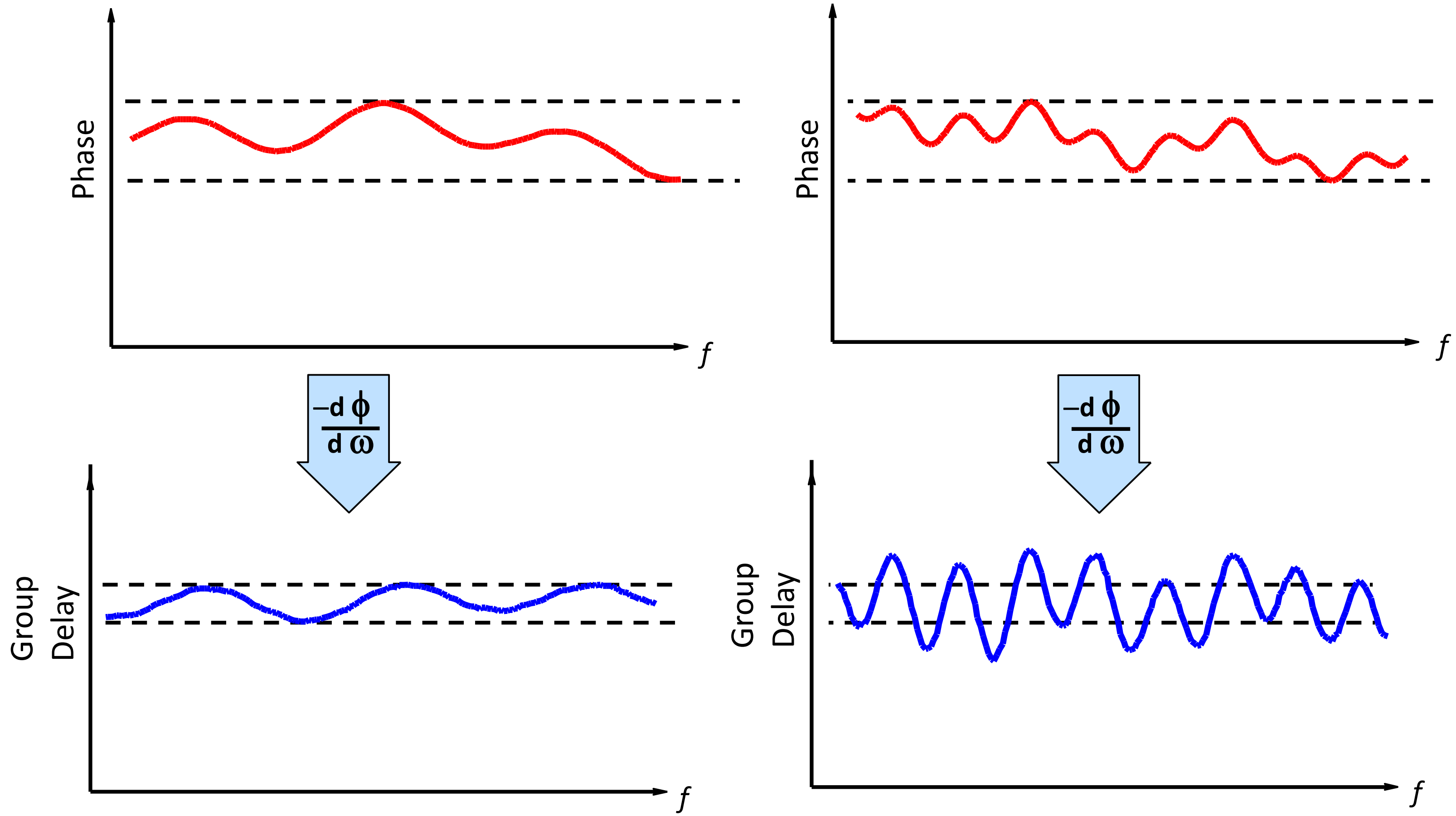
ϕ in degrees

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

- Group-delay ripple indicates phase distortion
- Average delay indicates electrical length of DUT
- Aperture ($\Delta\omega$) of measurement is very important

KEYSIGHT TECHNOLOGIES

Why Measure Group Delay?

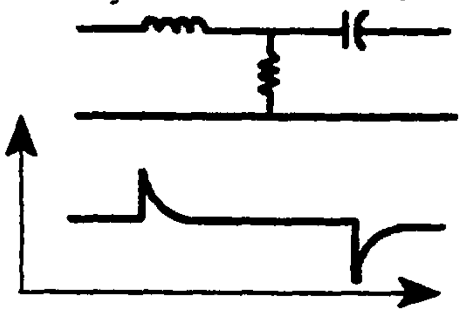


Same peak-peak phase ripple can result in different group delay

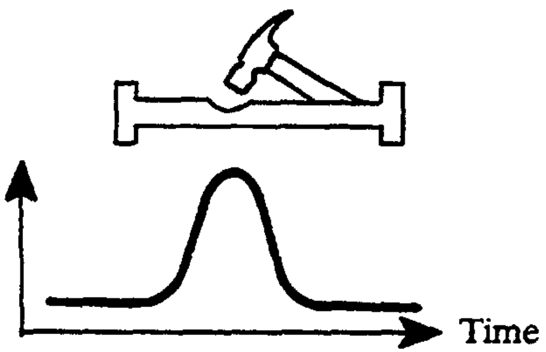
Why the Time Domain?

With the time domain information we can:

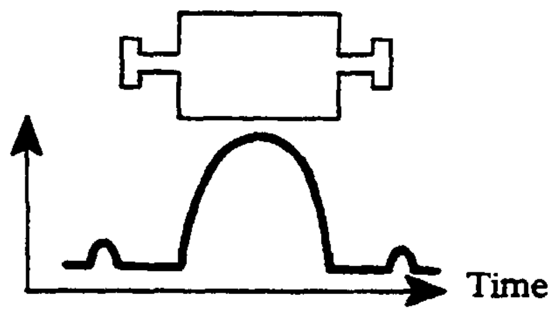
Identify Circuit Elements



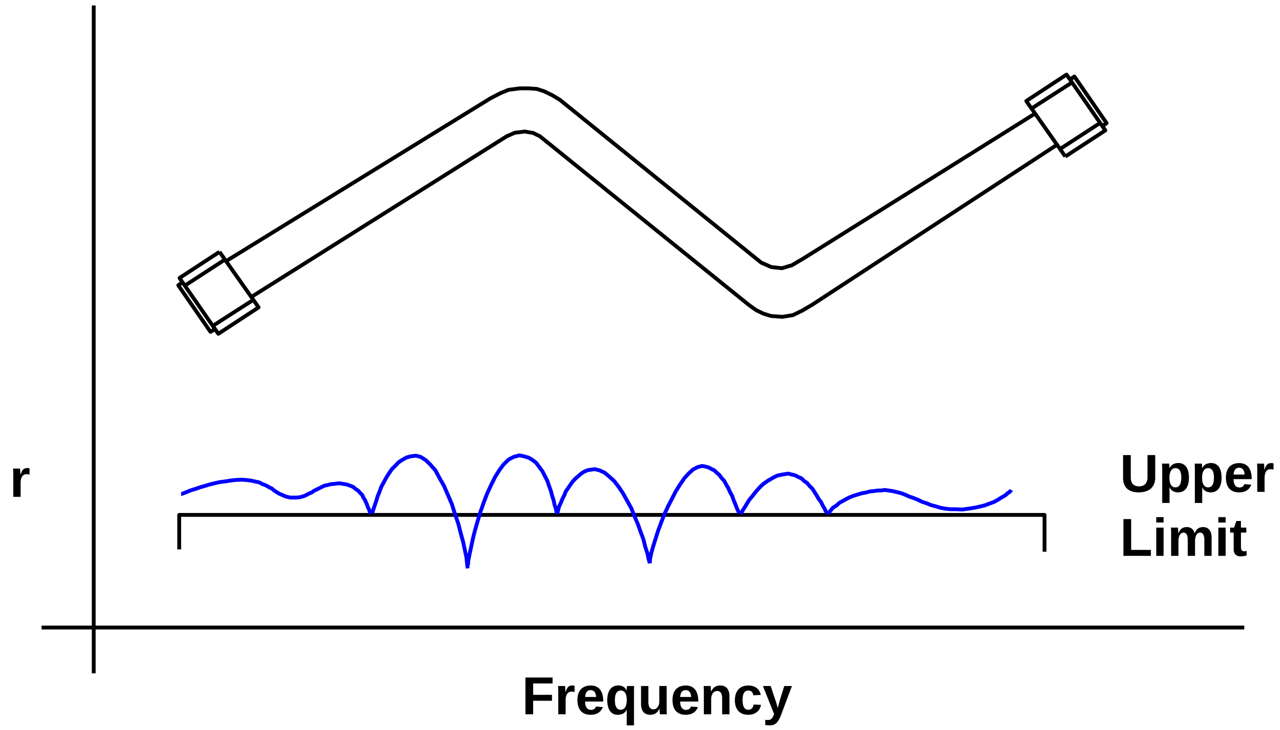
Locate Faults



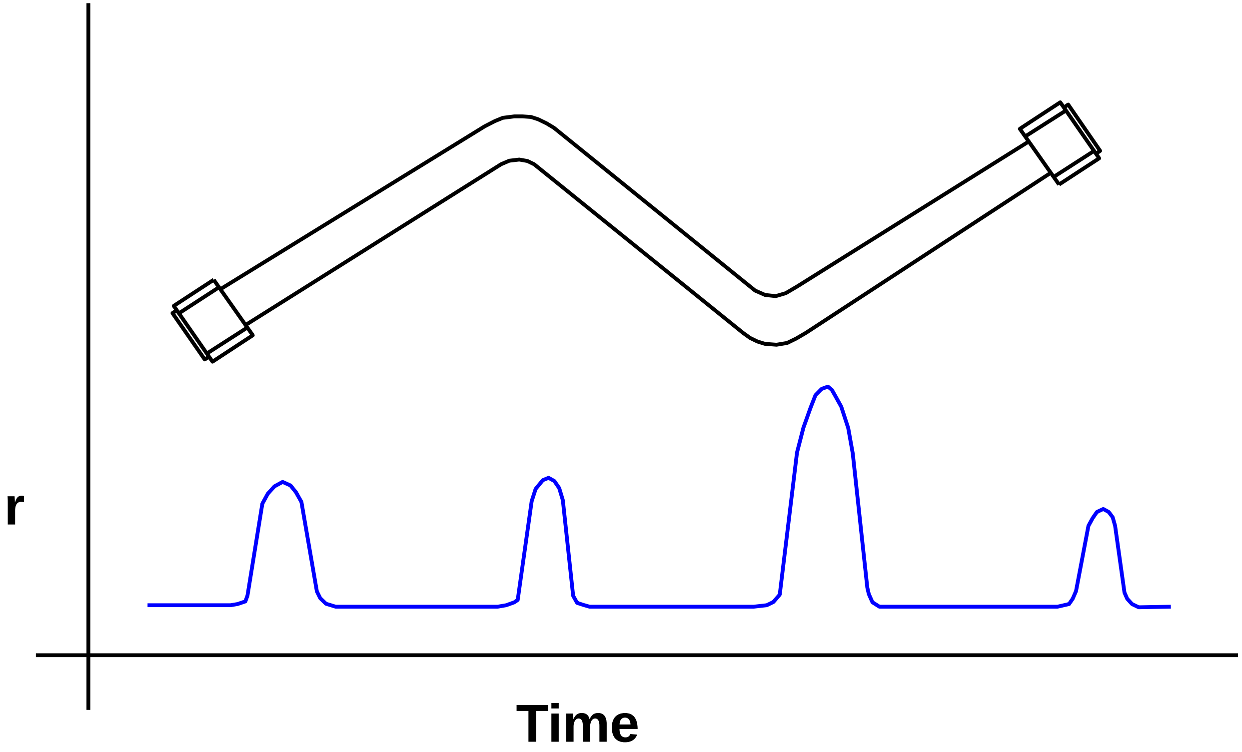
Identify and Remove Unwanted Responses



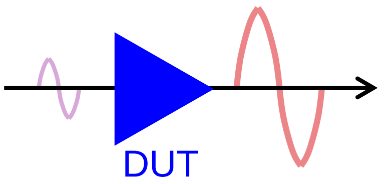
Frequency Domain S_{11} Response of Semirigid Coax Cable



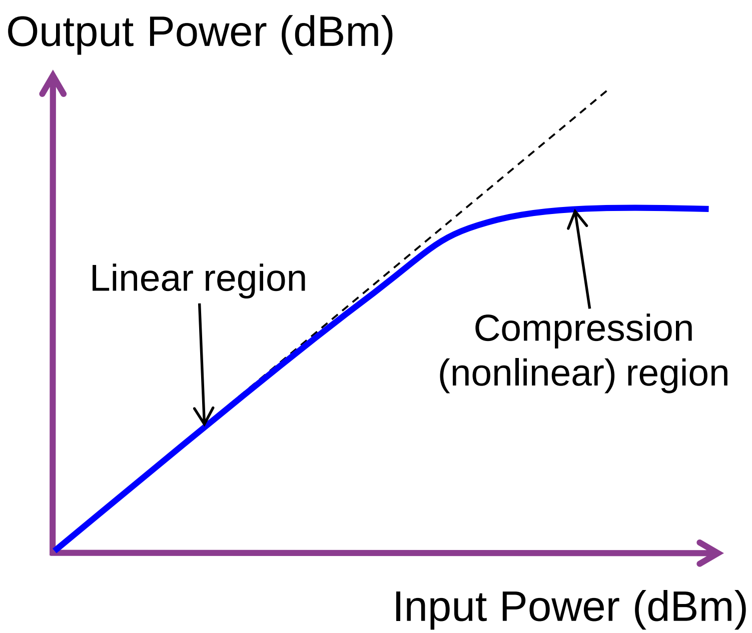
Time Domain S_{11} Response of Semirigid Coax Cable

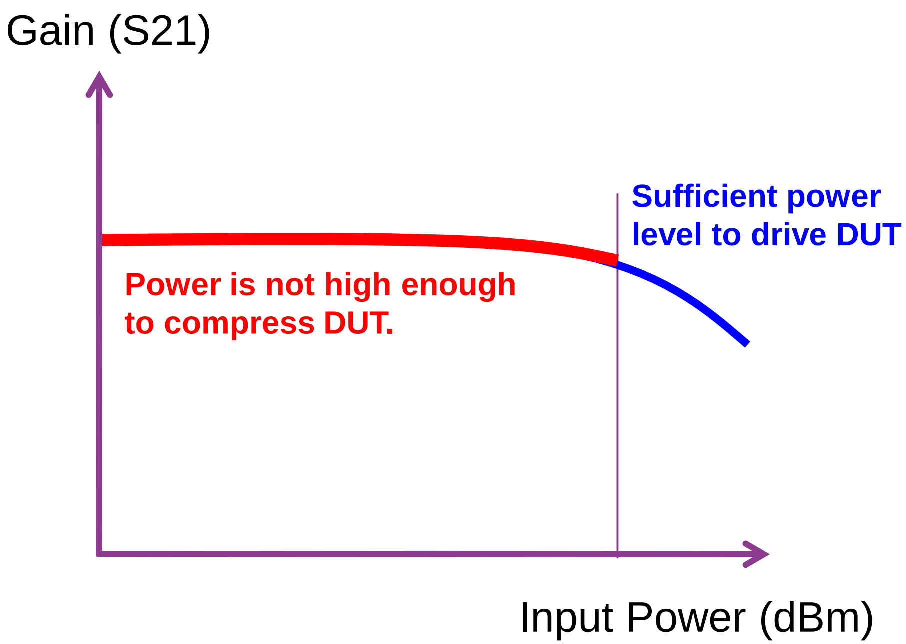


Gain Compression



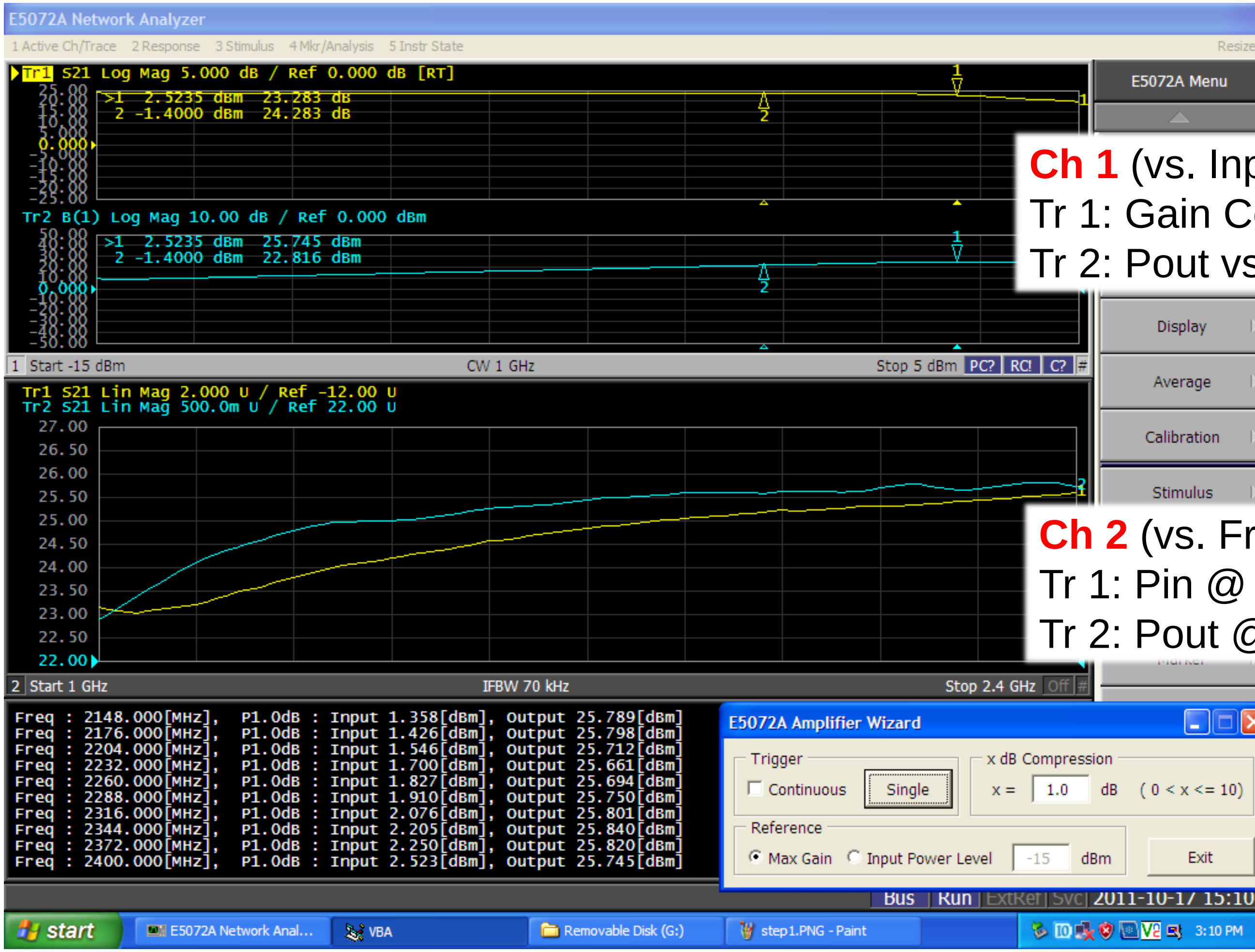
- Parameter to define the transition between the linear and nonlinear region of an active device.
- The compression point is observed as x dB drop in the gain with VNA's power sweep.





Enough margin of source power capability is needed for analyzers.

Gain Compression Measurement Example



Ch 1 (vs. Input power):
Tr 1: Gain Compresssion vs. Pin
Tr 2: Pout vs. Pin

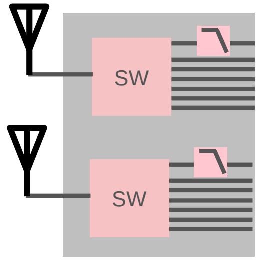
Ch 2 (vs. Frequency):
Tr 1: Pin @ P1dB vs. Freq
Tr 2: Pout @ P1dB vs. Freq

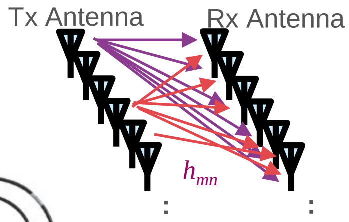
KEYSIGHT TECHNOLOGIES

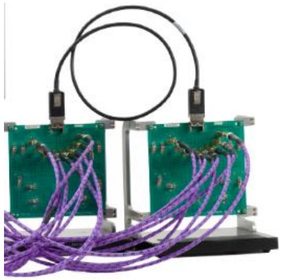
Multiport Measurement

Application Examples

- RF front end modules / antenna switch modules
- Channel measurements of MIMO antennas
- Interconnects (ex. cables, connectors)
- General-purpose multiport devices







Agenda

– Transmission Lines

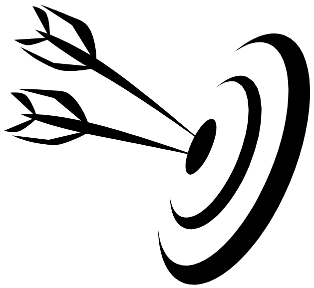
– S-Parameters

– The Smith Chart

– Network Analysis Measurements

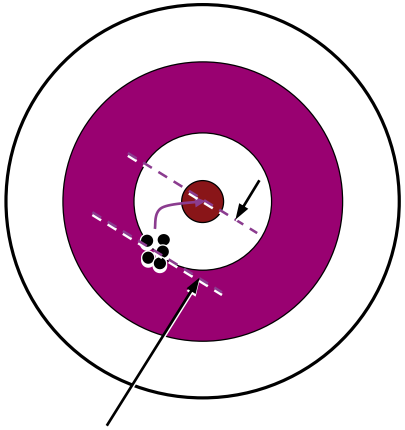
– Calibration and Error Correction

The Need For Calibration



– **Why do we have to calibrate?**
  - It is impossible to make perfect hardware
  - It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction

– **How do we get accuracy?**
  - With vector-error-corrected calibration
  - Not the same as the yearly instrument calibration



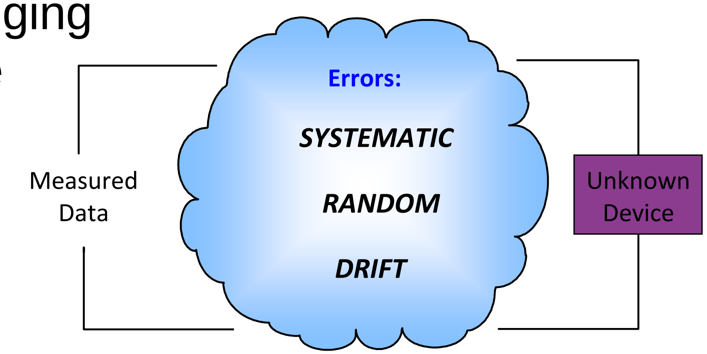
– **What does calibration do for us?**
  - Removes the largest contributor to measurement uncertainty: systematic errors
  - Provides best picture of true performance of DUT

Measurement Error Modeling

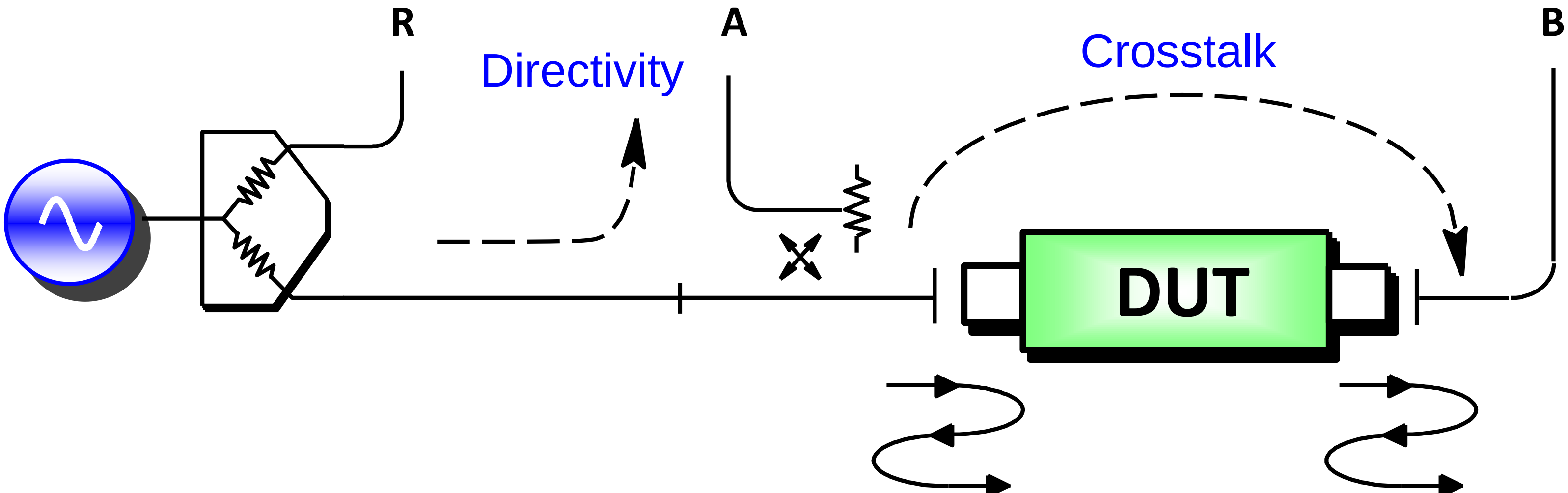
– ***Systematic errors***
  - Due to imperfections in the analyzer and test setup
  - Assumed to be time invariant (predictable)
  - Generally, are largest sources or error

– ***Random errors***
  - Vary with time in random fashion (unpredictable)
  - Main contributors: instrument noise, switch and connector repeatability

– ***Drift errors***
  - Due to system performance changing ***after*** a calibration has been done
  - Primarily caused by **temperature variation**



Systematic Measurement Errors



Frequency response

- Reflection tracking (A/R)
- Transmission tracking (B/R)

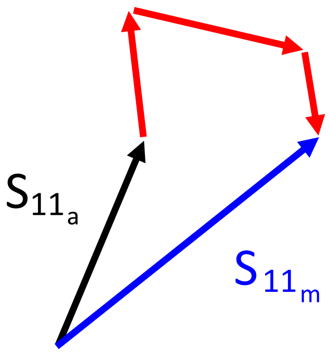
Six forward and six reverse error terms yields 12 error terms for two-port devices

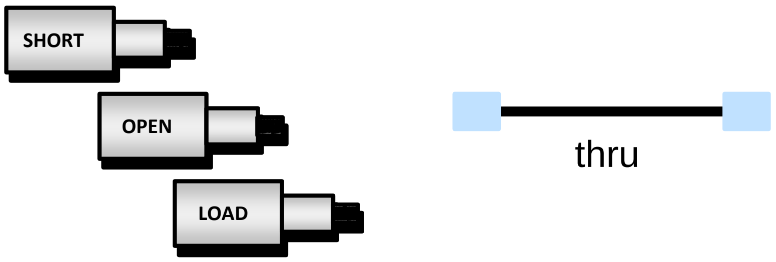
Types of Error Correction

– **Response (normalization)**

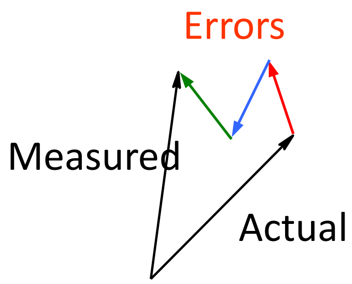
- Simple to perform
- Only corrects for tracking (frequency response) errors
- Stores reference trace in memory, then does data divided by memory

– **Vector**
- Requires more calibration standards
- Requires an analyzer that can measure phase
- Accounts for all major sources of systematic error





What is Vector-Error Correction?



– **Vector-error correction…**
  - Is a process for characterizing systematic error terms
  - Measures known electrical standards
  - Removes effects of error terms from subsequent measurements

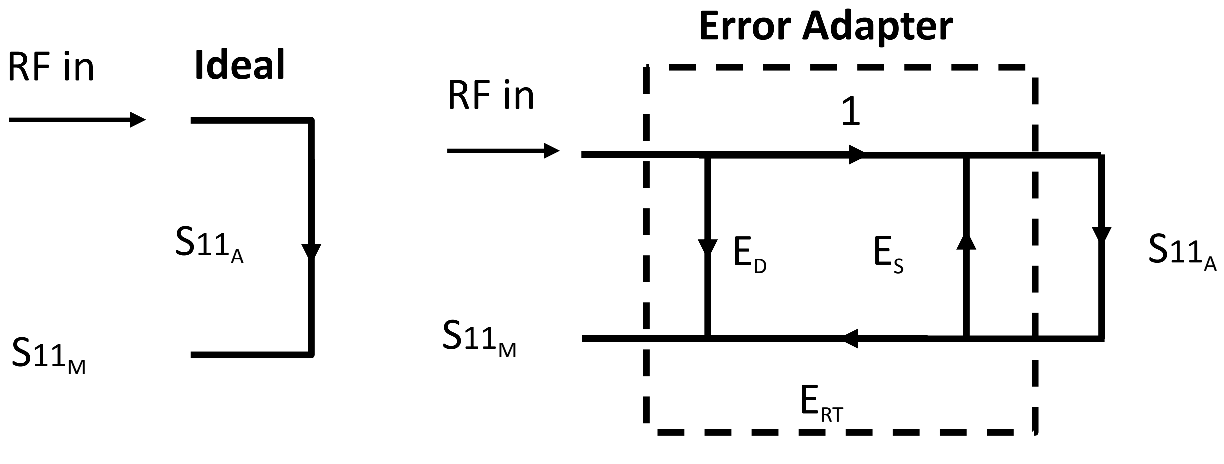
– **Electrical standards…**
  - Can be mechanical or electronic
  - Are often an open, short, load, and thru, but can be arbitrary impedances as well

Using Known Standards to Correct for Systematic Errors

- **1-port calibration** *(reflection measurements)*
  - Only three systematic error terms measured
  - Directivity, source match, and reflection tracking
- **Full two-port calibration** *(reflection and transmission measurements)*
  - Twelve systematic error terms measured
  - Usually requires 12 measurements on four known standards (SOLT)
- **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

KEYSIGHT TECHNOLOGIES

Reflection: One-Port Model



E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

$S11_A$ = Actual

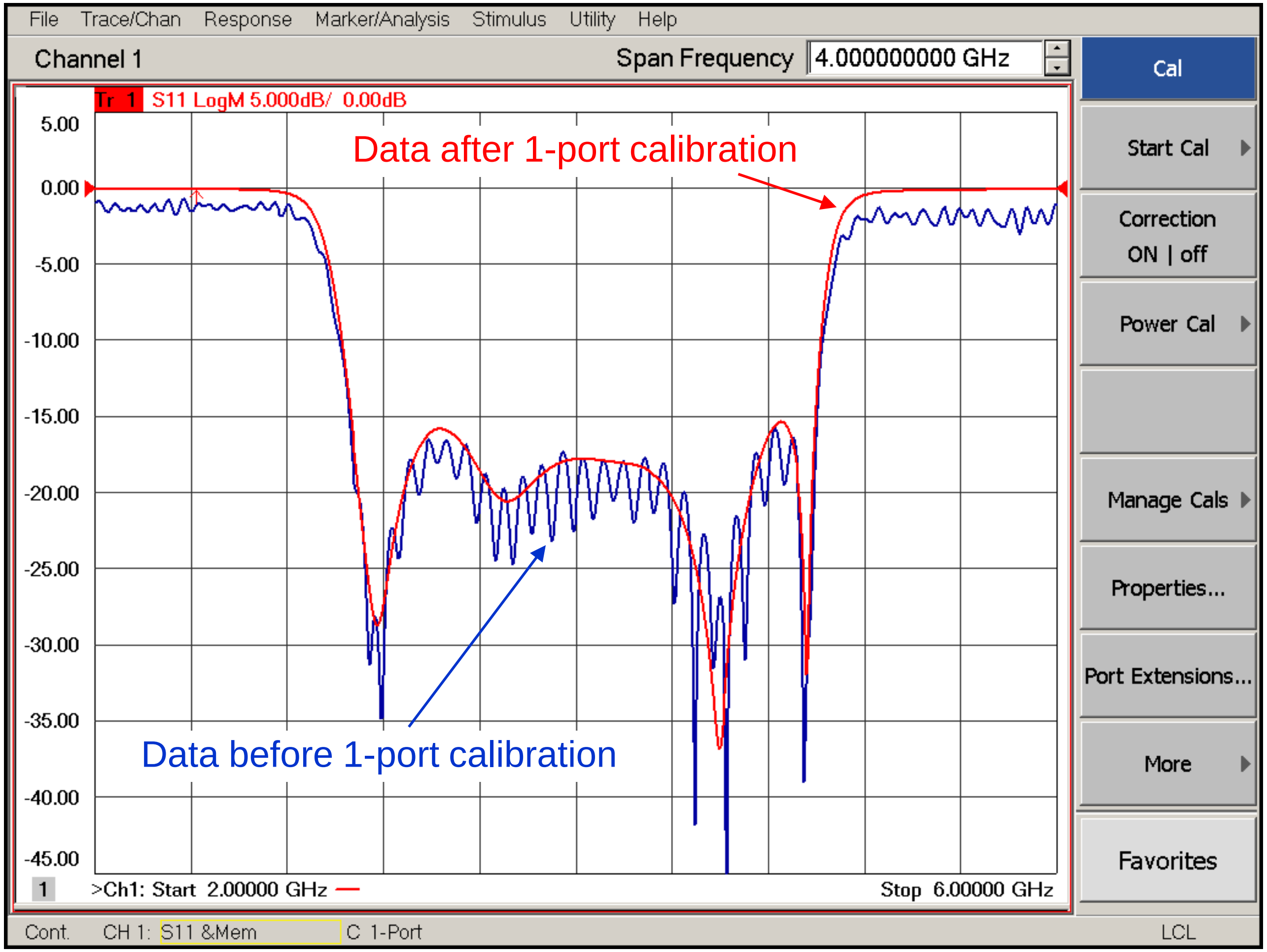
To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

$$S11_M = E_D + E_{RT} \left[\frac{S11_A}{1 - E_S \, S11_A} \right]$$

- Assumes good termination at port two if testing two-port devices
- If using port two of NA *and* DUT reverse isolation is low (e.g., filter passband):
  - Assumption of good termination is not valid
  - Two-port error correction yields better results

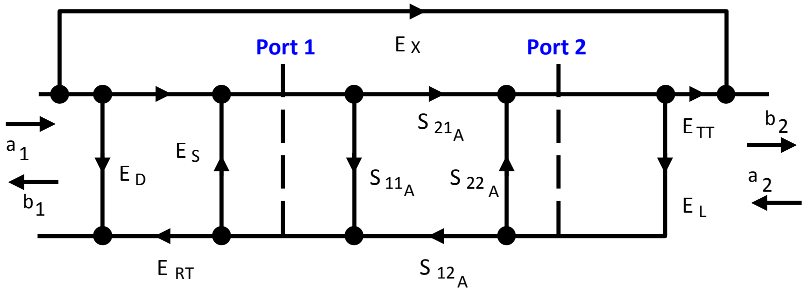
KEYSIGHT TECHNOLOGIES

Before and After A One-Port Calibration

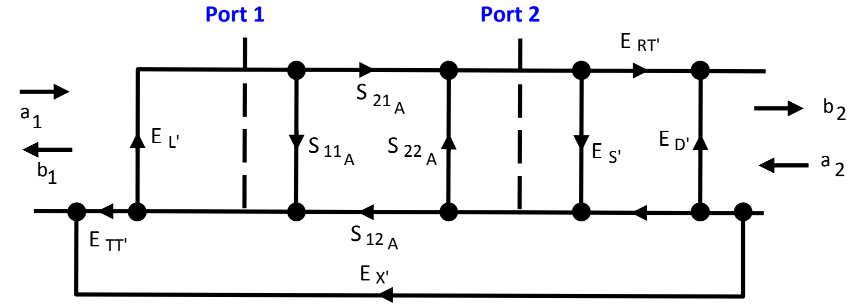


Two-Port Error Correction

Forward model



Reverse model



E_D	= fwd directivity	E_L	= fwd load match
E_S	= fwd source match	E_{TT}	= fwd transmission tracking
E_{RT}	= fwd reflection tracking	E_X	= fwd isolation
$E_{D'}$	= rev directivity	$E_{L'}$	= rev load match
$E_{S'}$	= rev source match	$E_{TT'}$	= rev transmission tracking
$E_{RT'}$	= rev reflection tracking	$E_{X'}$	= rev isolation

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** a network analyzers!!!

$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D'}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

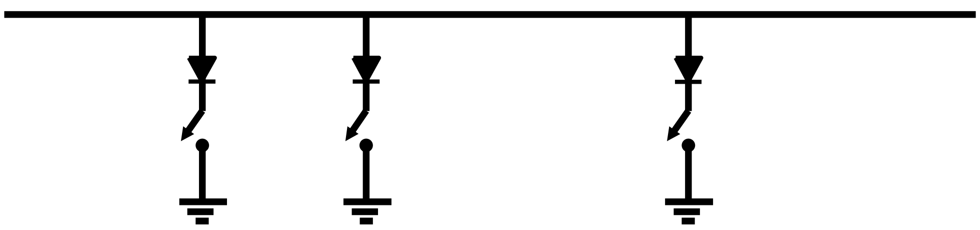
$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

KEYSIGHT TECHNOLOGIES

ECal: Electronic Calibration

- Variety of two- and four-port modules cover 300 kHz to 67 GHz
- Nine connector types available, 50 and 75 ohms
- Single-connection calibration
  - dramatically reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated characterized terminations provide excellent accuracy

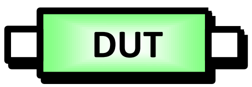
USB Controlled



Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

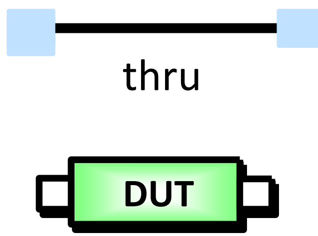
Errors and Calibration Standards

UNCORRECTED



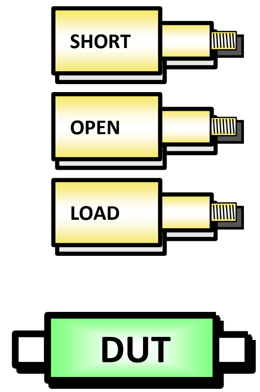
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



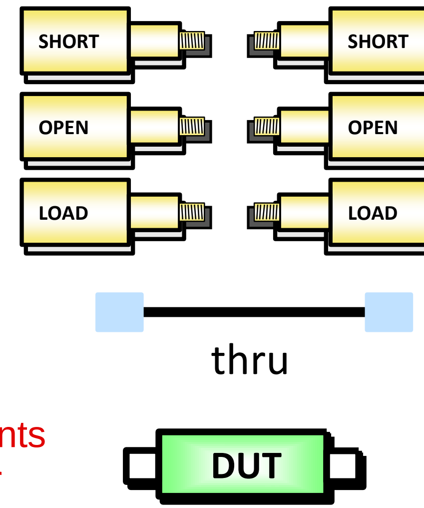
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

ENHANCED-RESPONSE

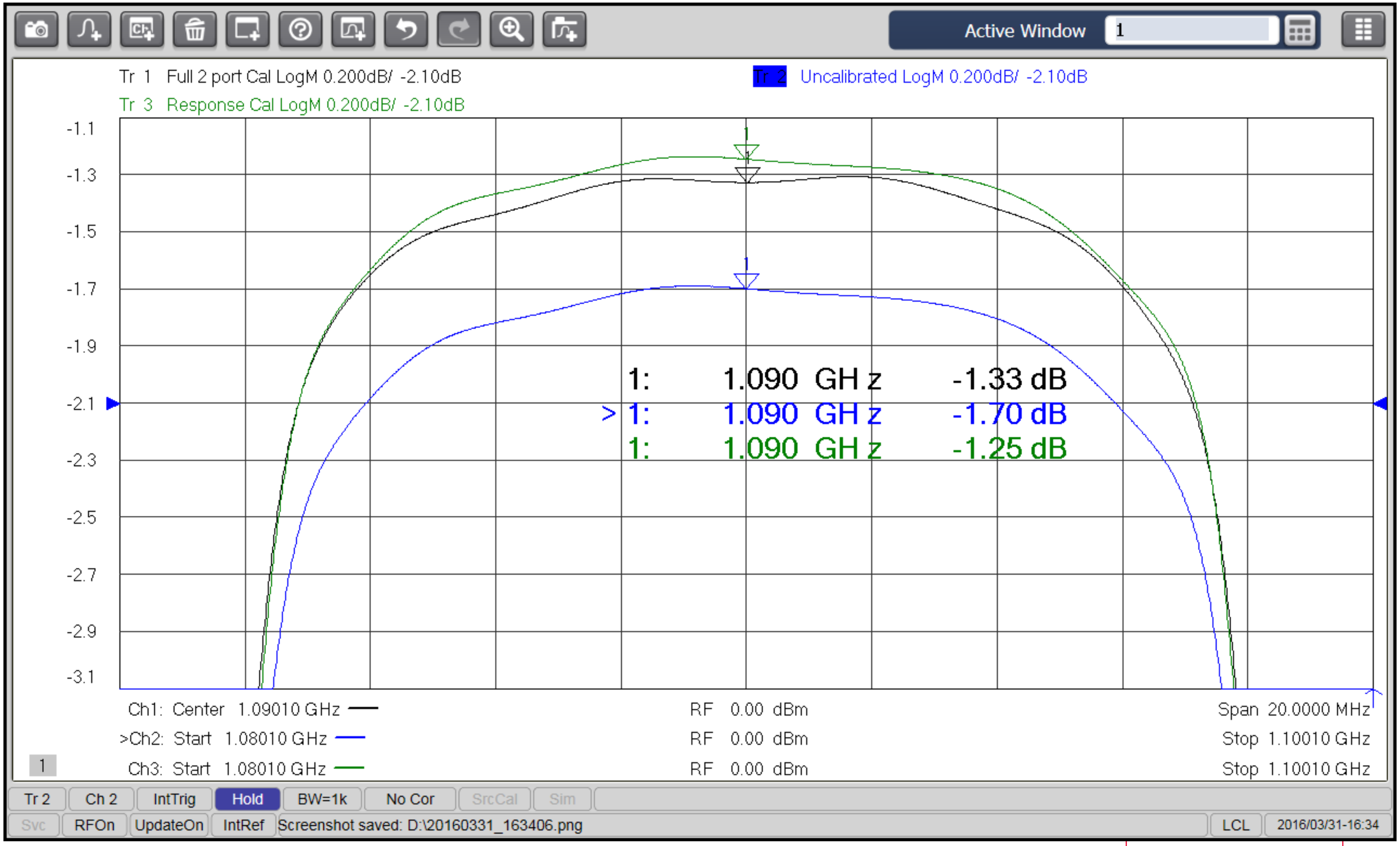
- Combines response and 1-port
- Corrects source match for transmission measurements

KEYSIGHT TECHNOLOGIES

Demonstration

VNA showing Band Pass Filter

Uncalibrated, Response Cal and Full 2 port calibration



Wrap-Up

– Transmission Lines

– S-Parameters

– The Smith Chart

– Network Analysis Measurements

– Calibration and Error Correction

The End

For more information,
www.keysight.com/find/na